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Effects of Local Thickening on Surface Precision Control of Membrane Structures

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Abstract. It is difficult to maintain the surface flatness like other materials for membrane structure under working conditions, and working performance will be greatly affected due to the extremely low bending stiffness of the membrane. In this paper, the finite element software ABAQUS is used to discuss effects of local thickening on the precision of the membrane structures from three aspects: tilt angles of the wrinkle equilibrium position, out-of-plane deformation of the structures and the wrinkle amplitude of membrane structures were analysed. Also the possible negative effects on the maximum principal stress. By comparing the local reinforcement model with the ordinary model, the accuracy of the local thickening model is far superior to the ordinary model, and little effect on distribution of maximum principal stress. The research results indicated that local thickening membrane structure can achieve better control to surface flatness at a lower cost.
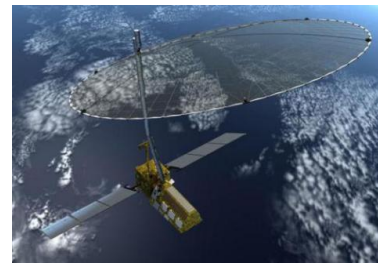
1 Introduction

The membrane structure is widely applications in the modern era due to its flexible structure, elegance shape and excellent adaptability in large-span wide-space structures and space structures [1](figure 1).Surface precision control[2] is a key issue in the practical application of membrane structures. The accuracy of the surface of the structure has a significant impact on the appearance. For some space membrane structures, insufficient precision will result in excessive signal reflection errors and poor performance.

At present, the research on precision control of membrane structure mainly focuses on the elastic modulus, thickness, pre-tension, loading of the material [3] and so on at home and abroad. The precision control by these parameters is sufficient, but obviously the cost is relatively high. However, enhancement of certain key parts of the membrane stricture can not only achieve better control effects, but also lower on costs, both of which are economical to analyse. In this paper, an example, the finite element software ABAQUS is used to analyse   classical ring-torsion model[4]. By comparing the local thickening model with the common model, the control effect of local strengthening on the structural precision of the membrane is studied.

(a) Berlin Olympic Stadium   (b) Radar satellites
Figure 1 Application of membrane structures

2 Classic ring torsion model

2.1 basic model

The annular Kapton membrane has an inner diameter of 50 mm and an outer diameter of 300 mm, the thickness of membrane is 0.18mm and the properties of the membrane are shown in Table 1. The boundary condition is that the outer circle is completely fixed, the inner circle is fixed with the rotating shaft, and the rotating shaft only rotate in the plane around the point O (figure 2(a)). A torque of $2*10^6$ N·mm act on the rotating shaft counter clock wisely, and the model diagram is as shown in figure 2.

Table 1. Parameters of membrane material

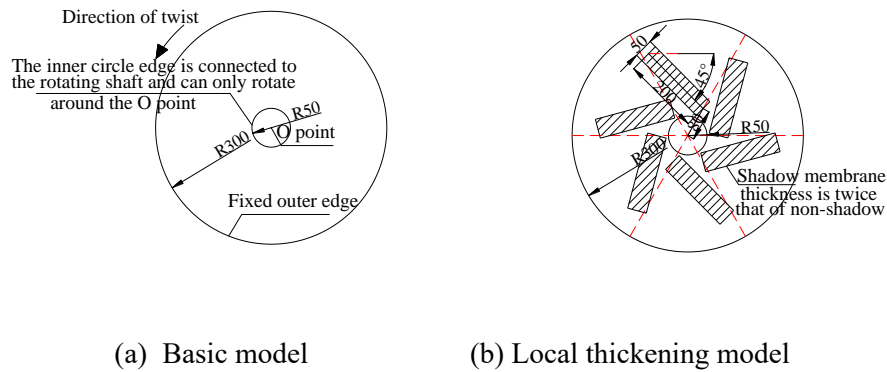| Type	Density (Kg/m3)	Poisson's ratio	Modulus of elasticity (MPa)
Kapton	1420	0.267	5677.8

2.2 Local thickening model

On the basis of the basic model(section 2.1), the membrane is partially reinforced, that is, the thickness of the shaded portion the membrane is increased to twice the thickness of the non-shaded portion(As shown in ficture2(b)).

