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Wrinkling simulation of membrane structure

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Abstract: Due to a high ratio of load carrying capacity to self weight, membrane is widely used in various applications such as gossamer space structures One major design issue that is inherent to membrane structures is the formation of wrinkling patterns. In this paper, a geometrically nonlinear, updated Lagrangian shell formulation is employed using the ABAQUS finite element code to simulate the formation of wrinkled deformations in thin-film membranes. Two effective modeling strategies are introduced to facilitate convergent solutions of wrinkled equilibrium states. Several numerical studies are carried out, and the results are compared with recent experimental data. Good agreement is observed between the numerical simulations and experimental data.

Keywords: membrane, wrinkling, simulation

1. Introduction:

Due to a high ratio of load carrying capacity to self weight, membrane is widely used in various applications such as gossamer space structures, including NGST shield, solar sail and space inflatable reflector[1,2]. Because of the low bending stiffness, the wrinkles will occur when the membrane subjects to the action of the compressive stress. Wrinkling affects significantly the performance and reliability of the membrane. Therefore, the research on the wrinkling of membrane is essential.

Wrinkle is the major factor to be considered in the structural design and precision control. Tension Field Theory [3, 4] (TFT) is firstly used to analyze the in-plane stress and deformations in the wrinkled membrane structures with zero bending stiffness. By eliminating compressive stresses through a modification of the constitutive relations, TFT enables the prediction of the basic load transfer and wrinkle orientations in membranes; however, it cannot predict the out-of-plane wrinkled shapes, wavelengths, and amplitudes. Stein and Hedgepeth [5] explored a modified version of TFT by identifying partially wrinkled domains. Following their methodology, Miller and Hedgepeth [6] performed a finite element analysis using a recursive stiffness-modification procedure termed the Iterative Membrane Properties (IMP) method. The main utility of these TFT approaches is to enable adequate load-carrying predictions to be made and to enable the general regions where structural wrinkles develop to be identified. The major shortcoming of the TFT schemes, however, is their inability to predict the wavelengths and amplitudes of wrinkles. This shortcoming may be overcome by modeling thin-film structures using shell-based finite element analysis that includes both membrane and bending deformations.

In this paper, the wrinkled deformations in thin membrane is simulated using shell-based analysis. Several modeling ideas are explored for the purpose of aiding the geometrically nonlinear, updated Lagrangian shell analysis of thin-film membranes with emphasis on the wrinkled equilibrium/deformation state. Several numerical studies are carried out using the ABAQUS code. These studies include analyses of (1) a rectangular membrane loaded in shear, and (2) a square membrane loaded in tension by corner forces.

2. Analysis Framework and Modeling Strategies

Elastic, quasi-static shell analyses and parametric studies of thin-film membranes loaded in plane are carried out using the Geometrically Non-Linear, updated Lagrangian description of equilibrium formulation implemented in ABAQUS.

The selection of a four-node, shear-deformable shell element, S4R5, incorporating large-displacement and small-strain assumptions, is made because of the following considerations. The element is based upon Mindlin theory and uses C^0-continuous bilinear kinematics. To allow adequate modeling of thin-shell bending, the element employs reduced integration of the transverse shear energy and an ad hoc correction factor that multiplies the transverse shear stiffness. The latter device imposes the Kirchhoff constraints (i.e., zero transverse shear strains) numerically. Both of these “computational remedies” are intended to facilitate locking-free bending deformations in thin shells. To improve the element’s reliability, an hourglass control method is used to suppress spurious zero-energy (hourglass) modes that result from under-integrating the shear strain energy. Such low-order, C^0-continuous shell elements are commonly preferred for nonlinear analysis because of their computational efficiency, robustness, and superior convergence characteristics.

