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Damage Detection and Suppression System of CFRP Laminates with FBG Sensor and SMA Actuator

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In this research, a small-diameter fiber Bragg grating (FBG) senor and a shape memory alloy (SMA) foil were embedded into carbon fiber reinforced plastics (CFRP) cross-ply laminates. Since the form of reflection spectrum from the FBG sensor is very sensitive to non-uniform strain distribution, the occurrence of damages in the laminates can be detected by the FBG sensor. On the other hand, when the pre-strained SMA foil is heated, shape memory effect produces compressive stress (recovery stress) to suppress the occurrence and progress of damages. The recovery stress of SMA can be actively controlled by ohmic heating. Thus the damages in the laminates can be suppressed by the SMA actuator. Based on these techniques, a smart composite with damage detection and suppression system was constructed.
Key words: Fiber Bragg Grating, Shape Memory Alloys, CFRP, Crack Detection, Crack Suppression

1. Introduction

While CFRP composites have high specific strength and specific modulus, there is the possibility that they are fractured at lower stress than the potential strength and may cause serious accidents, depending on the progress of internal damage. Thus the applications of CFRP are restricted in many cases. For the widen application of CFRP, it is necessary to clarify the mechanism of fracture and to construct smart composites that have damage detection and suppression system.

Smart composites are the composite materials possessing the functions that living things have, such as self-restoration and self-diagnosis. In order to realize the smart composites, three fundamental elements are required: the first one is a sensor detecting environmental changes, the second one is an actuator adapting the structure for the changes, and the third one is a processor controlling the actuator optimally according to the information from the sensor.

In this research, the authors attempted to construct the damage detection and suppression system using a small-diameter FBG and a SMA foil as a sensor and an actuator, respectively.

2. FBG Sensor

A FBG sensor consists of a periodic refractive index change formed in the core of an optical fiber as shown in Figure 1. When a broad-band light propagates to the FBG sensor, only the component at Bragg wavelength λ_0 corresponding to the grating period and the refractive index is reflected. When the sensor is under strain, the Bragg wavelength λ_0 shifts. From the amount of the shift, the strain can be evaluated quantitatively.

Generally FBG sensors are used for the measurements of strain or temperature that is almost uniform in the gage length of the sensors. Meanwhile, when the non-uniform strain is applied to the FBG sensor, both of the grating period and refractive index also become non-uniform. Thus various wavelength components are reflected from the FBG. Consequently the form of the reflection spectrum is distorted and the width of the spectrum increased[1] as schematically shown in Figure 1.

In this research, a small-diameter FBG sensor (Hitach Cable Ltd.) whose outside diameter was 52μm was embedded in the 0° ply of a CFRP cross-ply laminate for the detection of transverse cracks in the 90° ply. When the transverse cracks in the 90° ply induce the non-uniform strain distribution in the 0° ply, the form of the reflection spectrum changes. Thus the occurrence of the cracks can be detected.

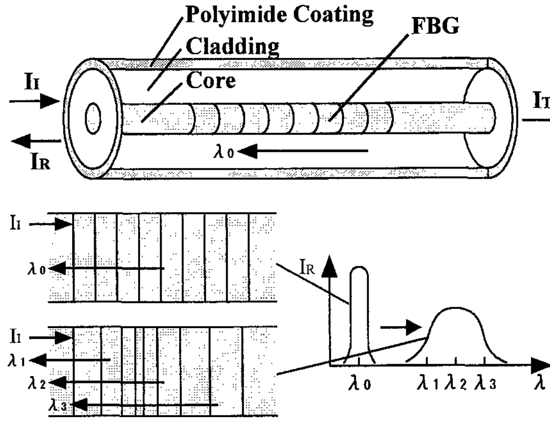

Figure 1 Schematic of FBG sensor.

