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Mechanical analysis of carbon fiber shape memory polymer composites

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ABSTRACT

Shape memory polymer (SMP) is one of smart polymers which exhibit shape memory effect upon external stimuli. The mechanical properties of SMPs are not sufficient for aerospace applications, e.g., plane wings and self-deployable space structures. In this research, carbon fiber reinforced shape memory polymer composites (CF-SMPCs) were studied to design self-deployable structures in harsh space conditions. CF-SMPCs were prepared using woven carbon fabrics and a thermoset SMP. Four-layered composites were manufactured using vacuum assisted resin transfer molding process. The mechanical and shape memory properties of CF-SMPCs were characterized using a universal tensile machine with a temperature control chamber. For mechanical analysis of CF-SMPCs, a 3D constitutive equation of SMP, which had been developed using multiplicative decomposition of the deformation gradient and shape memory strains, was used with material parameters determined for CF-SMPCs. The actuation behavior of CF-SMPCs was simulated for a longeron and their results were compared with experiments.

I. Introduction

Shape memory polymer (SMP) is one of smart materials that exhibit shape memory effect upon external stimuli. Due to their great recoverability and molding property, SMPs have been studied in various fields as smart materials, e.g., biomedical stents and robotic actuators [Chiodo, Jones 2002, Hyun Kim, Jin Kang 2010, Lan, Liu 2009, Sahoo, Jung 2005]. The actuation temperature of SMPs can be easily controlled so that various applications have been suggested. SMPs have great potentials as smart materials; however, there are some limitations to their structural applications in aerospace engineering because of low mechanical strength and stiffness. To overcome these demerits, some studies have focused on reinforcing SMPs using various fillers [Gall, Dunn 2002, Lan, Liu 2009, Liu, Gall 2004, Ohki, Ni 2004, Sahoo, Jung 2005, Schultz, Francis 2007, Zhang and Ni 2007]. Fiber reinforcements have been suggested as the most powerful way to enhance the mechanical properties of SMP, demonstrating improved elastic modulus and fracture strength of fiber-reinforced shape memory polymer composites (SMPCs) [Lan, Liu 2009, Ohki, Ni 2004, Zhang and Ni 2007]. Nevertheless, mechanical analysis models of SMPCs are limited, hampering technical applications of SMPC.

In this research, carbon fiber-reinforced shape memory polymer composites (CF-SMPC) were studied, focusing on their manufacturing method and mechanical simulation including actuation behavior using a constitutive model. The constitutive model used in this study was originally developed for pure SMPs, however, it was used by obtaining the material properties for the constitutive model from CF-SMPCs. The experiments for simulation parameters were conducted by following characterization methods suggested in [10]. Finally, self-deployable behavior of CF-SMPCs was simulated to investigate a possibility of designing antenna or deployable longeron for aerospace applications.

II. Experimental

1. Materials and fabrication

A thermoset shape memory polymer (MP5510, Diaplex®) was used as a matrix. The weight ratio of resin and curing agent was set to be 6:4. The glass transition temperature of such SMP after curing was about 60℃.

For thermomechanical testing, the SMPs were formed into rectangular specimens in 10 mm x 50 mm x 1 mm size using a molding method. The mixed solution of SMP and curing agent was stirred at the rate of 60 rpm, poured into a Teflon mold, and cured at 70℃ for 1 hr. CF-SMPC samples with the same size were manufactured using vacuum assisted resin transfer molding (VARTM). Unidirectional and woven carbon fiber fabrics with the thickness of 0.15 and 0.3mm, respectively, were stacked in four layers. The thickness of VARTM mold was 1mm. By vacuum condition maintained in the mold, the mixed solution of SMP and curing agents was injected to fabric layers. After transferring SMP resin, the mold was hot pressed at 70℃ for 1hr. The schematic for the manufacturing of SMPCs is illustrated in Fig.1.