For a localized structural instability such as wrinkling, the ABAQUS code provides a volume-proportional numerical damping scheme invoked by the STABILIZE parameter. The stabilization feature adds fictitious viscous forces to the global equilibrium equations. This enables the computation of finite displacement increments in the vicinity of unstable equilibrium and thus circumvents numerical ill-conditioning due to stability issues. The default value of the stabilization parameter (2.0×10^{-4}) is used in the numerical examples that follow.

Next, quasi-static shell solutions for two thin-film membranes are discussed. The deformations in these membranes are associated with the highly nonlinear, low-strain-energy equilibrium states that possess structural wrinkles. Enabling modeling strategies for the solution of these computationally challenging problems are discussed.

3. Numerical example

3.1 Rectangular membrane analysis

This example is based on the experiment proposed in [7] to verify the numerical simulation. The model is a 2D rectangular membrane, which is fixed at lower ege while the upper one is allowed to move only in horizontal direction, whose horizontal displacement is $\delta = 3mm$, is simulated. The initial geometry of the model is a rectangular membrane with the properties shown in Table1(as shown in Fig.1).

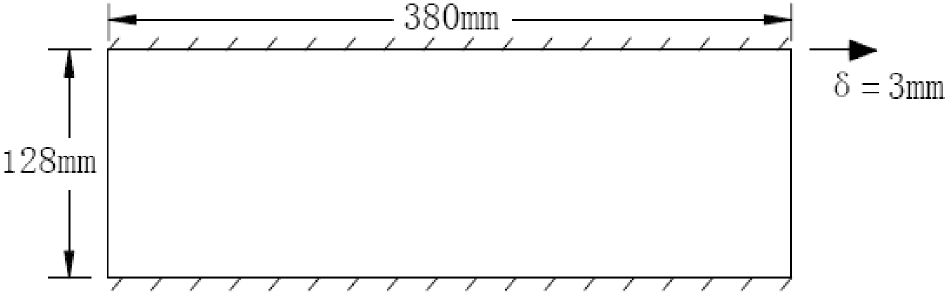


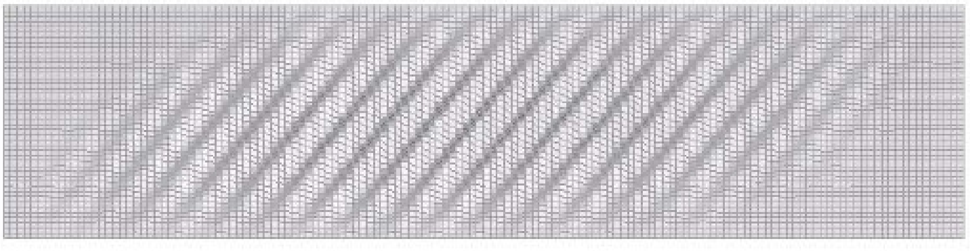
Fig.1 Rectangular membrane model

Table1: Properties of FE-models

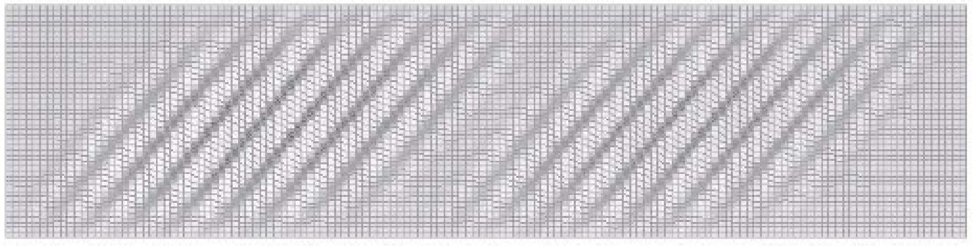
Length, *L* (mm)	380
Height, *H* (mm)	128
Thickness, *t* (μm)	25
Young's Modulus, E (MP	3530
Poisson's ratio, ν (–)	0.3

The membrane will not buckle and form the wrinkles unless there are imperfections that can trigger an out-of-plane deformation. The eigenvalues were generated in a separate eigenvalue extraction step and then introduced as imperfections with a normalised magnitude of 5﹣100% of the membrane thickness in the postbuckling analysis.

