DESIGN AND THERMAL TESTING OF SMART COMPOSITE STRUCTURE FOR ARCHITECTURE APPLICATIONS

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Summary. A composite structure consisting of a Shape Memory Polymer (SMP) matrix and three Shape Memory Alloy (SMA) strips was constructed. The SMA strips act as actuators which create forward and backward angle bends of 90 degrees of the composite structure. The function of the polymer matrix was to give the structure enough stiffness. During the morphing stage the polymer was heated locally into rubbery condition to allow shape changes. The new structural shape was fixated by cooling the polymer into the glassy state.

Since the exact timing and amount of heating power of both the SMA strips and the SMP matrix was crucial for the functioning of the smart structure, a detailed numerical thermal model was build and validated using thermal imaging. With this validated numerical model the optimum activation conditions were determined. The working principle of the smart composite structure was demonstrated with a small scale prototype.

1 INTRODUCTION

Smart materials are materials which can sense a change of external stimuli and react with a certain action, e.g. property or shape change. [1,2]. Application areas of these material include aerospace engineering, adaptive medical devices and architecture. Imagine buildings with a smart light regulating system consisting of shape changing lamellae (fig.1) and floor plates which transform into chairs and tables when needed (fig.2).
In this paper we investigate the feasibility of a composite plate as such a smart structure element. The composite consists of three shape memory alloy (SMA) strips and is surrounded by a shape memory polymer (SMP) matrix (Fig. 3). The polymer matrix provides the stiffness of the structural element in its initial flat and its final deformed configuration, but is flexible during the shape transition. This flexibility is obtained by local heating such that the polymer switches from its glassy to its rubbery state. The heating of the SMP will be realized by embedded heating wires. The actual shape change is initiated by heating the SMA strips. These strips are pre-programmed by annealing them in a bent state, followed by backward bending at room temperature until the strips are flat again.

A shape transformation thus involves heating of the matrix polymer for a predetermined time and with a predetermined heating power at the to be deformed area. After that, the outer two SMA strips are heated above the SMA activation temperature until the shape change is finished. The timing of the heating periods is critical: if the polymer heating power is too low or too short, the material is too stiff and the deformation process is not possible or incomplete.
Too long or too hot heating on the other hand will result in spontaneous activation of both the SMA actuator strips and the SMA antagonist strip (middle strip). A similar reasoning applies to the heating of the SMA strips. The determination of the heating settings depends on the thermal and electrical properties of both the SMA and SMP materials, as well as on the material thicknesses and precise positions of the SMA strips in the matrix. Because of the complexity of these issues, a numerical model would be a valuable tool for the design of the smart composite structures proposed here. In the present paper we present the construction of a smart composite prototype, the development of a numerical simulation model, as well as the validation of it by comparing simulated and measured heating curves.

2 PROTOTYPE CONSTRUCTION

In order to prove the feasibility of these smart composite structures a small scale prototype was constructed consisting of Veriflex as the shape memory polymer and Nitinol as the SMA material. Veriflex (Cornerstone Research Group Inc., Dayton, Ohio) is a thermoset material with a storage modulus of 800 MPa at room temperature and a rubbery modulus of 0.5 MPa at 110°C. As its softening point we take the temperature where the modulus drops below 100 MPa which is at 58 °C. This value corresponds well with the 62 °C given by the supplier for the onset of the glass transition. SMPs can be deformed in the rubbery state after which the new shape can be fixed by cooling the material below the glass transition. After reheating, the SMP exerts a force which tends to return it to its original, molded shape.

The shape memory alloy (SMA) used in this study is a nickel-titanium alloy called Nitinol. This material has a strong shape memory effect. After cooling, the material can be deformed in its martensite phase to a new shape. After heating above its activation temperature, a phase transformation from martensite to austenite occurs and the material regains its original shape. The exact values of the activation temperatures depend both on the alloy composition and the annealing procedure. For the present material the martensite-to-austenite transformation takes place in the narrow temperature range between 92 and 106 °C.

The composite was constructed by first casting two SMP strips in which the constantan heating wires were embedded. On the surface of each of these strips three parallel slits were
milled with the size of the SMA strips. The two SMP castings were then carefully glued together after which the SMA strips were inserted (Figures 1 and 4). More details about the construction and mechanical testing can be found in ref.[3].

