Experimental study of ETFE cushion-inflated form-developing through flat-patterning

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Abstract

ETFE membrane structure has become more popular because of its advantages of transparent, lightweight, durability, especially in the form of cushion-inflated due to rather low strength. Compared with the classic way, flat-patterning way is proposed to be the other way to determine ETFE form. An experiment set-up system was developed, which mainly consisted of ETFE cushion structure model, pressure control system and measurement system. The ETFE cushion is 2.5 m side triangle. The measurement system includes untouched photogrammetry and laser displacement sensor. The test procedure mainly experiences three phases, ETFE cushion form-developing, creep and creep-recovery. The inflation pressure, inflation rate, lasting time, deflation time and final pressure were tested thoroughly with the ETFE cushion rise and surface geometry surveyed precisely, as validate the design methodology. The experimental results demonstrated the applicability of flat-pattern of ETFE cushion and unveiled more ETFE properties, structural behavior and analysis theory need studying furtherly.

Keywords: ETFE cushion, flat-patterning, form-developing, creep, creep-recovery, photogrammetry.

1. Introduction

There are some advantages of ETFE foil, such as transparent, lightweight, durability. Therefore, it has been used in membrane structures over the past two decades, especially in the form of cushion-inflated due to rather low strength [1].

Normally membrane structure needs form-finding and is stressed to develop the form and stiffness. Generally there are two basic ways to determine ETFE form, one can be called classic way, and another is named flat-patterning way. As the classic way, the general Gaussian curvature surface is firstly calculated through form-finding, the surface is cut and flatted numerically, usually including strain compensation, the draped panels are welded together in sequence, the ETFE cushion is installed and pneumatically inflated to realize stable form. As the so-called flat-patterning way, there is no traditional form-finding analysis, cut and flatening analysis. Only simple flat-patternings are fabricated to cushion. The cushion is inflated till the stress approach or pass the first yield point, keep a period, then deflate to zero differential pressure. The cushion is inflated again with normal pressure about 300Pa in site, this form is obviously not flat, is a curved surface due to residual strain of ETFE film. The second way has distinguished advantages of simple fabrication, easy to install, material cost efficiency .

As the classic way concerned, there are many literatures. Robinson-Gayle S., Wolfgang Rudorf-Witrin and Edward M. P. et al. introduced buildings, basic mechanical properties and applications of ETFE foil in detail [2-4]. Christan H. and Annette B. et al. proposed the air unit, modelled the air for load carrying of ETFE cushion [5]. Moritz K. et al. investigated systematically design and engineering application of ETFE cushion, pointed out the phenomenon of time-temperature-shift (TTS) [6-8]. Borgart, A. studied mechanical behaviour of multi-layered air inflated cushions through the numerical analysis and experiment [9]. Minger Wu and Jianmin Liu et al. studied ETFE film mechanical property, analysis of ETFE inflated cushion and cushion-form with spring strut to support between layer, as well as test work [10,11]. Lei Gu and Peng Wang et al. conducted analysis and model experiment of ETFE cushion, proposed a corase way to measure stress[12]. Kai Wang and Wujun Chen et al. carried out series tests for ETFE cushion experiencing high temperature variation from 40 degree to 80 degree, as well as ETFE film, which testified the applicability of ETFE film cushion in Middle East hot area [13]. Wujun Chen and Bing Zhao et al. made experiments of ETFE cushion-inflated, studied mechanical behavior and ultimate capacity under normal and low temperature environment [14, 15].

As the other way named flat-patterning, there are less work public found. Schiemann L. made ETFE bursting test to exhibit nonlinear visco-elastic behavior [16]. Weininger F. and Schoene L. et al. made series experiments of ETFE cushion-inflated through Flat-patterning, studied post-harding behavior [17, 18]. Boegner B. H. and Blum R. et al. studied mechanical properties of ETFE foil, realized plane multiaxial experiment for the first time [19].

