Wrinkle/Slack Control Using Shape Memory Polymer Films for Large Membrane Structures

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Atsuhiko Senba[*], Yoshiro Ogi[†], and Nozomu Kogiso[‡]

[*]*Composite Engineering Research Center, Nagoya University, Nagoya 464-8603, Japan*

[†]*Institute of Industrial Science, the University of Tokyo, Tokyo 153-8505, Japan*

[‡]*Department of Aerospace Engineering, Osaka Prefecture University, Osaka 599-8531, Japan*

This paper shows experimental results for demonstrating the shape control of the large membrane structure to reduce the wrinkling or slacking area by a small patch-type shape mempry polymer films. Each film is given to 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. The results of measurement of the out-of-plane displacement of the square membrane indicated that this method worked well especially for a specific area.

I. Introduction

In large space systems that use large, lightweight structures, the folding and the deployment technologies of the ultra-thin films (membranes) are indispensable. The applications of such structures can include solar sails, large space reflectors, and space solar power satellites (SSPS). The folding methods of large membranes definitely require a folding theory and its implementations that relies on the point of view of mathematical aspect. Furthermore, deploying methods for the membrane that can achieve a high deployment ratio without damaging the membranes have been investigated.

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 in the next section (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. Of course, 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

[*]Assistant Professor, Composite Engineering Research Center, Furo, Chikusa, Nagoya 464-8603, Japan. Senior Member AIAA.
[†]Project Lecturer, Department of Human and Social Systems, 4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan. Member AIAA.
[‡]Associate Professor, Department of Aerospace Engineering, 1-1 Gakuen, Naka, Sakai, Osaka 599-8531, Japan. Member AIAA.

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].

Not only the shape recovery characteristics but also the shape fixation capability of the SMPs have attractive advantages for both the storage and the shape control of the membranes. Because the deformation of the SMPs can be kept without any external force under glass transition temperature, the fixed shape with a given deformation is used as a stowed configuration. Also, once the control of the shape of the membranes is completed, the shape can be fixed without any holding force as well. Thus, the SMPs also have an advantage from the point of view of the energy saving. Furthermore, the shape fixation can be performed multiple times by repeats of heating and cooling.

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].

The objective of this study is to extend our previous preliminary investigation [8] that indicated the novel concept of the shape control of membrane structures by SMPs. Let us consider a one-dimensional membrane with a SMP actuator (patch) fixed on the surface of it as shown in Fig. 1, which is a simplified model for large membrane structures. The specific boundary condition of the membrane is not assumed here. We assumed that the support structure of the membrane are slightly deformed from the ideal one due to manufacturing errors, aging and creep effects during the mission in space. In this case, a distance between each support end decreases and it is assumed to be ΔL. Then, a large deformation can occur due to lack of the tension of the membranes. We try to use the SMP films installed before launch where a pre-elongated part is given to change the stress filed of the membrane so that the slack is reduced.

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.

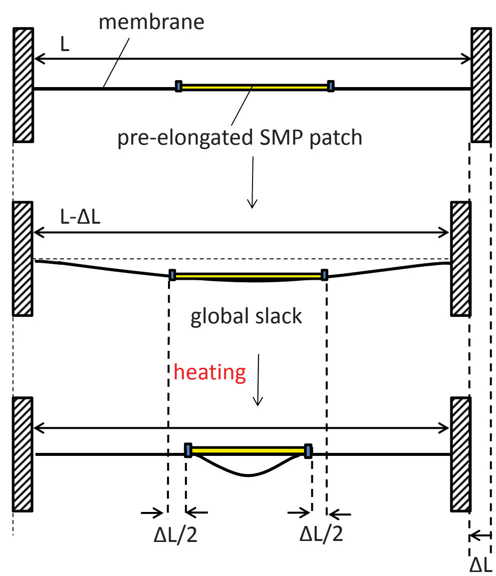


Figure 1. Concept of the shape control by SMP film on the membrane surface.

Although the possibility of the proposed concept has been shown by our previous work, a two-dimensional distribution of the deformation after the control by the multiple SMP films has not yet been investigated. Therefore, this paper uses a square membrane that has a stress distribution making both wrinkling and slacking areas. The details in the experimental procedure will be explained in the next section.

