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Deployment simulation of foldable origami membrane structures

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ABSTRACT

In recent years, with the development of the space structures, thin film reflector structures have the feature of lightweight, high compact ratio, easy to fold and unfold and so on. Its form has received wide attention from researchers and a broad application prospect. In this paper, the nonlinear finite element software ABAQUS was used to carry out the numerical simulation of the deployment of membrane structures based on Miura-ori, by taking advantage of the variable Poisson's ratio model to revise the stress distribution of membrane elements. Then the uniaxial tension tests were carried out to study the material properties of the polyimide film. The effective elastic modulus was used to simulate the crease of the membrane. The deployment of a membrane structure based on Miura origami pattern was studied. Moreover, effects of some parameters, such as the number of loading nodes and the loading rate on the numerical results were discussed.

1. Introduction

There is currently much interest in the use of ultra-light space structures, especially the gossamer structures [1,2]. Thin-film membranes stretched in tension are found to meet the requirements of future gossamer spacecraft [3–5]. If the size of the gossamer spacecraft is large, it is envisaged that the membrane structure will be folded for packaging purpose. The folding process can be realized based on the concept of origami.

Origami, a traditional Asian paper craft, has been proved as a valuable tool to develop various deployable and foldable structures [6–9]. Miura-ori, which is a well-known rigid origami structure utilized in the packaging of deployable solar panels for use in space or in the folding of maps [10]. Every node of Miura-ori has four creases/fold lines, three mountain fold lines and one valley fold line or three valley fold lines and one mountain fold line. The deployment of the Miura-ori is given in Fig. 1. The Miura-ori crease pattern can also be used to pack and deploy the membrane [11, 12]. Therefore, the Miura-ori membrane structure is selected as the objective for this study.

The membrane structure is prone to wrinkling [13–17]. The existence of wrinkled regions may have adverse influence on the deployment of a membrane structure. Tension field theory, was firstly proposed by Wagner [18] to consider the wrinkled membranes. Then Reissner [19] developed a numerical method to obtain a non-compression solution for isotropic membranes based on the tension field theory. However, the tension field theory cannot give the amplitude, wavelength and numbers of wrinkles. Therefore the bifurcation analysis based on shell elements was introduced [14,20]. But the results are dependent on the element mesh, and the numerical simulation is hard to converge [21]. Stein and Hedgepeth [22] proposed a variable Poisson's ratio model to study the wrinkling of membranes. Then Miller and Hedgepeth [23] further developed a new algorithm for the numerical simulation. Recently, Patil et al. [24,25] studied the wrinkling of non-uniform membranes with non-uniform thickness.

Creases, or folding lines, of an origami pattern may also have great effects on the mechanical behavior and deployment performance of foldable membrane structures. Gough et al. [26] carried out experimentally and numerically studies on a square creased membrane. Woo et al. [27] studied the effective modulus of creased membranes based on the geometrically and materially finite element simulation of the whole process of creasing. The results were also compared with experiments. Then Woo and Jenkins [28] studied the wrinkling of a creased square membrane under different corner loads. Moreover, they also studied the effects of

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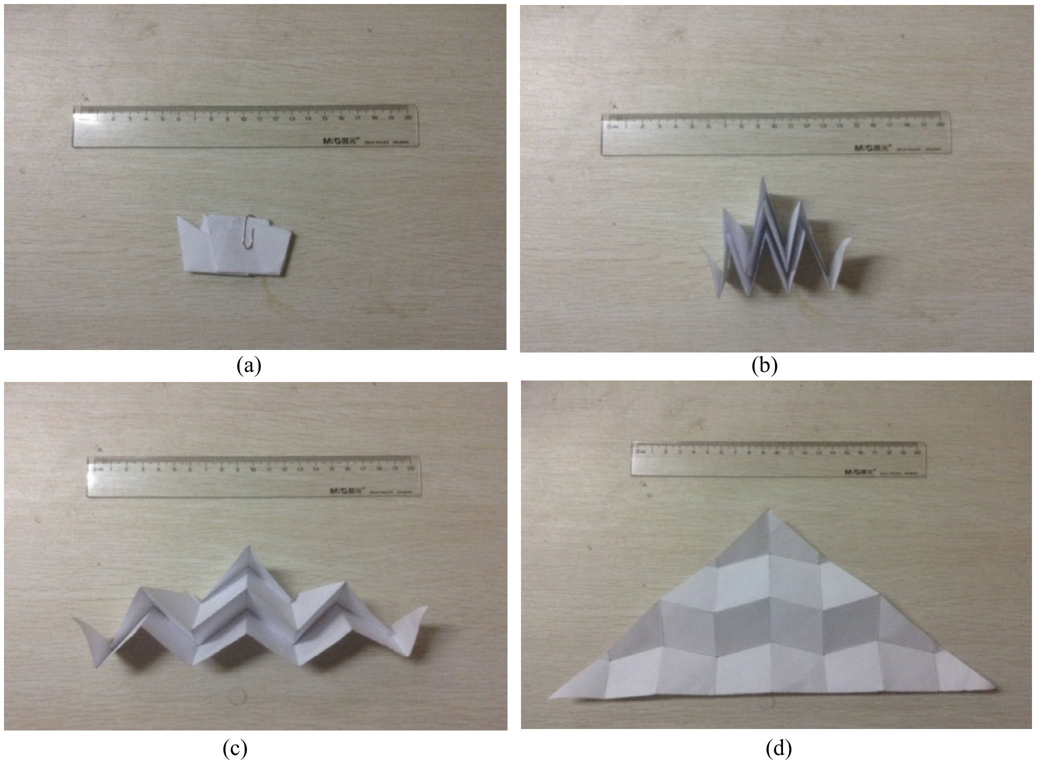