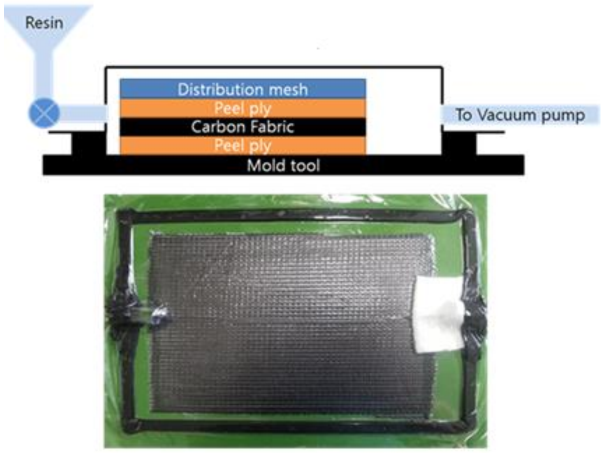

Figure 1. A schematic explaining VARTM and a picture of CF-SMPC sample

2. Thermomechanical testing method

The thermomechanical behavior of SMP and CF-SMPC was characterized using universal tensile machine (UTM). One-way shape memory behavior of SMP was characterized in uniaxial tensile mode. The SMP specimen was deformed at 80℃, cooled down to 30℃, keeping the deformation, and unloaded. This SMP was reheated to 80℃ in stress free condition to measure the shape memory effect. The recovery and fixity rates of pure SMP matrix were obtained. For obtaining the material parameters of SMPs in rubbery state for the constitutive equation, rapid extension-relaxation test was conducted at 80℃. The head speed of UTM was set to be 45mm/min. For obtaining the material parameters of SMPs in glassy state for the constitutive equation, slow extension-relaxation test was also conducted at 30℃ with the crosshead speed of 0.12 mm/min. The shape memory behavior of CF-SMPC was measured using bending test because CF-SMPCs exhibited high stiffness and tensile strength due to the carbon fibers (see Fig.2).

Lastly dynamic mechanical thermal analysis (DMTA) was used to measure the transition temperature of SMP and CF-SMPC. The dynamic tensile mode with a frequency of 1 Hz and temperature condition of 0℃ to 120℃ was set.

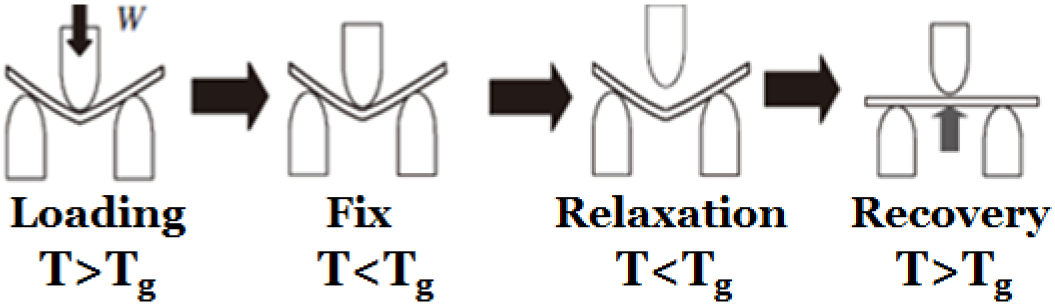

Figure 2. Characterization of CF-SMPCs using bending test

III. Results and discussions

The time-strain and time-stress behavior of the SMP during the test are shown in Fig.3. The recovery and fixity rate of the SMPs were calculated using equation (1) and (2).

$$Recovery\ ratio = \frac{\varepsilon_p - \varepsilon_r}{\varepsilon_p} \times 100(\%) \qquad -(1)$$

$$Fixity\ ratio = \frac{\varepsilon_f}{\varepsilon_p} \times 100(\%) \qquad -(2)$$

where ε_p was the strain applied during tensile loading and ε_r was residual strain after heating process. ε_f was the reduced strain during the cooling process in fixing state. The recovery and fixity rate were 90 and 96 %. The maximum recovery stress in one-way shape memory test was about 4MPa.

