A Shape Control Method for Large Membrane Structures Using Shape Memory Polymer Films with Pre-elongation

A Shape Control Method for Large Membrane Structures Using Shape Memory Polymer Films with Pre-elongation

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This study investigates the shape control of large membrane structures to reduce the out-of-plane displacements by small patch-type shape memory polymer films. Each film is given a pre-elongation before both ends of the film are attached to the membrane. By heating the film up to the glass transformation temperature, each film is recovered to its original shape, then the reaction compression force is provided to the membrane through the attached both ends. As a result, out-of-plane displacement distribution of the membrane is changed to reduce the wrinkling or slacking area. Basic experiments on a square membrane with four shape memory polymer films were conducted to investigate the significance of the location and heating sequence of the film on the shape control performance. Each film was sequentially heated and the out-of-plane displacement of the membrane was measured. As a result, the observed displacement distribution of the membrane after all of the films were heated was asymmetric to one of the diagonal lines although the four films were symmetrically located on the membrane to it. Therefore, the effect of the SMP films on the shape control of the membrane was complicated depending on the heating sequence of SMP films. Also, the results showed that the two films near the diagonal line did not effectively control the displacement of the membrane than other two films.

Key Words: Membrane Structures, Shape Memory Polymers, Shape Control, Actuators

1. Introduction

The use of large membrane structures has become more important in space applications such as solar sails and large space reflectors. Although the folding and deployment methods of the membranes have been sophisticated by many researchers' efforts, the accurate predictions of the complicated phenomenon such as a creep and a fatigue effect induced in the membrane structures are still challenging issues. In particular, for long-term missions, slight change of membrane's tension state can be occurred when the tensioned material such as installed cables has creep effects, and accordingly, the slacking and wrinkling areas in the membranes are changed during their operation.

The slacking and wrinkling of membrane may severely affect the system's mechanical characteristic because they may change the response of the membrane. Such kind of sensitive behaviors of the membrane is basically due to their small bending stiffness, and therefore their mechanism has been studied analytically and experimentally [1, 2)]. The technology that controls the shape of the membranes is therefore required after the deployments if the actual shape of the membranes has a significant effect on the missions required for the membrane structure systems.

The shape control of the membranes can be realized by controlling the tension of the membranes by some kinds of actuators fixed on the surface or boundary of the membranes. For example, piezoelectric films such as PolyVinylidene DiFluoride (PVDF) are the candidate materials for effective control of the membrane by increasing or decreasing the strain in the membranes. However, because available strain controlled by PVDF is normally up to about 1 % and it is not always enough when approximately 10 to 100 % strain is required to control the slacking area of the film, which is explained later (see also Fig. 1). Also, the PVDF needs a high voltage amplifier with power supply whenever the actuation is required, which is not ideal for membrane space structures.

Another possible materials for the shape control of the membrane are shape memory polymers (SMPs). SMPs meet the requirement of high strain capability as mentioned above. The actuation mechanism is very simple; just heating up to their glass transition temperature T_g induce the shape recovery from the deformed to their original shape [3)]. The deformation of the materials given above T_g can be fixed and the elastic modulus is also recovered when the temperature becomes below T_g. Because of these characteristics, various applications of the SMPs for deployable space structures have been investigated [4, 5)].

SMPs can also be used as a matrix resin for functional, smart composite materials, which are simultaneously reinforced by glass and carbon fibers to increase the strength and stiffness for various engineering applications [6)]. We also have investigated the synthesis of the SMPs, thin-film, and heating devices as a deployable composite structure targeting future solar paddles [7)].

In our previous studies [8, 9)], we have demonstrated that the shape recovery of the SMP films fixed to thin membranes is able to provide the reaction force to reduce the out-of-plane displacement due to slacking or wrinkling of the membrane. Figure 1 shows how the global deformation can be replaced by the localized one. The two ends of the SMP film are bonded on the membrane surfaces because this way is more suitable for easily inducing the local buckling of the membranes. If the pre-elongation is greater than ΔL, the global slacking is replaced by the local one which is induced by the reaction force due to the shape recovery of the SMP film. The tension in other part of the membrane is also recovered with the local buckling of the membrane. Although these studies indicated the feasibility of the use of SMP materials for membrane structures, further investigation will be required for the optimal design of the SMP films with appropriate heating devices.

