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Mechanical Properties of Wavy SMA Fiber Reinforced Smart Composite

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It is well known that the residual stress of composite influences the mechanical properties of the composite. If the composites are reinforced by the shape memory alloy fiber that shrinks in the matrix, the mechanical properties of composites will be improved significantly. In our previous study, we have reported the fabrication method and mechanical properties of a straight Fe-28.2mass%Mn-6.0mass%Si-5.1mass%Cr shape memory alloy (SMA) fiber / plaster smart composite, which can be used in architectural and civil engineering applications. It was found that the bending strength of the composite increases with increasing level of pretensile strain in the straight SMA fiber. However, it was also found that imperfect bonding at interface between straight SMA fiber and plaster matrix reduced the strengthening effects. It is expected that replacement by wavy SMA fibers would enhance the macroscopic bonding strength. In this study, wavy Fe-Mn-Si-Cr SMA fiber reinforced smart composite is fabricated. For the mechanical property characterization, three-point bending test is performed. Based on the experimental results, potential applications of this smart composite are discussed.

Key words: smart material, shape memory alloy (SMA) composite, Iron-Manganese-Silicon-Chromium shape memory alloy, fiber, plaster, residual stress, three-point bending test

1. INTRODUCTION

It is widely recognized that the residual stress of composite, as well as volume fraction of reinforcement, influences the mechanical properties of the composite [1]. If the composites are reinforced by the shape memory alloy (SMA) fiber that shrinks in the matrix, the mechanical properties of composites will be improved significantly. Last few years, there has been much interest in developing SMA composites, particularly NiTi SMA fiber reinforced composites [2-6]. The motivation of our researches was to develop an SMA fiber / plaster composite [7,8], which will be commercially applicable for architectural and civil engineering materials applications. For this purpose, the NiTi SMA is not suited, since the NiTi SMA is unacceptably expensive.

It is also known that some Fe-Mn-Si alloys with suitable composition exhibit a good shape memory effect of a one-way type with the large temperature hysteresis [9]. Fe-Mn-Si alloys appear to be commercially applicable owing to their inexpensiveness and excellent workability. With addition of Cr, it is possible to achieve a good corrosion resistance, which enhances commercial significance to this type of alloy.

In Ref. [7], we have reported the fabrication method and mechanical properties of a straight Fe-Mn-Si-Cr SMA fiber / plaster smart composite, which can be used in architectural and civil engineering applications. It was found that the bending strength of the composite increases with increasing level of pretensile strain in the straight SMA fiber. However, earlier work has clearly shown that imperfect bonding at interface between straight SMA fiber and plaster matrix reduced the strengthening effects [7]. It is strongly suggested that the strengthening effects may be emphasized with increasing the macroscopic bonding strength at interface between SMA fiber and plaster matrix. It is expected that replacement by wavy SMA fibers would enhance the macroscopic bonding strength. Accordingly, in this study, an attempt was made to fabricate wavy Fe-Mn-Si-Cr SMA fiber reinforced smart composite. For the mechanical property characterization, three-point bending test is performed. Based on the experimental results, potential applications of this smart composite are discussed.

2. EXPERIMENTAL PROCEDURES

The fiber used in the present study is the Fe-28.2mass%Mn -6.0mass%Si -5.1mass%Cr SMA fiber, whose diameter is 1 mm. The fabrication process and the strengthening mechanism of a wavy Fe-Mn-Si-Cr SMA fiber reinforced smart composite are summarized in **Fig. 1.** The Fe-Mn-Si-Cr SMA fiber was sealed in an evacuated quartz capsule in the fiber holder with fixed rollers as shown in Fig. 1 (a). Shape memory treatment was given to the SMA fibers to memorize the wavy shape by heating up to 950 °C and keep it for 20 min, then followed by air cooling. The wavy SMA fibers were subjected to pretensile strain at room temperature (below the M_d temperature) using fiber holder with rotatable rollers (Fig. 1 (b)). The given overall prestrain is 3% in this study. The blueprints and photographs of the fiber holder with rotatable rollers can be seen in **Fig.2**. The wavy SMA fibers were then embedded into plaster plus water matrix (Fig. 1 (c)). Since the previous experiments were performed for 2.9 ~ 3.1 vol% SMA fiber reinforced composites [7, 8], the volume fraction of fiber is fixed to be 3.3. The