Since the wrinkles formed by the annular torsion membrane are monodirectional wrinkles, the wrinkle discrimination criterion [5]:
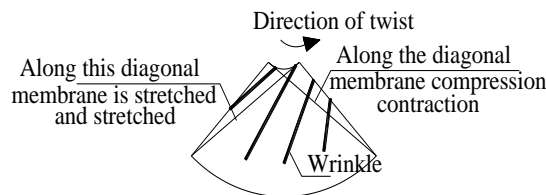
(1) When $\sigma_2 > 0$, the membrane is in a purely tension state;

(2) When $\sigma_1 > 0$, $\sigma_2 < 0$, the membrane is in a unidirectional wrinkle state;

(3) When $\sigma_1 \ll 0$, the membrane is in a bidirectional wrinkle state.

Here, σ_1、σ_2 is maximum and minimum principal stresses respectively.

Therefore, in the direction in which the wrinkles are formed, the main stress of the membrane is less than zero, that is, under pressure, consideration and the principal stress of the membrane perpendicular thereto is greater than zero, that is, tension. The outer circular edge is fixed, and the inner circle is twisted. Actually, the inner and outer circles have relative shear displacement, as shown in figure 3. The angle between the direction in which the wrinkles are formed and angles between the tangential line of the displacement is about 45 degrees [6], and the membrane is compressed and contracted in this direction, so that the thickened region of the membrane is set in this direction, and the thickness of the membrane in this region is enhanced. Increasing the bending rigidity of the membrane material and using the bending rigidity of the membrane material to effectively hinder the shrinkage of membrane, thereby achieving the effect of controlling the surface precision of the membrane material. Similarly, it is also possible to achieve a better control effect by providing a thickened area of the membrane perpendicular to the direction of the wrinkle. The principle is to use the tensile stiffness of the membrane to resist torque.

(a) Basic model   (b) Local thickening model
Figure 2 Schematic diagram of the model

Figure 3 Detail with enlarged scale

3 Establishment of finite element model

The finite element model of annular Kapton membrane is shown in the figure 4;

The model is built using the dynamic display method [7]. The steps are as follows:
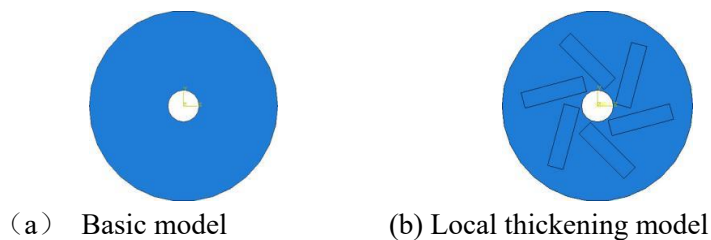
First, couple fully the inner circle to the six degrees of freedom of the reference point O and fix the six degrees of freedom. The side load of the shell is applied at the outer circumference to create a tensile prestressing of the membrane, which stored in a prestressed ODB file.

Second, the prestressed ODB file is imported into the model through a predefined field, the appropriate torque in the Z-axis direction is imposed at the O point, the modal buckling analysis is conducted, and the buckling mode is selected for linear combination as the initial geometric imperfection, which as shown in figure 5. The combination formula is as follows [8]:
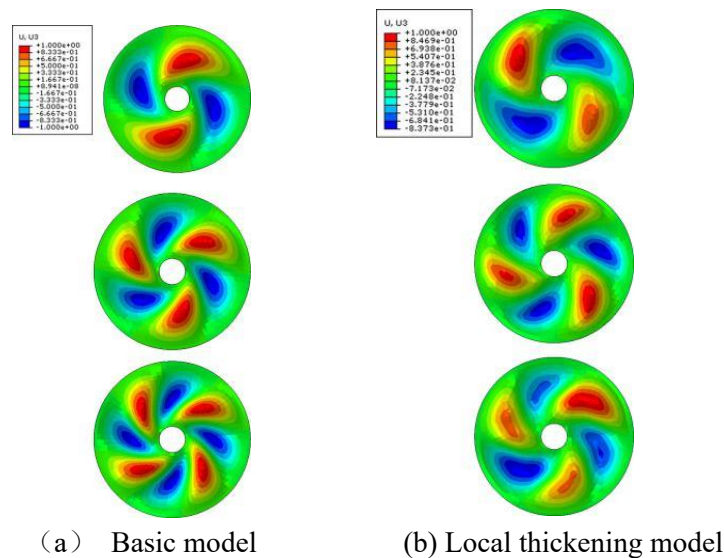
$$\Delta z = \sum_i \omega_i \varphi_i$$

Where：Δz is the out-of-plane displacement; ω_i is the modal order; φ_i is the reduction factor.

