Proceedings of the IASS-SLTE 2014 Symposium
"Shells, Membranes and Spatial Structures: Footprints"
15 to 19 September 2014, Brasilia, Brazil
Reyolando M.L.R.F. BRASIL and Ruy M.O. PAULETTI (eds.)

Parametric Analysis of Triangular ETFE Cushions

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Abstract
The triangle ETFE cushions were analyzed using theoretical analysis and numerical simulation. The relationship of the double triangle ETFE cushions' span, internal pressure, rise and the internal forces of membrane were obtained. The conclusions of this paper can provide reference for other engineering.

Keywords: ETFE; triangular cushion; parametric analysis.

1. Introduction
ETFE (Ethylene Tetra Fluoro Ethylene) film is used widely in architecture because of its lightweight, corrosion resisting, good light transmitting and wonderful architectural expression, with thickness of 50 μ m to 300 μ m, tensile strength of 40MPa to 60MPa and the breaking elongation of 300% to 400%.

Due to the insufficient tensile strength of ETFE film, a single-layer ETFE membrane only used for smaller spans. In order to across a large span, and meet the building performance requirements of thermal insulation, double or triple ETFE cushions were mostly used in engineering. ETFE cushions which formed through pumping the air into the multi-layered ETFE membrane, have a larger carrying capacity, and can meet the mechanical requirements of general building roofing systems.

In the projects have been completed, hexagonal, elongated or diamond ETFE cushions were used. Because hexagonal ETFE cushions or the cushions having closing circle shape have superior mechanical properties, they can span a larger space, have smaller deformation bearing the wind, snow and other external loads, less prone to wrinkle phenomenon. For example, the UK's Eden, Germany's Allianz Arena, China's Water Cube used these kinds of form. Triangle cushions are more prone to wrinkles, ETFE membrane surface stress is more uneven, so the project has been completed rarely used the triangle ETFE cushions.

ETFE cushions are kind of roof maintenance system, which' design need to meet the need of the main load-bearing structure system, such as single-layer lattice shells, trusses, etc. And in particular they are used in single-layer lattice shells project.

Single-layer lattice shell is composed of many beams which according to certain rules forming surface mesh structure. Triangle and quadrilateral mesh are commonly used in the project. Because of the stability of the triangular mesh, this kind of mesh are used the most widespread by structural engineers. So the triangular air pillow can't be avoided when ETFE membrane structures are used widespread. For example, China's Heixiazi Island Botanical Garden plans to use multi-layered triangular ETFE cushions. So the morphological and mechanical properties analyzing of triangle ETFE cushions have good engineering significance.

In this paper, the triangle ETFE cushions were analyzed using theoretical analysis and numerical simulation. By parametric analysis, the relationship of the double triangle ETFE cushions' span, internal pressure, rise and the internal forces of membrane were obtained. The conclusion of this paper can provide reference for other engineering.

2. Basic mechanical properties of ETFE film

The basic mechanical properties of ETFE film are adopted as shown in Fig. 1.

Properties	Units	ETFE film
Thickness	mm	0.25
Density	g/cm^3	1.75
Young's modulus	N/mm^2	650
Possion's ratio		0.42
Thermal expansion	1/℃	0.00025

Figure 1: Mechanical Properties of ETFE Film

3. Theoretical analysis of form-finding

Liu kaiguo[1] studies the form-finding analysis of ETFE cushions and gives the form-finding formulas of equilateral triangle ETFE cushions as follows by solving the differentiating equation of membrane structures which is deduced by the membrane theory with the twist analysis of elastic mechanics.

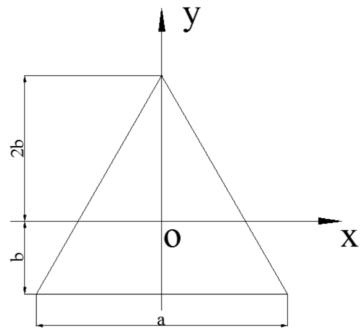

Figure 2: Equilateral triangle plane

$$\mathrm{f}_0 = \frac{P_c b^2}{3T}\ ,\ T = t\sigma \tag{1}$$

where P_c is the internal pressure

T is the tension of the film in a unit length

t is the thickness of the film

σ is the initial stress

f_0 is the rise of the membrane structure

4. Numerical analysis of form-finding

The finite element program ANSYS is employed for form-finding analysis of triangular air pillow. The form-finding process is simulated by the thermal stress method. Firstly, give a very small Young's modulus (usually 10-3 of the actual Young's modulus), a zero stress surface can be obtained through the thermal stress method. Then give an internal pressure and get the equilibrium surface. Finally renew the actual Young's modulus, solve the model until the stress of membrane surface tends to equal. The meshing figure and form-finding shape are shown in Fig. 3 and Fig. 4.