In this paper, flat-patterning is proposed to be the second way to determine ETFE form. An experiment set-up system was developed, which mainly consisted of ETFE cushion, pressure control system and measurement system. A series of experiments have been conducted. The two models were manufactured for inflation, creep and creep-recovery test. In addition, the whole processes were surveyed through three-dimensional photographic measurement system and laser displacement sensor.

2. Experiment set-up system

An experiment system which is accurate and advanced is a prerequisite to ensure the successful completion of scientific experiment. In this study, a reasonable experiment plan was proposed. An automatic pressure control system and a three-dimensional photographic measurement system were independently developed to monitor, control and measure the pressure and deformation, as have been verified that they are feasible, advanced and precision in several experiments [15, 16]. In this paper, the experiment set-up system mainly consists of ETFE cushion structure model, automatic pressure control system and measurement system.

2.1. ETFE cushion structure model

The ETFE cushion structure model is composed of an ETFE cushion, steel frame structure and aluminum extruder profile detail, shown in Fig. 1. There were two holes on the lower layer near the corners, as shown in Fig.2, one is blower inlet through valve, and the other set pressure sensor. The planar dimension of the cushion is equilateral triangle of side length 2.5 m. ETFE film is 250NJ from Japanese Ashi Glass Co. ltd. The thickness is 250 μm. Due to the limitations of the width of ETFE foil, the upper layer and lower layer are both welded with two sheets. The edges of the two layers are sealed to be a cushion. The seams are 10 mm width. Aluminum extruder profiles are used to connect ETFE edge pocket with ∅12 PE bar, and tensioned backward with M6 about uniform bay 21 cm to the bracket plates on the steel square hollow section (SHS100×100) frame rig. The steel structure is 3.3 m side length triangle in the horizontal direction and 1.1 m in height.

2.2. Automatic pressure control system

As ETFE cushion pressure control, it requires high accurate. The pressure will change sharply if use conventional blower because of its small volume. The control system will switch too fast if the threshold of internal pressure variation set about 10 Pa. Therefore, an automatic pressure control system was developed to monitor and control the pressure of ETFE cushion, as shown in Fig. 4.

The ETFE cushion system is very sensitive to the pressure due to much small volume, thus this requires high speed response and high accurate operation system. The pressure varies sharply even vary small air blow-in or out. And the system requires high pressure, which is invalid to adopt normal blower fan with small outlet pressure less 1kPa and big air flow. Thus the air compressor with high pressure and stable air flow was employed in pressure operation system.

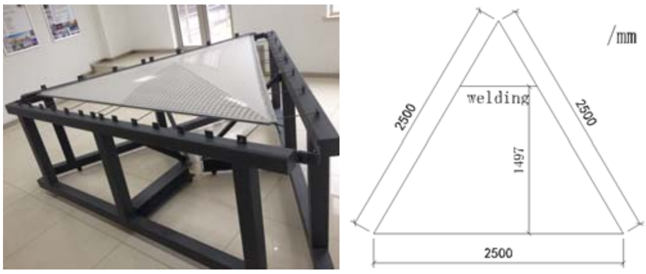
As shown in Fig. 4, the automatic pressure control system is mainly composed of computer, air compressor, USB data acquisition card, power relay output board, one-way valve, pneumatic FRL, high-speed pneumatic on-off valve, muffler, pressure sensor, stabilized voltage supply, etc.

As aforementioned, the threshold of internal pressure variation set about 10 Pa. This means that the pressure range 3.99-4.01 kPa, when the target value is 4 kPa. The pressure operation flow is illustrated as Fig. 5.

2.3. Measurement system

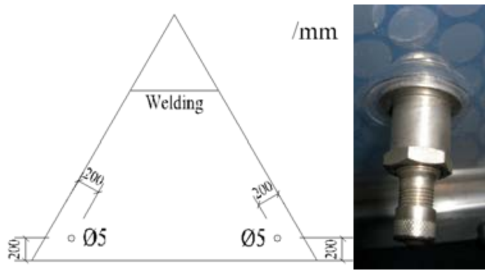
ETFE foil is too thin and flexible to measure the strain, displacement with conventional way. In the past, several measurement ways were used to detect the behavior of ETFE cushion subjected to cycle wind load [15,16]. It was found that the accuracy and range were not accurate enough. Therefore, a photographic measurement system was developed to measure the geometry, correlated strain of ETFE cushion, as shown in Fig. 5. In addition, a laser displacement sensor was used to survey the displacements of lower layer, as shown in Fig. 6.