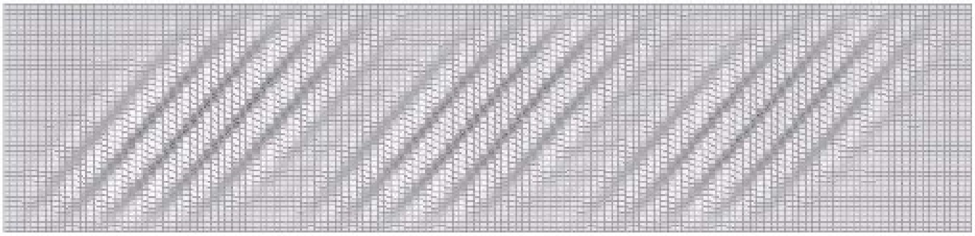
The five first eigenmodes of the membrane, are shown in Fig. 2, whose eigenvalues are larger than 0.2. The NO.1, 3, 5 and 7 mode shapes The magnitude of 5% of the membrane thickness is introduced into the postbuckling analysis as imperfection.



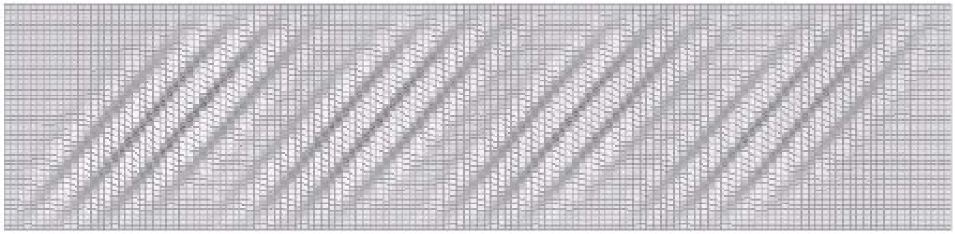
(a) Eigenvalue: 0.26490



(b) Eigenvalue: 0.26492



(c) Eigenvalue: 0.26495



(d) Eigenvalue: 0.26499

Fig.2 the five first eigenmodes of the membrane, eigenvalues > 0.2.

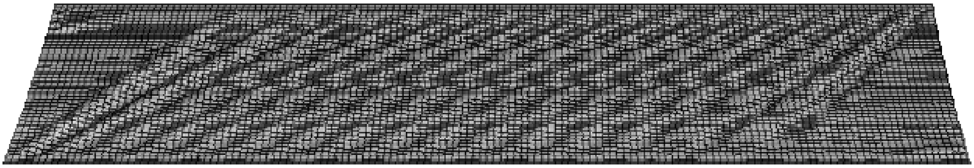
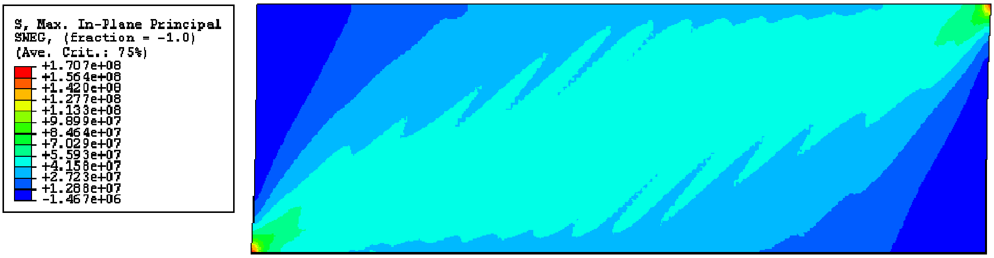
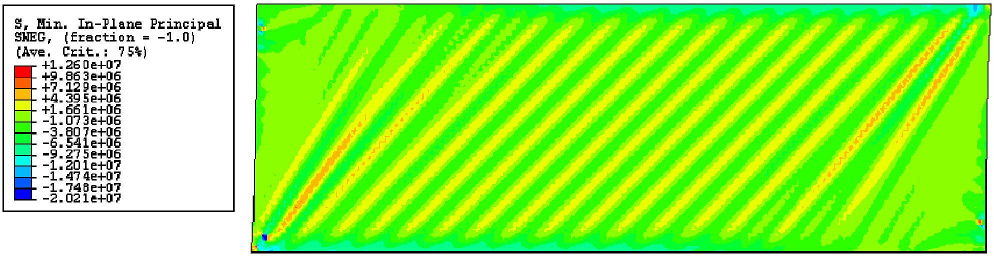


