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MESH REINFORCED MEMBRANE AND ITS WRINKLING CHARACTERISTICS

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1. INTRODUCTION

Membrane structures have received a wide range of attention in applications of large-scale spacecrafts, such as inflated wing, light-than-air (LTA) airship and membrane antenna reflector, and so on. These spacecrafts need to be designed as high loading-efficiency components or structures, especially with high shape precision [1]. Therefore, some special processing and design should be done on the membranes so as to satisfy with special requirements, such as free wrinkle, ultra-lightweight, high shape precision, and high load-carrying ability, etc..

Several applications may give us good ideas to deal with abovementioned problems in membrane structures. One example is easy to be remembered, that is, the Super-Pressure Balloons (SPB) [2-4] covered by some ropes on membrane surface to make the balloon stable and strong. The similar considerations are also applied to some gossamer spacecraft components or structures, taking the Lunar habitat [5] as an example.

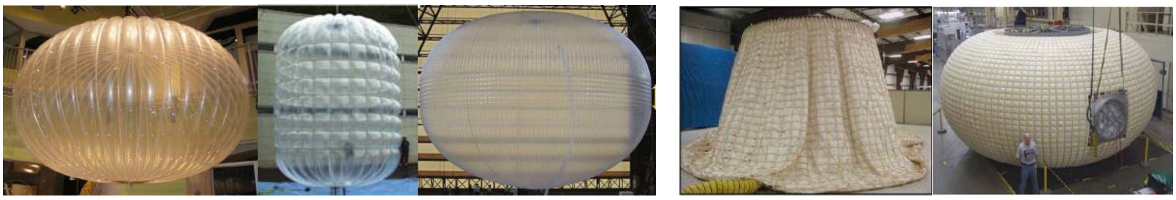

Fig.1 Two examples using reinforced ropes on membranes (SPB and Lunar habitat in ILC Dover)

Experiments on small scale ground models have shown that wrinkles are present over a wide range of applications. Thus membrane wrinkling has attracted much interest in the past, starting from the development of tension force filed theory, the bifurcation simulations to the explicit time integration etc.. [6-10]

2. MRM AND ITS PROPERTICES

In order to make the material isotropic, we need to design some special forms of mesh. They are as follows, see Fig 2.

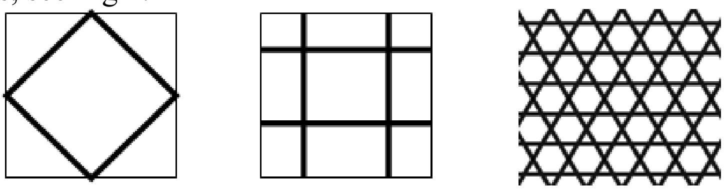

Fig.2 Layout of meshes on MRM.

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We classify the reinforced ribbons placed in a parallel pattern as a series and separate each series (suppose it has *n* layers), and divide the membrane into a number of layers (each has a thickness of *1/n* layer), with a range of reinforced ribbons and a single-layer film combining into a composite structure consisting of layers. We call this scheme as the "pseudo-laminate method." Taking the reinforced membrane structure by using ribbons in three directions for example, it depicts equivalent process for analyzing the mesh reinforced membrane by using ribbons in three directions. We combine each range of ribbons and a *1/3*-thin layer of membrane into one composite laminate, then MRM can be divided into 3 composite layers.

Decomposition schematic and its cell element of 3-direction mesh reinforced membrane is shown in Fig.7. Here, the layer with *0°* reinforced belts is named as "standard layer". The other non-standard layers may be obtained by transforming the standard layer. In order to make the analysis easy to understand, this paper analyzes MRM by using ribbons in three directions, using the reinforcing method of “isogrid”. We call the smallest periodic unit "cell element".

