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Research Paper

Analysis of Wrinkled Composite Membrane of Inflatable Antenna Using Shape Memory Alloy

Ankit Pandey[1*], V. Huzuer Saran[2], Suraj Prakash Harsha[2]

[1]Teaching Assistant, Vibration and Noise Control Lab., Mechanical and Industrial Engineering Department, Indian Institute of Technology, Roorkee, India

[2]Associate Professor, Mechanical and Industrial Engineering Department, Indian Institute of Technology, Roorkee, India

[*]Email of Corresponding Author: pandeyank@gmail.com

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Abstract

Wrinkling is a common phenomenon observed in thin membranes when subjected to different loading and boundary conditions. This paper presents the modeling and simulation of wrinkling patterns in the composite membrane using finite element analysis, in which a thin sheet of shape memory alloys (SMAs) material, is used. Shape memory alloys remember their shape even after plastic deformation. Initially, during the analysis a small uniform prestress is applied to the membrane, to stabilize it. Then in the next step of the analysis, we determine buckling mode-shapes of the prestressed membrane. In the next step, these modes are used as small, initial imperfections that trigger the formation of wrinkles in the preceding nonlinear geometric simulation. Thermal effect on the shape memory alloy sheet was considered after it has deformed/wrinkled and wrinkle characteristics are obtained. The result is then demonstrated by computing the characteristics of wrinkles in two membrane structures one without the shape memory alloy sheet and one with the shape memory alloy sheet. It has been observed that smart structure, shape memory alloy has an effective control of the wrinkle of the membrane.

Keywords

Wrinkling, SMAs, Composite Membrane, Buckling Mode Shape

1. Introduction

There has been increasing interest in the application of membrane structures in space, such as in inflation antennas, space telescope optics, solar sails, and synthetic aperture radar. A plate or shell structure that has zero bending stiffness is called a membrane structure. The inflatable structure is a thin film structure compactly packaged and expanded to the desired configuration by the internal gas pressure. But, the structures can be easily distorted and even collapsed by wrinkling. Membranes experience local buckling deformation which is usually defined as wrinkling Wrinkling can occur when a membrane structure is in shear due to boundary displacement, or an in-plane concentrated force is applied [1]. The presence of wrinkles in membrane structures may significantly influence the static and dynamic behavior of space systems containing membranes [2]. Their delicate nature makes them more susceptible to distortions caused by the various thermal and mechanical loadings in space environments. It is therefore essential to minimize such distortions to maintain the high accuracy of antenna measurements. Shape memory alloys have the capability of retaining their initial shape even after a large deformation, just by applying temperature effects. Shape Memory Alloys (SMA) with abilities to change their material properties such as Young's modulus, damping capacity, and the generation of large internal forces [3] when integrated with composite material structures allow active control of their static and dynamic behavior. Precise tuning of SMA components [4] enables control of certain static and dynamic characteristics of composite material structures such as maximum deflection and shape, natural frequencies and modes of vibrations, amplitudes of forced vibrations, or damping properties. A thorough study of the Shape Memory Alloys and their application to actuators for deployable structures also was done in another research [5]. Even though there have been many experimental as well as numerical studies of wrinkled membranes over the years[6-17], the research on the strategies to minimize or suppress membrane wrinkling remains limited. In this paper, modeling and simulation of the wrinkling pattern are done, and a shape memory alloy sheet made of Nitinol is used to suppress the membrane wrinkling up to a certain extent by applying a temperature field. Numerical modeling and simulation of a composite membrane made up of Kapton is done using ABAQUS 6.13. This paper is organized as follows. Section 1 gives a brief introduction to the membrane structure and wrinkling causes. It also gives a brief introduction to shape memory alloys and their properties. Section 2 deals with the numerical modeling and applied boundary condition on membrane structures with and without the use of an SMA sheet. Section 3 describes the results and discussion. Section 4 gives the conclusion.

2. Modeling and simulation of the rectangular membrane

2.1 Numerical modeling

ABAQUS finite element software is used to obtain the wrinkle profiles for membranes with and without the use of a shape memory alloy sheet. The schematic representation of the rectangular membrane and the shape memory alloy configurations studied are shown in Figure 1(a)

Figure 1. (a) Dimension of Rectangular Membrane (Kapton) Figure 1(b) Sandwich Model

In this model shape memory alloy sheet is sandwiched between the membrane layers (Figure 1(b)). Kapton membranes are considered for this numerical analysis as they are commonly used for space inflatable structures.