As shown in Fig. 5, three-dimensional photographic measurement system, based on close-range photogrammetry, is composed of software Photomodeler software, single lens reflex (SLR) camera, calibration plate, invar bar kit, wireless remote control and target stickers.



(a) ETFE cushion Structure model (b) Cutting and pattern

Figure 1: ETFE cushion model



(a) Holes on lower layer (b) Valve core

Figure 2: Holes and valve core

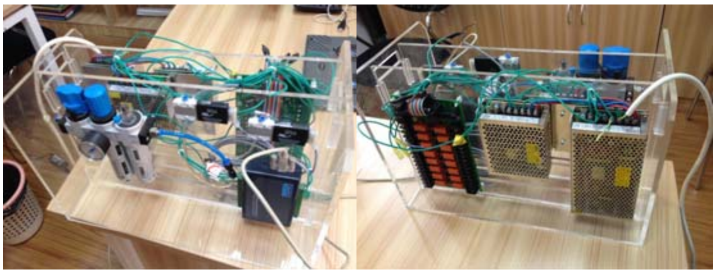


Figure 3: Snapshot of the automatic pressure control system

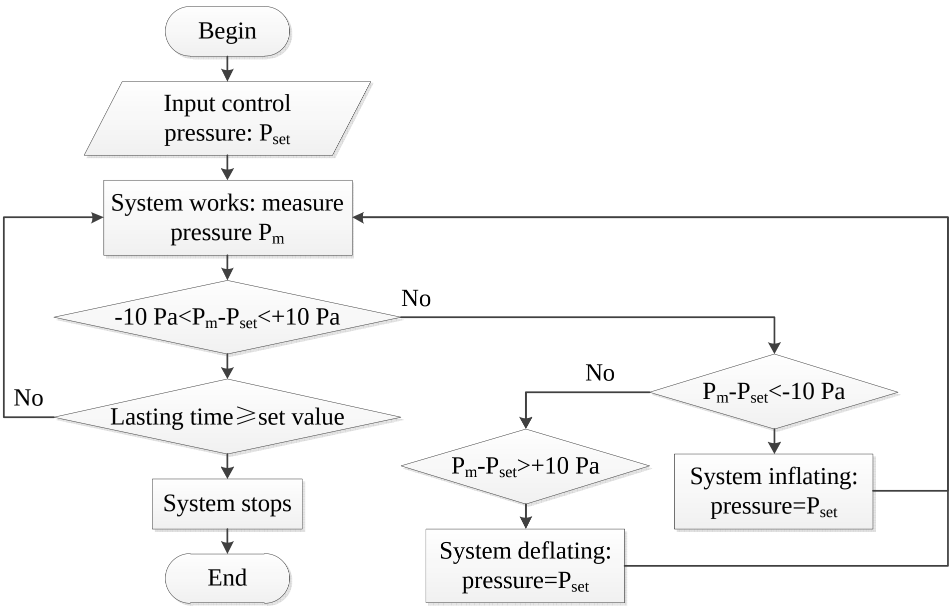


Figure 4: Pressure management flow

3. Experiments

A series of experiments were conducted successfully with each model. There were two identical models. According to different experimental requirements, such as different stress (through pressure control) and lasting time, the two models were performed with inflatable formation, creep and creep-recovery test in sequence in

Febuary, 2014. The temperature was about 5°C. The whole processes were surveyed through the laser displacement sensor and the three-dimensional photographic measurement system.

Figure 5: Three-dimensional photographic measurement system

Figure 6: Laser displacement sensor

For the first model, named Model-A, the ETFE cushion was inflated from 0 kPa to 4 kPa, taking increment 0.25 kPa. In addition, it lasted 3-5 sec to measure the parameters of the ETFE cushion on each increment. When it reached 4 kPa, the inner pressure was kept 4 kPa for 25 min. And then the cushion was deflated to 0.5 kPa and lasted for 24 h.