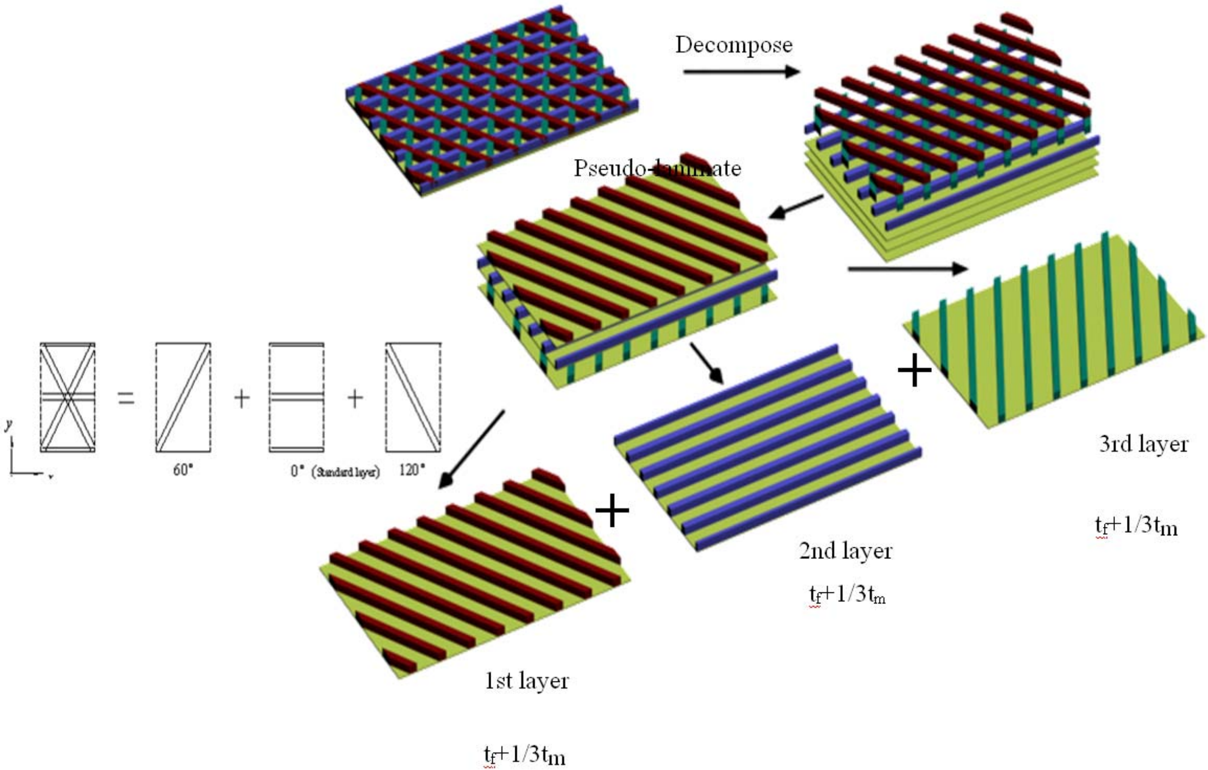

Fig.3 Decomposition schematic of 3-direction reinforced mesh membrane and cell element

If the reinforced ribbons in each direction are placed with equal space, assuming there are *n* directions, the reinforced ribbons in *i*-direction has an angle of θ_i with the initial direction. If the membranes are divided into *n* layers and we regard each layer and a series of corresponding reinforced ribbons as one laminate, then the corresponding layer can be regarded as a simple laminate. We can get the elastic modulus, Poisson's ratio and shear modulus in the *x, y* direction under the same coordinate based on the formula. We remark the material parameters of *i*-laminate are E_x^i , E_y^i , ν_{xy}^i and G_{xy}^i , and we remark the corresponding volume weight as V^i （$\sum_{1}^{n} V^i = 1$）. Using parallel model for composite materials, we can obtain the elastic modulus:

$$\overline{E}_x = \sum_{i=1}^{n} V^i E_x^i \;;\quad \overline{E}_y = \sum_{i=1}^{n} V^i E_y^i \;;\quad \overline{v}_{xy} = \sum_{i=1}^{n} \frac{E^i V^i v_{xy}^i}{\sum_{i=1}^{n} E^i V^i} \;;\quad \overline{G}_{xy} = \sum_{i=1}^{n} V^i G_{xy}^i \tag{1}$$

The tensile stiffness along reinforce belt can be expressed as:

$$\overline{E}_x A = A \sum_{i=1}^{n} V^i E_x^i \tag{2}$$

For getting the parameter for each laminate, we can divide the laminate into two parts, including the reinforced ribbons and the membrane. We can first get the parameter of the ribbons of the standard layer. By transforming from the standard layer to the layer with an angle of θ_i, we can get the parameters like $E_x^{i'}$, $E_y^{i'}$, $v_{xy}^{i'}$ and $G_{xy}^{i'}$. Then using the formulas (1) and (2) and take the ribbons and membrane as a laminate, we obtain its E_x^i , E_y^i , v_{xy}^i and G_{xy}^i . We assume the elastic modulus directed toward the fiber of a standard layer is E_1, the elastic modulus perpendicular is E_2, Poisson's ratio is v_{12} and v_{21} and the shear modulus is G_{12}. Then any cell layer can be created by rotation from the standard layer. So we can get the material parameters of any cell layer by the rotation angle and the properties of the standard layer. In this section, we analyze its elastic modulus, Poisson's ratio and shear modulus.

