SMA HYBRID COMPOSITES:
SELF-HEALING, SELF- STIFFENING, AND SHAPE CONTROL SIMULATIONS

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Summary The design and simulation of SMA Reinforced Composites is investigated with particular attention to self-healing, adaptive stiffening and shape control functions. The two types of composites studied use SMA ribbons or wires inside a matrix material to create a self-healing material and a panel/beam with adaptive stiffening or shape control. Finite element analysis is used to simulate the structural response of the composites.

INTRODUCTION

The usage of shape memory materials has extended rapidly to many fields, including medical devices, actuators, composites, structures and MEMS devices. For these various applications, shape memory alloys (SMAs) are available in various forms: bulk, wire, ribbon, thin film, and porous. In this paper, we consider two different types of SMA Reinforced Composites: SMA wires in a low melting point metallic matrix for self-healing materials and SMA ribbons in a polymeric based composite panel/beam for adaptive stiffening or shape control via selective resistance heating. Here we present modelling considerations that are compared to experimental work [1,3,6]. To simulate the structural response of the SMA reinforced composites using finite element analysis, we develop an ABAQUS user element with an SMA constitutive law. Several examples are presented in which the critical design features and possibilities are highlighted. The modelling is introduced next followed by applications and simulations for specific types of composites.

CONSTITUTIVE MODEL AND FINITE ELEMENT IMPLEMENTATION

The Brinson one-dimensional constitutive model for SMA materials is used [4]. It separates the martensite volume fraction into temperature-induced (self-accommodated) and stress-induced (oriented) fractions.

$$\sigma = E\left(\varepsilon - \varepsilon_L \xi_d\right) + \Theta \Delta T \qquad \xi = \xi_d + \xi_t$$

The martensite transformation is determined by the loading path in a (σ-T) phase diagram (Figure 1a). Since the transformation is history-dependent, the kinetics are determined by using “switching points” ([5], Figure 1b).

$$\xi = F^A\left(Z^A;\xi_j\right) = \xi_j f^A\left(Z^A(T,\sigma;T_j,\sigma_j)\right)$$

FEA simulations were done with the ABAQUS code. To accomplish this, a user subroutine (UEL) was developed to incorporate the coupled SMA constitutive and kinetics models, including algorithms to handle complex overlapping transformation regions and compressive stress states. The UEL defines a one-dimensional truss which is suitable for SMA wires or ribbons.

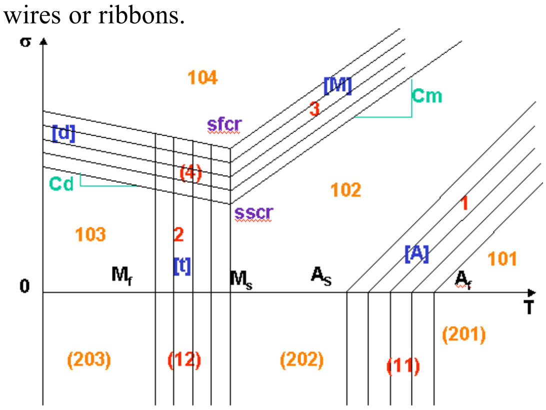

Figure 1a: Transformation phase diagram.

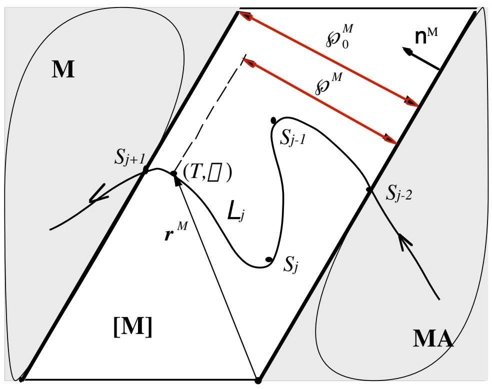

Figure 1b: loading path and switching points in a subregion.

SELF-HEALING MATERIAL

The self-healing metallic composite is composed of SMA wires in a tin-bismuth matrix material. In the situation that is analyzed, a crack develops in the matrix, perpendicular to the reinforcement wires. The SMA wires serve both to increase toughness of the material through “bridging” and also to initiate “healing” of cracks in the composite when heat is applied. “Bridging” can occur because martensite detwinning allows the SMA material to sustain large strains. If the cracked composite is heated above the austenite finish temperature, the SMA wires transform back to the shorter austenite form, pulling the cracked matrix back together. If the wires initially have some detwinned martensite, then transformation from the stress-induced martensite to austenite will cause a negative strain which has the effect of applying a positive closure force to the crack. The model is able to simulate crack opening, closing, and clamping, and the results can be used to guide the development of high performance NiTi based SMAs for use in composites.