The properties of the Kapton membrane and Nitinol (shape memory alloy) which is used are listed in Table 1 and Table 2 respectively.

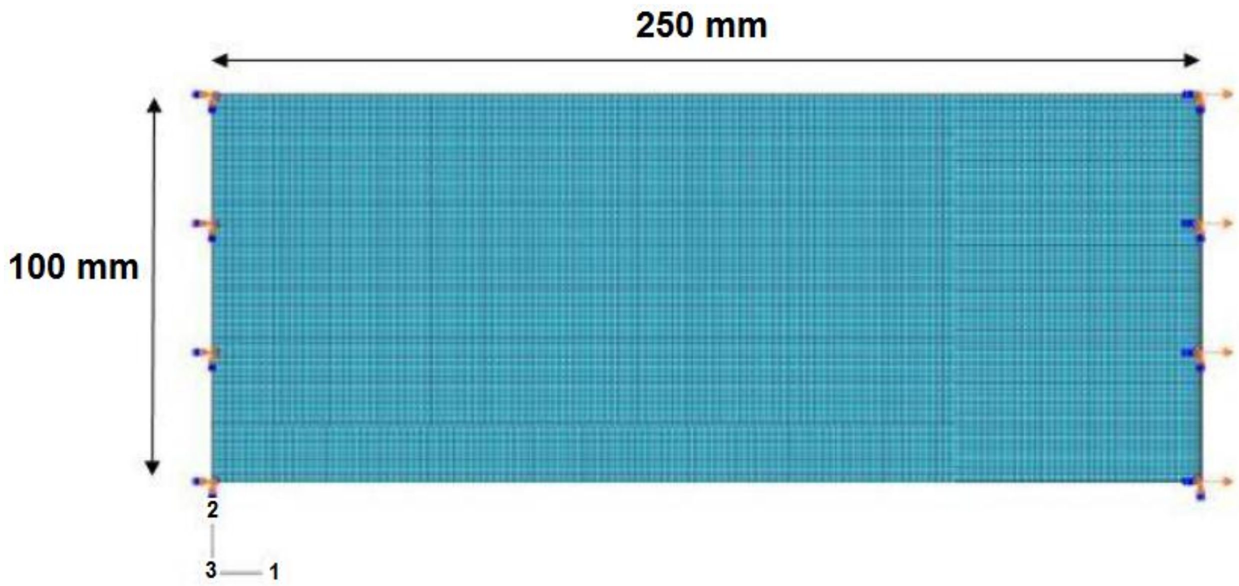

Figure 2. Boundary Condition and Mesh of the Finite Element Model

Figure 2 shows the finite element mesh and the boundary conditions used for a preliminary analysis. The membrane contains 25,351 nodes and 25,000 S4R5 thin-shell elements. The left edge of the membrane was fully constrained in all its degrees of freedom by using the *BOUNDARY, ENCASTRE option in ABAQUS. On the right edge, only the translation in the *x*-direction was allowed. The top and bottom edges are free edges. This set of boundary conditions remained active in all analysis steps.

2.2 Analysis Procedure

Figure 3 shows the flow chart for wrinkling analysis using a thin shell model.

