Transactions of the Materials Research Society of Japan 28 [3] 683-686 (2003)

Smart Composite Materials By Using SMA (Shape Memory Alloy) Strain Sensor

Ryutaro Oishi, Hideki Nagai, Ya Xu, and Hitoshi Yoshida
for the Integration Process Team
at the Smart Structure Research Center,
National Institute of Advanced Industrial Science and Technology,
Tsukuba, Ibaraki, Japan
Fax 81-298-61-3126, e-mail: r-oishi@aist.go.jp

Composite materials, such as CFRP (Carbon Fiber Reinforced Plastics) with embedded SMA (Shape Memory Alloy) wires, have widely been studied for damage control. In this case, the SMA wires are used as an actuator to suppress propagating damages or to control damages. We have studied to use the SMA wires as a strain sensor to estimate damages of composite materials for constructing multi-functional SMA (sensor and actuator material).

Keywords: Shape Memory Alloy(SMA), Smart Structure, Strain Sensor

I. INTRODUCTION

Composite materials, such as a CFRP (Carbon Fiber Reinforced Plastics) plate with embedded SMA (Shape Memory Alloy) wires, have widely been studied for damage control [1, 2]. In this case, the embedded SMA wire is used as an actuator in order to suppress propagating damages by generating force due to its phase transformation. We intend to use the embedded SMA wires as both a strain sensor and an actuator, in order to estimate (or monitor) damages and to control damages, respectively. The SMA wire becomes to have multi-functions (sensor and actuator functions), that is a direction of "smart structure" with a processor for self-damage control and self-damage monitoring.

In general, an amount of damages in materials is related with strain. We have already obtained the correlation between the number of transverse cracks and the strain for a CFRP plate in Fig. 1 [3], where the number of transverse cracks corresponds to the amount of damages for the case. Strain is an index for damage monitoring of materials. The strain of a matrix can be estimated from an electric resistance change of an embedded SMA wire in composite materials as described in this article. Usually, strain is measured by additional embedded fiber Bragg grating (FBG) sensors [4] or sticking strain gauges. For strength of composite materials, however, it needs to be reduced the number of materials to be embedded as throughly as possible. Multi-functional material, such as an SMA wire which acts as both an actuator and a strain sensor, is valid for reducing the number of embedded materials.

There are some advantages and disadvantages for using the embedded SMA wires as both an actuator and a sensor for damage control and damage estimating/monitoring. We listed the advantages of the SMA strain sensor as follows:

- It can reduce the number of embedded materials to monitor damages for strength of composite materials.
- It can monitor strain or estimate damages in a large region by using an SMA wire.
- It is a simple mechanism.

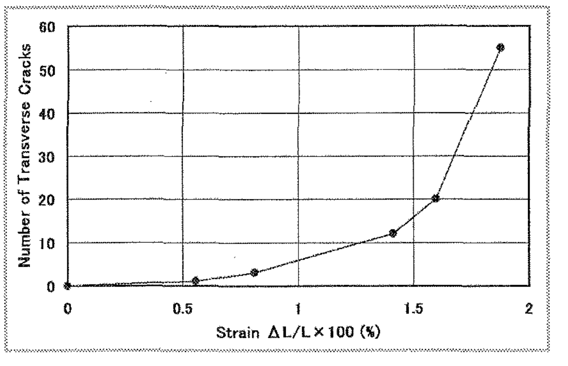

FIG. 1: The correlation between the number of transverse cracks and the strain for a CFRP plate. The number of transverse cracks corresponds to the amount of the damages for the CFRP plate case. This plot is taken from the reference [3].

The disadvantages are listed as follows:

- It is not so precise sensor rather than other strain sensors such as FBG sensors or usual strain gauge sensors.
- It is not a direct damage monitoring through strain.

To establish a damage estimating/monitoring by using an SMA wire, there are mainly two relations, one is a relation between an amount of damages and strain on materials, another is a relation between an electric resistance change and strain on embedded SMA wires. These relations connect an amount of the damages with the electric resistance change through strain, and provide to estimate damages by monitoring the electric resistance.