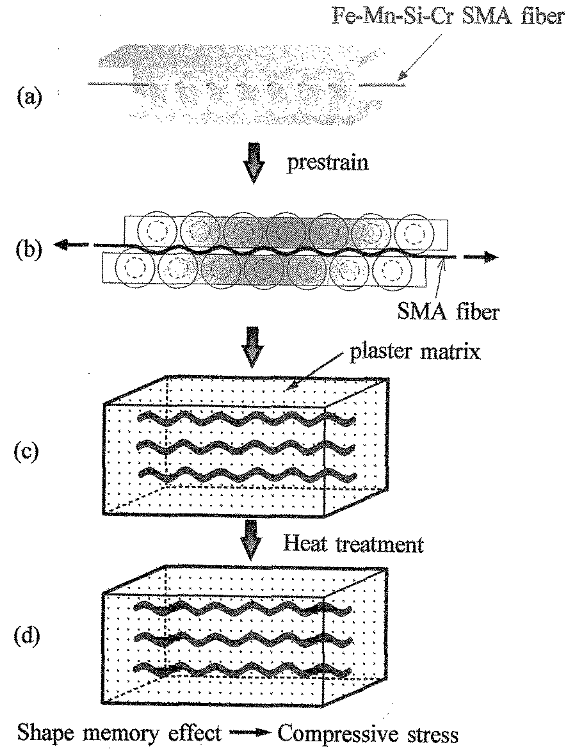

Fig. 1 Design concept of the wavy SMA fiber / plaster composite.

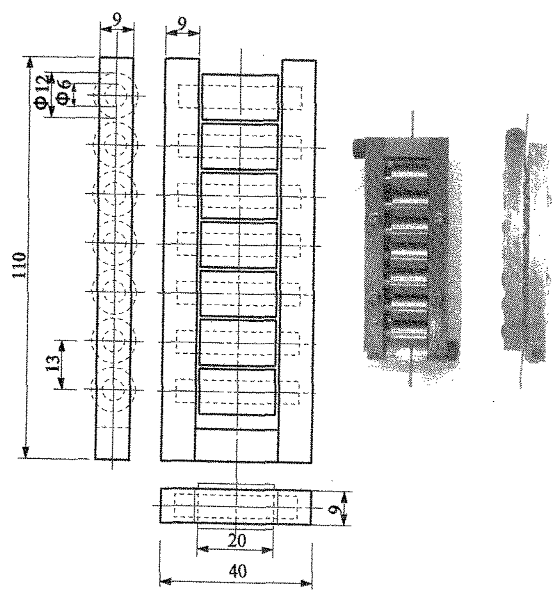

Fig. 2 Blueprints and photographs of the fiber holder with rotatable rollers.

dimensions of the specimen are shown in **Fig. 3**. Since the humidity and the temperature have effects on the setting of plaster [10], they were fixed to be 58 % and 20 °C, respectively [11], during the fabrication of composite. Specimens were dried at 20 °C for 2 days after solidification of the plaster matrix, and were kept in a dryer at 40 °C for 2 hours before the heat treatment. (Fabrication of a wavy SMA fiber / plaster composite) The wavy SMA fiber / plaster composite was heated to 250 °C (above A_s) to generate the compressive residual

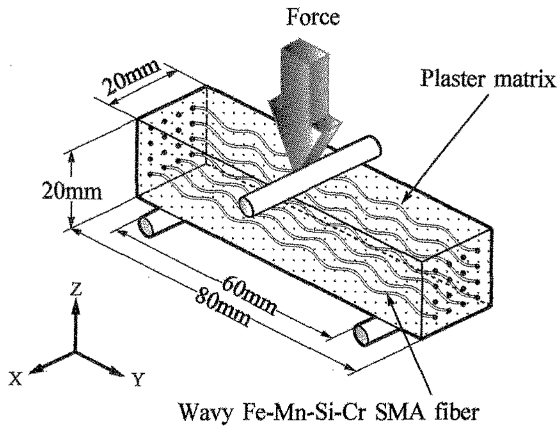

Fig. 3 The dimensions of the wavy SMA fiber / plaster composite.

stress in the matrix along the longitudinal direction of composite (Fig. 1 (d)).

Using a screw-driven test machine, a three-point bending test was conducted at a load displacement rate of 2 mm/min. The test span from the center to the outer load point was 30 mm, as also shown in Fig. 3. The number of bending tests was three. The details of test can be found elsewhere [7].

3. RESULTS AND DISCUSSION

3.1 Fracture behavior

Figure 4 shows macrographs of the wavy SMA fiber / plaster composites after three-point bending test. A typical macrograph of the plaster matrix without SMA fibers after three-point bending test is also shown in Fig. 4 [7]. It appears clearly that the plaster without SMA fiber shows brittle fracture, while the wavy SMA fiber / plaster composites show relatively ductile fracture.