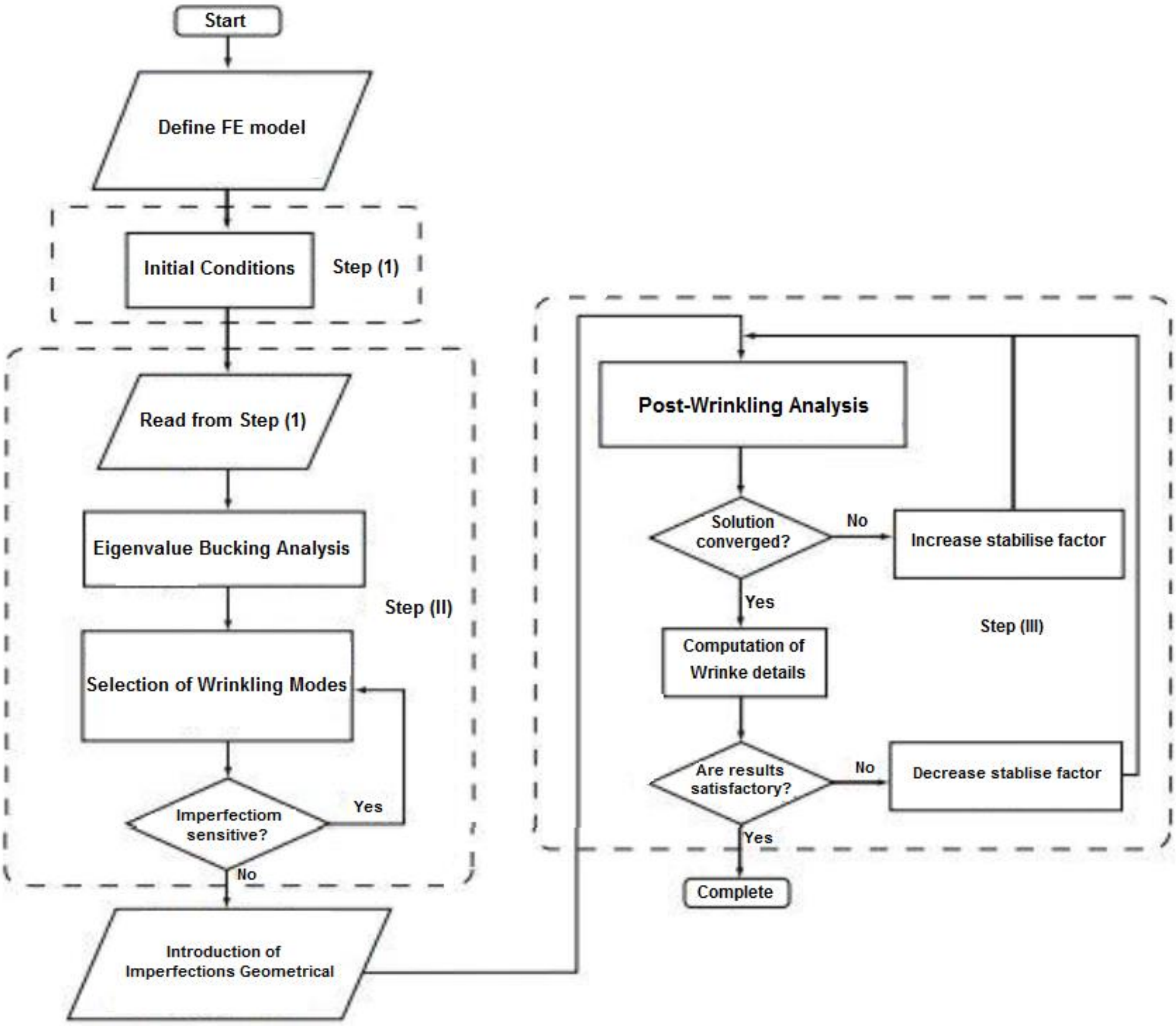

Figure 3. Flow chart for wrinkling analysis using thin shell model

2.3 Simulation Details

Each simulation consisted of three steps, as follows. The initial step consisted of pre-tensioning the membrane by moving the right edge by 3 mm, in the y direction. Then, a geometrically nonlinear equilibrium check was performed. The geometric stiffness provided by the prestress has the effect of increasing the out-of-plane stiffness of the thin membrane. The only translation in the x-direction was allowed for the right edges, and all six degrees of freedom of the left edge were completely constrained. The other two edges are completely free. In the next step, an eigenvalue buckling analysis, which essentially is a linear perturbation analysis, was carried out with a prescribed horizontal displacement of 1 mm at the right edge as an incremental load. The model boundary conditions were modified in this step by using the *BOUNDARY, OP=MOD option in ABAQUS. The Lanczos solver was set such that only Eigen modes corresponding to the positive eigenvalues are computed. Several different combinations of Eigenmodes and scaling factors were considered to test the sensitivity of the model to the magnitude of the prescribed imperfections to be introduced in the detailed wrinkling analysis. For each set, a complete wrinkling analysis was carried out, which involved the creation of a new input file, with geometrical imperfections seeding to the pristine mesh by the *IMPERFECTION command. The stabilize function was activated to facilitate the solution. The final step consists of two analysis sub-steps. The first substep was similar to the initial pre-tensioning step as described earlier, but this time with the right edge only displaced by 0.1 mm to give an initial prestress of approximately 0.04 MPa. Note that in the initial step, a much higher prestress value was required to avoid many localized modes (noise) in the eigenvalue buckling analysis step. However, a smaller prestress was prescribed in the final analysis to provide sufficient initial out-of-plane stiffness to the membrane without affecting the final results. Then in the second substep, the right edge was translated longitudinally by applying a temperature field (which causes strain) while all the other degrees of freedom were constrained.