Assuming these two kinds of materials are elastic, and that there is no relative displacement between the membrane and reinforced ribbons. The direction of reinforced ribbons is 1, and the vertical direction in the plane is 2. There is the same strain along the 1 direction between the membrane and the reinforced ribbons. The parallel model of theory of the simple laminates shows that:

$$E_1 = E_m V_m + E_f V_f = E_m \frac{b_m t_m}{b_m t_m + b_f t_f} + E_f \frac{b_f t_f}{b_m t_m + b_f t_f} \tag{3}$$

Among them, the elastic modulus of membranes is E_m, width of membrane is b_m, the thickness of membrane is t_m, the elastic modulus of reinforced ribbons is E_f, width of reinforced ribbons is b_f, the thickness of reinforced ribbons is t_m.

We divide the cell layers into two parts, which contains partly reinforced ribbons and pure membrane. The part with reinforced ribbons is a two-layer isotropic compound material which contains reinforced ribbons and pure membrane. We can get its elastic modulus with reinforced ribbons from a parallel model of theory of simple laminates:

$$E_{mf} = E_m \frac{t_m}{t_{mf}} + E_f \frac{t_f}{t_{mf}} \tag{4}$$

Assuming cell layer only bears the load of F_2 along the 2 direction, we combine this layer with theory of simple laminates model and can get that, the equivalent elastic modulus along the x-axis is:

$$E_2 = \frac{\sigma_2}{\varepsilon_2} = \frac{(E_m t_m + E_f t_f) E_m t_m b_m^2}{(b_m t_m + b_f t_f)\left[(E_m t_m + E_f t_f)(b_m - b_f) + E_m t_m b_f\right]} \tag{5}$$

For a standard layer of a cell layer in the structure by using reinforced ribbons, the deformation of the overlapping region between the reinforced ribbons and the membrane is coordinated.

We explore the part with reinforcing ribbons and the part without those respectively. According to Hooke's law, if one only subjects to the stress of 1 direction, we can get the equivalent Poisson's ratio by superimposing lateral deformation.

$$v_{12} = \left(1 - \frac{b_f E_f t_f}{b_m \left(E_m t_m + E_f t_f\right)}\right) v_m + \frac{b_f E_f t_f}{b_m \left(E_m t_m + E_f t_f\right)} v_f \tag{6}$$

Add the following main stress to the element in the 1, 2 coordinate system

$$\underset{12}{\sigma} = \{\sigma_{11} \quad -\sigma_{11} \quad 0\}^T \tag{7}$$

In the *x, y* coordinate system, for the standard level that has the rotation angle of *–π/4*, we can convert its main normal stress into tangential stress, namely:

$$\underset{xy}{\sigma} = \{0 \quad 0 \quad \sigma_{11}\}^T \tag{8}$$

According to the relationship between stress and strain of the materials we can get

$$\underset{xy}{\varepsilon} = \underset{xy}{C}\underset{xy}{\sigma} = \begin{bmatrix} -\dfrac{E_1 - E_2}{2E_1E_2}\sigma_{11} \\ -\dfrac{E_1 - E_2}{2E_1E_2}\sigma_{11} \\ \dfrac{E_1 + 2v_{12}E_2 + E_2}{2E_1E_2}\sigma_{11} \end{bmatrix} \tag{9}$$

In which, the flexibility matrix in the *x, y* coordinate system is conversion of the flexibility matrix of the standard layer. At this point, the shear strain can be expressed as:

$$\gamma_{xy} = \frac{E_1 + 2v_{12}E_2 + E_2}{2E_1E_2}\sigma_{11} = \frac{E_1 + 2v_{12}E_2 + E_2}{E_1E_2}\tau_{xy} \tag{10}$$

For the material parameters are not affected by the status under stress, the shear strain can be expressed as:

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} = \frac{E_1E_2}{E_1 + 2v_{12}E_2 + E_2} \tag{11}$$

