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Biaxial creep tests of ETFE foil

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Abstract

Recent decades have witnessed a widely application of ETFE foil in spatial structures, such as botanical gardens and stadiums. In membrane structural design, mechanical property of this material is one of key issues, which has attracted numerous researchers' interests. While ETFE foil creeps in long-term biaxial tension in structures, prior researches of its creep behavior were on the basis of uniaxial creep tests. This paper focuses on biaxial creep tests of ETFE foil and its numerical simulation. Two biaxial creep tests of ETFE foil in cruciform shape were performed for 24 hours. In these creep tests, stress ratio of the machine direction to the transverse direction was set as 1:1 and stress was at identical 6 MPa. These tests showed biaxial creep displacements were overestimated using merely uniaxial creep coefficients, counting one third as those in uniaxial tests. Hence, to establish a link between uniaxial and biaxial creep coefficients, biaxial reduction factor was introduced to consider this decline. Simulation results indicated this approach was practicable to determine biaxial creep coefficients. Meanwhile, a bubble creep test was performed for 10 hours. Stress in the circular specimen was generated by inner pressure 1845 Pa and ranging from 5.8 MPa to 8.5 MPa. Creep displacements of two points were monitored by laser sensors. Creep behavior of this test was simulated by FEM software package ANSYS. In numerical simulation, biaxial reduction factor and linear interpolation were applied to determine creep coefficients at the maximum stress. Simulation results showed good agreement with test data at both monitored points. Combining advantages of each biaxial test, this paper determined and verified biaxial creep property of ETFE foil.

Keywords: ETFE foil, biaxial creep test, bubble test, biaxial reduction factor, numerical simulation

1. Introduction

ETFE foil, a kind of polymers, has been widely used in spatial structures since the successful Jungle House being built in Arnheim, Netherlands (1981) [1]. For its high transparence and superior heat retaining property in cushion [2], this material is initially applied in zoos and botanical gardens, and recent decades, in stadiums and exhibition halls.

As other structural membranes, ETFE foil is maintained in tension during its whole serving life to form the shape of structures and avoid the wrinkling of surfaces. However, ETFE foil creeps in this long-term tension condition especially under high stresses or temperatures. The time dependent behavior increases creep deformation or causes stress relaxation of ETFE cushion. In this case, Kawabata and Wu studied creep behavior of ETFE foil basing on uniaxial tests [3,4], and established viscoelastic or viscoelastic-plastic modelling to simulate this behavior [5,6].

Yet, these studies were on the basis of uniaxial tests while ETFE foil is biaxial tensioned in structures. Even Galliot performed uniaxial and biaxial tensile tests of ETFE foil, showing similar mechanical property in these two loading conditions [7], long-term biaxial property of this material has not studied sufficiently. Because direction of molecule movement turning out to be two, rather than one, in biaxial tension condition, as well as the mutual dependence of molecule movement in each direction, biaxial creep property of ETFE foil might be different with that in uniaxial.

This paper focuses on biaxial creep tests of ETFE foil and its numerical simulation. Accordance with traditional biaxial tests of membranes [8], cruciform specimen was adopted to investigate creep property of ETFE foil under stress ratio 1:1. Relation between uniaxial and biaxial creep coefficients was then established. At last, a practical approach to simulate creep bubble was applied by FEM software package ANSYS.

2. Biaxial creep tests

Two main approaches to investigate biaxial mechanical property of membranes are biaxial test of cruciform specimen and bubble test. Biaxial test of cruciform specimen is widely adopted in coated fabrics, such as PVC and PTFE coated fabrics, and bubble test is suitable for those polymer membranes with large deformation.

Creep tests in cruciform shape could simulate ETFE foil being tensioned in uniform stress condition, which is similar as that in ETFE cushion, but creep deformation in these tests is too tiny to be well monitored. On the other hand, creep deformation in bubble test is large enough to be monitored, and high stress level could be easily achieved by air pressure, yet, stress distribution in this specimen is inhomogeneous. To take advantage of these two approaches, both biaxial creep tests were performed in this section.

In the following creep tests, ETFE foil specimens were all 250 μm in thickness, and temperature was kept in 20^0C $\pm 2^0$C. At first, uniaxial creep coefficients were obtained. To consider rates effect, stress rates in loading process of uniaxial and biaxial tests were maintained the same.

