Tensile property of ETFE foil after viscoplastic-forming process

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Abstract

ETFE cushion traditionally forms its shape by cutting pattern, cutting and welding plane foil to curved surface. Recently, a novel form finding process, called viscoplastic-forming process, has been studied. This method utilizes unrecoverable deformation of ETFE foil to form designed structural shape, which makes the form finding process of ETFE cushion simpler. Two series (S-1 and S-2) of viscoplastic-forming tests were performed to investigate factors that affect the unrecoverable deformation, namely the objective strain in loading process and the time in creep process. Three objective strains were set in S-1 and four kinds of time were set in S-2. While the objective strain determined plastic deformation in the viscoplastic-forming process, the time in creep process determined that viscoplastic deformation. Results of these tests showed unrecoverable deformation increased with the enhancement of the objective strain and the time in creep process. Also, in most cases, the objective strain contributed more than the time in creep process to the final unrecoverable deformation. For the objective strain must being above the first yield point, the tensile mechanical property of ETFE foil after viscoplastic-forming process was different with that in original material. Uniaxial tensile tests were performed to investigate the tensile property of ETFE foil. Results showed that the first yield point moved to the new yield surface and the second yield point also changed. Strain and stress of the first yield point both increased, strain of the second yield point decreased and stress of the second yield point kept the same. Meanwhile, after the viscoplastic-forming process, initial tangent modulus of ETFE foil kept identical, and modulus between two yield points increased.

Keywords: ETFE foil, viscoplastic-forming, tensile property, yield point, modulus

1. Introduction

Recent decades have witnessed a rapid development of ETFE foil structures, with some impressive engineering projects like the Eden Project in England (2000) and the Water Cube in China (2008) [1]. As a thermoplastic material, ETFE foil has its comparative advantages in light weight, high transparency and environmental friendly character [2]. Meanwhile, ETFE cushion, the most common type of ETFE foil, embraces novel architecture facade, sound structural reliability and excellent energy efficiency [3].

In traditional membrane structure design, ETFE cushion forms its shape by cutting pattern, cutting and welding plane foil to curved surface [4]. Recently, there is another form finding method, called viscoplastic-forming process, which is also suitable for ETFE cushion [5]. This method tensions ETFE foil up to the first yield point and lasts for a given time, in which viscoplastic deformation occurs, then utilizes the unrecoverable deformation to form designed structural shape. It takes full advantage of the high extensibility of ETFE foil and makes the form finding process of ETFE cushion simple and convenient.

Meanwhile, ETFE foil exhibits two yield points in uniaxial tensile tests, which are called the first yield point and the second yield point respectively [6,7]. The two yield stresses are very important and recommended as design values in structural design [8]. After the viscoplastic-forming process, uniaxial tensile property of ETFE foil might change because of the movement of yield point, especially for stress and strain of two yield points and its modulus.

This paper focuses on the viscoplastic-forming process of ETFE foil and tensile property of material after this process. Viscoplastic-forming processes were performed in two series to study the effect of the objective strain and the time in creep process. Uniaxial tensile tests of ETFE foil after viscoplastic-forming process were carried out and compared with those of original materials.

2. Viscoplastic-forming test

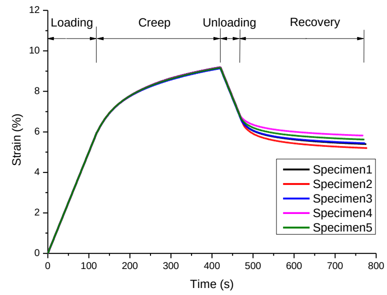
Viscoplastic-forming process of ETFE foil firstly tensioned specimen to the objective strain. The stain must be above the first yield point and contain plastic component. This process is called the loading process. Then, the force lasts for a given time, which is regarded as a creep process. During this process, viscoelastic and viscoplastic deformations both occur. After that, unloading process begins. When the force reaches zero, recovery process begins and lasts for a given time, in which most viscoelastic deformation recovers.

This novel form finding method utilizes the unrecoverable deformation of ETFE foil to form designed shape of structures, which major comes from the plastic deformation in the loading process and the viscoplastic deformation in the creep process.

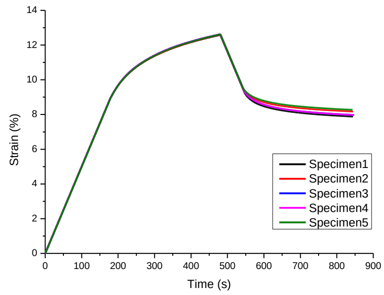
Two series (S-1 and S-2) of visceoplastic-forming tests were performed to investigate the significant factors in the method. In the loading process, the objective strain is the key factor that affects the final unrecoverable deformation, and this is studied in S-1. In the creep process, the time lasting in the process is significant factor, which is investigated in S-2.

ETFE foil used in both series was 250 μm in thickness and produced by Asahi Glass Company. Specimens were cut into rectangle shape with a length and width of 150 mm and 15 mm, respectively. Temperature in all tests was set as $20 \pm 2\ ^{0}$C.