For the *i*-th layer that is disposed randomly, we assume that the layer is rotated from the standard layer with the rotation angle of θ_i as shown in Fig.4. We assume that the 1 direction is along the longitudinal direction of the reinforced ribbons while the 2 direction is perpendicular direction. From plane stress problem, we can get that:

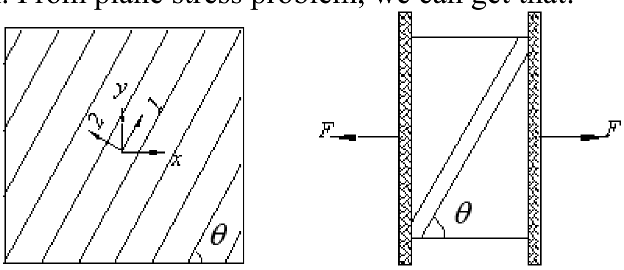

Fig.4 Non-standard layer model

For the model after coordinate conversion, the apparent constants are the following in the non-main direction of the *x, y* coordinate system:

$$E_x^i = \frac{1}{\dfrac{\cos^4\theta^i}{E_1} + (\dfrac{1}{G_{12}} - \dfrac{2v_{12}}{E_1})\sin^2\theta^i\cos^2\theta^i + \dfrac{\sin^4\theta^i}{E_2}} \tag{12}$$

$$E_y^i = \frac{1}{\dfrac{\sin^4\theta^i}{E_1} + (\dfrac{1}{G_{12}} - \dfrac{2v_{12}}{E_1})\sin^2\theta^i\cos^2\theta^i + \dfrac{\cos^4\theta^i}{E_2}} \tag{13}$$

We design several kinds of MRM, as shown in Fig.5. In order to obtain the tension properties of MRM, the tensile experiment of isogrid MRM is performed. The samples are composed of PI (mesh) and PU (membrane). Each sample consists of 4 cell elements. The elastic modulus of membrane (PI, 0.1mm) is 2.99GPa, and Poisson's ratio is 0.34. The elastic modulus of tape (PU, 0.025mm) is 67MPa, Poisson's ratio is 0.34. And the cell element is 23mm width, 40mm length. The size of membrane is 40m×138mm. The tension velocity is 10mm/min using Instron5965 with 5KN sensor. The tension properties of MRM is tested and compared to pristine membrane, shown as follows.

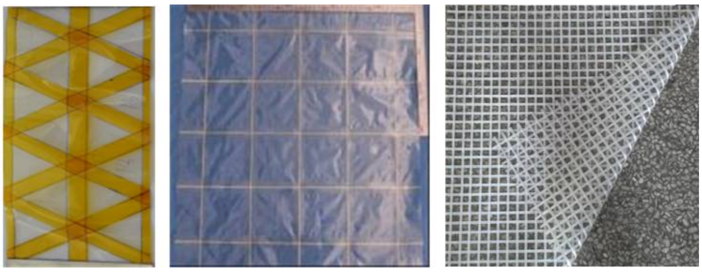

Fig.5 MRM reinforced by different tapes (Membrane/ Membrane, Composite fiber/Membrane, Composite tape/Membrane)

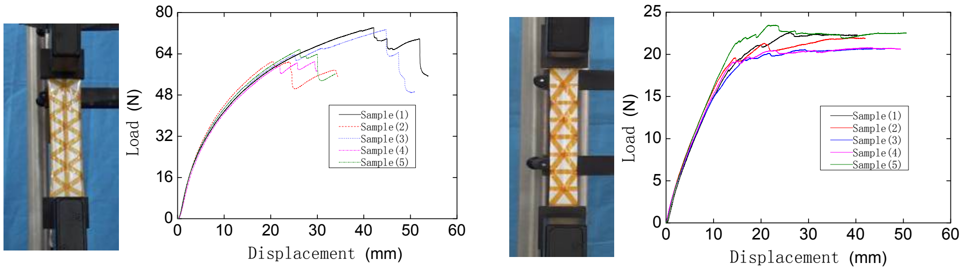

Fig.6 Tension displacement versus load in x and y directions

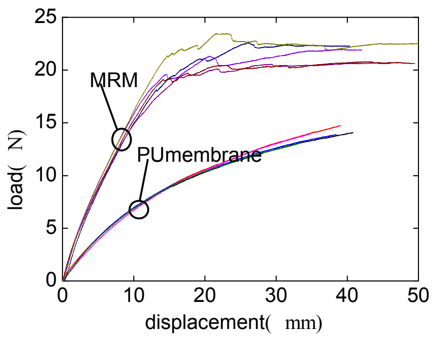

Fig.7 Comparisons of tension properties between MRM and pristine membrane (y direction)

We also simulate the tension performance of MRM, which shown as follows.