In this article, we concentrated to measure the relation between electric resistance of an SMA wire and strain on composite materials. In section II, the experimental setup to measure the electric resistance of an SMA wire is described. The measurement of the electric resistance is described in section III. The electric resistance of an SMA wire depends on strain as well as on temperature. The temperature dependence of the electric resistance change, which is unnecessary for the strain measurement, is needed to be eliminated. The electric resistance change due to a temperature change was compensated, which is described in section IV. In section V, we confirm that the temperature dependence can be reduced by the compensation method, and we show a possibility to use an embedded SMA wire as a strain sensor in order to estimate/monitor an amount of material damages. In section VI, we conclude our research about an SMA strain sensor for damage monitoring of composite materials.

II. APPARATUS

As SMA wire, Ti-Ni alloy with the composition of Ti-50 at.% Ni was used in this experiment. The diameter of the SMA wire is 0.4mm, and its the phase transformation temperature starting from the Austenite to the Martensite phase (from the Martensite and the Austenite phase) is 37°C (55°C), which was measured by a Differential Scanning Calorimeter. As a matrix of a composite material, GFRP(Glass Fiber Reinforced Plastics) prepreg with size of 180mm×20mm×3mm was used. The laminate configuration is cross-ply $[0_3/90_2/0_3]_{1S}$, where the SMA wire was embedded in the middle layer with the same direction of the glass fiber. The SMA/GFRP composites were fabricated by hot pressing at 130°C for 2 hours with a pressure of 0.3MPa. The embedded wire was well bonded with the GFRP plate. The interface shear stress of 0.02MPa was obtained from a pull-out test without splipping.

The illustrated figure of the electric resistance measurements is shown in Fig. 2-a). The electric resistance was measured by a multi-meter(IWATSU VOAC7513). Copper wires with a diameter of 1mm were used for the connection between an SMA wire and the multi-meter. The SMA wire and the copper wire were fixed by screws on a copper plate which is shown in Fig. 2-b). The electric resistance of the copper wires was measured and has been subtracted from the measured electric resistance. For a case of a composite material with embedded SMA wires, the strain of the composite material was measured by a strain gauge (KYOWA KFRP-5-120-C1-1L1M2R) which was sticked on the surface.

III. ELECTRIC RESISTANCE CHANGE VS. STRAIN FOR AN SMA WIRE

We measured an electric resistance of an SMA wire as a function of the strain. In this case, the SMA wire is not embedded into a material in order to simplify and to check if an SMA wire can be used as a strain sensor. The electric resistance change ($\Delta R/R$) was calculated by

$$\frac{\Delta R}{R} = \frac{R_S - R_{S0}}{R_{S0}} = \frac{\Delta R_S}{R_{S0}}, \quad (1)$$

where R_S is a measured electric resistance which varies with the strain, and R_{S0} is an electric resistance without strain which is a normalized constant. Figure 3 shows the measured electric resistance change as a function of the strain ($\Delta L/L$), where the strain was calculated from the position of the tensile machine cross-head. We obtained the almost linear relation between $\Delta R/R$ and $\Delta L/L$ on an SMA wire. From the relation, we found that the strain, which is related to an amount of damages, can be estimated from the electric resistance change of an SMA wire.

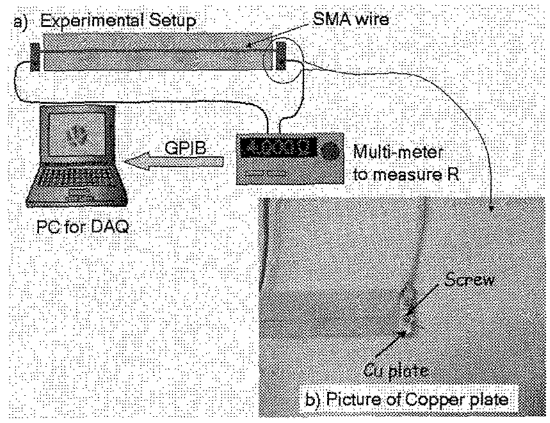

FIG. 2: a) Illustrated figure of the experimental setup to measure the electric resistance of an SMA wire, b) picture of the copper plate to connect between an SMA wire and a copper electric cable.