3 THERMAL TESTING OF SMART COMPOSITE STRUCTURE

The heating of the SMP polymer matrix by the embedded constantan heating wires and the heating of the SMA strips were tested separately by applying electrical power and observing the surface temperature using an infrared camera. For this we used the Fluke Thermal Imager, Ti55 IR flexcam with a 10.5 mm lens. Experiments were done with four different prototypes. In the first type of experiments the constantan wires were heated with three different power settings (10, 15 and 20 Volt, corresponding to about 6, 14 and 25 Watt). Examples of the infrared images for the 15 Volt experiment are shown in figures 6 and 7. The surface temperature increases to about 90 °C in 210 seconds. The temperature in the heated area is reasonable uniform (temperature differences of about 5 to 8 °C). In figure 8 and 9 the measured temperatures for the 10 and 15 Volt experiments are plotted for three different points as a function of time. These plots show that the surface temperature uniformity for the 10 V heating experiment is about ± 2 °C, whereas that for the 15 V experiment it is larger (± 7 °C). Note that the SMP softening temperature is reached after about 300 s for the 10 V experiment, whereas for the 15 V experiment this is already after 60 s.

In the second type of experiments the outer two SMA strips were heated by applying an electrical current. The purpose here was to find the allowable heating time before the temperature at the position of the middle SMA strip reached the SMA activation temperature. Currents of 10, 12.2 and 15 A were applied to prototype 3 and the temperature increase above the three SMA strips were monitored with the infrared camera. The results are shown in figures 10 and 11. The temperature above the heated SMA strips increases to above 40°C, whereas that of the passive SMA middle strip only slowly increases. The temperature of the outer SMA strips in this experiment is however still below the SMA activation temperature of 92°C.
The third type of experiments therefore consists to the combined heating of the constantan wires for a fixed period of time, followed by the heating of the outer SMA strips. In those experiments the temperatures of the outer SMA strips should be above 92°C while the middle SMA strip should be always below that temperature. The heating wires were switched on with 15 V followed by the activation of the outer SMA strips with 12.1 A after 120 seconds. The constantan heating wire and SMA strips were switched off at 156 s and 350 s, respectively. The results are shown in figure 12. Obviously, in this experiment the SMA activation temperature was not yet reached. Also note that here the difference between the temperatures above the outer two SMA strips and the middle one is only about 10°C which is relatively small. It will therefore not be easy to find a condition in which the outer strip temperatures are well above, and the inner strip temperature is well below the SMA activation temperature.
4 THERMAL MODEL AND VALIDATION

In order to be able to optimize the correct choice of switch-on and switch-off parameters of the heating wires and SMA strips, a numerical model was built using ANSYS. The SMP body is constructed out of SOLID 70 elements. SOLID 70 is a three-dimensional thermal solid, which contains heat conduction capabilities. Since the diameter of the constantan wires is considerably smaller in relation to the prototype, it was decided to use a LINK element for the integrated heating wires. The LINK element must enable both thermal and electrical conduction simulations, since the wires are used as resistive heating elements. LINK68 has both these characteristics. Comparable characteristics are required for the SMA strips, which are constructed using thermoelectric SHELL157 elements. The model is constructed with nodes on every mm. This is considered precise enough for the intended analysis. The SMA1 and SMA3 strips are electrically coupled in both the model and the prototype. Coupling of the
SMA strips required only one variable power supply. The strips are coupled in series, which enables an equal distribution of electric current by variable resistance. When the strips are coupled in parallel a slight difference of resistance may lead to unequal heating of the strips. The ANSYS model is presented in Figure 13 and a typical result in Figure 14.