Fig. 1. Deployment of Miura-ori.

the membrane thickness [29] and the crease orientation [30], deployment angle and load ratio [31]. Wang et al. [32] investigated the shear performance of a rectangular membrane considering the wrinkling and creases.

So far most of the previous studies only focus on the membranes with single or simple creases. Papa and Pellegrino [33] studied the mechanics of a systematically creased square membrane with the Miura-ori pattern. However, to use the thin shell method for creased membranes, the initial imperfections should be quantitatively introduced to the numerical model [34]. In addition, to obtain better results in deformation, the refined element meshes lead to a large number of shell elements. In this paper, the membrane element with the variable Poisson's ratio model is used to model the wrinkling of membranes and the effective crease modulus of thin films, which are obtained from experiments, is used to consider the creases of Miura-ori pattern. Moreover, effects of the number of loading nodes, the time of the loadings and loading positions of the membrane on the deployment performance are also discussed.

2. Modelling of membrane wrinkling

The variable Poisson's ratio model will be introduced in this section to model the wrinkling of membranes. The stress–strain relationship within a statically determinant region of uniaxial stress that could be an approximation to the state of stress within a wrinkled portion of the membrane should be constructed. In a taut region, the stresses and strains are related according to the usual plane stress elastic equations for isotropic and elastic solids. However, within a wrinkled region, the usual elastic equations don't apply. Instead the assumption of negligible bending stress in the membrane yields the stress

$$\sigma_1 = E\varepsilon_1, \qquad \sigma_2 = 0, \tag{1}$$

where σ is the stress, ε is the strain, E is the Young's modulus, the subscript 1 and 2 are the directions parallel and perpendicular to the wrinkles, respectively. For the purpose of numerical analysis, it is desirable to express the stress in terms of the strains in the matrix form as

$$\{\sigma\} = [D]\{\varepsilon\}, \tag{2}$$

where

$$\{\sigma\} = \left\{ \sigma_x \quad \sigma_y \quad \tau_{xy} \right\}^T \quad \text{and} \quad \{\varepsilon\} = \left\{ \varepsilon_x \quad \varepsilon_y \quad \gamma_{xy} \right\}^T. \tag{3}$$

Normally, the matrix $[D]$ can be written as

$$[D] = \frac{E}{1-\lambda^2}\begin{bmatrix} 1 & \lambda & 0 \\ \lambda & 1 & 0 \\ 0 & 0 & (1-\lambda)/2 \end{bmatrix}, \tag{4}$$

where the "variable Poisson's ratio" λ varies from point to point within the wrinkled region so that $[D]$ is not a constant matrix. However, because of the presence of the term $1/(1-\lambda^2)$, $[D]$ is not suitable for numerical implementation within the wrinkled region where $\lambda = 1$. Hence another representation for $[D]$ is given by Miller and Hedgepeth [19] as

$$[D] = \frac{E}{4}\begin{bmatrix} 2(1+P) & 0 & Q \\ 0 & 2(1-P) & Q \\ Q & Q & 1 \end{bmatrix}, \tag{5}$$

where $P = (\varepsilon_x - \varepsilon_y)/(\varepsilon_1 - \varepsilon_2)$ and $Q = \gamma_{xy}/(\varepsilon_1 - \varepsilon_2)$. No singularities of the matrix are observed for any value of P and Q between 0 and 1, and hence this numerical representation of $[D]$ has no difficulties.

The iterative membrane properties (IMP) method, which uses the variable Poisson's ratio theory to recursively modify the properties of membrane elements until all the compressive stresses disappear when tensioned, is implemented based on the software ABAQUS [13,28]. Then a user-defined material ABAQUS/Explicit subroutine (VUMAT) is written to incorporate the wrinkling effects into the membrane. In practice, the constitutive matrix $[D]$