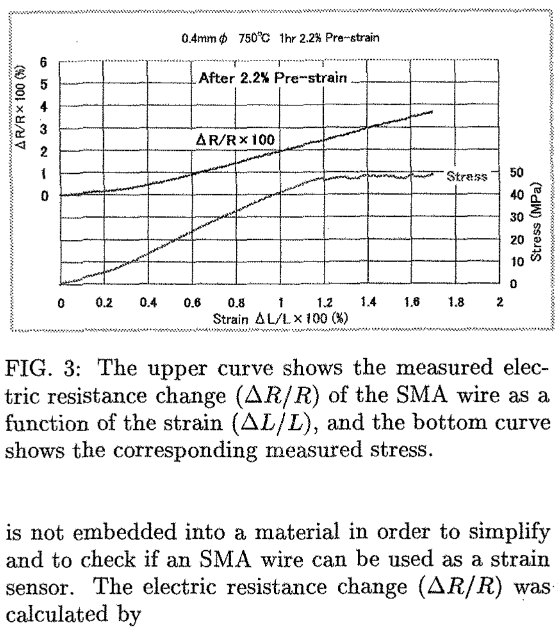

FIG. 3: The upper curve shows the measured electric resistance change ($\Delta R/R$) of the SMA wire as a function of the strain ($\Delta L/L$), and the bottom curve shows the corresponding measured stress.

IV. COMPENSATED $\Delta R/R$

The electric resistance of an SMA wire depends on temperature, therefore, the electric resistance change of an SMA wire (sample wire) contains a temperature dependence term of

$$\frac{\Delta R_T}{R_T} = \beta \Delta T \tag{2}$$

as well as a strain dependence term of $\Delta R_L/R_L$, where ΔT is a temperature change and β is the temperature coefficient. The electric resistance change of the sample wire (R_S) is represented as

$$\frac{\Delta R_S}{R_S} = \frac{\Delta R_T}{R_T}\frac{\Delta R_L}{R_L} = (\beta\Delta T)\frac{\Delta R_L}{R_L}. \tag{3}$$

The temperature dependence term of $\beta\Delta T$ is unnecessary for strain measurement. We extract the strain dependence term in Eq.(3) by compensating the temperature dependence. For the compensation, we used another SMA wire (reference wire) which is strain-free. The electric resistance change of the reference wire depends only on temperature, which is expressed by

$$\frac{\Delta R_R}{R_R} = \beta \Delta T. \tag{4}$$

Using the sample and reference wires, a compensated electric resistance change is calculated by

$$\frac{\Delta R}{R} \equiv \frac{\Delta R_S/R_S}{\Delta R_R/R_R} = \frac{(\beta\Delta T)\Delta R_L/R_L}{(\beta\Delta T)}. \tag{5}$$

The strain dependence term of $\Delta R_L/R_L$ remains, and the temperature dependence term of $\beta\Delta T$ is canceled in Eq.(5).

We experimentally checked that the compensation method worked well by using two SMA (sample and reference) wires. The reference wire was fixed, and the sample wire was provided tension in a thermostatic device. We measured the relation between $\Delta R/R$ and $\Delta L/L$ consecutively at the temperatures of 22°C, 12°C, 3°C and 31°C, which is shown in Fig. 4. In this figure, the non-compensated $\Delta R/R$ (the upper 4 curves) and the compensated $\Delta R/R$ (the bottom curve) are shown. The baselines of the non-compensated $\Delta R/R$ at each temperature are shifted into the vertical direction, which is the temperature dependence of the relation between $\Delta R/R$ and $\Delta L/L$. By using the compensated method, the temperature dependence is canceled, namely, the baseline shift is not seen, which is shown as the bottom curve in Fig. 4. The compensated method works well for SMA wires in a wide temperature range.