The objective of this study is to investigate the response (sensitivity) of the out-of-plane displacement of the membrane with respect to the location of the SMP film and to heating sequence of multiple SMP films. To this end, we will experimentally measure the distribution of the displacement every after heating one of the four SMP films on the membrane. The configuration of tested membrane is the same as that used in our previous study [9].

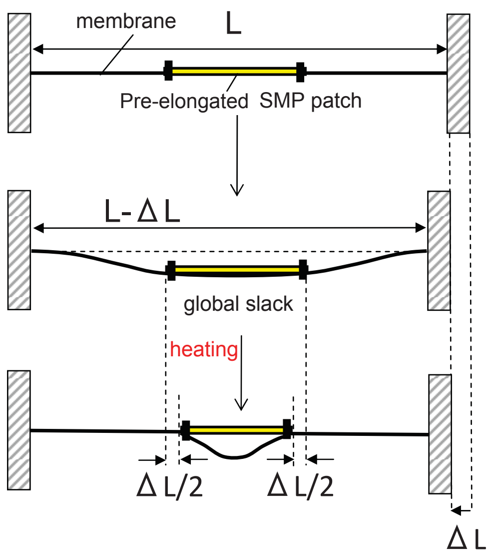


Fig. 1: Concept of the shape control by SMP film on the membrane surface.

2. Shape Control Experiments

In order to evaluate the effect of the shape recovery of the SMP films, we have conducted an experiment using a square membrane supported at four corners as shown in Fig. 2

2.1. Experimental Setup

Figure 2 shows the experimental setup, which includes a square membrane, a support jig, a laser displacement sensor (KEYENCE, LK-G80) controlled by a two-axis sliders (EZSM3E060MK(for vertical), EZSM4E050MK (for horizontal)), and some weights for tensioning the membrane. The tension is given at the four corners of the membrane, where $T_1 = 9.54$ [N] and $T_2 = 1.74$ [N], respectively.

In this experiment, we examine the effectiveness of our concept that described in the previous section by comparing the out-of-plane displacement of the square membrane. The displacement is measured at every 5 mm in the x-coordinate (horizontal) and 0.1 mm in the y-coordinate (vertical) before and after the control by the SMP films. These resolutions were determined because the variance of the out-of-plane displacement along the y-direction is larger than those along x-direction for the combination of T_1 and T_2, where $T_1 > T_2$.

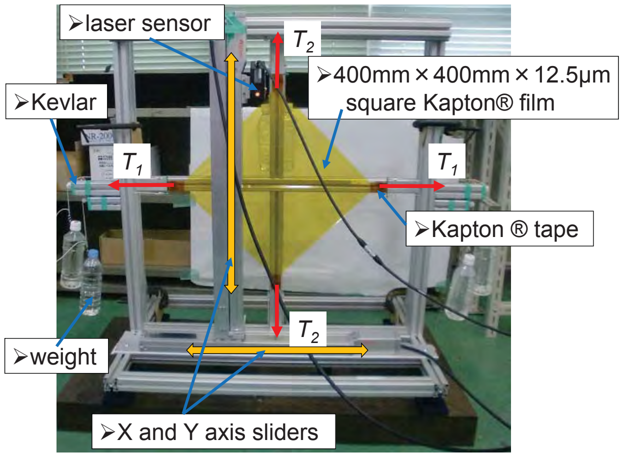


Fig. 2: Experimental setup for wrinkle/slack control experiments.

The shape recovery force of the SMP films that have the pre-elongated part is applied to the membrane so that the distribution of the tension in the membrane can be changed to control its out-of-plane displacement.