Finally, add initial imperfection to the model, use dynamic display analysis step for post-buckling analysis.
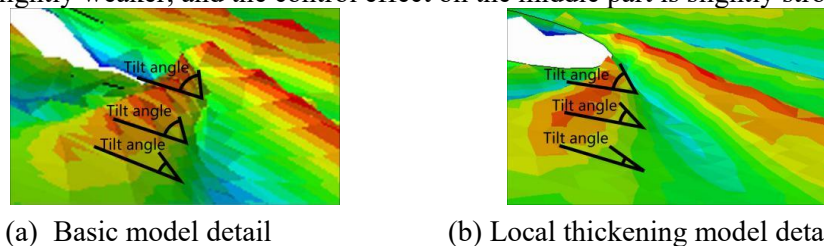

（a） Basic model   (b) Local thickening model
Figure 4 Finite element model of annular Kapton membrane
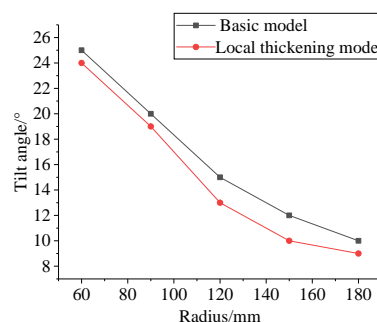
（a） Basic model   (b) Local thickening model

Figure 5 Buckling modal diagram

4 Analysis and discussion

Since the inclination of the membrane structure of the entire membrane structure at the wrinkle equilibrium position is the most serious, the horizontal angle average values of the equilibrium positions of the two models were compared and analysed. From the comparison of the inclination degree of the wrinkle equilibrium position (figure 6), we can visually see that the wrinkle equilibrium position of the local reinforcement model is less inclined. As shown in Figure 7, at the positions of R=60mm, 90mm, 120mm, 150mm, and 180mm, the horizontal angle of the equilibrium position is reduced, and the intermediate position is more obvious, and the reduction range is calculated to be 4%, 5%, 13%, 17% respectively. 10%. From this point of view, the local thickening has a certain degree of control on the inclination of the equilibrium position of the membrane structure, and the control effect on the inner and outer edges is slightly weaker, and the control effect on the middle part is slightly stronger.

(a) Basic model detail   (b) Local thickening model detail

Figure 6 Comparison of the inclination of the wrinkle equilibrium position
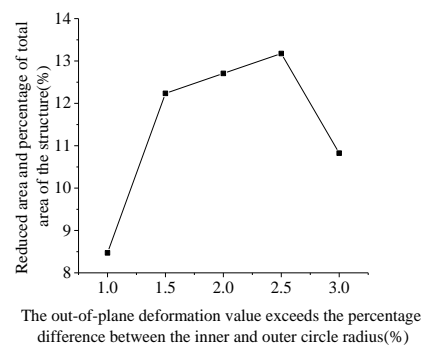

Figure 7 Inclination angle of wrinkle equilibrium position

The out-of-plane deformation is also an important parameter reflecting the surface precision of the membrane structure, which is shown in figure 8. We compared the area in which the out-of-plane deformation exceeded the inner-outer circle radius by 1%, the area over 1.5%, 2%, 2.5%, 3%, respectively. The comparison curve is shown in figure 9, and percentage ratio of between the reduced area and total area is 8.5%, 12.2%, 12.7%, 13.2%, 10.8%, respectively. In general, local thickening can play a role in the precision control of all parts of the entire membrane structure, and its control effect is relatively stable, Furthermore the position control effect on the out-of-plane deformation at middle location than the others is more obvious.