In order to validate our numerical model we simulated the experiments discussed in the previous section, evaluated the temperatures at the same locations as used in the experiments and combined the simulation results and measurements in one graphs. The results are shown in figures 15-21. In these graphs, dashed and dotted lines always represent measurement data and the full solid lines the result of ANSYS simulations. As can be seen in Fig.15-17, the ANSYS simulations results are always close to the measured temperatures during the constantan heating tests. Both the heating and the cooling parts are well predicted. The results of the tests during which the outer SMA strips were heated, can be found in figures 18-20. As can be expected, the middle SMA strip, which is not heated, remains much cooler (typically about 20°C in these experiments) and this effect is well captured by our numerical model. Figure 19 shows an experiment where the heating power is switched off after 210 seconds. After switching off, the temperature difference between the outer and the inner strips gradually becomes smaller. Again, all these effects are well captured by the ANSYS simulations.
To conclude, we show the results of the combined heating of the constantan wires and the outer SMA strips in Figure 21. Although the peak temperature is about 5°C underpredicted, the general heating and cooling trends are all well captured by the simulations and the conclusion of this section should be that the simulation model is well capable of predicting all experimentally measured temperatures, both for the heating wire and the SMA heating tests.

5 ACTIVATION TIME SETTINGS

Now we have a simulation code which can accurately simulate the temperature changes in our smart composite structures, we can use it to determine the limits for the heating time and power. This determination of optimum settings will be split into two parts: the settings for the
heating wires and the settings for the outer SMA strips.

5.1 Polymer matrix heating

The purpose of the heating wires is to locally soften the polymer such that deformation becomes possible. For this, the temperature should be above 58-62°C, as determined in section 2. From figures 15-17 we can see that for the positions above the SMA strips, this corresponds to heating times of 256, 102 and 62 seconds for the experiments with 10, 15 and 20 V (6, 14 and 24 W), respectively. More important to know is that not only the middle part of the smart composite structure is in its rubbery state, but also the outer edges. We therefore defined a point at 2 mm from the outer edges and determined the corresponds heating times for this point to be 450, 156 and 90 seconds, respectively. These, are plotted as the lower line in figure 22. The upper line in figure 22 represents the heating times at which the middle SMA strip becomes activated (above 92°C). The window of operation of the smart composite is between these two limiting lines. As can be seen, this window of operation is rather small, in particular for the higher heating powers. For the lower heating powers, the heating times become relatively long (large than 5 minutes) which is also often undesirable. Note that the selected heating condition should not be too close to the upper limiting line, since in the second step extra heat from the outer SMA strips may then activate the middle SMA strip.

![Activation Constraints for SMP Heating](image)

Fig.22: Activation window for the heating of the SMP matrix.

5.2 SMA heating

The heating conditions of the first step are chosen such that the smart composite temperature is about 58°C in the outer regions whereas the mid temperatures will be somewhat higher. For simplicity however we will neglect this temperature nonuniformity and start the SMA power optimization part with a uniform temperature of 58°C throughout the full
composite structure. The SMA transformation to the austenite phase is completed at 106°C as mentioned above, therefore the requirement for the SMA heating power is that the temperature of the two outer SMA strips should be 106°C or higher. For SMA heating powers of 8, 14 and 22 W, the required heating times then become 430, 90 and 40 seconds, respectively. The upper limits are found from the criterion that the SMA temperature should be kept below 150°C to prevent SMA high temperature fatigue [4]. An additional requirement is that the middle SMA strip should not be activated. The simulations however show that this midpoint temperature always remains below 60°C even for 400 s heating with 25 W. The resulting lower and upper limiting curves are shown in Figure 23. Typically SMA heating powers of 15-20 W should be applied for 150 to 100 seconds, corresponding to an energy input of about 2 kJ.

![Figure 23: Activation window for heating of outer SMA strips](image)

6 CONCLUSIONS

We presented the construction of a smart composite strip consisting of smart memory alloy strips and a polymer matrix. In order to determine the required thermal activation heating power settings, a numerical simulation model was developed. Laboratory experiments during which the polymer matrix and the SMA strips were heated with different power settings were used to validate the numerical model. The experiments showed that the temperature nonuniformity on the polymer surface as well as differences between different prototypes were about 5 to 10 °C. More important is that the numerical model was well capable to simulate all experimental heating and cooling experiments with an accuracy which is also about 5 to 10 °C.

By using the simulation model we could optimize the required heating conditions for
activating a smart composite structure of the present dimensions. For softening the polymer matrix, heating powers of 10-20 W are required in combination with heating times of 300 and 150 seconds, respectively (about 3 kJ energy input). For the subsequent activation of the SMA strips, about 15-20 W is required for 150 and 100 seconds, respectively (about 2 kJ).

REFERENCES