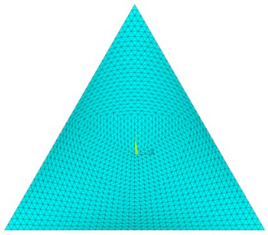

Figure 3: Meshing figure of ETFE cushion

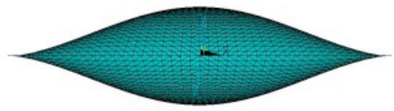

Figure 4: Form-finding shape of ETFE cushion

In order to examine the form-finding formulas, a series of numerical examples are given by the software ANSYS. In the paper, five different internal pressures which are 300Pa, 400Pa, 500Pa, 600Pa, 700Pa are given to analysis the relationship between rise and internal pressure. Meanwhile, five different internal forces which are 3MPa, 4MPa, 5MPa, 6MPa, 7MPa and five different side lengths which are 3m, 4m, 5m, 6m, 7m are adopted to have analysis. The corresponding shape-finding results of different conditions are shown in Fig. 5 to Fig. 7.

4.1 Effect of internal pressure

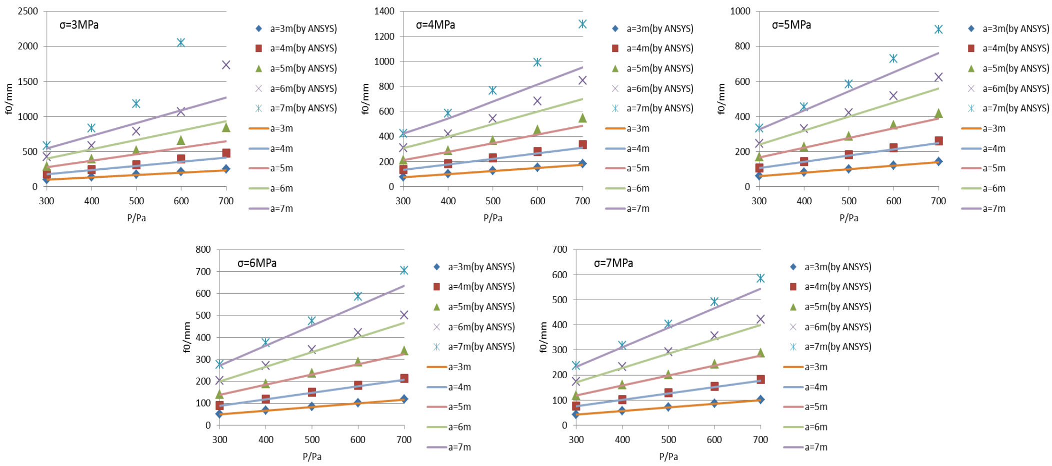

Figure 5: Relationship between Internal Pressure and Rise

From Fig. 5, the results shown that when span and internal force are given at a certain value, the rise increases mostly linearly as internal pressure increasing. While internal force is less than 4MPa, the increment of rise presents non-linear trends with internal pressure when the side length of triangle cushion is larger than 6m. The numerical results are very close to the theoretical results when internal pressure is no more than 500Pa. As internal pressure faces high value, the results from two methods are almost the same in small span but there is a large error between the two results when side length is more than 6m.

4.2 Effect of internal forces

Fig. 6 shows the relationship between internal force and rise. It can be known that rise decreases with the increase of internal force. The numerical results and theoretical results fit quite well when side length is no more than 5m at any internal forces and any internal pressure. As triangle cushion faces low internal force and high internal pressure, a big gap appears between numerical and theoretical results.