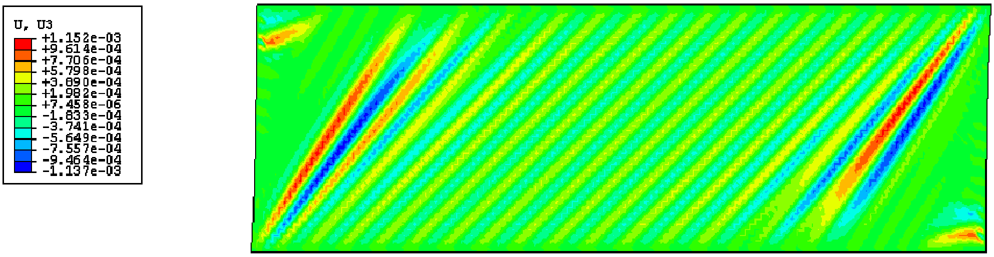
Fig.3 Shapes of wrinkle on ($\delta = 3mm$)



(a) maximum principal stress



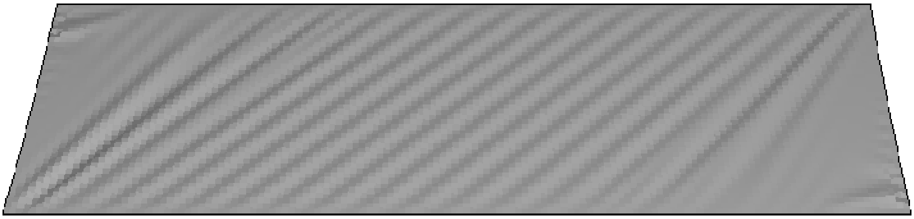
(b) minimum principal stress



(c) Displacement

Fig. 4 Distribution of stress and displacement ($\delta = 3mm$)

(a) Experiment



(b) Simulation

Fig.5 Contrast between experiment and simulation result

Fig.3 shows Shapes of wrinkle on $\delta = 3mm$. Fig.4 shows Distribution of stress and displacement. Fig.5 shows comparation between experiment and simulation result.

3.2 Square membrane analysis

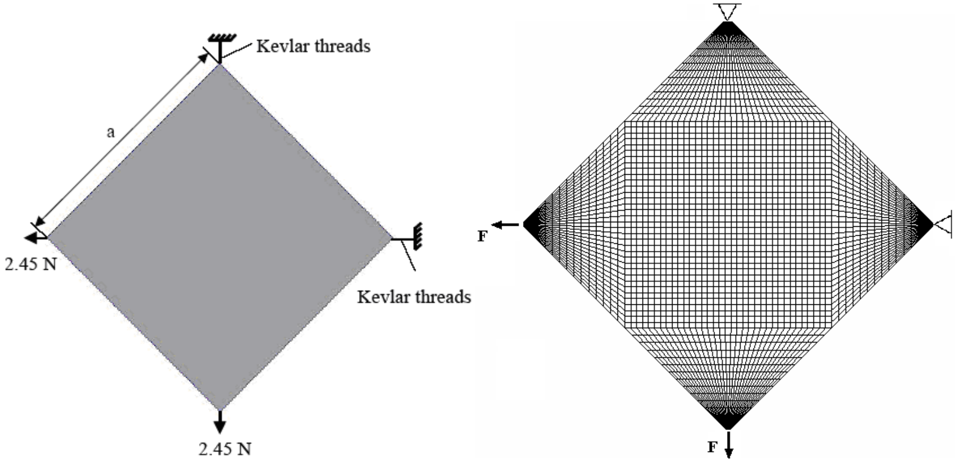
When a tensile load is applied at a corner of a thin-film membrane, wrinkles tend to radiate from the corner; subsequently, the corner wrinkling affects the wrinkled equilibrium state over the entire membrane domain.