2.1. Creep tests in cruciform shape

Equipment designed for creep tests in cruciform shape was illustrated in Fig. 1. This equipment used weights to generate constant stress 6 MPa in left and right sides, and adopted laser sensors to monitor creep displacements in the machine direction (MD) and the transverse direction (TD). Measuring range of laser sensors was 20.00mm $\pm$0.02mm.

As shown in Fig.1, specimens were set horizontal to the ground, and biaxial creep dimension of the specimen was 300.0mm$\times$300.0mm. Two clamps in the up were flexible to move with the creep of specimen, while the other two were fixed in the down. Creep displacement monitor dimension in the tests was the core 200.0mm$\times$ 200.0mm.

Stress ratio of the machine direction to the transverse direction was 1:1 with constant stress at 6 MPa. Two specimens were used in this test while each creep test lasting 24 hours.

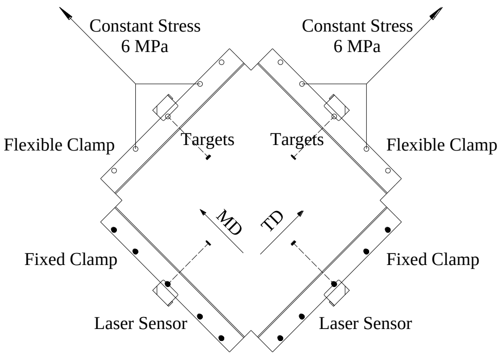

Figure 1. Equipment for cruciform creep tests

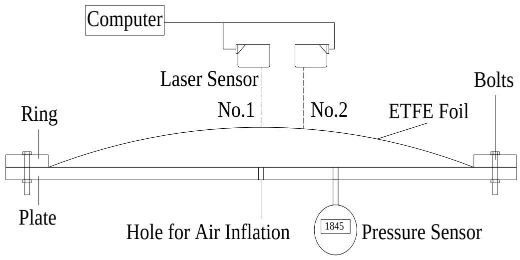

Figure 2. Equipment for bubble creep test

2.2. Creep tests in bubble shape

Equipment designed for creep tests in bubble shape was shown in Fig. 2. This equipment adopted inner pressure to generate stress in ETFE foil, which is similar as that in cushion. Pressure in this test was monitored by pressure sensor with measuring range 2000Pa$\pm$10Pa. Creep displacements of bubble at two specified points were both monitored by laser sensors with range 40.00mm$\pm$0.06mm.

Radius of this circular specimen was 500.0mm. Creep displacements of two points were recorded. The first one was the center point of circular, and the second one was 100.0mm distance with the center point. Single layer specimen was put in the up of steel plate and fixed by rings in the boundary. Two holes were set at plate to inflate air and monitor pressure.

During the creep test, inner pressure would decrease with time passing. To generate constant inner pressure, additional air was gassed in every half hour. Under this pressure control, inner pressure ranged from 1825 Pa to 1860 Pa, with average at 1845 Pa. This creep test was lasing 10 hours.

3. Results and simulation

Even though ETFE foil is biaxial tensioned in cushion, uniaxial test is more convenient in laboratory. To establish a link between them and be practicable in structure design, this section introduces a relation between uniaxial and biaxial creep coefficients, and its application in numerical simulation.

3.1. Creep coefficients

Schapery's nonlinear constitutive equation, which has been widely adopted to simulate viscoelastic behavior of polymers, can be simplified as following form:

$$\varepsilon(t)=g_0 D_0 \sigma + g_1 g_2 \Delta D(t)\sigma \tag{1}$$

where t represents time, $\varepsilon(t)$ is total strain, σ is stress, D_0 is initial value of compliance, $\Delta D(t)$ is transient component, g_0, g_1 and g_2 are coefficients relating to stress and temperature.

To simplify nonlinear calculation, generalised Kelvin model is adopted. The number of generalized Kelvin model is 5 and retard time is set as 10^i. Then, the viscoelastic modelling could be described by Eq. (2) and Eq. (3):

$$\varepsilon(t)=\left[D_0 + D(t)\right]\sigma \tag{2}$$

$$D(t) = \sum_{i=1}^{5} D_i (1 - e^{-\frac{t}{10^i}}) \tag{3}$$

where $D(t)$ is transient component, i is the number of generalized Kelvin model and D_i is creep coefficients in each generalized Kelvin model.

Because loading time in tensile process has significant effect on the creep coefficients, and the loading time in cruciform test was about 10 seconds and in bubble test was 120 seconds, two series of uniaxial creep tests were performed in each loading time. Creep coefficients are determined by the least squared method and listed in Table 1. Because part of creep behavior occurs in the loading process, most creep coefficients increase when loading time declines.