II. Wrinkle/Slack Control Experiments

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

A. 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

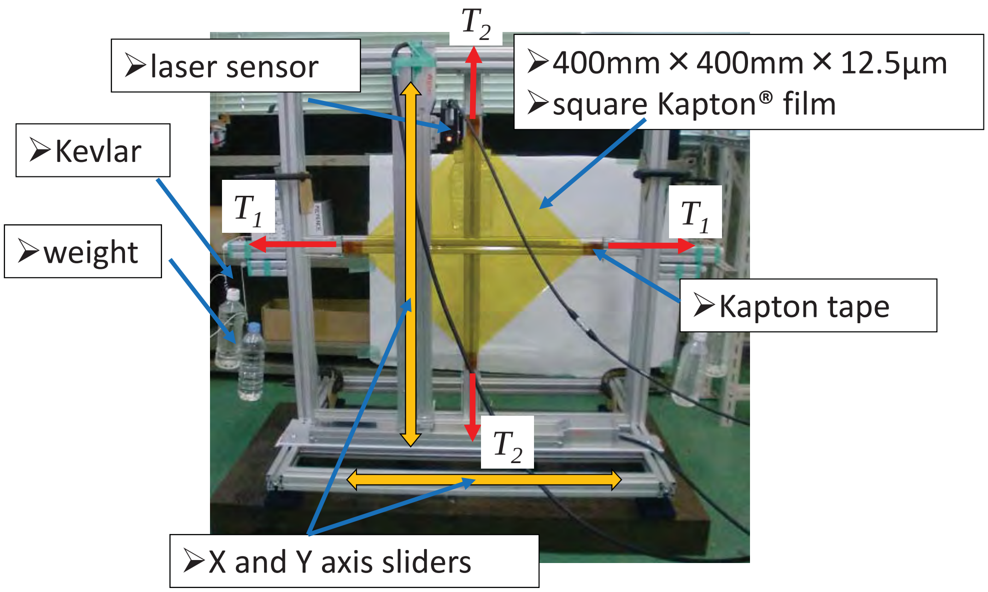


Figure 2. Experimental setup for wrinkle/slack control experiments.

larger than those along x-direction for the combination of T_1 and T_2, where $T_1 > T_2$.

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 wrinkling and slacking areas in the membrane, we used a configuration shown in Fig. 3(a) and (b), respectively. There are four SMP films for each configuration, where the total area of them is only about 0.3 % of the square membrane.

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, heating period, and the applied voltage were adjusted to about 30 mm, which was 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.

Table 1. Dimension and properties for SMP film.

Papameter	Unit	Value for wrinkle control	Value for slack control
length	mm	26	26
width	mm	5	5
thickness	μm	100	50
pre-elongation	mm	6	6
glass transition temperature	°C	65	55

B. Properties of SMP film

The properties of the SMP film 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. For the wrinkle control, the thickness of the SMP film for each