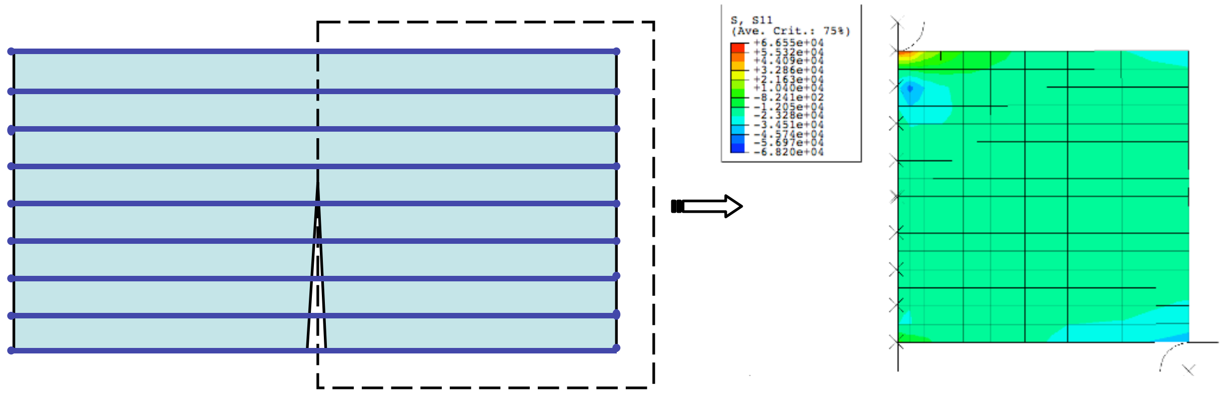

Figure 2: SMA self-healing composite: a) schematic showing wires and existing crack opening after loading; b) half model (symmetry b.c.) with rigid bodies to apply three-point bending; stress contour plot showing closed crack and uniform closure pressure (negative).

ADAPTIVE COMPOSITE

In a polymeric based composite, the pre-strained SMA actuator ribbons are embedded and bonded to the matrix and when actuated via thermal excitation they recover under almost rigid constraints to stiffen the composite or under soft constraints to alter the shape of the composite. Potential applications include suppressing vibration to reduce sonic fatigue and noise transmission and controlling the shape of the leading edge of an airplane. Turner [7] has examined the buckling and dynamic response of a thin beam. Figure 3a shows a prototype beam under investigation of buckling, stiffening, and re-buckling due to combined thermal expansion effects and the reverse transformation of the ribbons. Upon continuous heating, first the beam buckles before the SMA ribbons are actuated; then the deflection is diminished once the ribbons start to recover; and finally at a even higher temperature it re-buckles due to dominant thermal effect. The experimentally observed deflection of the beam is shown in Figure 3b. As shown in Figure 3b, the simulation results for bare matrix and the composite are exactly what one expects. Further simulation on shape control and dynamic problems are ongoing.

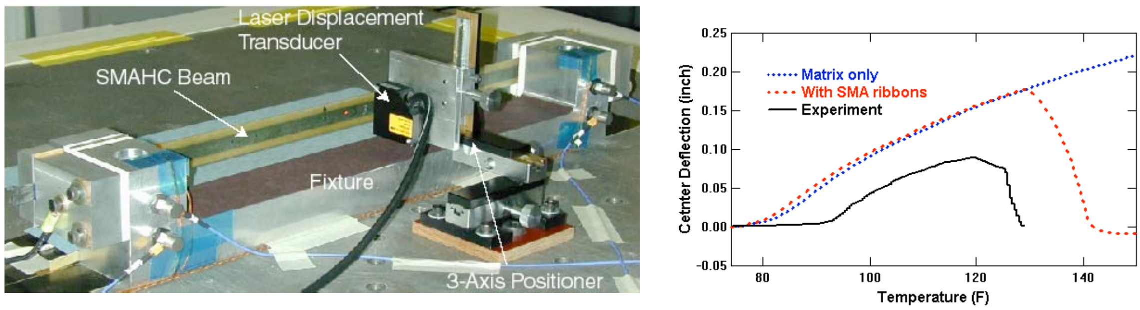

Figure 3: a) Conceptual airplane with airfoil made of shape memory alloy reinforced composite (SMAHC); b) Plate prototype of SMAHC. (Courtesy of Dr. Travis. L. Turner at NASA.)

CONCLUSIONS

The modeling approach and ABAQUS UEL have demonstrated robust performance and very good agreement in predicting self-healing behavior of SMA reinforced metal composite. Adaptive stiffening and shape control behavior of a constrained beam subject to temperature ramping has also been well captured.

References

[1] Files, B. S.: Design of a Biomimetic Self-Healing Superalloy Composite. Ph.D.dissertation, Northwestern University, 1997.

[2] Yamada, Taya: Strengthening of Metal Matrix Composite by Shape Memory Effect. Materials Transactions, 1993.

[3] Krag J., et. al.: Biomimetic Shape-Memory Reinforced Alloy Composite for Mars Rover Self-Healing Axles Project. Report for B.S. Files at NASA, Houston, June 8, 2002.

[4] Brinson, L. C., Huang, M. S: Simplifications and Comparisons of Shape Memory Alloy Constitutive Models. *J. Intell. Matl Syst & Struct.* **7**: 108-114, 1996.

[5] Bekker A., Brinson L. C: Phase Diagram Based Description of the Hysteresis Behavior of Shape Memory Alloys. *Acta Mater.* **46**: 3649-3665, 1998.

[6] Turner, T.L.: Structural acoustic response of a shape memory alloy hybrid composite panel (lessons learned). SPIE Vol. 4701, Paper No. 4701-60, San Diego, CA, March 2002.

[7] Turner. T.L.: Experimental validation of a thermomelastic model for SMA hybrid composite. SPIE Vol. **4326**, Paper No. 4326-24, Newport Beach, CA, March 2001.