Also, creep coefficients exhibit strong relation with stress. With the enhancement of stress levels, creep coefficients increase. As instance, from 6 MPa to 9 MPa, total creep compliance doubles in 24 hours uniaxial creep tests.

Table 1. Uniaxial creep coefficients

Loading time (seconds)	Stress σ (MPa)	D_0	D_1	D_2	D_3	D_4	D_5
10	6	1.171E-3	6.8145E-5	6.9354E-5	9.1560E-5	1.0106E-4	3.0039E-4
	9	1.204E-3	1.1746E-4	1.5076E-4	2.3053E-4	9.9931E-4	2.9800E-3
120	6	1.296E-3	1.0823E-5	6.8065E-5	1.6562E-4	2.4996E-4	7.5247E-4
	9	1.339E-3	1.6379E-5	1.3297E-4	2.7250E-4	8.0809E-4	2.1800E-3

Results of biaxial creep tests in cruciform shape are illustrated in Fig. 3. As shown, creep displacements in the machine direction and the transverse direction are similar. In this sense, ETFE foil is treated as isotropic material in the paper.

If we apply uniaxial creep coefficients and consider the Poisson's ratio to simulate curves in Fig. 3, it is found biaxial creep displacements in tests are much smaller than those simulated, indicating a significant gap between uniaxial and biaxial creep behaviors.

Therefore, a biaxial reduction factor is introduced to take account of this decline. Biaxial creep coefficients are assumed the same as those in uniaxial, only adding a reduction factor to better simulate tests' curves. Then, biaxial creep strain could be described by Eq. (4).

$$\varepsilon_c(t)=(1-\nu)\times D(t)\times\sigma\times R_D \tag{4}$$

where $\varepsilon_c(t)$ is creep strain, v represents the Poison's ratio, which is set as constant 0.42, R_D is biaxial reduction factor.

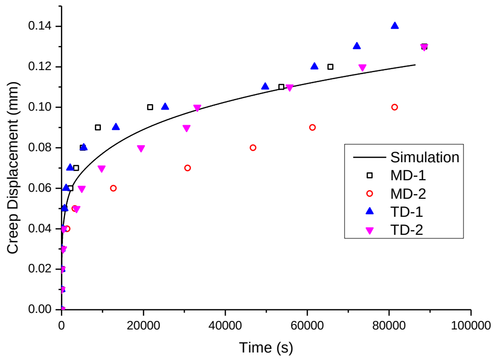

Figure 3. Creep displacements of cruciform specimens

After using curves in Fig. 3 and coefficients in Table 1, biaxial reduction factors are determined by the least squared method. The reduction factor in stress ratio 1:1 is 0.3391, meaning biaxial creep coefficients accounting only one third as those in uniaxial. That is to say, traditional method to calculate creep displacement in ETFE cushion from merely uniaxial creep coefficients has overestimated creep behavior of ETFE foil in structures.

Biaxial creep simulation is made on the basis of uniaxial creep coefficients and the reduction factor. Comparison results are shown in Fig. 3. As illustrated, simulation curve is located among tests' data, indicating the practicability of this simulation approach.

3.2. Numerical simulation

As stated in section 2.2, a bubble creep test was performed in 10 hours. Because initial specimen was in planar, and specimen was gassed in spherical crown during loading time, stress distribution in the creep test was inhomogeneous.

To analyze creep behavior in this bubble test, finite element method was adopted. ANSYS software was applied to take numerical simulation. In the analysis, element type was shell181 and element shape was triangle. Material nonlinearity and geometry nonlinearity were both considered in analysis.