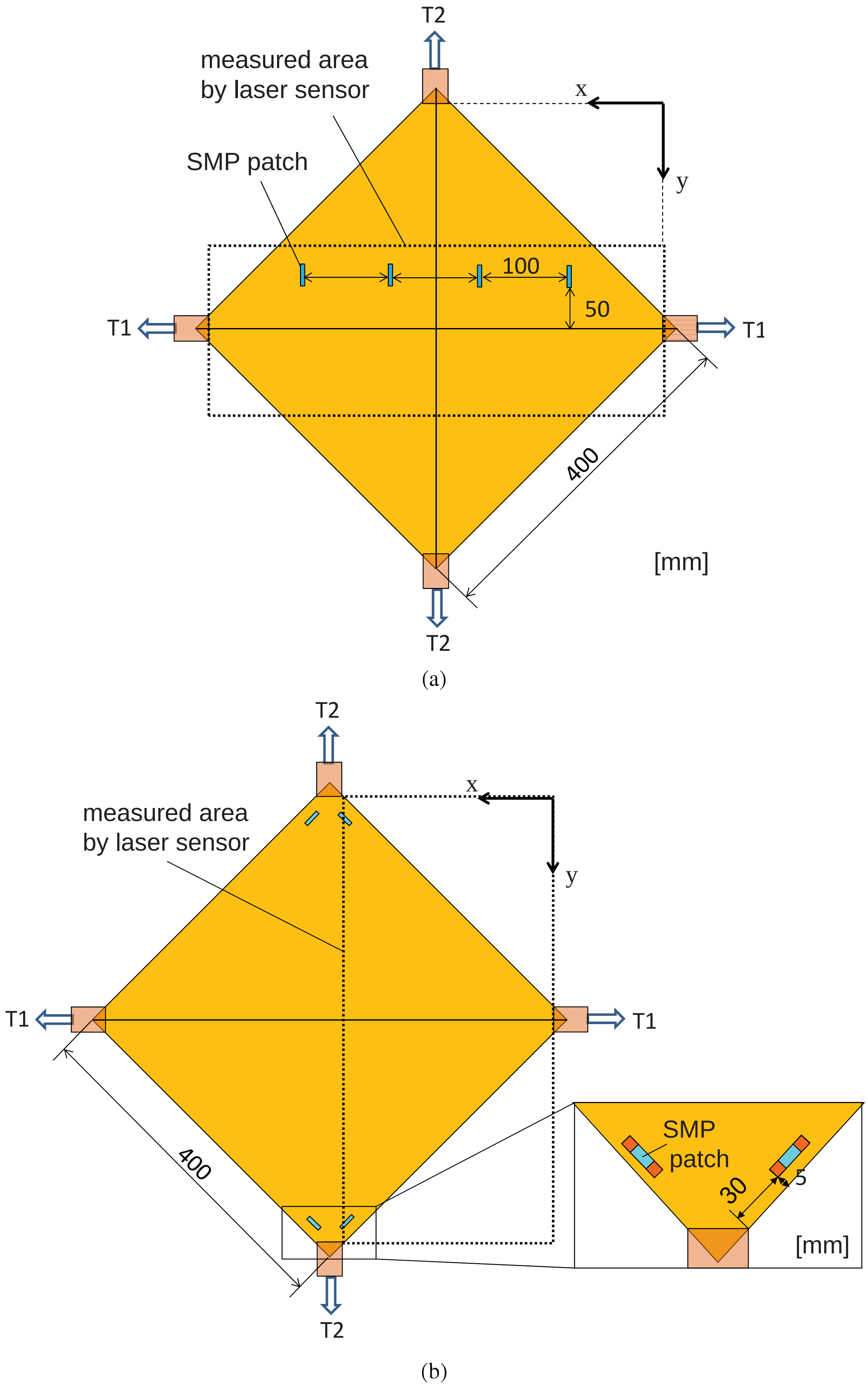


Figure 3. Square membrane subject to tensile forces $T_1 = 9.54$ [N] and $T_2 = 1.74$ [N] and the locations of the four SMP films: (a) for a wrinkle control experiment; (b) for a slack control experiment.

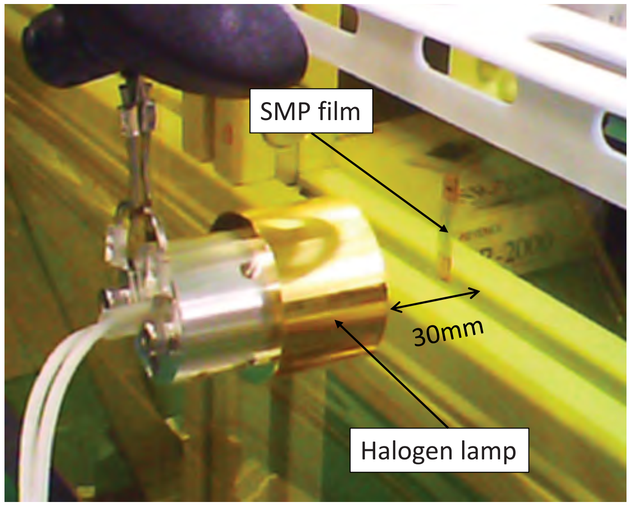


Figure 4. Photograph of halogen lamp for heating the SMP film.

experiment is different because larger force may be required to change the stress distribution in the wrinkling area than that to change the stress in the slacking area.