For the second model, named Model-B, the ETFE cushion was inflated from 0 kPa to 2 kPa. The inflating process is the same as conducted above. When it reached 2 kPa, the inner pressure was kept 2 kPa for 24 h. And then the cushion was deflated to 0 kPa and lasted for 24 h.

In this paper, series structural data, which mainly consisted of pressure of ETFE cushion, shape of upper layer, displacement of lower layer, etc. were successfully obtained from the series of experiments.

4. Results and discussions

The two ETFE cushion models were performed with series of experiments in sequence. We focuses on the structural performance under different conditions included stress (through pressure control) and lasting time. Regarding to the experimental observations, the results and interpretations are discussed in this section.

4.1. Numerical simulation

The numerical simulation was realized by finite element software ABAQUS Ver6.11. The material nonlinearity was considered in the numerical simulation. As presented previously, on each edge, there are eight M6 bolts used to connect the aluminum extruder profiles to the steel frame. So the boundary stiffness of singer layer in numerical simulation is comprehensively considered to be 22000 N/mm. The planar dimension of model is same to the cushion. The size of the grid is 2.5mm triangle.

The simplified nonlinear constitutive model is shown in Fig. 7. The constitutive model of ETFE foil is simplified as a three-line type. On the first yield point, the stress is 16 MPa and the strain is 2.42%. This yield the stiffness 660Mpa in first stage. On the second yield point, the stress is 22 MPa and the strain is 14.42%. And at the end of the simplified model, the strain is 50% and the stress is 23.067 MPa. As we know, the stress and the strain are nominal strain and nominal stress in Fig. 7. In order to accurately describe the variation of cross sectional area in the process of large deformation, true strain and true stress should be used in the numerical simulation. The transfer equations between nominal and true are written as

$$\varepsilon_{true} = \ln(1+\varepsilon_{nom}),\ \sigma_{true} = \sigma_{nom}(1+\varepsilon_{nom}) \tag{1}$$

ε_{nom} is nominal strain, that is Green strain, σ_{nom} is nominal stress, ε_{true} is true strain and σ_{true} is true stress.

The stresses of numerical simulation under different pressures are shown in Fig. 8. The maximum stresses of the cushion under 0.5 kPa, 2 kPa and 4 kPa are 4.72 MPa, 12.15 MPa and 19.69 MPa, respectively. It is found that the distributions of the biggest stress are similar. In the case of 4.72kPa, the maximum stress exceeds the first yield point, and the material experiences nonlinear stages.

In Fig.9, the displacement of numerical simulation under different pressures is shown. It is found that the biggest points lie on the center of the triangles under all three conditions. The displacements of the center of the cushion under different pressures include 0.5 kPa, 2 kPa and 4 kPa are 77.64 mm, 120.4 mm and 157.2 mm, respectively.