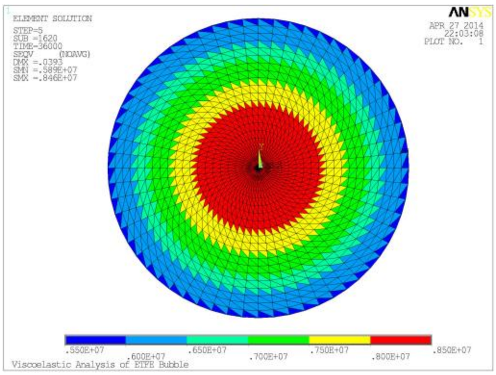

Figure 4. Stress distribution in bubble creep test

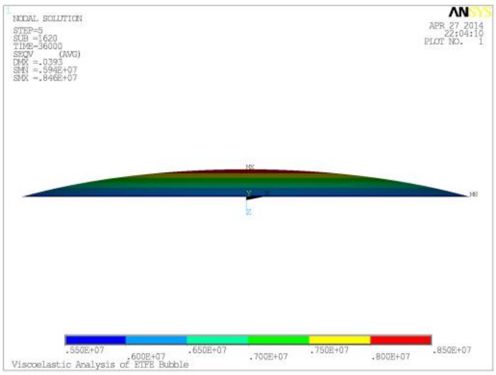

Figure 5. Bubble shape in creep test

In numerical simulation of loading process before creep test, ETFE foil was set as elastic material with modulus at 770 MPa. After the loading process, stress distribution and shape of the bubble are illustrated in Fig. 4 and Fig. 5. As shown, when the air pressure is 1845 Pa, stresses in the specimen range from 5.8 MPa to 8.5 MPa.

To simulate viscoelastic behavior of ETFE foil, Prony modelling was adopted. Relaxation modulus was described by Eq. (5), which inverses to the creep compliance in linear viscoelastic theory. Also, relative modulus α_i is difined as Eq. (6).

$$E(t)=E_\infty+\sum_{i=1}^{5}E_i e^{-\frac{t}{\tau_i}} \tag{5}$$

$$\alpha_i = E_i/(E_\infty+\sum_{i=1}^{5}E_i) \tag{6}$$

where $E(t)$ is relaxation modulus, E_∞ is steady modulus, E_i is transient modulus.

Considering biaxial effect on creep coefficients and boundary condition of the bubble, biaxial creep coefficients were all adopted those at 8.5 MPa with stress ratio at 1:1. Coefficients are calculated from linear interpolation, as listed in Table 2.

Results of bubble test and numerical simulation are illustrated in Fig. 6 and Fig. 7. As shown, simulation curves have good agreement with test data at the first and the second monitor points during the creep 10 hours.

Table 2. Biaxial creep coefficients in ANSYS

σ (MPa)	$E_\infty+\sum_{i=1}^{5}E_i$ (MPa)	α_1	α_2	α_3	α_4	α_5
8.5	770	0.004657	0.029747	0.062737	0.137203	0.208177

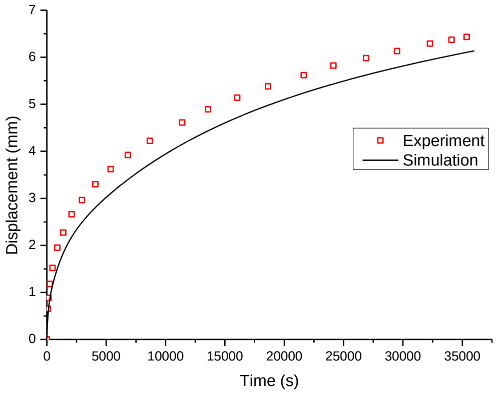

Figure 6. Creep displacement at 1st monitor point

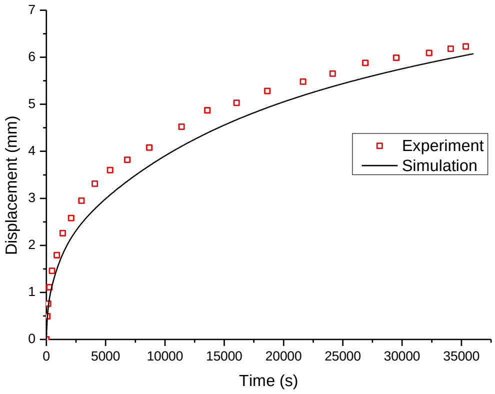

Figure 7. Creep displacement at 2rd monitor point

4. Conclusions

This paper performed two biaxial creep tests of ETFE foil, and introduced a practicable approach to simulate creep behavior of ETFE foil. This approach was verified by a bubble test and could be conveniently applied in practice.

On the basis of biaxial creep tests in cruciform shape, biaxial creep displacement of ETFE foil under stress ratio 1:1 were obtained. It showed creep compliance of ETFE foil in biaxial tension was much smaller than that in uniaxial. To consider this decline, a reduction factors was introduced. This factor established a link between uniaxial and biaxial creep coefficients, and indicated biaxial creep coefficients counting merely one third as those in uniaxial.

Meanwhile, a bubble creep test was performed in 10 hours and simulated by ANSYS. Creep displacements of two points were monitored. Applying the reduction factor in simulation, numerical results showed good agreement with test data at both monitor points. The approach to determine biaxial creep coefficients was also verified.

Acknowledgement

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