To evaluate the SMP films for shape control of the membrane, we used a configuration shown in Fig. 3. There are four SMP films where the total area of them is only about 0.3 % of the square membrane. On the other hand, the total mass of the four films is about 2 % of the whole mass, which can also be reduced by using thinner SMP films.

Other necessary instrument for this experiment that is not shown in Fig. 2 is a heater of the SMP films above glass transition temperature (T_g). We used a halogen lamp heater (Fintech Co. Ltd, HSH-35) as shown in Fig. 4 because it can heat the SMP films above T_g without contact. The distance between the lamp and the surface of the membrane was adjusted to about 30 mm and the applied voltage was 14 V. The heating is stopped when the shape recovery of the SMP film or the response of the membrane seems to be completed. These conditions were determined by other shape recovery experiments on the SMP film itself.

It is noted that SMP film was put on one side of the membrane by a double-face Kapton tape, and the heating and measuring the out-of-plane displacement are performed on the same side.

2.2. Experimental procedure

In order to evaluate the response of the out-of-displacement with respect to the shape recovery of the SMP film at four different locations, the distribution of displacement is measured as following procedures:

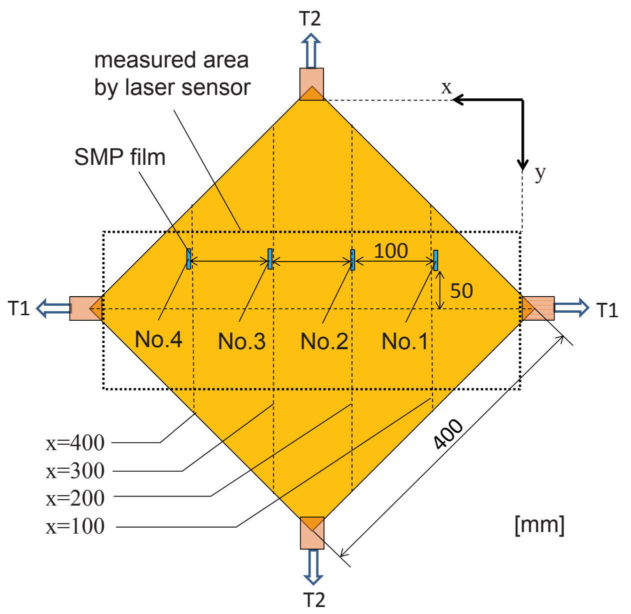


Fig. 3: Square membrane subject to tensile forces $T_1 = 9.54$ [N] and $T_2 = 1.74$ [N] and the locations of the four SMP films

1. Measure the out-of-plane displacement, z_0.
2. Heat the SMP film No.1 up to T_g and stop heating when the behavior of the SMP film and membrane seems to be equilibrium condition.
3. Measure z_1.
4. Heat up the SMP film No.2 and measure z_2.
5. Heat up the SMP film No.3 and measure z_3.
6. Heat up the SMP film No.4 and measure z_4.

Figure 5 also show how to move the halogen lamp in the experiments since only one halogen lamp was used to heat

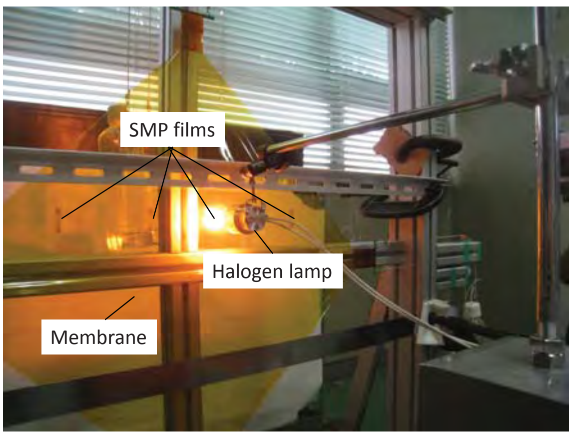


Fig. 4: Set up of the halogen lamp for heating the SMP film. (SMP film No.2 is being heated)