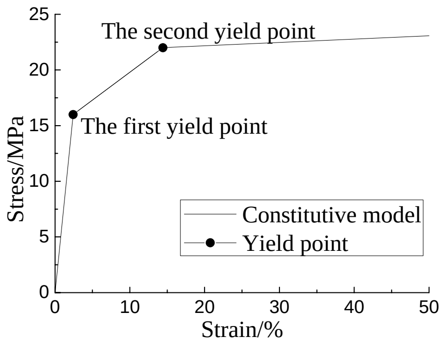
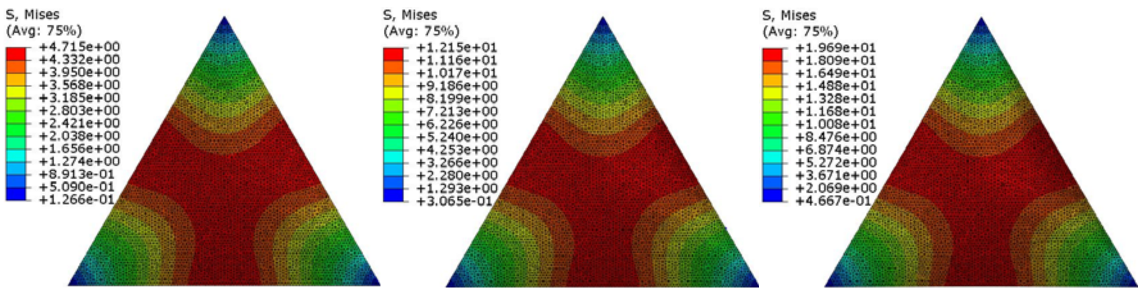
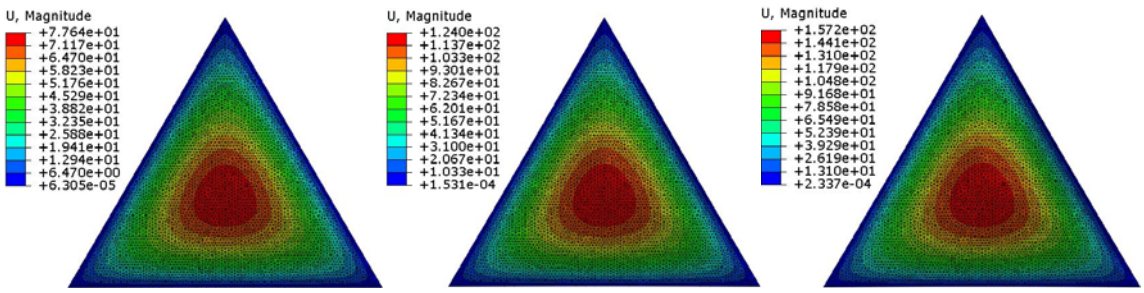


Figure 7: The simplified nonlinear constitutive model of ETFE foil



(a) 0.5 kPa (b) 2 kPa (c) 4 kPa

Figure 8: Displacement under different pressures (unit: MPa)



(a) 0.5 kPa (b) 2 kPa (c) 4 kPa

Figure 9: Stress under different pressures (unit: mm)

4.2. Form-developing study

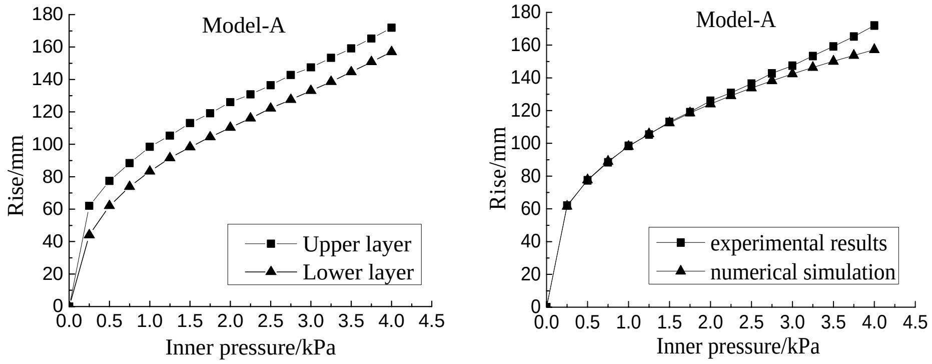
The two cushions were inflated to different inner pressures, Model-A was 4 kPa and Model-B was 2 kPa. They were inflated with an increment 0.25 kPa. At the moment of each increment, the parameters of the ETFE cushions were surveyed rapidly through measurement system.

Fig. 10a shows the rises of Model-A. It is found that the rises of ETFE cushion increase obviously with the increase of internal pressure, exhibit strong nonlinear. The three-dimensional photographic measurement system measures the upper surface geometry, and determines the upper rise. The laser displacement sensor detects the displacements of the center point of the lower layer, and determines the lower rise. The both rises vary in same tendency, overall offset difference is observed, and the maximum difference is 15 mm, as is expected mainly from ETFE foil gravity.