C. Results for wrinkle control

This section describes the effect of the SMP film on the reduction of the wrinkling area. 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.

Figure 5 shows the displacements at the line of $x = 50$ mm, $x = 100$mm, $x = 150$ mm, and $x = 200$ mm. The out-of-plane displacement due to the wrinkling at $y = 225$ mm was clearly reduced by the shape recovery of the SMP film. At the same time, large displacement can be observed that is ranging from $y = 150$ mm to $y = 200$ mm for the data after the control. However, this phenomena have not yet been fully analyzed.

On the other hand, it is interesting that the displacement in the specific area from $y = 250$ mm to $y = 350$ mm was not changed clearly even though the force by the SMP film was applied.

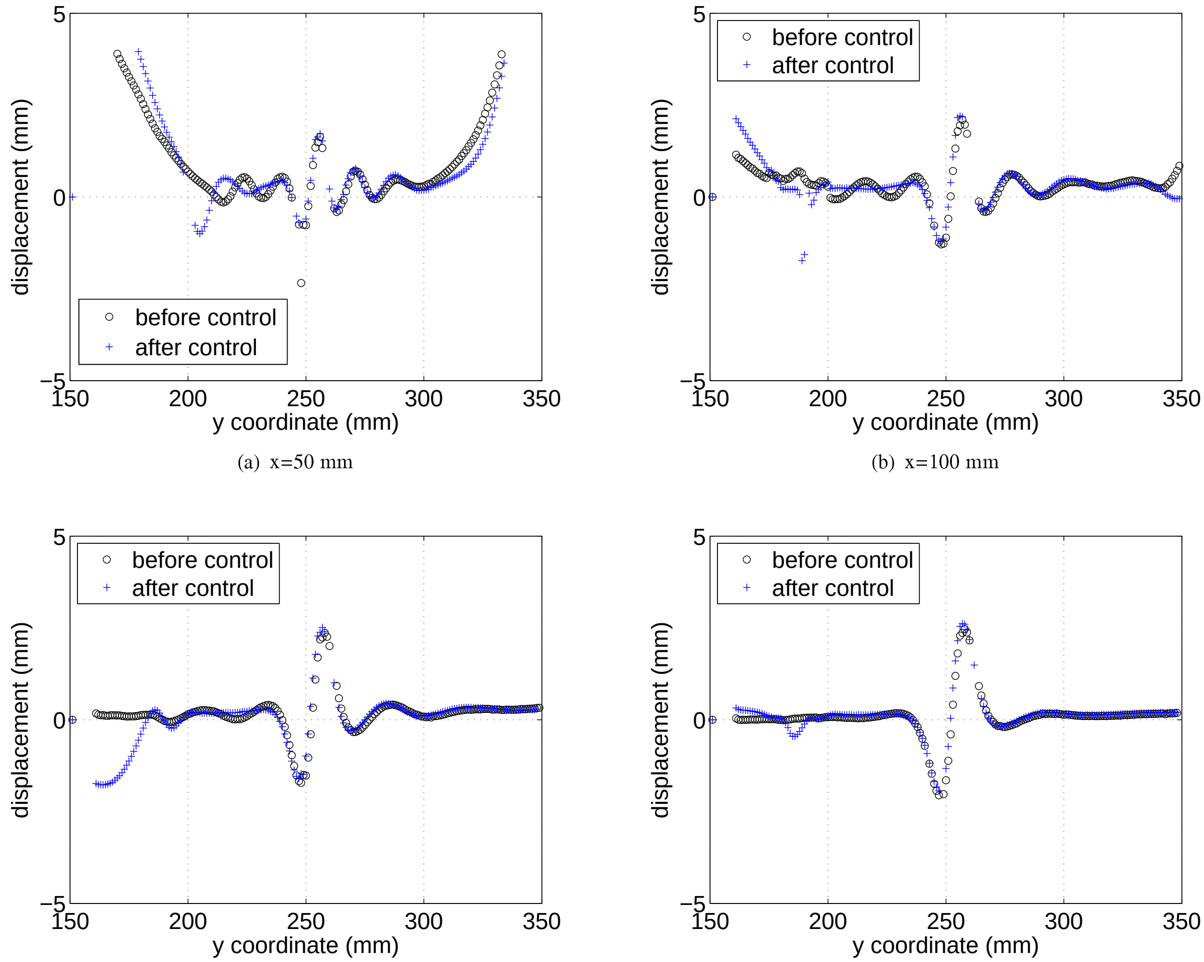
The whole view of the out-of-plane displacement distribution can be shown in Fig. 6. The symbol, $+$ in Fig. 6 is the location of the center of the SMP film. Although the reduction of the largest wrinkle along the diagonal line was not observed, the other part near the SMP film pointed by the black arrow became more flat as shown in Fig. 6. Figure 6 (c) shows the three areas that is categorized into (1) $\delta z > 0.1$ mm denoted by black areas, (2) $\delta z < -0.1$ mm denoted by gray areas, and (3) $|\delta z| \leq 0.1$ mm denoted by white areas, where $\delta z = |z_{before}| - |z_{after}|$, that is a difference between the absolute value of the displacement before and after the control. The categories (1) and (2) were distributed near the edge of membrane and near the SMP films. On the other hand, the category (3) was distributed especially in the area from $y = 250$ mm to $y = 350$ mm.