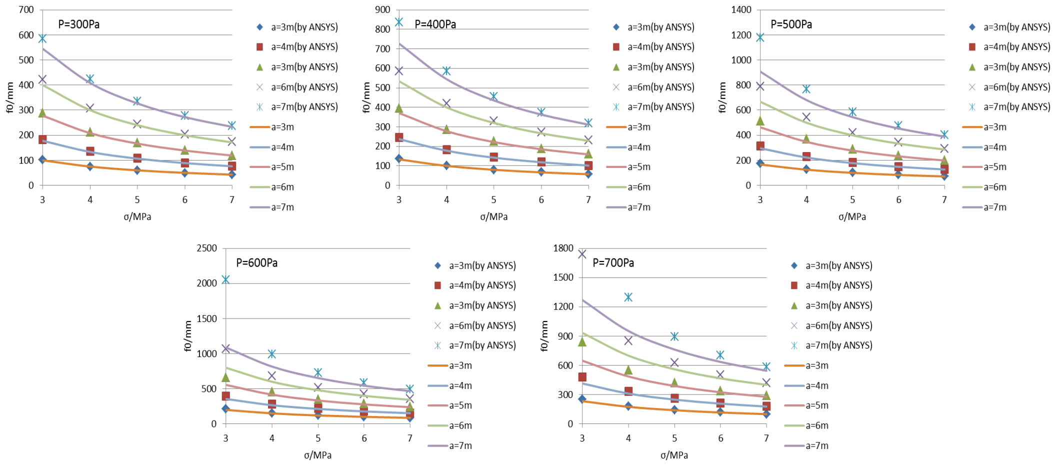

Figure 6: Relationship between Internal Force and Rise

4.3 Effect of span

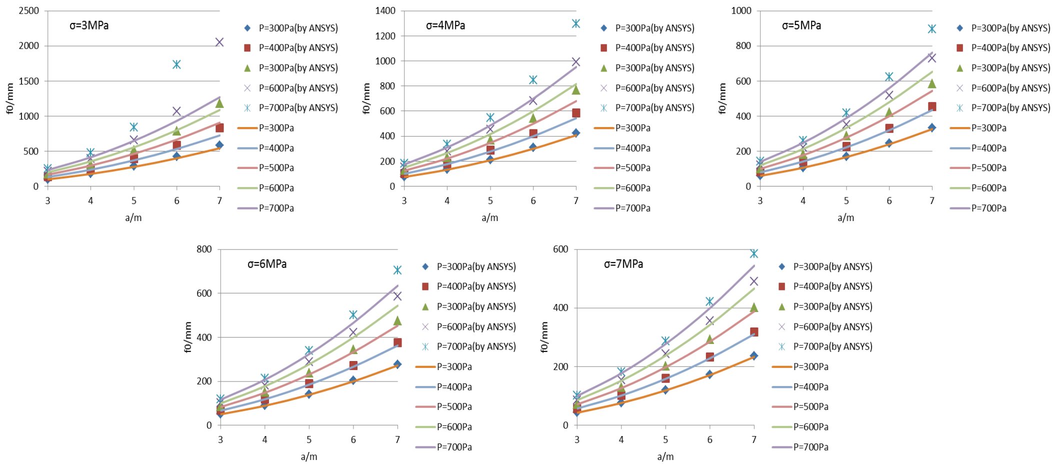

Figure 7: Relationship between Span and Rise

Fig. 7 gives the numerical results together with the theoretical results as span of triangle cushion changes. Along with the increase of span, the rise of triangle cushion increases. When span ranges from 3m to 4m, the numerical results and theoretical results are almost the same at any conditions. If span becomes larger than 4m, results fit well when internal force is no less than 6MPa at any internal pressure. And if span is larger than 4m, internal force is less than 6MPa at the same time, results can be close when internal pressure is no more than 600Pa.

5. Conclusion

ETFE foil cushion structures are favored by architects and civil engineers because of the advantages such as light weight, good self-cleaning, good light transmission and so on. The traditional ETFE cushions commonly use hexagonal, elongated or diamond form. Analysis of triangular ETFE cushions is necessary to meet the development of ETFE membrane structures.

In order to explore the relationship of the double triangle ETFE cushions' span, internal pressure, rise and the internal forces at the membrane surface, this paper gives five different spans, internal pressures as well as five different internal forces, and have form-finding analysis by the software ANSYS. The rise of triangle cushion increases along with the increase of span and internal pressure and decrease of internal force.

To test the form-finding formulas, numerical results and theoretical results are compared. Both results fit well when internal pressure is no more than 600Pa and internal force is no less than 4MPa. That is, in the form-finding process, control internal pressure in a range from 300Pa~600Pa and internal force from 4MPa ~7MPa, the form-finding formulas can be used in the initial form-finding of triangular ETFE cushions.

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