The comparisons of experiments results and numerical simulation are shown in Fig. 10b. The rises of experimental results in Fig. 8 are calculated from the upper layer. When the inner pressure is less than 2 kPa, the two curves are nearly identical. But when the inner pressure is greater than 2 kPa, the rise of experimental results are bigger than that of numerical simulation. This could be because the creep occurs in the whole inflation process, especially in the large stress phase.

The rises of the two models under 2 kPa are 123.42 mm and 125.99 mm, respectively. The difference between the two models was only 2.57 mm, about 2.1% in all. This shows that fabrication error plays little effect on the results, and the two models can be considered to be the same.

In summary, experiments were completed successfully, and the experiment set-up system operated well. Experimental results mainly coincide with numerical simulation, the difference could be caused by the creep occurs in the whole inflation process. In the initial measurement, the rise-span ratios of ETFE cushions under 0.5 kPa are 1:18.6 both in the two models.



(a) Experimental results (b) Numerical simulation

Figure 10: Rise under different pressures

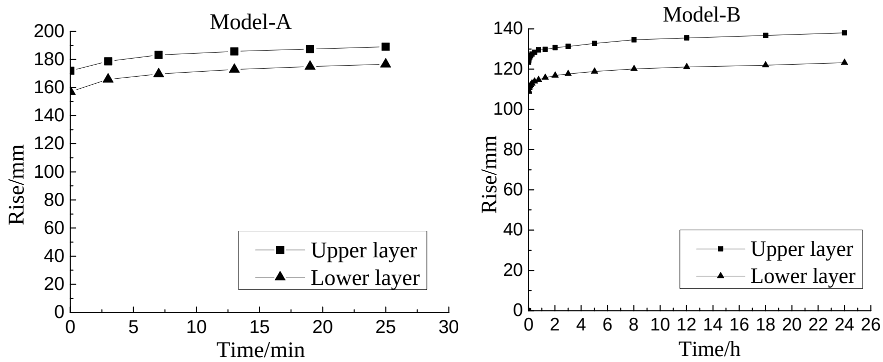
4.3. Creep study

The Model-A with high pressure under constant 4 kPa was placed for short time 25 min, on the contrary, the Model-B with low pressure under constant 2 kP was placed for long time 24 h. The main goal is to test the creep of ETFE foil with respect to the relationship of stress and last time.

In Fig. 11a, the rises of the Model-A under 4kPa with the time going are shown. On the whole, the tendency of the rise is increased due to ETFE creep. The rise change, which is 8.89 mm (45.3%) in the 3rd min (12%) and 12.66 mm (64.5%) in the 7th min (28%), is observed greater at the beginning than that in the last 18min.

The rise of the Model-B with 2kPa with the time going is shown in Fig. 11b. As same as the model-A, the tendency of the rises is increased from the overall graph. The rise mainly occurrs in the 1st hour.

In summary, the creep behavior of ETFE cushion is found obviously in both models. The rises of the two models change from 171.9 mm to 189 mm and from 123.4 mm to 138 mm, respectively. Because of the bigger inner pressure, the creep of the Model-A is bigger than that of the Model-B. The creep behavior occurs in the whole test procedure, but great part takes place at the beginning.



(a) Model-A (b) Model-B

Figure 11: Rises under different durations and pressures

4.4. Creep-recovery study

The Model-A with 0.5 kPa was placed for 24 h, and the Model-B with 0 kPa was placed for 24 h. The Model-A set 0.5kPa, and keep the pressure control operation after the former stage of inflation. The Model-B open the two holes of the lower layer to air and completely blow-out air till the two layer close together, then lay on the experiment rig for 24 hours.

Fig. 12 shows the inner pressures of the ETFE cushion Model-A in the process of creep-recovery. Overall, the pressures remain mainly at about 0.5 kPa, and are slightly more than 0.5 kPa. It is found that the cushion is shrinking, which results in decrease of volume and contrary increase of pressure, it could be thought that the ETFE foil shrinkage quantity is little bigger than the creep quantity. The shrinkage and creep of ETFE exhibit simutaneously.