Recently, Blandino et al. [8] performed a laboratory test on a 500 mm square, flat membrane made of a KAPTON® Type HN film. The material properties, membrane dimensions, and loading are shown in Figure 6(a). The membrane is subjected to tensile corner loads (F=2.45 N) applied in the diagonal directions via Kevlar threads at the left and bottom corners of the membrane. The top and right corners of the membrane are fixed to the test frame with Kevlar threads. The corners are also reinforced on both sides with small patches of a transparency film (approximately 10 mm in diameter).

A suitable analytical model, that is statically equivalent to the experimental one, would be simulated. The initial geometry of the model is a square membrane with the properties shown in Table2(as shown in Fig.6(b)).

Table2: Properties of FE-models

Edge length, a (mm)	500
Thickness, h (mm)	0.0254
Young's Modulus, E (N/mm^2)	2590
Poisson's ratio, ν	0.34

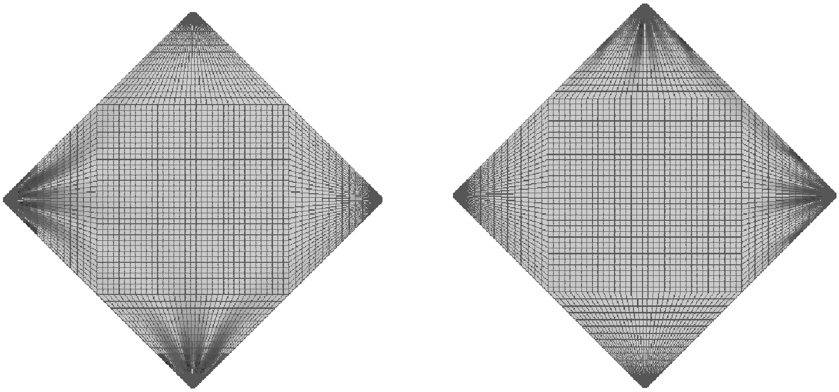


(a)Test model (b) Simulation model

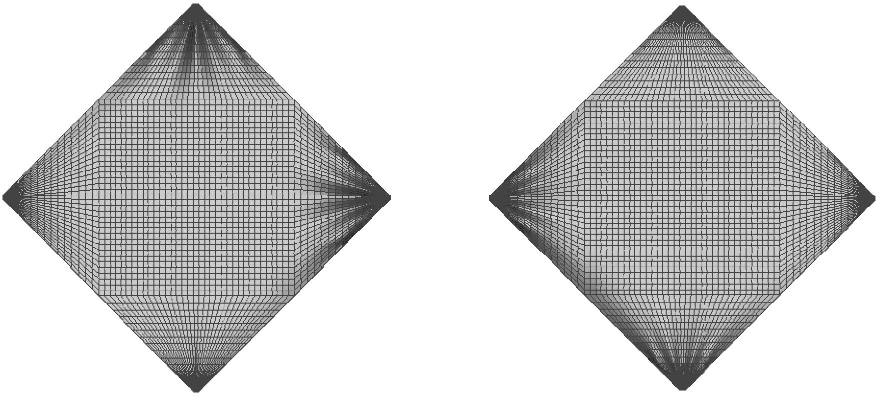
Fig.6 Square membrane model

The NO.1, 3, 4 and 13 mode shapes are shown in Fig. 7. The results of 5% multiplied by the thickness of the membrane is put into the postbuckling analysis as intial defect.