Because the present locations of the SMP film were not optimized to reduce the amount of the wrinkles in the membrane, the performance can be improved to get a better reduction of the specific wrinkling area.

D. Results for slack control

Next, we show the effect of the SMP film for slacking areas along the edge of the membrane, where the tension is almost zero even though the forces, T_1 and T_2 are applied at the four corners. As well as previous experiment, the limited area from $x = 0$ to $x = 250$ mm and from $y = 0$ to $y = 535$ mm was measured. The measured area is also shown in Fig. 3(b) which is a rectangular area defined by the dotted line. The specific configuration of the SMP film was determined by considering the less-tensioned area near the edge of the membrane.

Figure 7 shows the out-of-plane displacements along the y-coordinate at $x = 50$ mm, $x = 100$ mm, $x = 150$ mm, and $x = 200$ mm. It is clear that the large out-of-plane displacement at both edges of the membrane was decreased as shown in Figs. 7 (a)-(c). For example, the displacement at y=200 mm before the control in Fig. 7 (a) was changed from -2.7 mm to -1.9 mm after the control.



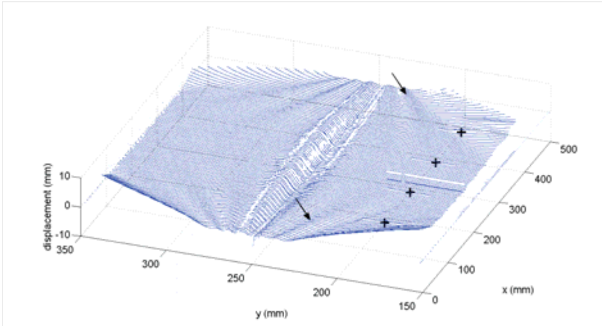
(a) x=50 mm

(b) x=100 mm

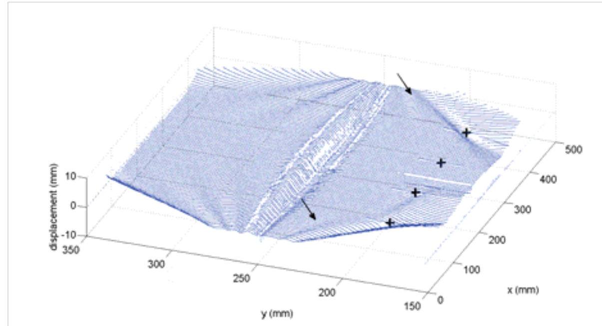
(c) x=150 mm

(d) x=200 mm

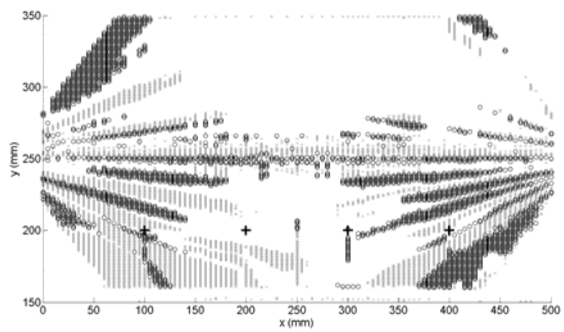
Figure 5. Results for wrinkle control.