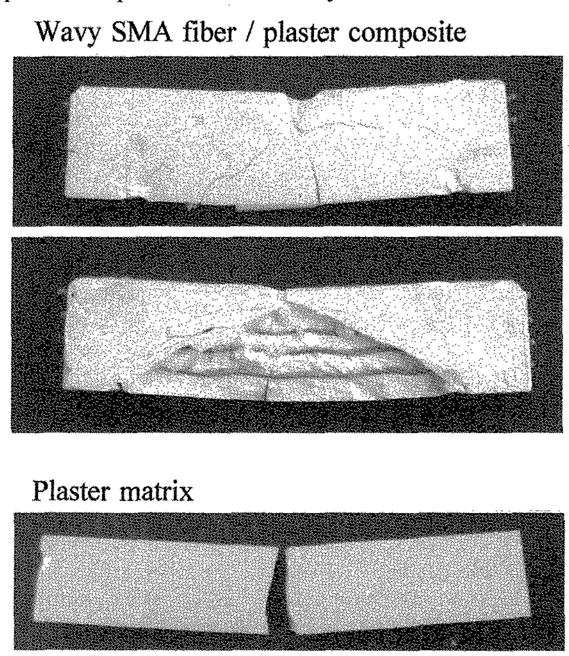

Fig. 4 Macrographs of the wavy SMA fiber / plaster composites and the plaster matrix without SMA fibers after three-point bending test.

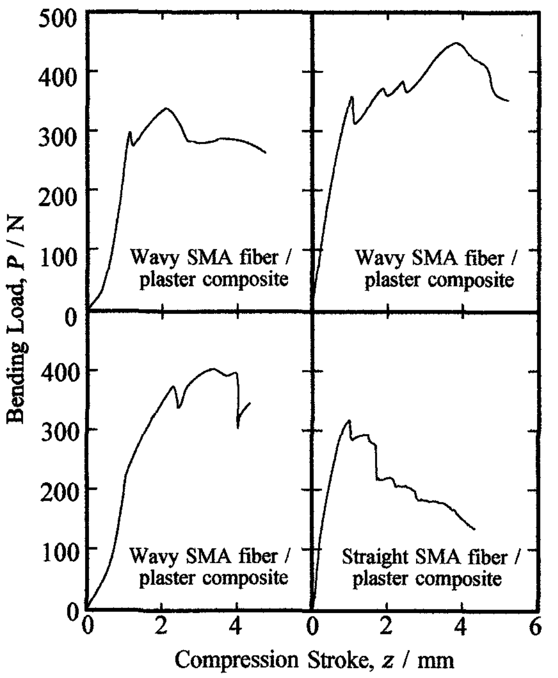

Fig. 5 Bending load *versus* compression stroke curves for the straight and wavy SMA fiber / plaster composites.

Bending load *versus* compression stroke curves for the wavy SMA fiber / plaster composites are shown in **Fig. 5**. A reference data form a straight SMA fiber / plaster composite is also seen in Fig. 5 [7]. It is seen from this figure, in case of straight SMA fiber / plaster composite, the bending load increases with increasing compression stroke up to about 1.0 mm, and then decreases. It is worthwhile to notice that the bending load of the wavy SMA fiber / plaster composite increases with increasing compression stroke up to about 1.0 mm, and then keeps its level. This difference will be discussed next.

3.2 Bending strength and deformation energy dissipation

Figure 6 shows the bending strength of the wavy SMA fiber / plaster composites, evaluated using the load-stroke curves shown in Fig. 5. Data form the plaster composite with 3 vol% straight SMA fiber is also seen in Fig. 5 [7] for comparison. From Fig. 6, it can be observed that there is no observable difference in bending strength between the straight and wavy SMA fiber / plaster composites. In this way, presently, we cannot found the effect of fiber shape on the bending strength of the SMA fiber / plaster composites.

Despite the fact that no remarkable difference was found in the bending strength between the straight and wavy SMA fiber / plaster composites, there was a notable difference in the deformation energy, as shown in Fig. 5. To discuss this phenomenon quantitatively, the energy of deformation until compression stroke becomes 4 mm, $E_{0\text{-}4}$, is calculated from following equation,

$$E_{0\text{-}4} = \int_{0\mathrm{mm}}^{4\mathrm{mm}} P dz \quad (1)$$

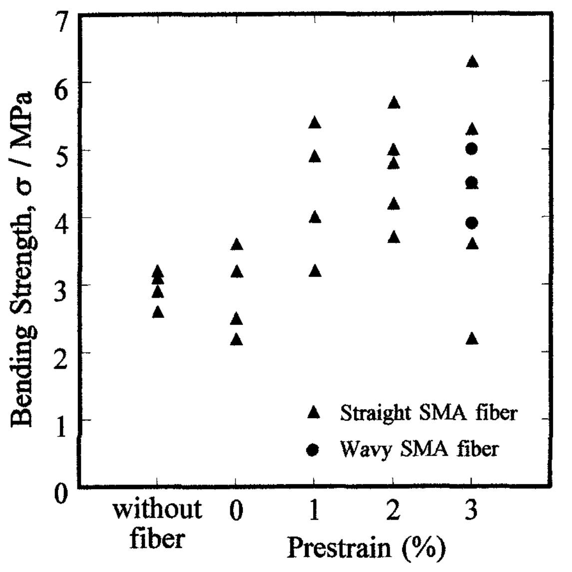

Fig. 6 Bending strength of the straight and wavy SMA fiber / plaster composites. The abscissa in this figure is the given prestrain.