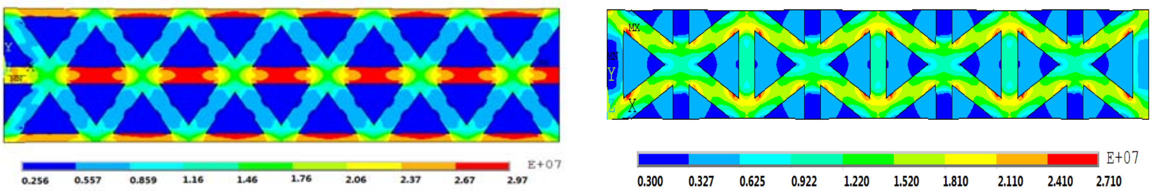

Fig.8 Major principle stress in x and y direction.

Observed from Fig.8, the major principle stress is located fully on the reinforced ribbons which reveal the reinforcement component in MRM.

Surface density of PU is 130g/m^2, while that of PI is 36g/m^2. We define modulus/weight as elastic modulus efficiency. Comparing with performance predictions using pseudo-laminate method, we can get the predictions of elastic modulus of MRM (as shown in Tab.1). From the Tab.1, we can see that the experiments agree well with the predictions.

Tab.1 Comparison of elastic modulus between experiments and predictions

Items	Experiment	Prediction	Error (%)
Modulus, $\overline{E}_x$ (MPa)	250	239	4.4
Modulus, $\overline{E}_y$ (MPa)	140	150	7.1

Then we can get the modulus efficiency of pristine membrane and MRM as follows in Tab.2.

Tab.2 Comparison of elastic modulus efficiency (EE) between pristine membrane and MRM

Items	PM	MRM	MRM/PM
Experiment EEx（MPa*m^2/kg）	515.4	1592.4	3.09
Prediction EEx（MPa*m^2/kg）	515.4	1522.3	2.96
Experiment EEy（MPa*m^2/kg）	476.9	885.4	1.86
Prediction EEy（MPa*m^2/kg）	476.9	987.3	2.07

Based on above comparisons, MRM has higher elastic modulus efficiency than pristine membrane which reveals a high load-carrying ability of MRM.

3. MRM WRINKLING

We simulate the membrane wrinkling using explicit time interation and verify it using DIC technology. In order to capture the major wrinkles in membrane we choose a special square membrane under corner tension. Square membrane (size and material properties are same with specimen in Part 2) is 100mm side length and 25mm loaded corner width. The wrinkling patterns in simulation and experiment are compared and shown as follows. The simulation agrees well with experiment with 5% difference.

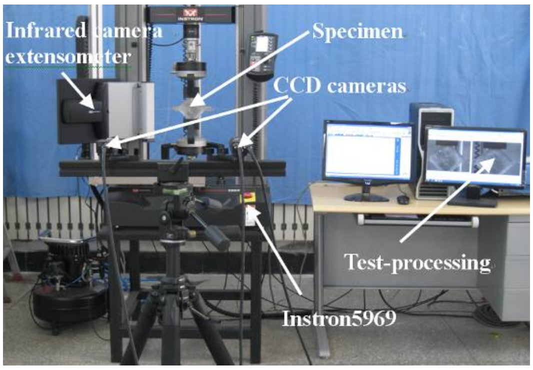

Fig. 9 DIC test system and tension wrinkling test machine

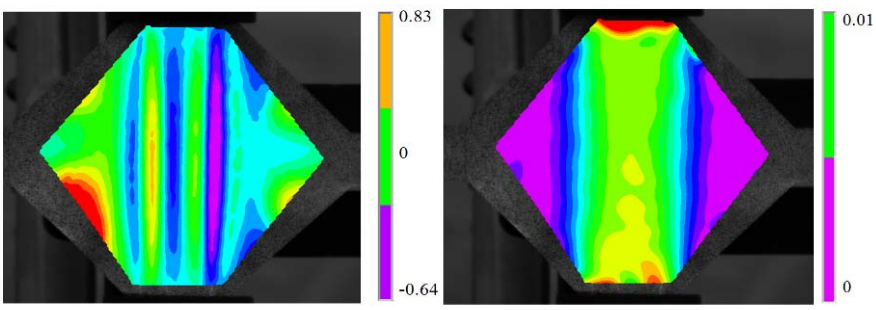

Fig.10 Experimental wrinkling patterns and y-strain of pristine membrane (1mm tension)

The simulated wrinkling patterns and y-strain as well as the out-of-plane displacement comparisons are shown in Fig.11.