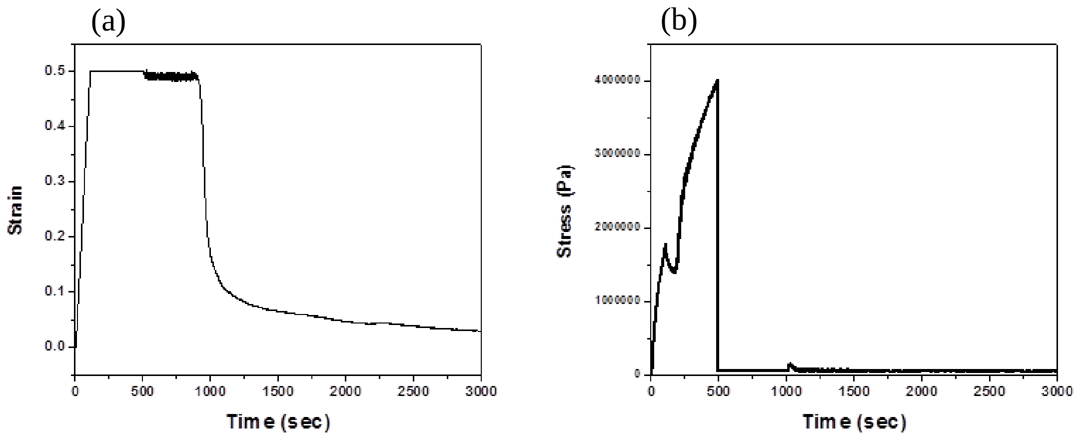

Figure 3. Strain and stress curve of SMP. (a) Time-strain and (b) time-stress curve for 3000 s.

To analyze the thermomechanical behavior of SMP, a constitutive model developed in a previous study was used [Hyun Kim, Jin Kang 2010, Yu 2014]. This model consists of Mooney-Rivlin hyper elastic spring, Newtonian fluid and viscoplasticity elements as shown in Fig.4. The rubbery phase consists of Mooney-Rivlin spring and spring-dash pot element for analyzing viscoelastic behavior in high temperature condition, while the glassy phase contains additional viscoplastic element for non-recoverable deformation on glassy state and non-mechanical strain element for simulating shape memory strain. Basic equations on each element are shown in Table.1. Details on the implementations of this constitutive equation will be discussed at the conference. The simulation results gained from this model are shown in Fig.5, demonstrating reasonable agreements with experimental results.