3. SMA Actuator

SMA has shape memory effect. Even if plastic strain is applied to the SMA at room temperature, the plastic strain can be released by heating as shown in Figure 2. Taking advantage of the effect, the SMA foils were used as an actuator in this research.

Though many researches about composites with embedded SMA fibers have been reported, the effect of SMA is estimated small because the volume fraction of SMA fibers to the composite laminate is small. On the other hand, SMA foils have larger volume than SMA fibers and can be embedded easily in laminates.

In this research, Ti-50.2%Ni foils (Furukawa Electric Co. Ltd.) whose thickness is 0.04mm were used as SMA foils. The surfaces of the foils were treated with 10%NaOH anodic oxidation. The treatment improved the adhesion performance to the resin of CFRP laminates[2].

First, tensile plastic strain was applied to the SMA foil beforehand at room temperature. The plastic strain given by this process is called pre-strain. Then, the pre-strained SMA foil was embedded between two 90° plies of CFRP. When the SMA foil embedded into the laminate is heated, the shape memory effect produces compressive stress instantaneously. It is called recovery stress. The recovery stress is generated along the longitudinal direction so that it closes the transverse cracks in 90° ply. Hence the occurrence and progress of damages can be suppressed[3].

Furthermore, since the electric resistance of the SMA is comparatively high, ohmic heating of the SMA is possible. Thus, recovery stress can be controlled by the adjustment of an electric current. This characteristic is also suitable for smart composites.

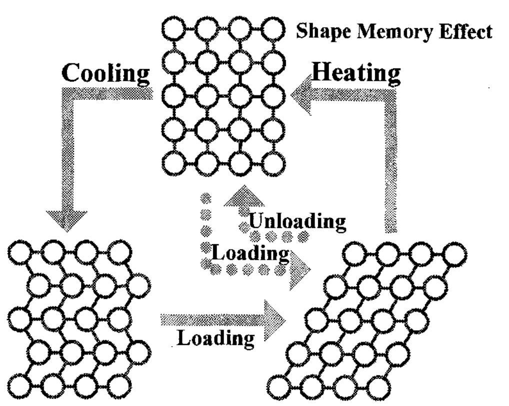

Figure 2 Schematic of shape memory effect.

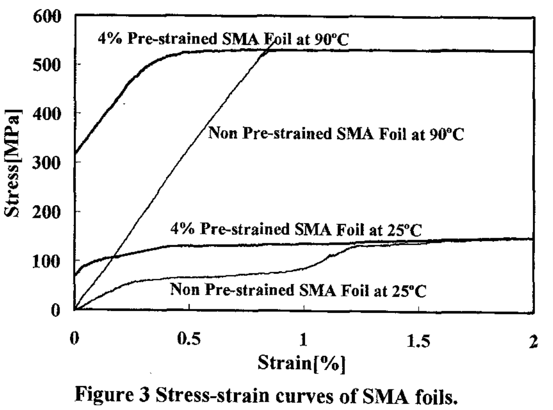

Figure 3 Stress-strain curves of SMA foils.

Figure 3 shows stress-strain curves of the SMA foils that were pre-strained by 4% or non pre-strained. The specimens of 4% pre-strained SMA foils were pre-strained at room temperature and then heated for two hours at 180°C that is curing temperature of the CFRP laminates. Thus the SMA foils embedded into laminates behave following these stress-strain curves. 4% pre-strained SMA foils generated the residual stress after cooling from 180°C to room temperature. Consequently, 4% pre-strained SMA foils have different hysteresis curves from those of non pre-strained SMA foils, and the 4% pre-strained SMA foils store more strain energy than the non pre-strained ones.

4. Experiments

Three types of experiments were conducted in this research. Load Frame 5582 (Instron Corporation) was used as the testing machine.

First, loading-unloading tests at 25°C and 90°C were performed for three types of laminates: CFRP cross-ply laminates without SMA foils, the laminates with non pre-strained SMA foils, and the laminates with 4% pre-strained SMA foils. The tests at 90°C were performed in thermostatic chamber. From the comparison of the results, it was confirmed whether the recovery stress of the SMA suppressed crack occurrence and progress.