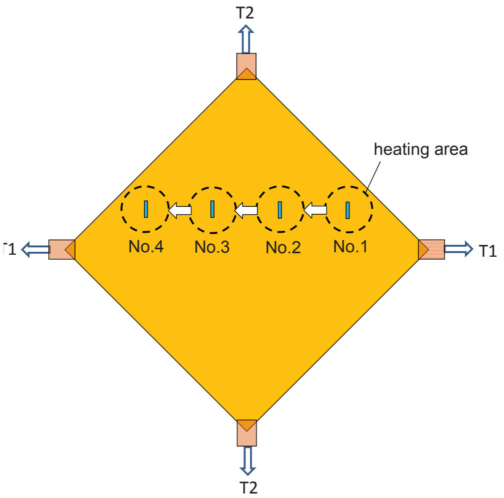


Fig. 5: Heating sequence in experiments.

the SMP film in this experiment. Because of the property of the used halogen lamp, we have confirmed by other experiments that only small circular area like the dotted line in Fig. 5 near the SMP film is heated above T_g. Figure 4 also shows that the SMP film No. 2 is heated by the lamp.

Table 1: Dimension and properties for SMP film.

Papameter	Unit	Value for
length	mm	26
width	mm	5
thickness	μm	100
pre-elongation	mm	6
glass transition temperature	$^\circ$C	65

2.3. Properties of SMP film

The properties of the SMP film (SMP Technologies Inc.) are shown in Table 1. The length of the SMP film shown in Table 1 includes a pre-elongated part that was given before the experiment. It is also noted that each end of the SMP film whose length is 6 mm are attached to the membrane by a double-face Kapton tape. Thus, the effective area of the SMP film is about 14 mm since 12 mm of the both ends is corresponding to the Kapton tape and cannot effectively contract due to the stiffness of the Kapton tape.

3. Results and discussions

This section describes the effect of the SMP film on the displacement of the square membrane. Only the limited area, which is from $x = 0$ to $x = 500$ mm and from $y = 150$ mm to $y = 350$ mm was selected to be measured as shown in Fig. 3.

3.1. Distribution of displacement after heating SMP films

Figures 6 (a)–(d) show the displacements at the lines of $x = 100$ mm, $x = 200$ mm, $x = 300$ mm, and $x = 400$ mm. Figure 6 (a) shows that the out-of-plane displacement due to the wrinkling from $y = 200$ mm to $y = 225$ mm became more flat by the shape recovery of the SMP film. At the same time, large displacement that may be equivalent to a local buckling of the membrane was observed that is ranging from $y = 175$ mm to $y = 190$ mm in Fig. 6 (a). Because the y-coordinate of the center of all the SMP films is 187 mm, the local buckling observed in Fig. 6 (a) is probably due to the compressive reaction force given by the SMP film No. 1 as described in Fig. 1. Such local buckling behavior was also seen in Figs. 6 (b) and (d) (i.e., the plot after control of SMP No.4), but Fig. 6 (c) does not indicate any clear local buckling.

Figure 6 (d) also shows that the displacement at an interval from about $y = 170$ mm to $y = 190$ mm was decreased after the SMP film No.1 was heated. In other words, the sensitivity of the displacement at $x = 400$ mm with respect to the force applied by the SMP film No.1 was relatively large. This behavior was not found in our previous study [9].

In addition, Figs. 6 (a) and (d) showed slight change of displacement from $y = 300$ mm to $y = 350$ mm. However, in Figs. 6 (a) and (d), the displacement from $y = 250$ mm to $y = 350$ mm was not changed clearly even though the force by the SMP film was applied.

