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Keynote lecture of the 30th anniversary of the JSCM

Shape and vibration control of smart composite structures

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CONGRATULATORY WORDS

It is my great pleasure to write a paper for the plenary lecture at the 29th annual symposium organized by JSCM (Japan Society for Composite Materials). I would like to express my sincere congratulations to JSCM for the 30 years anniversary in 2004.

The relation between JSCM and KSCM (Korean Society for Composite Materials) has been very well established. Japan/Korea joint symposiums on composite materials were already held 4 times under the co-organization of JSCM and KSCM. The last 4 joint symposiums were very successful and I believe those joint symposiums proved fruitful for the mutual cooperation between the two societies. Starting in 2000, the joint symposiums were held annually and the future joint symposiums will be continued. I congratulate again the 30 years historical anniversary of JSCM.

1. INTRODUCTION

Increasing demands for improving the structural performance with recent advances in material science have produced smart structures, which include the ability to sense, diagnose and actuate in order to perform the desired functions effectively. The typical materials of interest in developing smart structures are piezoelectric crystals, electrostrictive and magnetostrictive materials, shape memory alloys, electrorheological fluids, and fiber optics. These smart materials have the ability

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to change stiffness, shape, natural frequency, damping, and other mechanical characteristics in response to change in temperature, electric fields, or magnetic field. Many smart materials have great potential in a variety of applications. So, many applied researches have been performed to enhance the structural performance using smart materials. Han and Lee [1] investigated the composite plates with distributed piezoelectric actuators and showed that the distributed actuators can effectively predict dynamic behaviors and control performance of composite plate. Oh *et al.* [2] analyzed thermopiezoelastic post-buckling and vibration for several lamination and loading types. They showed that piezolaminated composite plate could enhance effectively the thermal buckling load and reduce the post-buckling deflection within some boundary. Also, shape memory alloys (SMAs) have appeared that have significant advantages in the area of structural response control, structural shape control, and damping enhancement. Lee *et al.* [3] investigated the aerothermoelasticity of shape memory alloy hybrid composite shell panel. The numerical results showed that SMA actuator could increase structural stiffness and suppress structural instability induced by thermal load. Roh and Kim [4] considered a low velocity impact for the hybrid smart plate. The hybrid smart plate using SMA actuators and piezoelectric sensors can enhance its global resistance to low velocity impact. Marfia *et al.* [5] investigated the behavior of SMA laminated beams. The numerical results demonstrated the SMA actuators are very effective in changing the shape of beam structure by performing temperature cycles on the SMA layers.

This article introduces the analytic and experimental study on the application of smart materials, especially shape memory alloys (SMAs), optical fiber, and piezoelectric materials. SMAs produced in the form of wire or strip are combined with elastic host structures to increase their application range as smart structural systems. The possibilities that SMAs and their application to composite structures can be smart structure systems are investigated by providing the potential and remaining limitation for their applications.

The first part of this article introduces the numerical analysis of the thermo-mechanical responses of the shape memory alloy hybrid composite (SMAHC) cylindrical panels. In this structure, the recovery force generated by shape memory effect behaves like a concentrated force on the edge. Therefore, the resulting in-plane forces adaptively change the static and dynamic response of the structure.

Also, the shape adaptive structure combining SMA strip with elastic structure is investigated. The shape change of structure is caused by initially strained SMA strip bonded on the surface of host structure when thermally activated. The SMA strip starts transformation from the martensite into the austenite state upon actuation through heating, simultaneously recovering the initial strain, thus making the host structure change shape.

In the second part, experimental studies for hybrid composite structures with SMA actuators are performed to control position, shape and vibration of the structures. SMA wire actuators are attached on the surfaces of the composite structures and active shape control is performed by using active control algorithms. In addition, the applications of fiber optic sensor systems and piezoceramic actuators to the vibration measurement and suppression of composite structures have been investigated using adaptive controller based on neural-networks.