3. Result and Discussion

3.1 Results

The numerical analysis of membrane wrinkles in a rectangular membrane subjected to different temperature fields i.e. different planer strain values is discussed in this section. Two different configurations are presented one without the SMA sheet and one with the SMA sheet.

(a) *Membrane without SMA sheet*

The numerical solution results for a membrane without the use of an SMA sheet are presented here. The membrane is subjected to a temperature field after wrinkles occur on the surface. Figure 4 shows the numerical results for the wrinkle counterplots for the temperature field at 50, and 75,100 degrees respectively.

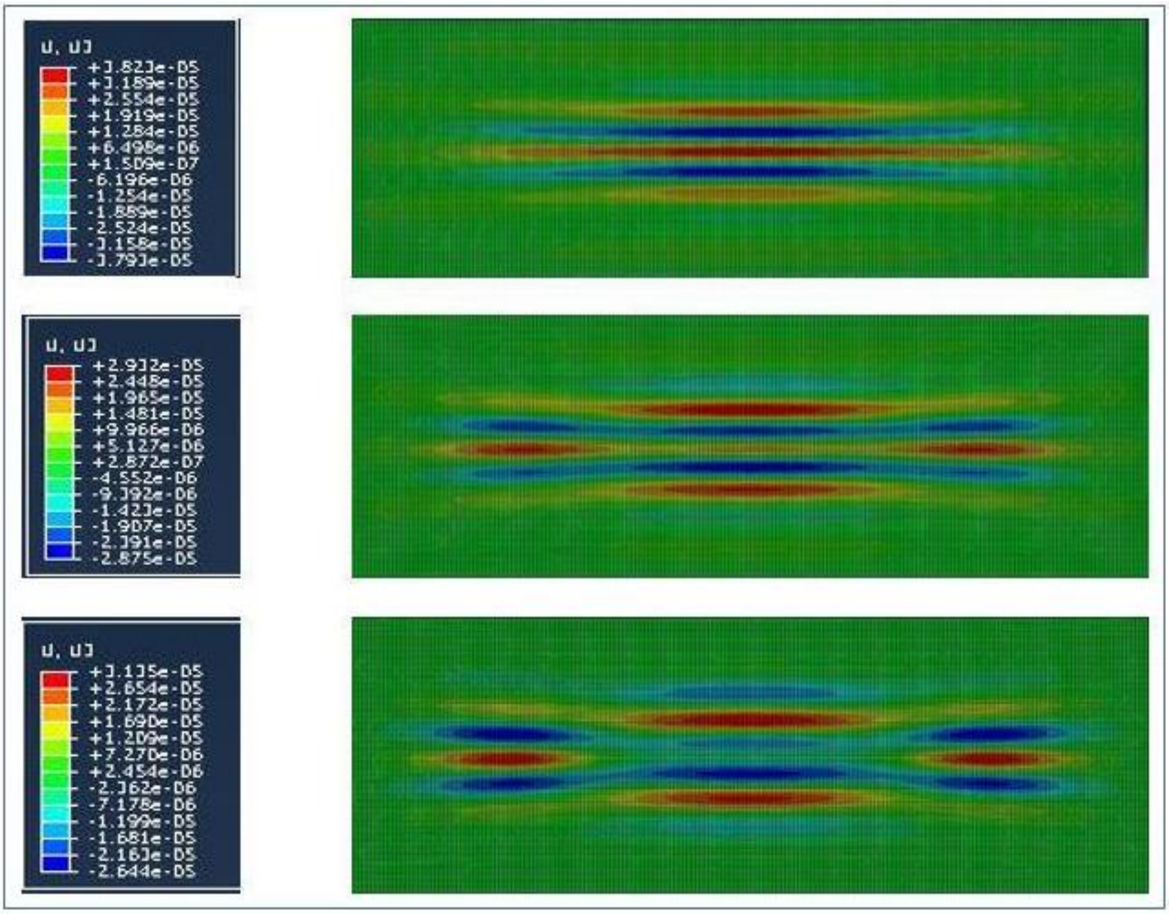

Figure 4. Numerical out-of-plain displacement of the membrane without SMA sheet at 50, 75, and 100 degrees respectively

(b) Membrane with SMA sheet

The numerical solution results for a membrane with an SMA sheet are presented here. The membrane is subjected to a temperature field after wrinkles occur on the surface. Figure 6 shows the numerical results for the wrinkle contour plot for the temperature field at 50, 75, and 100 degrees.