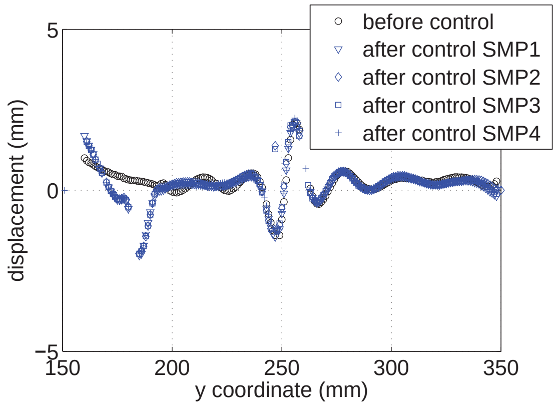
The whole view of the out-of-plane displacement distribution is shown in Figs. 7 (a)–(e). The symbol, **+** in Fig. 7 is the location of the center of the SMP film. Figure 7 (b) shows that the area near the SMP film No. 1 pointed by the black arrow became more flat. This behavior is also shown in Fig. 7 (e).

On the other hand, in Fig. 7 (c), a new wrinkle pointed by the black arrow can be seen, which may be generated by the compressive force given by the SMP film No.2. On the contrary, in Fig. 7 (d), no new wrinkle or change of the distribution of the displacement near the SMP film No.3 was observed. Hence, it can be explained that the SMP film No.3 did not provide enough force to the membrane after heating SMP film No.3.

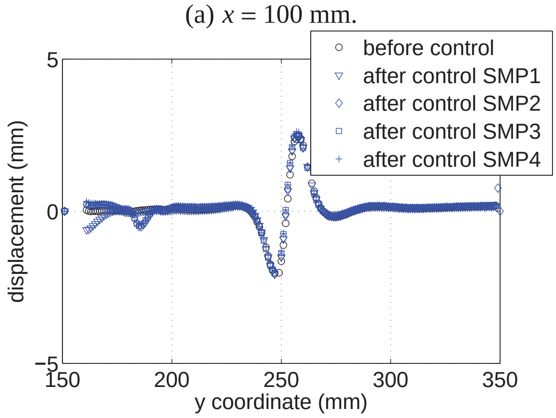
The observed behavior in Figs. 7 (c) and (d) is very interesting because the SMP films No.2 and No.3 were symmetrically located on the membrane to the diagonal line in y-direction, but the distribution of the displacement became asymmetric to the diagonal line. In other words, simultaneous heating of SMP films No. 2 and No. 3 may lead to a symmetric distribution of the displacement; this should be examined by performing additional experiments or numerical analyses.

3.2. Discussion on the sensitivity of displacement with respect to SMP films

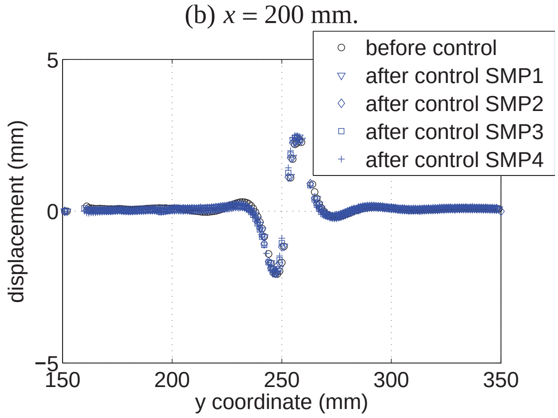
If one needs to optimize the location of the SMP films to get a better shape control capability, the sensitivity of the displacement with respect to the SMP film at arbitrary lo-



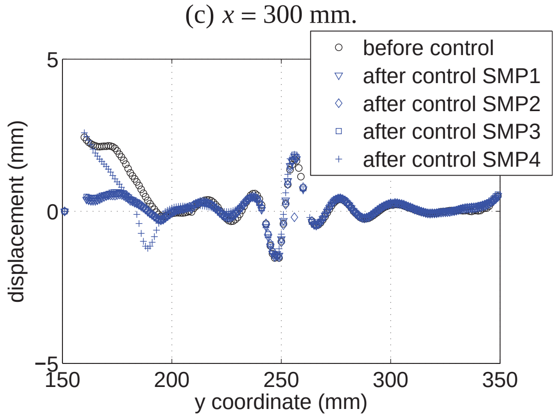
(a) $x = 100$ mm.