2. THERMO-MECHANICAL RESPONSES OF COMPOSITE AND SMART STRUCTURES

In this study, the thermal post-buckling analysis of shape memory alloy hybrid composite (SMAHC) shell panels has been performed using the finite element method formulated on the basis of the layerwise theory. The von Karman nonlinear displacement–strain relationships are applied to consider large deflections due to thermal loads. With the material properties of SMA/epoxy lamia calculated with multi-cell model as well as the material properties of graphite/epoxy lamina, the stiffness of the shape memory alloy hybrid composite (SMAHC) can be calculated. The Newton–Raphson iteration with cylindrical arc-length method is applied for the investigation of thermal snapping. A detailed description of the numerical calculation for the cylindrical arc-length method can be found in [6]. The numerical results for post-buckling deflections of SMAHC panel are compared with those of composite panel to show the effectiveness of SMA actuator for the enhancement of post-buckling suppression. The composite panel is made of graphite/epoxy. The SMAHC panel consists of graphite/epoxy laminates and SMA/epoxy lamina with 10% volume fraction of SMA wires. So, the SMAHC panel has only 80.6% weight of the composite panel without SMAs. The composite and SMAHC panel boundary conditions are simply supported at four edges. The geometry of the cylindrical laminated shell is illustrated in Fig. 1 and the geometric dimensions are length $(a) = 0.8$ m with the ratio $a/b(= R\phi) = 1$, the thickness of graphite/epoxy $(h_l) = 0.125$ mm and SMA/epoxy lamina $(h_s) = 0.25$ mm, and the shallow angle $(\phi) = 20$ deg. The stacking sequences of composite and SMAHC panel are $[90^0_4/0^0_4]_s$ and $[90^0_2/0^0_2/\text{SMA}/0^0_2/90^0_2]$, respectively. Figure 2 shows the post-buckling deflection of the composite and SMAHC panels with 1% initial strain values of SMA. As can be seen, the thermally buckled deflection of SMAHC panel decreases compared with the panel without SMAs. However, at the low temperature, the deflections of SMAHC are slightly larger than those of composite panel because the SMA fibers are not fully activated at that relatively low temperature. Since the SMAHC panel has less weight than that of the composite panel, the SMAHC panel adapts well on thermal post-buckling compared with composite panel without SMA wires.

Also, the interactions between SMA strip actuator and the elastic host structure are investigated by using ABAQUS finite element program. The SMA strip actuator coupled with elastic host structure can be used to generate bending force for the shape modification. The host structure is made of aluminum. For the numerical analysis, the following assumptions are made: (i) SMA strip is perfectly bonded with aluminum by using epoxy adhesive. (ii) SMA strip actuator is activated by

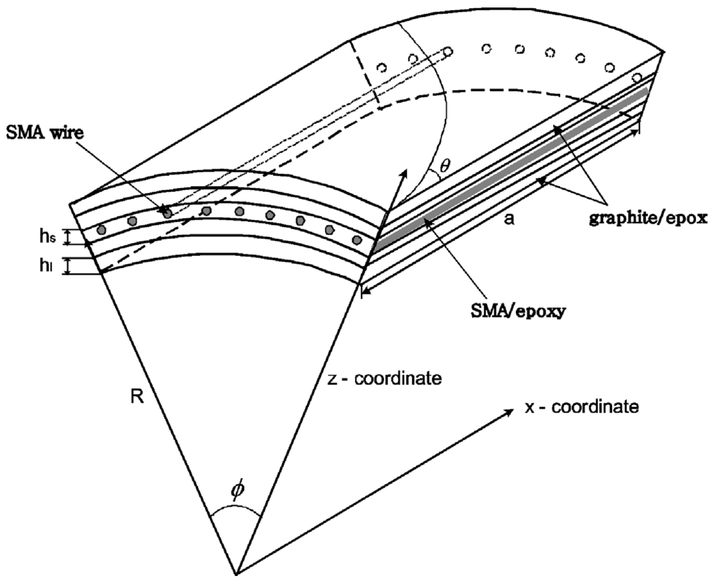

Figure 1. Geometry of cylindrical SMAHC shell.

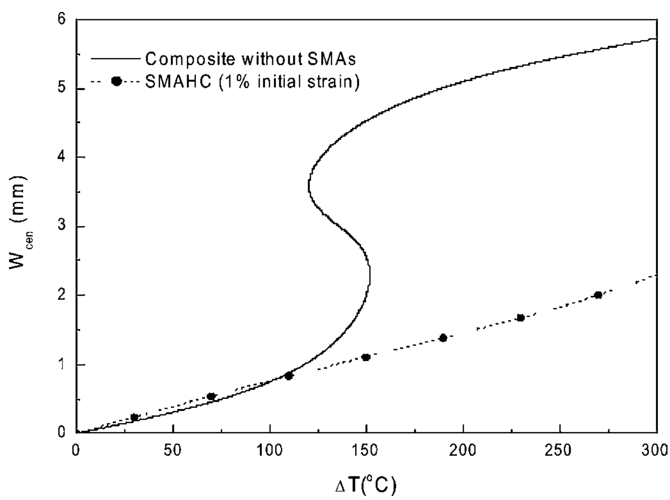

Figure 2. Effectiveness of SMAHC panel on post-buckling deflection.