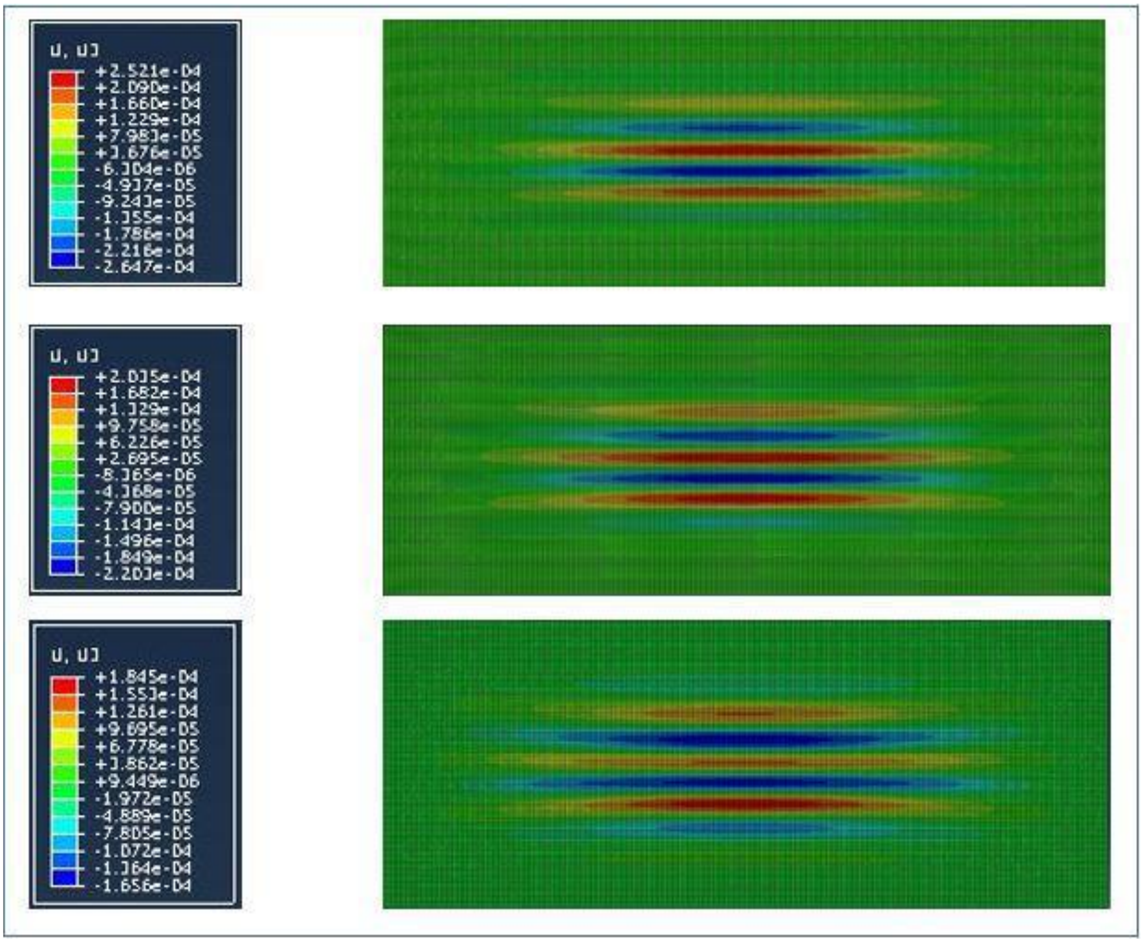

Figure 5. Numerical out-of-plan displacement of the membrane with SMA sheet at 50, 75, and 100 degree

3.2 Comparison and discussion of a rectangular membrane with and without the use of an SMA sheet

Comparing the results for the two cases discussed for the rectangular membrane with clamped-sliding boundary conditions, one can see that the membrane without an SMA sheet along the length experiences the largest wrinkle heights compared to the other membrane. From Figures 4 and 5 it can be also seen that no. of wrinkles on the membrane without an SMA sheet are more as compared to the membrane having an SMA sheet. Wrinkles are more spread across the width in the case of the membrane without an SMA sheet. It can be seen that when the temperature is increased from 50 degrees to 75 degrees the out-of-plane displacement of the membrane is also reduced in the case of Figure 5. Similarly, when the temperature is increased up to 100 degrees the out-of-plane displacement is reduced. From both figures, it can be seen that the out-of-plane displacement of the membrane having an SMA sheet is more than compared of the membrane without an SMA sheet. This is because when the SMA sheet is embedded between the membrane layers, the stiffness of the whole is increased.

4. References

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