where P is the bending load and z is the compression stroke. Deformation energy calculated by equation (1) represents the amount of deformation energy dissipated in the structure. **Figure 7** shows energy dissipation for the straight and wavy SMA fiber / plaster composites.
It is clear from this figure that the energy of deformation for the wavy SMA fiber / plaster composite is much larger than that for the straight SMA fiber / plaster composite. Thus, we can conclude that the shape of the SMA fibers plays an important role on improvement of the toughness of plaster. The observed variation in the fracture is likely to be due to the easier deformation in the wavy fibers. More experiments are required to discuss in detail, and will given in a future report.

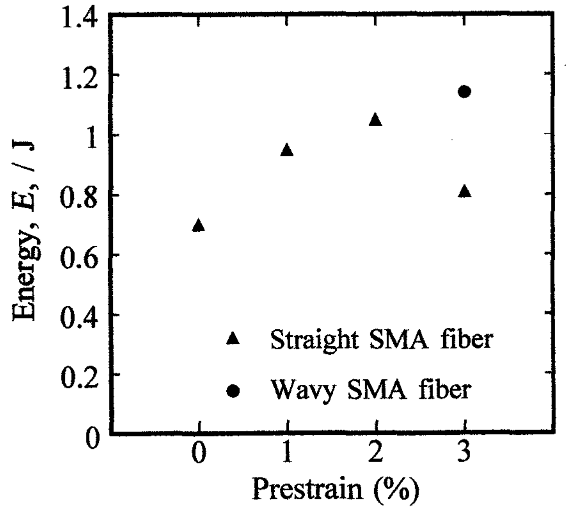

Fig. 7 Energy dissipation for the straight and wavy SMA fiber / plaster composites.

3.3 Advantages of wavy SMA fiber / plaster composite

In this study, it was found that the toughness of plaster was remarkably improved by reinforcing with the wavy SMA fibers. Since our purpose is to develop the wavy SMA fiber / plaster composites for practical engineering applications, the fabrication cost may be one of the most important issues. The cost of Fe-Mn-Si-Cr SMA fiber with 1.0mm diameter is 170 yen/m, whereas that of available NiTi SMA fiber is 1400 yen/m (without shape memory treatment) or 2200 yen/m (with shape memory treatment). In this way, the fiber used here is much less expensive than NiTi SMA fiber. Therefore, by using the Fe-Mn-Si-Cr SMA for reinforcement of wavy SMA fiber / plaster composites, we can provide a high toughness composite plaster for practical engineering applications at an acceptable cost.

4. CONCLUDING REMARKS

In this study, wavy Fe-Mn-Si-Cr SMA fiber reinforced smart composites were fabricated and bending tests were carried out. It was found that there is no observable difference in bending strength between the straight and wavy SMA fiber / plaster composites as far as present results show. In contrast, replacement by wavy SMA fibers was found to enhance the toughness of the plaster. We concluded that the shape of the SMA fibers plays an important role on improvement of the toughness.

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References

[1] K. Wakashima, Y. Suzuki and S. Umekawa, *J. Comp. Mater.*, **13**, 288-302 (1979).

[2] Y. Furuya, A. Sasaki and M. Taya, *Mater. Trans., JIM,* **34**, 224-27 (1993).

[3] Y. Yamada, M. Taya and R. Watanabe, *Mater. Trans., JIM,* **34**, 254-60 (1993).

[4] J. B. Berman and S. R. White, *Smart Mater. Struct.*, **5**, 731-43 (1996).

[5] G. Murasawa and K. Tohgo, *Trans MRS-J,* **26**, 163-66 (2001).

[6] T. Kobayashi, H. Toda and T. Hashizume, *Trans MRS-J,* **26**, 247-50 (2001).

[7] Y. Watanabe, E. Miyazaki and H. Okada, *Mater. Trans.*, **43**, 974-83 (2002).

[8] E. Miyazaki and Y. Watanabe, *Mater. Sci. Forum, accepted for publication.*

[9] A. Sato, E. Chishima, K. Soma and T. Mori, *Acta metal.*, **30**, 1177-83 (1982).

[10] P. Coquard, R. Boistelle, L. Amathieu and P. Barriac, *J. Mater. Sci.*, **29**, 4611-17 (1994).

[11] Y. Watanabe, A. Kawamoto and K. Matsuda, *Comp. Sci. and Tech.*, **62**, 881-88 (2002).

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