electrical heating, and (iii) SMA strip is thermally insulated from the rest of the aluminum. For the numerical model, a conical shell structure which should be applied to the variable area fan nozzle (VAFN) is investigated. The object of VAFN structure is to decrease jet noise during takeoff and reduce drag by changing the area of inlet or outlet fan nozzle. Figure 3 shows the numerical model of conical shell structure. The conical shell structure of aluminum and SMA strip are modeled using $20 \times 10 \times 1$ mesh with 3D eight-node elements. SMA strip is subjected to initial strain in axial direction and bonded on the surface of host structure. Boundary con-

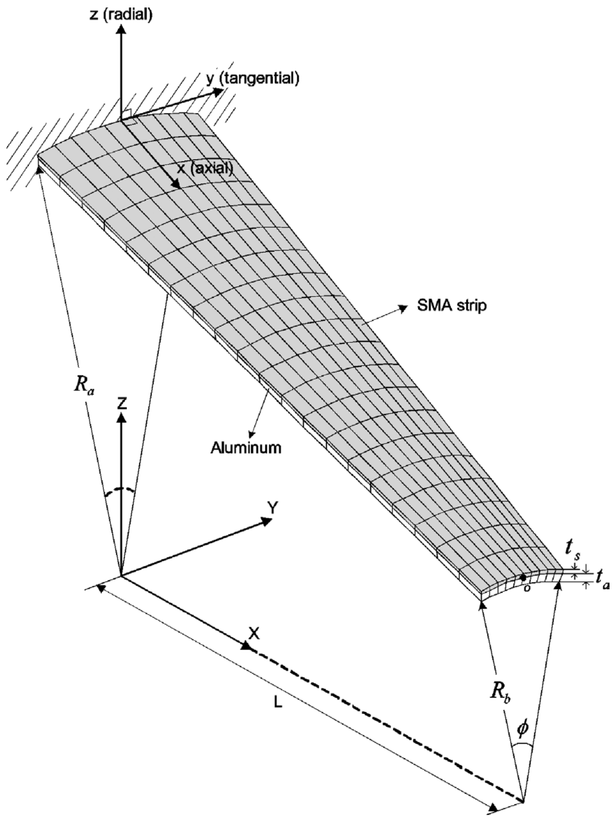

Figure 3. Geometry of shape adaptive conical shell structure.

dition of the structure is cantilevered and each geometric dimensions are aluminum thickness $(t_a) = 2$ mm, SMA strip thickness $(t_s) = 0.5$ mm, length $(L) = 150$ mm, shallow angle $(\phi) = 30°$, radius $(R_a) = 100$ mm and $(R_b) = 50$ mm. The numerical algorithm of the 3-D SMA thermo-mechanical constitutive equations based on Lagoudas model [7] is implemented to analyze the unique characteristics of SMA strip. Figure 4 shows the hysteresis of tip deflection versus temperature cycle on SMA strip with 3% and 5% initial strain. As can be seen, SMA strip can generate enough bending force to deform the host elastic structure as desired shape. But the deformed shape can not recover its original shape at the end of the temperature cycle, even if an elastic structure compels SMA to recover the initial condition. To investigate the internal conditions of SMA strip at the end of temperature cycle, the recovery stress is investigated. Figure 5 shows the distribution of residual recovery stresses in the case of 3% initial strain of SMA strip. As can be seen, recovery stress of SMA strip does not decrease to zero at the end of temperature cycle. So, this residual recovery stress of SMA strip causes the host structure to remain as deformed shape. It is difficult to design a reversible shape adaptive structure using this one-way shape memory effect strip, even if the strip is coupled with elastic structure. The two-way shape memory effect could be a solution to make the actuation reversible. However, if high precision is needed in terms of activation magnitude versus the number of cycles, the issues of thermal fatigue and drift in the response are still not completely solved. So, accurate prediction of the thermomechanical behavior of the SMA is needed to design the actuator and shape-adaptive structure, taking into account the nonlinear and hysteretic behavior of the SMAs.