Second, loading-unloading tests were performed for CFRP cross-ply laminates with SMA foils at 90°C using ohmic heating for the control of temperature. These tests revealed that ohmic heating could be applied appropriately to SMA foils.

At last, tensile tests were performed for a CFRP cross-ply laminate that had both a SMA foil and a small-diameter FBG sensor. At 25°C, the specimen was loaded until FBG sensor detected the first crack in 90° ply. After unloading, the specimen was loaded at 90°C similarly and the form of the reflection spectrum was compared with that at 25°C. This observation clarified the recovery stress effects on damage suppression.

4.1 Loading-unloading Tests at 25°C and 90°C

4.1.1 Specimens

The dimensions of the specimens are 150mm long and 15mm wide. Three types of laminates were prepared as follows.

CF : [0/90]s
SMA0% : [0/90/ad/non pre-strained SMA/ad/90/0]
SMA4% : [0/90/ad/4% pre-strained SMA/ad/90/0]
ad : adhesive sheet, 0.125mm thickness
SMA : Ti-50.2%Ni foil, 0.04mm thickness
0/90 : CFRP T300/F593, 0.4mm thickness

4% pre-strained : Before embedment, pre-strain of 4% was applied to the SMA foils in the longitudinal direction. It was expected that the compressive recovery stress appeared at 90°C.

4.1.2 Method

Tensile loading-unloading tests were performed at 25°C and 90°C. The loading speed was 0.5mm/min. The temperature was controlled with a thermostatic chamber. Loading and unloading were repeated and transverse cracks in the 90° ply were observed at the edge surface of the specimen.

4.1.3 Results

Figure 4(a) and Figure 5(a) show the results at 25°C. CF, SMA0%, and SMA4% have the same tendency of the increase in the crack density. This result reveals that the SMA embedded into the laminates do not deteriorate the mechanical properties of the laminates. Meanwhile, Figure 4(b) shows that the first crack strain of SMA4% is 0.4% larger than that of CF at 90°C, and Figure 5(b) shows that the first crack strain of SMA4% is 0.1% larger than that of SMA0%. These results reveal that not only the difference of the laminate constitutions but also the effect of recovery stress suppress the damages.

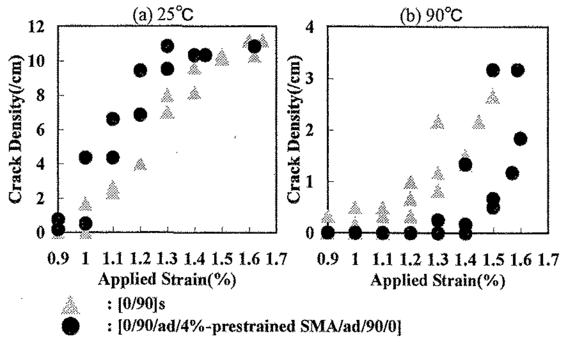

Figure 4 Comparison of transverse crack density in 90° ply between CF and SMA4%.

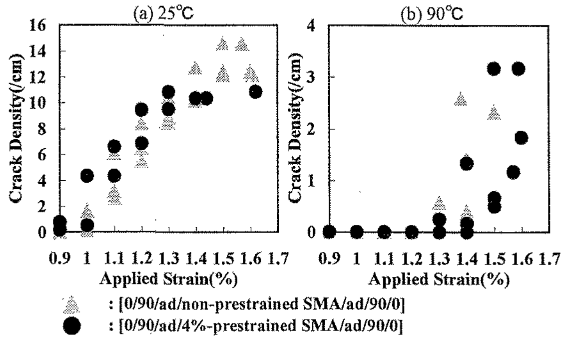

Figure 5 Comparison of transverse crack density in 90° ply between SMA0% and SMA4%.