(a) before control



(b) after control



(c) difference

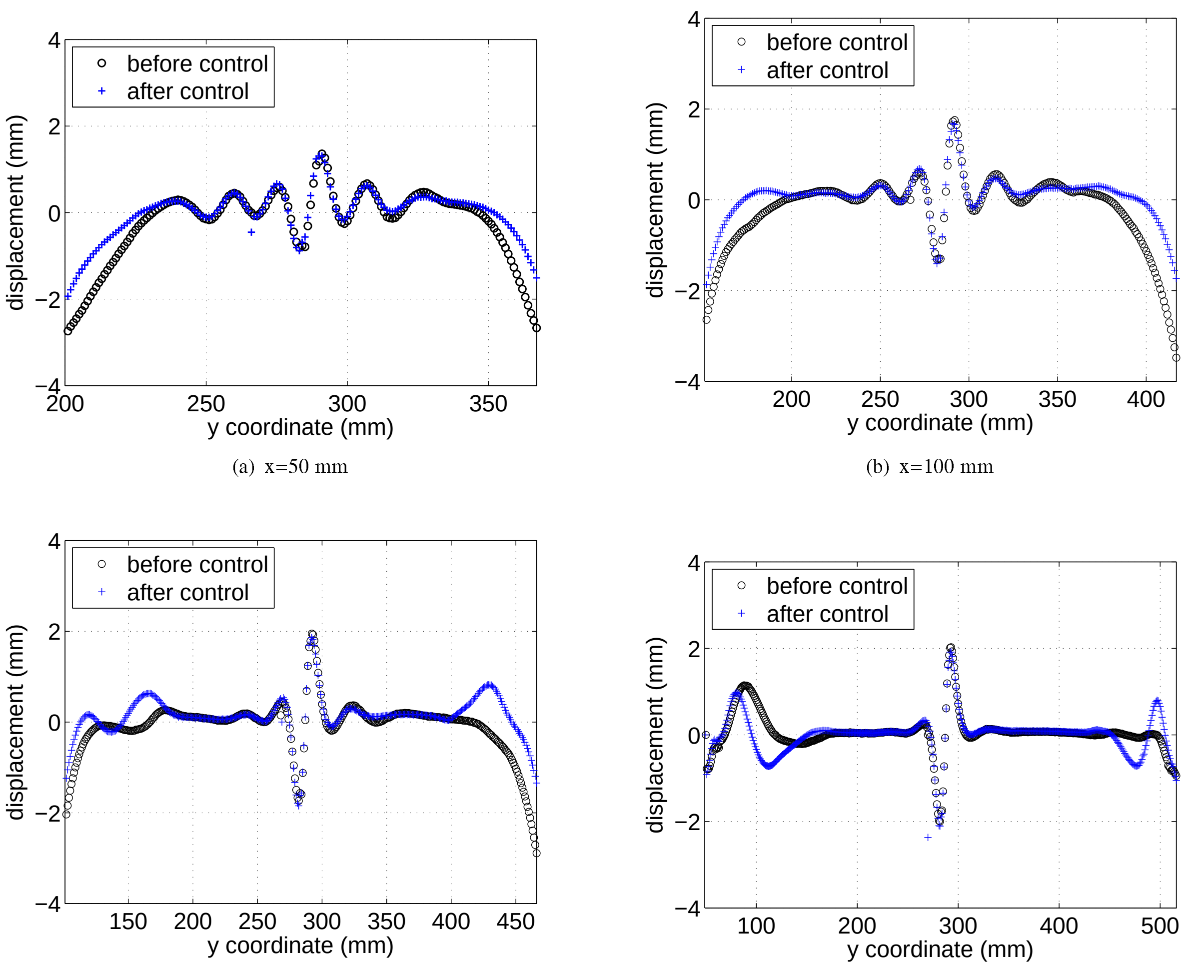
Figure 6. Comparison of measured out-of-plane displacement before and after wrinkle control by SMP.

