Study and Application on Tension Measurement of Structural Membranes

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KEYWORDS
membrane structures, tension measurement, validating test, project application

1 Introduction

Due to its varied shapes and extreme lightness, the modern membrane structure has been favored by architects and engineers, and has already become one of the important structural styles in the field of the large-span space structures. The structural membrane is a kind of flexible materials, which can only bear tensions but compressions and bends. And pretensions have to be introduced into the membrane structures to make them erect and bear the outside loads. Therefore, the introduction of an appropriate pretension level is one of the key factors to ensure the quality and safety of the membrane structures. Compared with the wide applications of membrane structures and the rapid developments of the correlative analyzing theories and computational methods, the measuring techniques for membrane tensions are still far behindhand. In most cases, technicians judge whether the real tension levels of the actual membrane projects accord with the design levels only by their experiences.

According to [Sun Zhanjin et al 2005], the pretension measurement of the membrane structures which have already been introduced certain pretensions belongs to the nondestructive examinations. Based on different principles, some membrane companies in Europe, America and Japan put forward three kinds of methods and devised corresponding machines. However, the shortcomings of the existing methods and machines are obvious, such as the higher price of the measuring machine, lower measuring precision and inconvenience for operations. Especially, when the Japanese method is adopted, its machine needs to be calibrated according to different kinds of membranes before its on-site inspection, which increases the workload greatly. Consequently, these existing measuring devices have not been widely applied in practice.

This paper accomplishes a high-precision measuring method of membrane tensions that is reliable in theory, and devises the equipment for measuring membrane tension. Furthermore, the results of a large number of validating tests using PVC and PTFE membranes of different brands show that the device is of high stability and accuracy. Finally, several membrane projects which are detected by the device are introduced and the on-site applications display that the device itself is small, light and convenient for on-site operations.

2 Measuring method

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The principle of Stiffening Effect of Stress is the main basis of the theoretical deduction. According to [Sun Zhanjin & Zhang Qinlin 2005], while being introduced in-plane pre-tensions, membranes are of a certain out-plane stiffness. When a certain uniform load \( q \) is applied vertically, there is an out-plane displacement \( w \) in the middle of the rectangular part of membrane with pre-tension \( T \), as shown in Fig. 1, that is, a definitive mechanical relation exists.

\[
T = f(w, q, E)
\]

where, \( E \) represents the mechanical properties of membrane, especially the Young’s Modulus.

By examining the out-plane displacement \( w \) and the uniform load \( q \), the pre-tension \( T \) can be calculated through Eq. 1.

In the process of deductions of Eq.1, *as-cable method* is brought forward to simplify the 2D problem of the pretension membrane as the 1D problem of the pretension cable. Therefore, tensions in each direction of the membrane plane can be measured respectively. Meanwhile, the interferences of the mechanical properties of membrane, especially the Young’s Modulus, are eliminated from the deduction process by mathematic methods, which makes the deductive conclusion applicable to different kinds of membrane materials including PVC and PTFE membranes.

Shapes of membrane structures are curved spatial surfaces. However, for the sake of their huge areas, a local rectangular membrane area, as long as it is small enough, may be supposed as a membrane plane, shown as Fig. 2. Finite element parameter analysis, using the orthotropic plane element, is carried out on this rectangular membrane plane, to emphatically study the effects of the parameters along the b direction (long edge) on the displacement and stress level of the mid-point of the rectangular area under the condition of different uniform vertical loads and different placement of the warp and weft directions of the membrane.

Further FEA [SUN Zhanjin & ZHANG Qinlin 2005] shows that as long as the ratio of the long edge to the short edge of the rectangular membrane area is not less than 5, the effects of the mechanical properties along the long edge are small enough to be omitted, and that the behavior of the membrane area under the vertical uniform loads \( q \) is similar to that of a unidirectional plate. Thus, the study on the unidirectional membrane plate may be changed to that on the membrane strip of a unit width along the short edge (a direction). And because the mechanical properties of the membrane strip are identical with the single cable which has the same across section and Young’s Modulus, the related theory of the single cable [Shen Shizhao et al 1997] can be adopted to accomplish the deduction.

3 Machine invention and validating tests

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On the basis of the theoretical research, a measuring machine for membrane tension is invented, and a large number of validating tests are carried out, shown as Fig.3. The measuring device includes two main parts, a controlling box and a measuring box. And a vacuum pump, a laser displacements sensor and a vacuum sensor are the main components. A vacuum pump is adopted to introduce negative pressure on the local rectangular membrane area beneath the measuring box. And a vacuum sensor and a laser displacements sensor are responsible for detecting the vertical loads $q$ and the out-plane displacements $w$ respectively. The data process and results display are automatically controlled by the controlling box.

According to [MSAJ/M-02-1995], slit cross-shaped specimens with two force sensors in two perpendicular directions are adopted in the validating tests, as shown in Fig.3. The results of dividing the detecting value of the force sensors by the width of the core area of the cross-shaped membrane specimens may represent the membrane tension of the core area along the same direction. So the results are adopted as the true values of the membrane tension to validate the detecting values of the measuring machine.

Six kinds of membrane are adopted in the tests, including five kinds of common PVC membrane, and a kind of common PTFE membrane. Parts of the validating tests results of several kinds of membrane are shown in Fig.4. Results of a large number of tests show that the device for measuring membrane tensions is of high stability and accuracy, and the average error is about 10%.

4 Projects applications

By far, the measuring machine of membrane tensions has applied in several actual membrane projects. The on-site applications show that this device does realize the measurement of the actual pre-tension levels of membranes in the process of membrane structures’ installations, and that the device itself is small, light and convenient for on-site operation.
The first application case is a small scale membrane canopy, which model and measuring points’ layout is shown in Fig. 5. On-site measurement shows that the average pretension of the whole membrane is 1.31 kN/m, while some local parts are less than 1 kN/m. Such as the B direction of point 2, it is hard to increase its pretension level because the point is near the fixed wall edge and the B direction is parallel to the edge direction. So the results are reasonable.

Another two larger membrane projects were measured by this device, including a stand canopy of a stadium, a 300 m² steel frame membrane structure, and a tensioned membrane structure about 2,000 m². The models, measuring points’ layouts and the on-site operation pictures are shown in Figs 6 and 7.

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5 Conclusion

Tension measuring of membrane structures is a multi-discipline question involved in engineering, materials, mechanics and device inventions. This paper proposes the as-cable method, simplifies the deduction procedure, accomplishes the simple and practical theoretical formulas, and finally invents the corresponding measuring machine. A large quantity of validating tests and several on-site applications show the method is scientific and the machine is small, light and easy for on-site operation. Of course, the study is just a beginning and further detailed theoretical study and machine developments need much more work, such as, a more accurate theoretical deduction, a more delicate measuring machine and the problem of measuring the edge area which curvature is relatively bigger.

In conclusions, the invention and application of measuring machine of membrane structures does realize scientific, quantitative examinations of the actual tension levels of membranes in the process of membrane structures installations, which is benefit to improving the construction qualities of membrane structures and helps the healthy developments of membrane structures fields.

7 Acknowledgments

This work is sponsored by National Natural Science Foundation of China (grant number: 50478104) and Shu-Guang Fund of the Commission of Shanghai Education Foundation (grant number:97SG04)

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