4.2 Loading-unloading Tests with Ohmic Heating

4.2.1 Specimens

Two types of specimens were prepared as follows.

SMA0% : [0/90/ad/non-prestrained SMA/ad/90/0]
SMA4% : [0/90/ad/4%-prestrained SMA/ad/90/0]

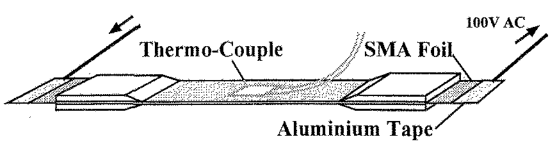

Figure 6 Schematic of the specimen with ohmic heating.

4.2.2 Method

Tensile loading-unloading tests were performed at 90°C. Temperature was controlled using ohmic heating. The ohmic heating was carried out by passing the AC current through SMA foils. Temperature controller controlled the AC current and set SMA foils to 90°C within only a few seconds.

Loading and unloading were repeated and transverse cracks in 90° ply were observed from the edge surface of the specimen.

4.2.3 Results

Figure 7 shows the results obtained with thermostatic chamber and those with ohmic heating. The tendency of the increase in the transverse crack density with ohmic heating is almost the same as that with thermostatic chamber. These results reveal that ohmic heating can be applied to SMA appropriately and SMA foils have sufficient capacity of an actuator driven by electric current.

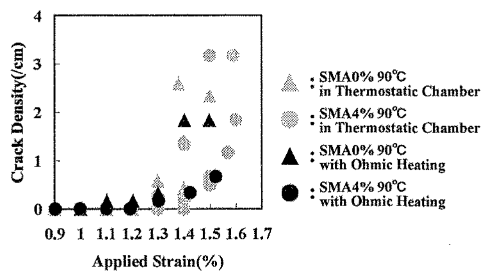

Figure 7 Comparison of crack density in 90° ply between thermostatic chamber and ohmic heating.

4.3 Tensile Tests for The Laminates with FBG Sensor and SMA Actuator

4.3.1 Specimen

The laminate configuration was [0/90/ad/4% pre-strained SMA/ad/90/0] and a small-diameter FBG sensor was embedded in the 0° ply to be parallel to the carbon fibers for the protection of the optical fiber from the breakage caused by the occurrence of transverse cracks in the 90° ply. In order to avoid the transverse compression load on the embedded optical fiber under tabs when the specimen is held in a testing machine, the optical fiber penetrates through the 0° ply perpendicular to the surface of the specimen as shown in Figure 8.

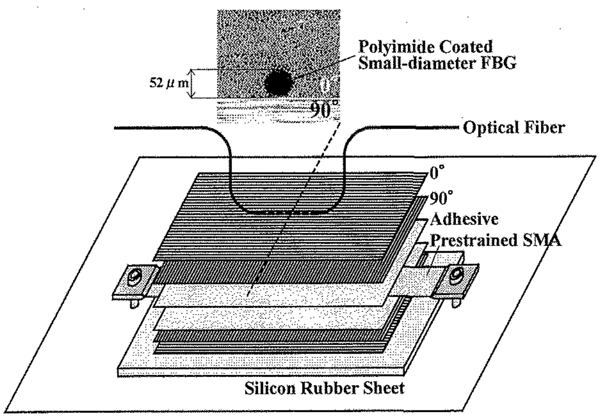

Figure 8 Hot-press fabrication of the specimen with an embedded FBG sensor and a pre-strained SMA foil.

4.3.2 Method

Reflection spectra were measured before and after the embedding of the FBG sensor. Then, tensile test was performed at 25°C and the reflection spectra were measured at various levels of tensile strain. The specimen was loaded until a transverse crack appeared in 90° layer. The crack appearance and location were observed with digital microscope VH-Z450 (Keyence Corporation). After unloading, the specimen was loaded again at 90°C in the thermostatic chamber. Also the reflection spectra were measured at various levels of tensile strain.