The displacement was reduced by approximately 30 to 40% compared to them before the control at x = 50 mm, x = 100 mm, and x = 150 mm. At the same time, another large wrinkling area appeared after the control for the results of x = 150 mm and x = 200 mm. This is due to the local out-of-plane deformation (buckling) of the membrane that was caused by the compression force of the SMP film. Like the previous experiments, the location of the SMP film for slacking area should be optimized by considering the whole stress distribution in the membrane. Otherwise, this kind of shape control with SMP film is not always effective. We will focus on the optimal design for the SMP film that includes not only the location but also the number and the shape of them.

Finally, Fig. 8 (a) and (b) shows the distribution of the out-of-plane displacement before and after the control by the SMP film. The symbols, + denote the center of the SMP films. Figure 8 (c) shows the three areas that is categorized into (1) $\delta z > 0.1$ denoted by black areas, (2) $\delta z < -0.1$ denoted by gray areas, and (3) $|\delta z| \leq 0.1$ denoted by white areas, as well as Fig. 8. It can be seen in Fig. 8 (c) that the reduction of the displacement along the edge of the membrane was clear. On the other hand, the category (2) was also distributed near the edge of the membrane. This configuration of the SMP film was therefore effective only for the edge of the membrane.

III. Conclusions

We conducted basic experiments that demonstrate the effect of the SMP films on the wrinkle/slack control for the square membrane. The results showed that although the SMP films were very small compared to the square membrane, the effect of them on the shape of the specific area in the membrane were clear. In particular, out-of-plane displacement in the slaking area in the membrane was drastically reduced. On the contrary, the effect of the SMP films near the wrinkling area was localized in the region close to the SMP films. The current experimental results suggested that the location of the SMP films was significant to control the out-of-plane displacement of the square membrane. Therefore, we can consider the optimization of the locations of the SMP films by considering stress distribution in the membrane.



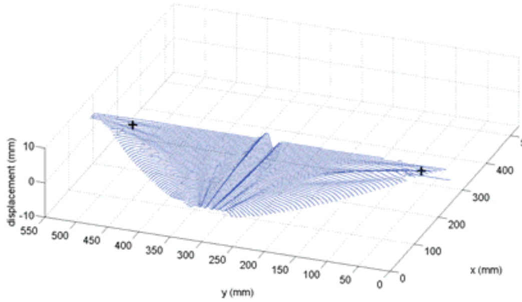
(a) x=50 mm

(b) x=100 mm

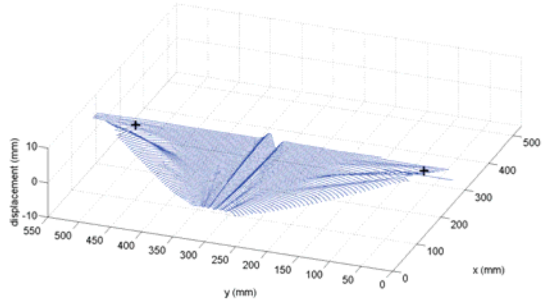
(c) x=150 mm

(d) x=200 mm

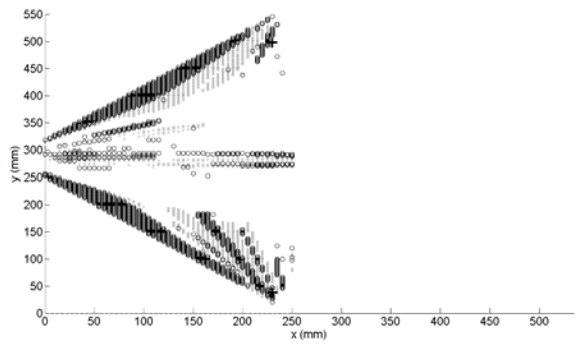
Figure 7. Results for slack control.



(a) before control



(b) after control



(c) difference

Figure 8. Comparison of measured out-of-plane displacement before and after slack control by SMP.

Acknowledgment

This work was partly supported by the grant for strategic research and development by ISAS/JAXA and JSPS KAKENHI(24760663).

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