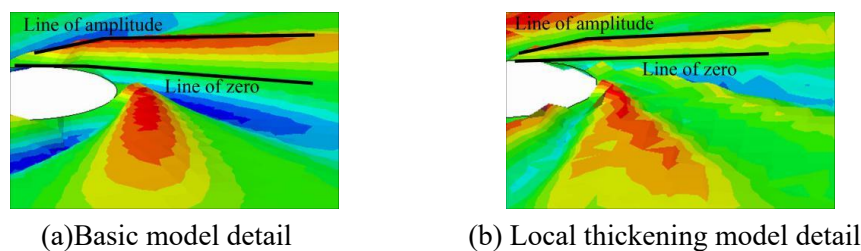| (a) Basic model | (b) Local thickening model |

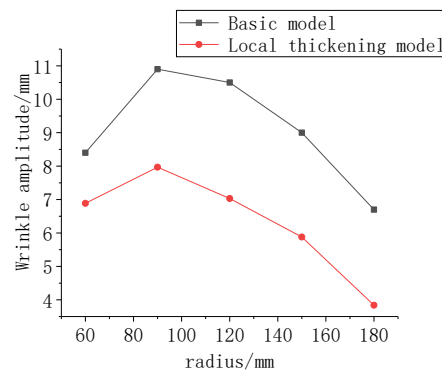**Figure 8** Out-of-plane deformation comparison

Figure 9 Amount of out-of-plane deformation under different conditions

Finally, comparison of the average values of the wrinkle amplitudes in the two models were conducted, the curve which is shown in figure 10. From the figure 11, we can see that the effect of local thickening to control the wrinkle amplitude is noticeable. At the locations of 120mm, 150mm, and 180mm, the wrinkle amplitudes of the two models are 10.5mm and 7mm, 9, mm and 5.9mm, 6.7 and 3.8mm, respectively, with a large reduction of 33%. 34%, 43%, respectively. At respectively the locations of 60mm and 90mm, the wrinkle amplitudes of the two models are 8.4mm and 6.9mm, 10.9 and 8mm, respectively, and the reduction is relatively small, 18% and 27%, respectively.

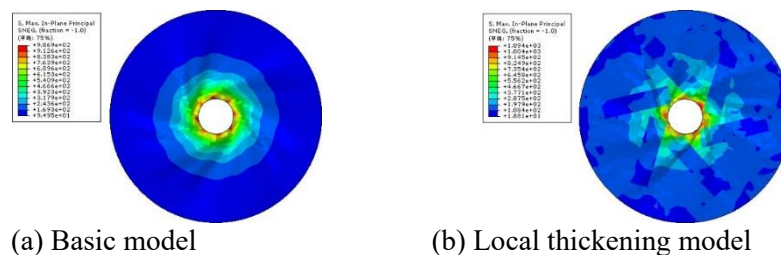| (a)Basic model detail | (b) Local thickening model detail |

Figure 10 Comparison of wrinkle amplitude

Figure 11 Wrinkle amplitude at different location

However, although local thickening can achieve the effect of controlling the precision of the membrane, it may also cause a change in the distribution of the maximum principal stress of the structure, which result in destruction of the membrane. Therefore, it were necessary to   analyse the maximum principal stress of the membrane structure and the results as shown in the figure 12. From the figure 12, we found that the effect of local thickening on the maximum principal stress distribution is not obvious and only the maximum principal stress is reduced at the thicker membrane.

(a) Basic model   (b) Local thickening model
Figure 12 Maximum principal stress

In summary, from the three aspects of the inclination degree of the wrinkle equilibrium position, the amount of out-of-plane deformation, and the amplitude of the wrinkle, we can found that the local thickening is effective and obvious for controlling the precision of the membrane structure. In addition, we also found that the control effect at the middle part is relatively strong than that at inner and outer area, because the outer edge is fixed, the inner edge is connected to the rotating shaft, and the inner and outer edges are constrained, so that effect of local thickening is not so obvious, while the middle of the membrane does not affected by boundary constraints and the effect of local thickening can be revealed completely.

5 Conclusion

In this paper, the classical toroidal torsion model is used for finite element analysis to explore the surface precision control of membrane structure. The surface precision of the basic model and the local thickening model is compared, and the control effect of local strengthening on precision is discussed from the aspects inclination degree of the wrinkle equilibrium, the amount of out-of-plane deformation and wrinkle amplitude. The research results show that local thickening has a good effect on the surface precision control of the membrane structure.

Acknowledgement

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