Form-finding Analysis of the Tensioned Membrane Structure considering Cutting Lines

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Abstract. Cutting analysis and form-finding analysis are two key problems in the design of membrane structure. In the traditional analysis, the cutting lines are not considered in the form-finding analysis, but structural damages often emerged from these locations. So the form-finding analysis including the cutting lines is analyzed in this paper. Firstly using the least square method and gradient method to cut the membrane; and then using equivalent plate element method to flat membrane surface; finally through the thermal sealing way, all the cut sections are connected into a whole, and the Form-finding analysis was done. The solutions show that the cutting lines are important parts in the design of membrane structure.

Introduction

Membrane structure is the flexible structure, different pre-stress has different structural form. Form-finding analysis, loading analysis and cutting analysis are the main components on the membrane structure[1]. Many scholars have many studies on the Form-finding analysis and cutting analysis of the membrane structure.

According to form-finding analysis, the force density method, the dynamic relaxation method and the nonlinear finite element method are the main methods. H. J. Schke[2] firstly proposed force density method in 1964. Later, L. Gundig[3] et al adopted the concept of minimal surface to supplement the force density method. In 1965, A.S. Dya, and J.H. Bunce[4]proposed the dynamic relaxation method and using it to form-finding the cable net in Munich stadium. In the 70's of the last century, E. Huag and G.H. Powell put the nonlinear finite element method to the analysis of membrane structures. Next, Ye Xiaobing[5] and other scholars adopted three node curved mask element instead of planner membrane element to simulate.

For cutting analysis, many scholars were studied and the geodesic line method is the main method. This method was first proposed by Japanese scholar Ishii Yifu[6] and he adopted the geodesic lines on a polyhedron to obtain the cutting slices of the membrane structure. Next, Aikaa and Kozuka[7] simulated the geodesic line as the linear element.

On the basis of the above researches, the analyses of the membrane structure were based on the nonlinear finite element theory. Firstly using the least square method and gradient method to cut the membrane; and then using equivalent plate element method to flat membrane surface; then through the thermal sealing way, all the cut sections are connected into a whole, and the Form-finding analysis was done. At last, the form-finding solutions were compared with traditional membrane structure and the structure considering cutting line.

Form-finding analysis

In this paper, the nonlinear finite element method was used to realize form-finding of the membrane structure by software ANSYS.

The initial planar membrane is a square, and the length of the diagonal direction is 5m(figure1). The initial pre-tension of the membrane is 20kN/m, the tensile stiffness is 255kN/m, the shear stiffness is 80kN/m and Poisson's ratio is 0.3. The 4 corners of the structure are fixed, the 4 sides of the structure are cables, and its initial pre-tension is 30kN. The cable element adopted Link 10 and the membrane element selected Shell 41.

The steps of form-finding:

(1) Establishing the planar geometry model.

(2) Giving the material features to cable and membrane element, and the pre- stress is given also.

(3) Setting the boundary conditions, the lift height of the seat is 4m.

(4) Using the method of little Young's modulus of elasticity, fixing two fixed points, lifting two upgrade points, the first form-finding was realized.

(5) Given the actual elastic modulus of the structure and real pre-stress value. The self equilibrium iteration is solved.

(6) Repeating steps (5), until the results of the self balanced iterative solution reach the setting accuracy range, then form-finding end. The model of form-finding was shown in figure2. The displacement distribution and stress distribution of the membrane was illustrated in figure3 and figure4.

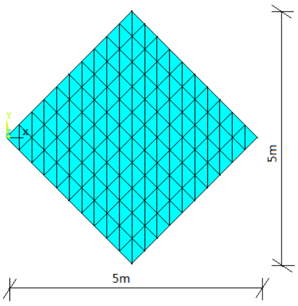

Fig.1 Planar membrane model

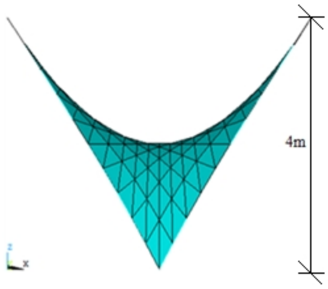

Fig. 2 Form-finding model

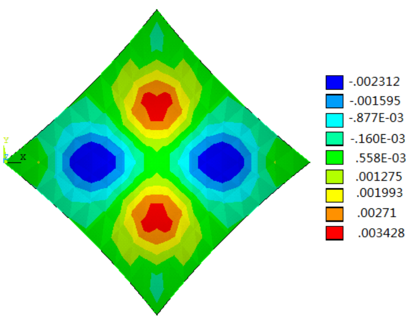

Fig. 3 Displacement distribution

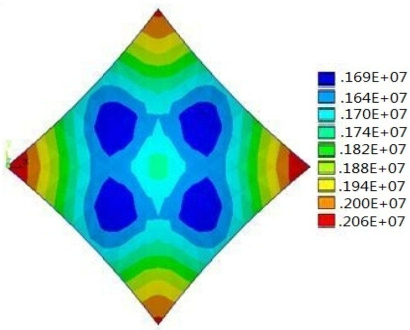

Fig. 4 Stress distribution

From figure 3 and figure 4, the minimum stress of the membrane surface is 1.53kN/m, the maximum stress is 2.06kN/m, and the difference value is 4.8%. The lifting points have the maximum stress.