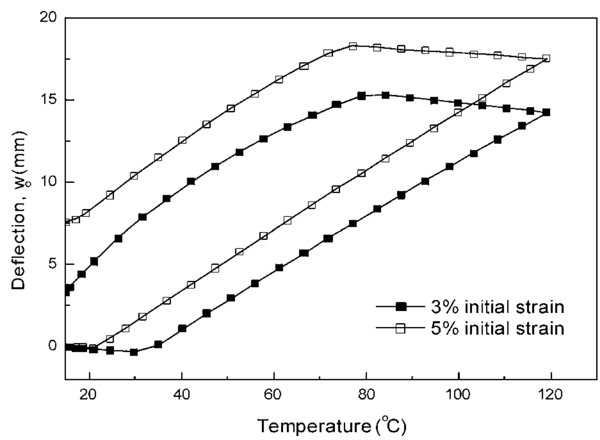

Figure 4. Tip deflection with temperature cycle on SMA strip.

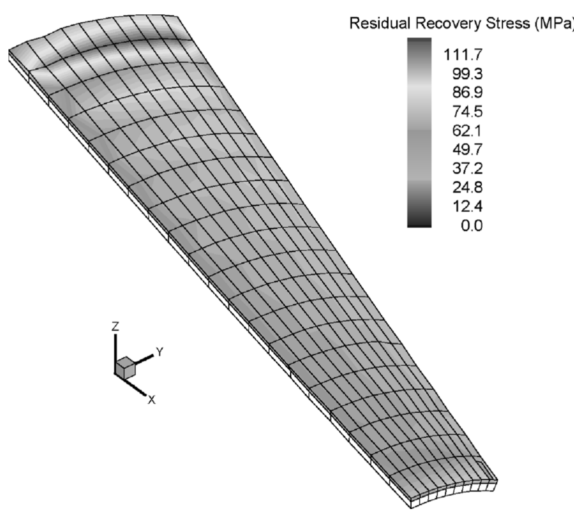

Figure 5. Distribution of residual recovery stress (σ_{xx}) with 3% initial strain of SMA.

3. ACTIVE SHAPE AND VIBRATION CONTROL OF SMART COMPOSITE STRUCTURES

In this section, hybrid composite structures with SMA actuators are being investigated for position, shape and vibration control of the structures. A simple model, the first order model, is adopted to describe the responses of the hybrid composite beam with SMA actuators. The specimen used for the experiments and the active shape control is graphite/epoxy, $[0_2/90_2]_S$ composite. The SMA actuators have 3.5% initial strain, and are attached on the both surfaces of the composite beam as shown in Fig. 6. For the activation of the SMA actuators, a 2-channel high current power supply was used and each channel was connected to each SMA actuator. The deflection at 20 mm point from the tip of the specimen, measured by LDV (Laser Doppler Velocimetry), was used as a system output signal.

Figure 7 shows the experimental results of shape control using the feed-forward and the PID feedback controller and the numerical simulation using the PID controller and the first order model. In the case of feed-forward control, settling time is more than 10 seconds and the steady-state error is quite large. However, in

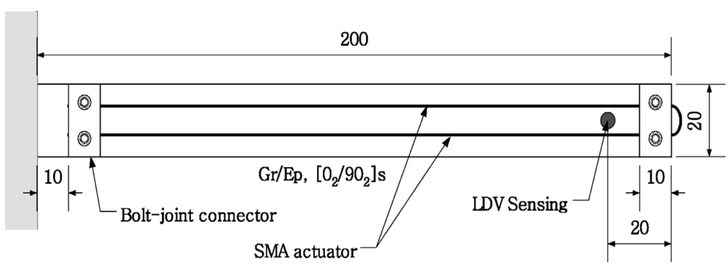

Figure 6. Configuration of hybrid composite beam with SMA actuators.

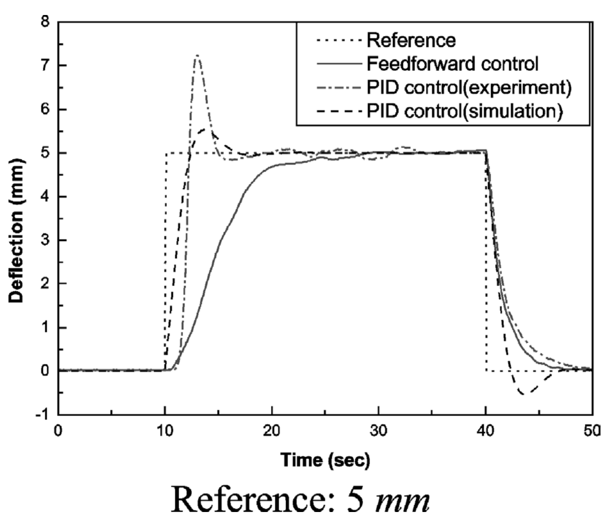

Figure 7. Experimental and numerical results of active shape control of the composite beam.