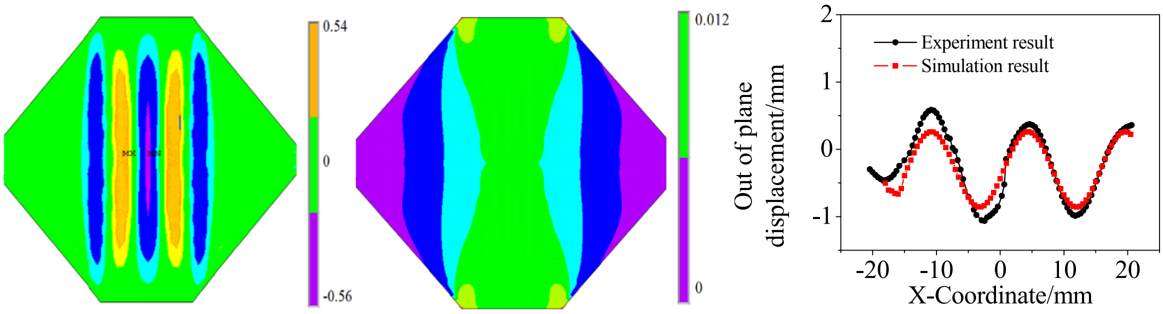

Fig.11 Simulated wrinkling patterns, y-strain and out-of-plane displacement comparison of simulation and experiment (1mm tension)

Then we simulate the wrinkling patterns in square MRM. The wrinkling results are shown as follows.

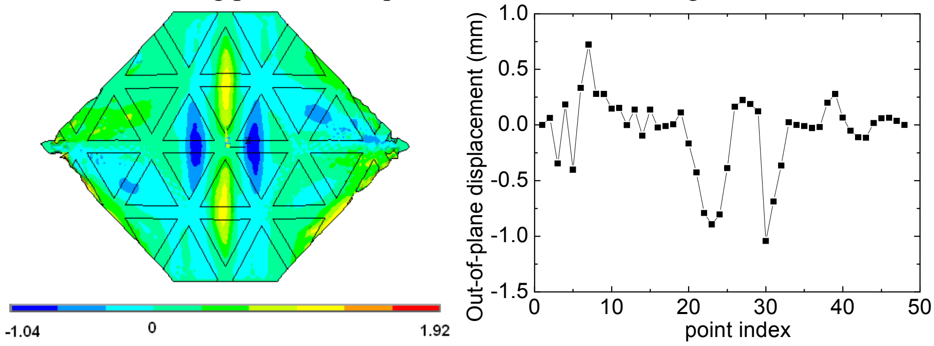

Fig.12 MRM wrinkling patterns and out-of-plane displacement

The simulated wrinkling parameters of MRM, wrinkling wavelength is 14.37mm, wrinkling amplitude is 0.56mm, wrinkling numbers (crest, trough) is 3(1,2), which are smaller than those in pristine membrane, they are 15.05mm, 0.75mm, and 5(2,3), respectively. In addition, for 1mm tension displacement, the y-stress of MRM and pristine membrane are 3.82MPa and 1.69MPa, respectively. We use a loading efficiency (y-stress/total mass) to evaluate the load-carrying ability of these two kinds membrane. We have loading efficiencies of MRM and pristine membrane which are 1.91 and 1.3, respectively. These comparisons reveal the reinforced mesh may make MRM more stable and stronger than pristine membrane.

CONCLUSIONS

This paper presents a concept of mesh reinforced membrane (MRM) as well as simulates its tension properties which verified by the experiment. The membrane wrinkling is then simulated and verified by DIC test. In the end, the MRM wrinkling is simulated and compared with the pristine membrane. The results reveal the reinforced mesh may make MRM more stable and stronger than the pristine membrane.

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