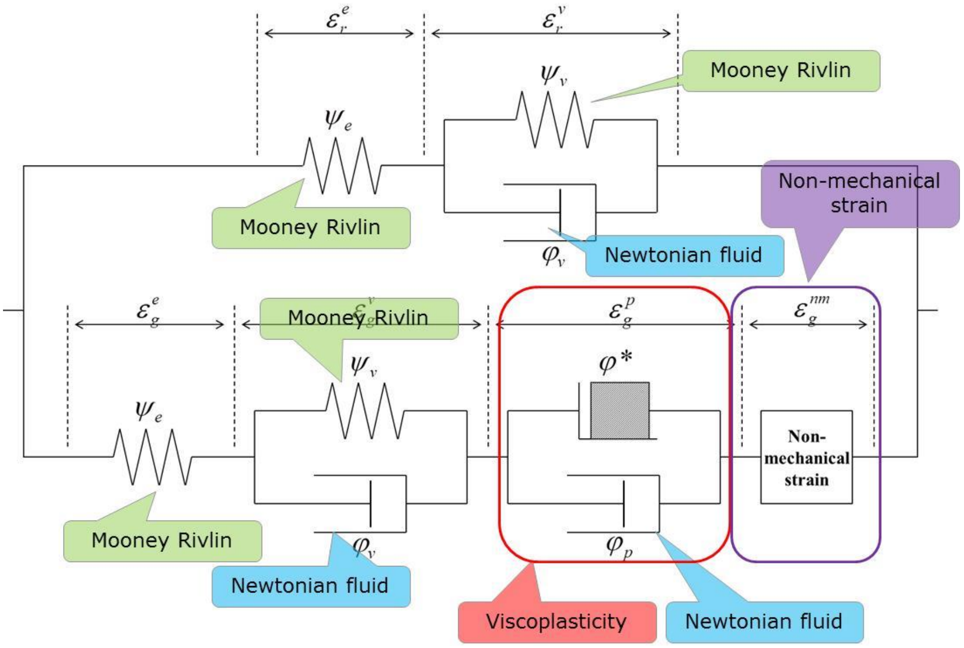

Figure 4. Phenomenological constitutive model for SMP & CF-SMPC

Table 1. Basic equations for elements in constitutive model

Mooney-Rivlin hyperelastic spring	$\psi_l^k\left(\overline{I}_l^k, \overline{II}_l^k, J_l^k\right) = C_{10,l}^k\left(\overline{I}_l^k - 3\right) + C_{01,l}^k\left(\overline{II}_l^k - 3\right) + \frac{\kappa_l^k}{2}\left(J_l^k - 1\right)^2$
Newtonian fluid	$\phi_g = \frac{1}{2} k_g \dot{\mathbf{C}}_g^v : \dot{\mathbf{C}}_g^v$
Viscoplasticity	$\dot{\mathbf{F}}_g^p = \frac{1}{k_g^p} \langle f \rangle \frac{\partial f}{\partial \mathbf{P}_g}$
Non-mechanical strain	$\frac{dE_{g,\,ij}^{nm}}{dt} = \begin{cases} \alpha\xi_r\left(-E_{g,\,ij}^{nm} + \beta E_{ij}\right) & \text{for} \quad \lvert \beta E_{ij} \rvert > \lvert E_{g,\,ij}^{nm} \rvert \\ \alpha\xi_r\left(-E_{g,\,ij}^{nm} + E_{ij}\right) & \text{for} \quad \lvert E_{ij} \rvert < \lvert E_{g,\,ij}^{nm} \rvert \end{cases}$

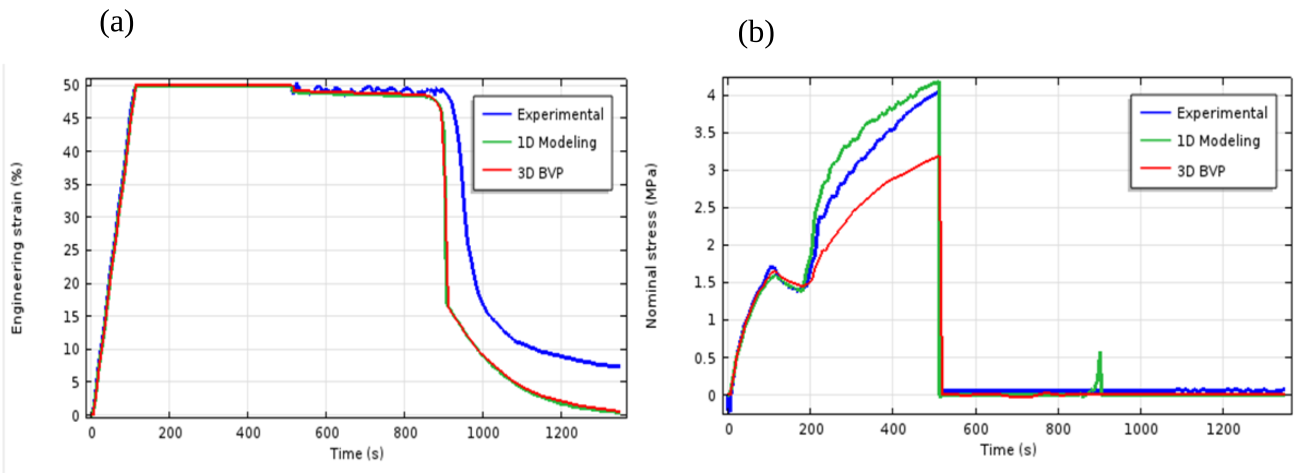

Figure 5. Simulation result for SMP. (a) Time-strain simulation in 1D modeling and 3D boundary value problem (b) Time-stress simulation in 1D modeling and 3D boundary value

Using the bending test of CF-SMPCs, the material parameters of CF-SMPCs will be determined for the constitutive equation. Then, the mechanical simulation of CF-SMPCs will be carried out and reported in detail at the conference.

IV. Summary

To investigate a possibility of designing self-deployable structures using SMPs for aerospace engineering, various types of CF-SMPCs were manufactured. First, the thermomechanical behavior of SMP and CF-SMPC was characterized. The shape memory behavior of SMP was then characterized using simple uniaxial test and its deformation behavior was simulated using a constitutive equation developed based on two-phase modeling of SMPs. For CF-SMPC, a bending test was carried out to characterize their shape memory behavior and obtain the material properties for the constitutive equations. Experimental and simulation results will be presented at the conference.

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