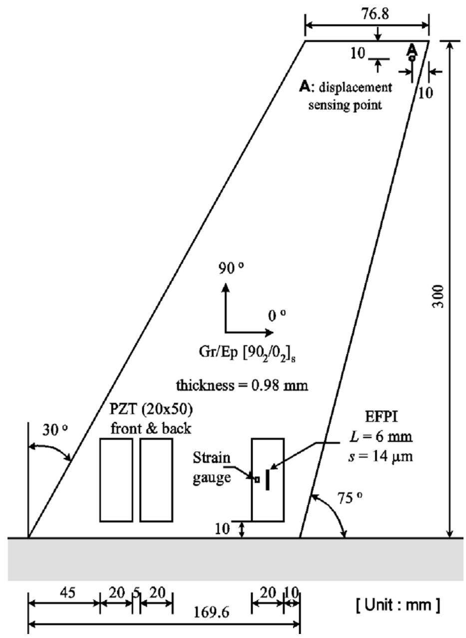

Figure 8. Wind tunnel test model.

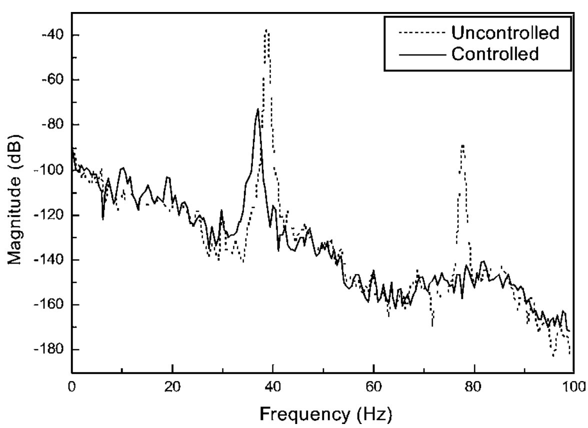

Figure 9. Vibration control of wind tunnel model.

the case of feedback control, settling time is about 5 seconds, a half of the feed-forward control and the desired deflection is accurately maintained.

Due to the nonlinearity of the SMA actuators, the numerical model did not exactly predict the experimental results. The present study employed a simple but practically numerical model based on the experimentally determined parameters so that the nonlinearity of SMA actuators may not be fully taken into account. Experimental results show that SMA actuator can be used as an actuator to deform and maintain the desired deformation, accurately. However, composite beam with SMA actuator needs some settling time to reach the desired deformation.

In addition, Fig. 8 illustrates the wind tunnel test model to measure and suppress the vibration using fiber optic sensor systems and piezoceramic actuators in the subsonic wind tunnel. In the experimental results, the amplitudes of the flutter mode and its harmonics are significantly reduced (Fig. 9).

4. CONCLUSIONS

The present study introduces the numerical and experimental investigation of the application of smart materials to structures. The possibilities that SMAs and their application to composite and smart structures can be smart structural systems are investigated. In the first part, thermal post-buckling analysis of shape memory alloy hybrid composite (SMAHC) shell panels has been performed using the finite element method formulated on the basis of the layerwise theory. In numerical results, it is illustrated that SMA wire can be an excellent actuator to improve structural performance in a thermal environment. However, SMA actuator has a limitation at low temperature region to enhance the structural adaptation.

Also, the thermo-mechanical responses of shape adaptive composite structure with SMA strip have been investigated. The interactions between SMA strip and host structure are studied by using ABAQUS finite element program. In this study, SMA strip can generate enough bending force to deform the host structure. But it is difficult to design reversible adaptive structures with one-way shape memory effect, even if SMA strip is coupled with elastic host structures which compel SMA to recover its initial condition.

In the second part, the hybrid composite structure with SMA actuator is investigated for position, shape and vibration control. In experimental results, SMA actuator can be used as an actuator to deform and maintain the desired deformation, accurately. But it needs some settling time to reach the desired deformation. As can be seen from these numerical and experimental results, SMAs can provide an excellent smart material to improve the structure performance. In addition, the application of fiber optic sensor systems and piezoceramic actuators to wind tunnel model has been investigated for the adaptive flutter suppression and the vibration reduction has been performed successfully.

Acknowledgements

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