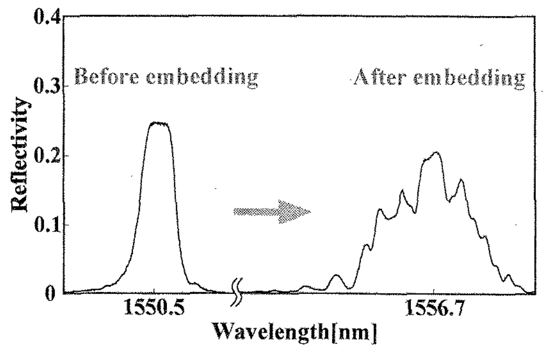

Figure 9 Reflection spectra measured before and after the embedding of the FBG sensor.

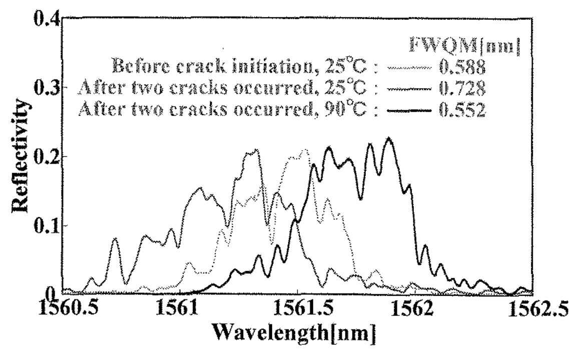

Figure 10 Reflection spectra measured before and after the occurrence of cracks.

4.3.3 Results

Figure 9 shows the reflection spectra measured before and after the embedding of the FBG sensor into the laminate. The width of the reflective spectrum increased after the embedding. That may be due to thermal residual strain of the CFRP laminate and non-uniform recovery stress of the SMA. When SMA foils were pre-strained by testing machine, non-uniform strain was remained in SMA foils because of unstable martensitic transformation of SMA. This non-uniform pre-strain caused non-uniform recovery stress in SMA foils.

Figure 10 shows the comparison between the reflection spectrum measured before crack initiation in 90° ply and that after the appearance of two cracks in the gage length of the FBG sensor at the applied strain of 0.4%. FWQM means the full width at quarter maximum of the spectrum. It was reported that FWQM was a good indicator to evaluate the transverse crack density[4]. The FWQM increased after the crack occurrence at 25°C. However, the FWQM decreased after the laminate was heated to 90°C and became close to the FWQM measured before crack occurrence. This is because the non-uniform strain distribution around the transverse crack returned to uniform strain distribution before crack occurrence. The recovery of the strain distribution is caused by the effect of the relief of residual stress owing to heating and the compressive recovery stress of SMA.

5. Conclusions

Loading-unloading tests were performed for CFRP cross-ply laminates with pre-strained SMA foils and that with non pre-strained SMA foils. The first crack strain of the specimens with pre-strained SMA foils was larger than those with non pre-strained SMA foils. Through these tests, it was found that the recovery stress of SMA potentially had damage suppression effect.

Then, ohmic heating was performed by passing AC current through SMA foils. The results showed that recovery stress of SMA could be controlled by electric current.

At last, tensile tests were performed for a specimen in which a FBG sensor and a SMA foil were embedded. The FWQM increased after the crack occurrence at 25°C. However, the FWQM decreased after the laminate was heated to 90°C and became close to the FWQM measured before crack occurrence. This is due to the effect of the relief of residual stress owing to heating and the compressive recovery stress of the SMA.

The cracks could be detected by using a FBG sensor that was very sensitive to non-uniform strain distribution. Also the cracks could be suppressed by using a SMA actuator whose recovery stress could be controlled by electric current. Consequently, it could be concluded a smart composite that had damage detection and suppression system was constructed.

7. References

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