The contour plots depicting the deflection distributions in the experiment and the present geometrically nonlinear shell analysis are shown in Figure 8. The computer simulation is able to effectively predict four wrinkles radiating from the truncated corner regions just as those from the measured experimental results. The analysis also shows that curling occurs at the free edges as observed in the experimental results; however, the amplitudes of the experimental deflections are somewhat greater. Although intended to be symmetric, the experimental results are somewhat asymmetric. As in the previous example, the actual initial geometric imperfections, not incorporated in the analysis, may have contributed to a significant asymmetry in the experiment and the differences with the analysis. This again is evidence to the fact that such ultra-flexible and lightly stressed spatial structures are not only difficult to model analytically but also to test experimentally, requiring further refinements in the experimental methods for these thin-film membranes.

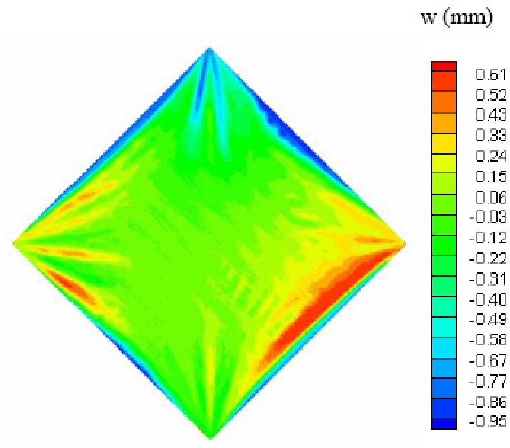


(a) Eigenvalue: 0.28233 (b) Eigenvalue: 0.28234

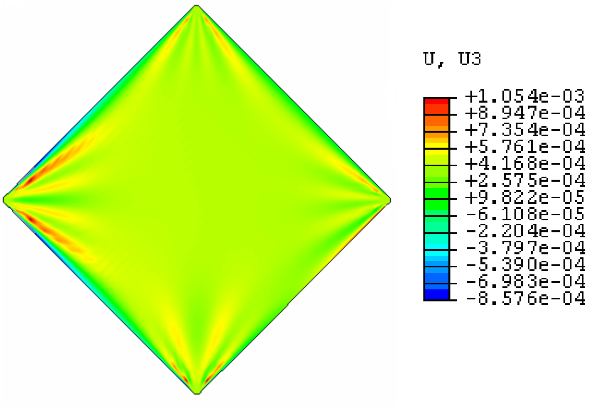


(c) Eigenvalue: 0.28362 (d) Eigenvalue: 0.36565

Fig. 7 The number of 1、3、4、13 mode shapes



(a) Experiment



(b) Simulation

Fig.8 Wrinkling deformations of square membrane

4. Conclusion

In this paper, the formation of highly nonlinear wrinkling deformations in thin-film membranes was simulated. The analyses were carried out within the framework of the geometrically nonlinear, updated Lagrangian shell formulation using a commercial finite element code ABAQUS.

A concept of shell-membrane and the post-wrinkling analysis in a clamped rectangular shell-membrane subjected to uniform transverse in-plane displacement and a square thin-film membrane subjected to corner tensile loads are presented in this paper. The detailed stress field and wrinkling deformation and wrinkling evolution in the wrinkled shell-membrane structure can be obtained based on the nonlinear post-wrinkling analysis. According to the results, the post-wrinkling analysis presented in this paper has been shown to be robust and capable of producing good results in predicting the wrinkle deformation in membrane. Results from experiment and simulations are agreed well, and show simulation is effective to predict the wrinkle behavior of shell-membrane structures accurately.

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