(b) $x = 200$ mm.

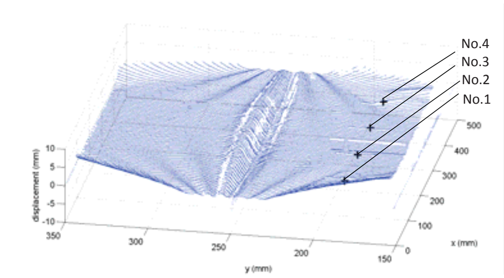


(c) $x = 300$ mm.

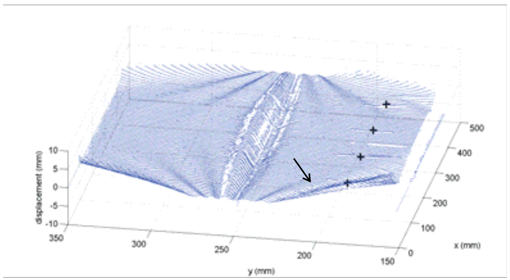


(d) $x = 400$ mm.

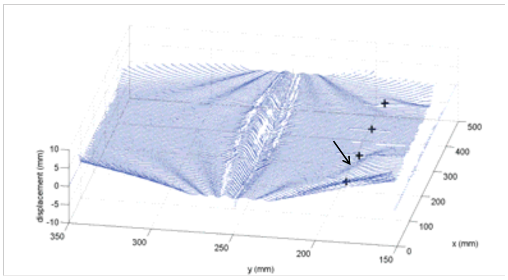
Fig. 6: Measured displacement distributions along y-axis for four different positions.



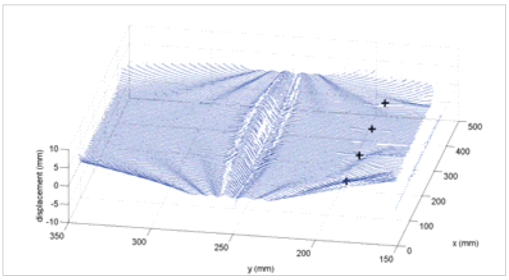
(a) z_0, before control.



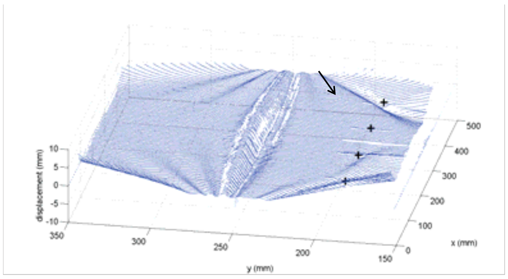
(b) z_1, after control of film No.1.



(c) z_2, after control of film No.2.

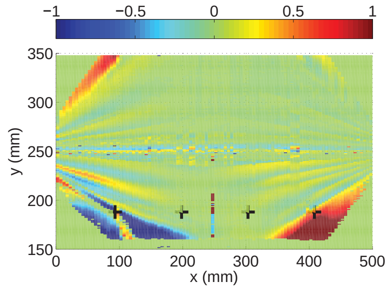


(d) z_3, after control of film No.3.

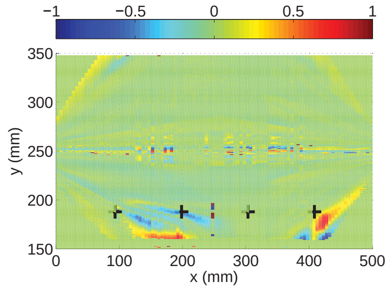


(e) z_4, after control of film No.4.

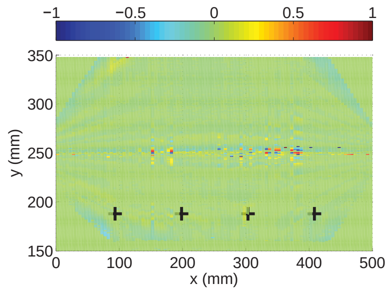
Fig. 7: Comparison of measured out-of-plane displacement before and after heating SMP films.