Cutting analysis

In this paper, the method of geodesic line is used to cut the membrane surface. This method was realized by generalized functional extremum. The geodesic line of the curved surface is the shortest line from two points along the surface[8]. According to the membrane surface width, four pairs starting points were given in figure5. On the assumption that the curved surface is $f(x,y,z)=0$, then the geodesic line was written as:

$$l=\int_{x_1}^{x_2}\sqrt{1+y'^2+z'^2}\,dx \quad (1)$$

Based on these geodesic lines, five cutting slices were obtained in figure6.

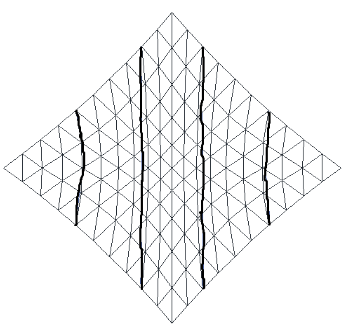

Fig. 5 Geodesic graph

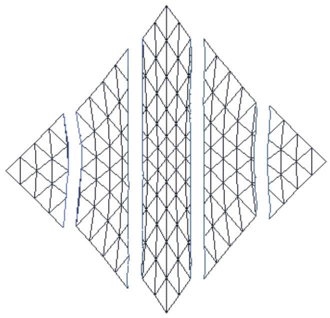

Fig. 6 Cutting slices

These cutting slices are curved. To obtain the planar flatten slices, the equivalent plate element method is used in this paper.

Form-finding analysis considering cutting lines

Through heat seal and considering 50mm connection bandwidth, the planar flatten slices were connected. According to the requirements of heat seal, the connecting strip thickness is 1.03mm. Thermal expansion coefficient is 10, the initial temperature is 0. Based on this planar model, the second form-finding was done.

The Form-finding results with cutting lines are as follows:

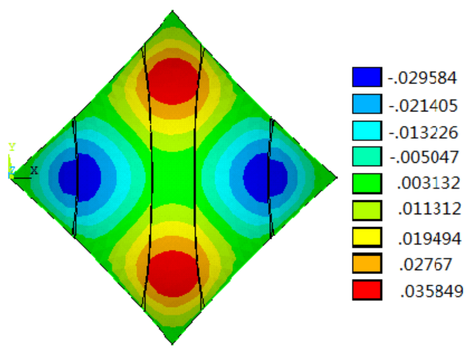

Fig. 7 Displacement distribution with cutting lines

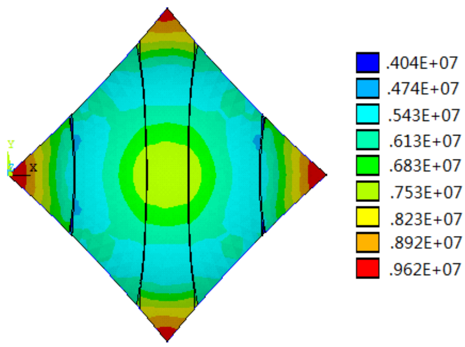

Fig. 8 Stress distribution with cutting lines

From figure7 and figure8, the maximum stress position is located at the four corners, while the maximum displacement is located in the upper and lower two parts of the membrane surface. Comparison figure 3 and 7, the membrane surface displacement maximum value is 0.0034m without cutting line, while the maximum value arrived 0.035m with cutting line. Comparison figure

4 and 8, the maximum stress value of the membrane surface can reach 2.06N/m without cutting line, while the maximum stress value can reach 9.62N/m with cutting line. After Form-finding, the maximum stress value of the membrane surface with cutting line is far larger than without cutting line, especially the connected position.

Conclusion

In this paper, a saddle membrane was analyzed by using the least square method and gradient method. Then using equivalent plate element method to flat membrane surface, through the thermal sealing way, all the cut sections are connected into a whole and the form-finding analysis was done. At last, the form-finding solutions were compared with traditional membrane structure and the structure considering cutting line. The maximum stress value of the membrane surface with cutting line is far larger than without cutting line. So the cutting line is very important for the form-finding of membrane.

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