V. SMA $\Delta R/R$ IN COMPOSITE MATERIALS

We confirmed that an SMA wire alone could be used as a strain sensor as described in the previous sections. We experimentally confirm that the embedded SMA wire in the composite material of the SMA wire and the GFRP plate also have the similar relation between $\Delta R/R$ and $\Delta L/L$. We measured the relation between $\Delta R/R$ of the embedded SMA wire and $\Delta L/L$ of the matrix (GFRP).

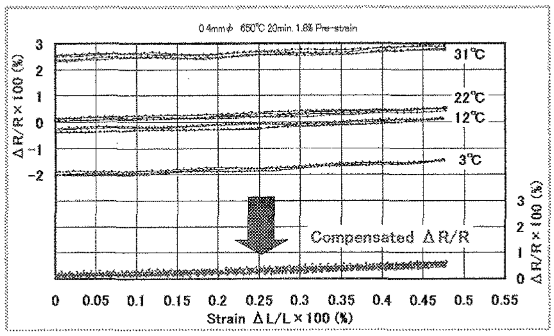

FIG. 4: The temperature dependences of the relation between $\Delta R/R$ and $\Delta L/L$ are shown, The upper 4 curves show the non-compensated $\Delta R/R$ at the temperatures of 22°C, 12°C, 3°C and 31°C. The bottom curve shows the temperature compensated $\Delta R/R$ at the temperatures. By the compensation, the upper 4 curves are merged into the bottom curve.

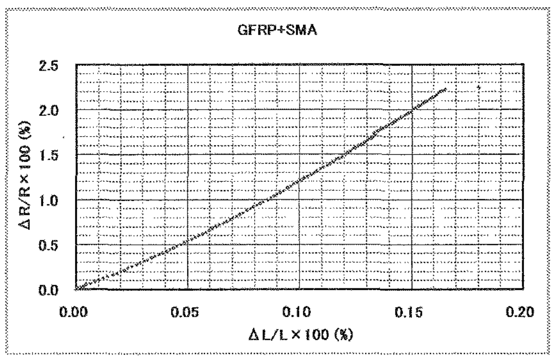

FIG. 5: The measured electric resistance change of the embedded SMA wire in the GFRP plate ($\Delta R/R$) is shown as a function of the strain ($\Delta L/L$).

A sample SMA wire with a diameter of 0.4mm was embedded into a GFRP plate with the size of 180mm×20mm×3mm. A reference SMA wire of the same diameter was put on the surface without influence of the matrix strain. We sticked a strain gauge (KYOWA KFRP-5-120-C1-1L1M2R) on the plate to measure the strain of the composite material plate. We measured the similar relation for the GFRP plate, which is shown in Fig. 5.

To check the temperature compensation for the composite material (GFRP) case, we consecutively measured the relation between $\Delta R/R$ and $\Delta L/L$ at temperatures of 0°C through 30°C in the thermostatic device. The measured $\Delta R/R$ curves are shown in Fig. 6. In this figure, the upper three dotted lines show the relation for the non-compensated case, and the lower dotted line shows the ones for the compensated case. The temperature dependence, which is the baseline shift, is reduced by using the compensated $\Delta R/R$, however, the small baseline shift has been remained. That corresponds to be 0.4% change of the sample and the reference wire resistance ratio

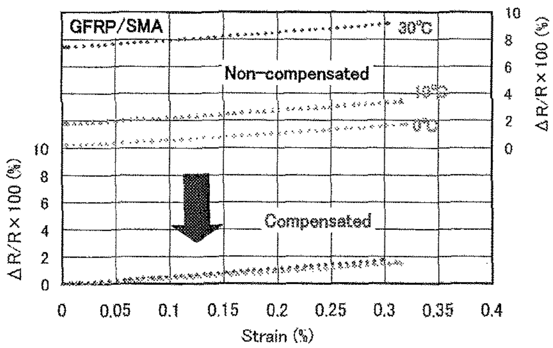

FIG. 6: The measured electric resistance changes ($\Delta R/R$) of the embedded SMA wire in the GFRP plate at the temperatures of 0°C, 10°C and 30°C are shown as a function of the strain. The upper 3 dotted lines and the lower dotted lines show the non-compensated $\Delta R/R$ and the compensated $\Delta R/R$ curves, respectively. The baseline shift due to the temperature dependence is reduced by the compensation.