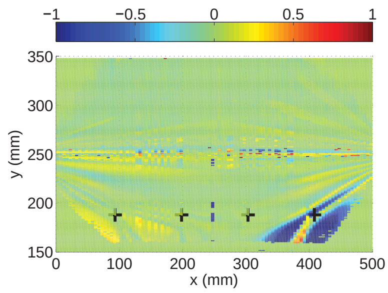
(a) $|z_0| - |z_1|$.



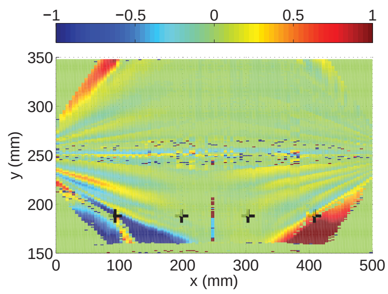
(b) $|z_1| - |z_2|$.



(c) $|z_2| - |z_3|$.



(d) $|z_3| - |z_4|$.



(e) $|z_0| - |z_4|$.

Fig. 8: Comparison of difference out-of-plane displacements before and after heating each SMP films.

cations have to be considered. Although Fig. 7 (a)–(e) can indicate that the displacement of specific areas can be controlled by the SMP films than others, more convenient way is to see the difference between the displacement for each figure. Thereby, we calculated the change in absolute value of the displacement every after heating of one SMP film.

As a result, Figs. 8 (a)–(e) were obtained, where the color scale for each figure was set between -1 mm to 1 mm. Each figure shows the difference of the displacement calculated by $\delta z = |z_i| - |z_{i+1}|$ (i = 0, 1, 2, 3), that is, a difference between the absolute value of the displacement before and after $i + 1$th SMP film is heated. Note that the symbol, **+** in Fig. 8 is the location of the center of the SMP film and Fig. 8 (e) is the difference between the initial and the last states.

Each result in Fig. 8 shows that red areas can be seen near the edge of the membrane and wrinkling areas. At the same time, blue areas, where the absolute value of the displacement increased, can also be seen in the near areas to the red areas because the displacement at wrinkling area with a bias displacement was increased when the membrane became more flat after heating the SMP film.

From Figs. 8 (b) and (c), it is apparent that the effects of the SMP films No.2 and No.3 were smaller than others since green areas were widely distributed. This fact indicates that the sensitivity of the displacement with respect to the SMP films No.1 and No.4 are higher than those with respect to the SMP films No. 2 and No. 3. In other words, the number of SMP films can be reduced while keeping almost same performance or the location of them can be optimized to get a better performance with four SMP films.

In addition, the green areas where less change of the displacement occurred were widely distributed especially in the area from y = 250 mm to y = 500 mm since there is no SMP film in this area. It is noted that the green areas include the areas that do not have to be controlled by the SMP films because the original displacement as initial state was small enough to be ignored.(e.g, Fig. 6 (c)) For the shape control of other areas with relatively less sensitivity, more SMP films at different locations need to be attached; however an appropriate method based on additional experiments or nonlinear analyses needs to be developed, which will be presented in our future study.

4. Conclusions

We conducted experiments to examine the effect of the location of the SMP films and their heating sequence on the shape control performance for the square membrane. Four SMP films with pre-elongation were attached on the square membrane that was supported at four corners. Each film was sequentially heated and the out-of-plane displacement was measured every after heating one of the films. As a result, the observed displacement distribution of the membrane was asymmetric to a diagonal line in the y-direction although the four films were symmetrically located on the membrane to the diagonal line. Therefore, the effect of the SMP films on the shape control of the membrane was complicated depending on heating sequence of SMP films. Also, the results showed that the sensitivity of the displacement of the membrane with respect to the two of four SMP films, which were located near the diagonal line, were less than others. These results observed in the experiments are very useful to investigate optimization of the location, the number, and their heating strategy to obtain better shape control performance.

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