The rises of the Model-A in the period of creep-recovery are shown in Fig. 13. On the whole, the rises of ETFE cushion are decreasing as time goes on. It is found that the creep- recovery mainly occurs at the beginning.

For the **Model-B**, the cushion was performed with creep-recovery test under 0 kPa, that is, zero stress applied on the ETFE surface more, only the internal residual stresses exsist, as result in ETFE resilent shrinkage, and no creep in the creep-recovery phase. At the end of the creep-recovery test, the cushion was inflated again to 0.5 kPa, and measured the form.

In summary, the process of creep-recovery is found after the creep test, and tends to be constant after 24 h in the Model-A. Finally, the rise-span ratios of ETFE cushion under 0.5 kPa are 1:12 in Model-A and 1:16 in Model-B, which are bigger than 1:18.6 in initial measurements.

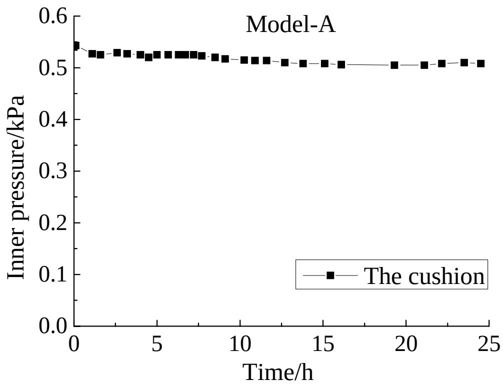


Figure12: Pressures during creep-recovery phase

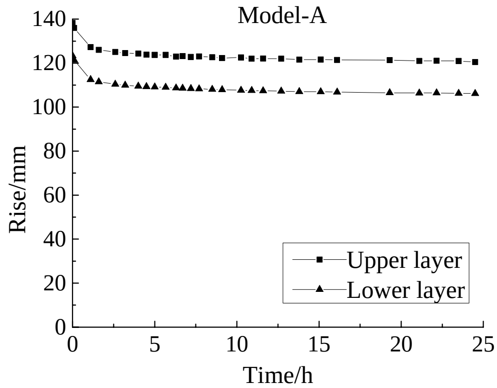


Figure 13: Rises during creep-recovery phase

5. Conclusions

An experiment set-up system was developed, which mainly consisted of ETFE cushion structure model, automatic pressure control system and measurement system. And a series of experiments have been conducted. The experimental results show that the flat-patterning way to determine ETFE form is feasible. According to the analysis of experimental results and numerical simulation, some conclusions can be drawn as the following:

1. Experiments were completed successfully, and the experiment set-up system operated well. The rises of the two models under 2 kPa are 123.42 mm and 125.99 mm, respectively. The difference between the two models is only 2.57 mm, about 2.1% in all. This shows that the fabrication error plays little effect on the results, and the two models can be considered to be the same.
2. Experimental results mainly coincide with numerical simulation, the differences are caused by the creep occurs in the whole inflation process. In the initial measurement, the rise-span ratios of ETFE cushions under 0.5 kPa are 1:18.6 both in the two models.
3. The creep behavior of ETFE cushion is found obviously in both models. Rises of the two models change from 171.9 mm to 189 mm and from 123.4 mm to 138 mm, respectively. Because of the bigger inner pressure, the creep of Model-A is bigger than that of Model-B. The creep behavior occurs in the whole test procedure, but great part take place in the beginning one hour.
4. The process of the creep-recovery after the creep test is observed, and tends to be constant after 24 h. Finally, the rise-span ratios of the ETFE cushion under 0.5 kPa is 1:12 in Model-A and 1:16 in Model-B, which are bigger than 1:18.6 in the initial measurement.

This study demonstrates the technical feasibility of flat-patterning way, as provides an efficient way to determine ETFE form which has distinguished advantages of simple fabrication, easy to install, material cost efficiency.

However, some limitations are worth noting in this paper. The numerical simulation is basic, advanced simulation need developing and validation. More tests need verifying, different geometry as hexagonal cushion, various pressure, last time, temperature, etc.

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