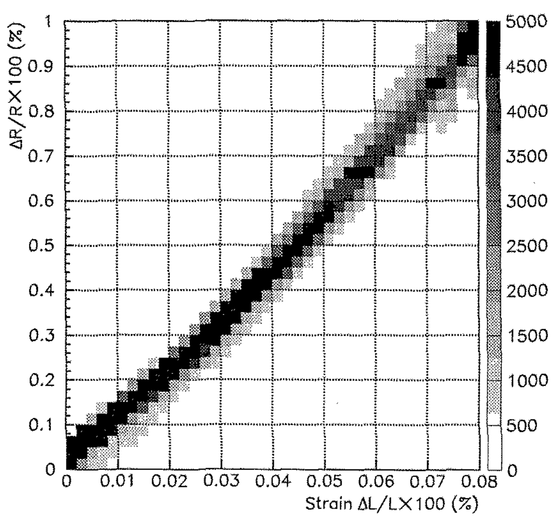

FIG. 7: Two dimensional histogram of the correlation between $\Delta R/R$ of the SMA wire and the strain of the matrix (GFRP) for 12000 cycle tensile tests in 12 days is shown. The contents of the histogram are represented as a shaded index on the left side of the plot.

at the temperatures of 0°C and 30°C. This remaining temperature dependence provides a dominant uncertainty on the strain measurement by using the SMA wire. The uncertainty ($\Delta\epsilon$) on the strain measurement (ϵ) is obtained to be $\Delta\epsilon = \pm 0.03\%$ in a temperature range from 0°C to 30°C, which corresponds to be $\Delta\epsilon = \pm 0.001\%/^\circ$C uncertainty.

We checked the reproducibility of the relation between $\Delta R/R$ and the strain of matrix (GFRP) at the room temperature around 20°C. The tensile stress of 12000 cycles in 12 days was provided to the GFRP/SMA composite material. During the tensile tests, we observed $\Delta R/R$ and the strain of the GFRP plate, and the relation between $\Delta R/R$ and the strain is shown in Fig. 7. From the measurement, the uncertainty of the strain measurement due to the reproducibility of 12000 cycle tensile tests is obtained to be $\Delta\epsilon = \pm 0.005\%$.

VI. CONCLUSIONS

To use embedded SMA wires in a composite material as a strain sensor for a damage estimating/monitoring, we measured the relation between the electric resistance change of the embedded SMA wire and the strain of the composite materials. We found the almost linear correlation between the electric resistance change and the strain. From the relation, we found that an amount of material damages can be estimated from the measured electric resistance change through the strain. The temperature dependence on the strain measurement was compensated, however, the small dependence has been remained. This remaining temperature dependence provides a dominant uncertainty on the strain measurement, which is $\Delta\epsilon = \pm 0.03\%$ in the temperature range from 0°C to 30°C, which corresponds to $\Delta\epsilon = \pm 0.001\%/^\circ$C uncertainty. The uncertainty due to the reproducibility of the relation between $\Delta R/R$ and the strain is obtained to be $\Delta\epsilon = \pm 0.005\%$.

Acknowledgments

We thank the Smart Structure Research Center staff for their vital contributions. This work was supported by the Ministry of Economy, Trade and Industry of Japan; Japan Science and Technology Corporation.

[1] J.A. Balta, M. Parlinska, V. Michaud, R. Gotthardt and J.A.E. Manson, Mat. Res. Soc. Symp. Proc. Vol. 64, 141, 2000.

[2] B.K. Jang, N. Toyama, J.H. Koo and T. Kishi, Int. J. of Mat. and Pro. Tech. 16, 1-3, 117, 2001.

[3] B.K. Jang *et al.*, Proceedings of SPIE, Vol. 4699, 182-190.

[4] Y. Okabe, S. Yashiro, T. Kosaka and N. Takeda, Smart Mater. Struc. 9, 832, 2000.

(Received December 21, 2002; Accepted Febuary 19, 2003)