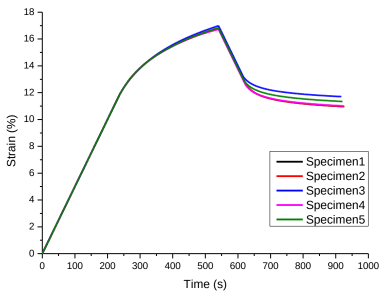
In S-1, specimens were firstly tensioned to the different objective strains, 6 %, 9 % and 12 % respectively, using the strain rate 3 %/min. And then, the force maintained for 300 seconds in which creep deformation occurs. After that, the force unloaded to zero in the same strain rate 3 %/min. Finally, recovery test began and lasted for 300 seconds. The viscoplastic-forming processes in S-1 are shown in Fig. 1.



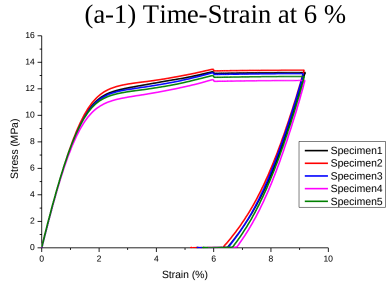
(a-1) Time-Strain at 6 %



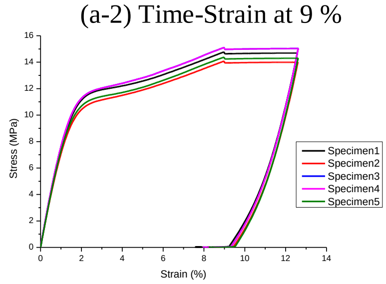
(a-2) Time-Strain at 9 %



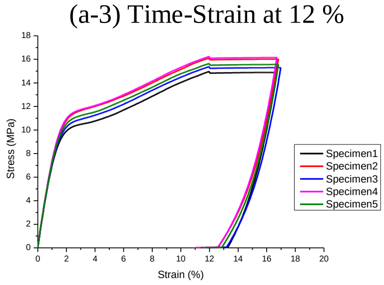
(a-3) Time-Strain at 12 %



(b-1) Strain-Stress at 6 %



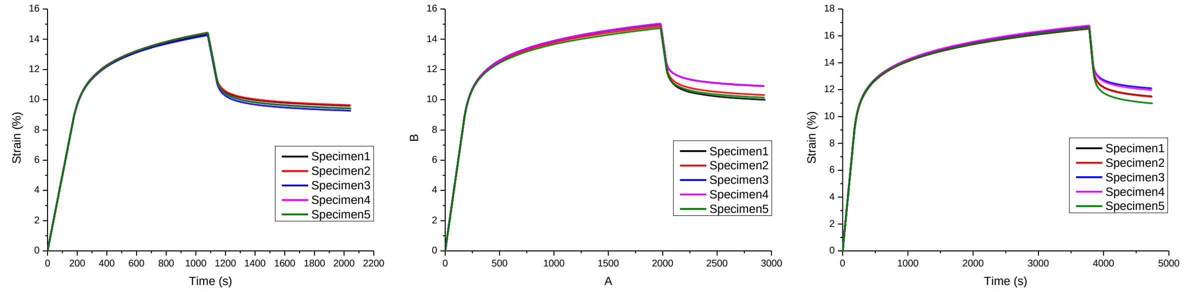
(b-2) Strain-Stress at 9 %



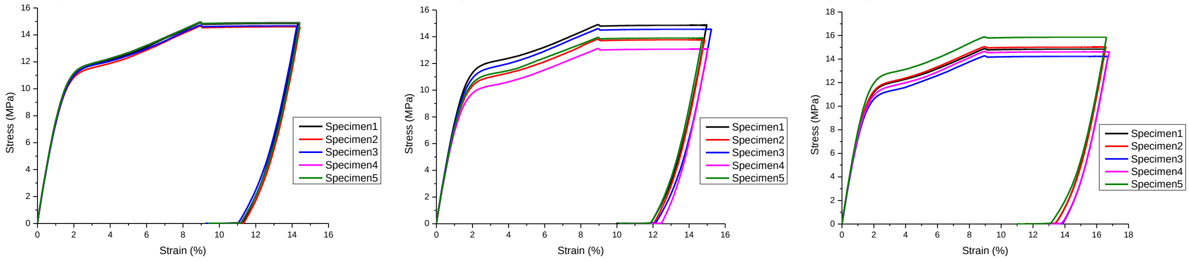
(b-3) Strain-Stress at 12 %

Figure 1. Viscoplastic-forming process in S-1

In S-2, specimens were tensioned to the same objective strain 9 % using the strain rate 3 %/min, And then, the force lasted for 300 seconds, 900 seconds, 1800 seconds, 3600 seconds, respectively. The unloading and recovery processes were the same as those in S-1. The viscoplastic-forming processes at 900 seconds, 1800 seconds and 3600 seconds are shown in Fig. 2.



(a-1) Time-Strain at 900 seconds (a-2) Time-Strain at 1800 seconds (a-3) Time-Strain at 3600 seconds



(b-1) Strain-Stress at 900 seconds (b-2) Strain-Stress at 1800 seconds (b-3) Strain-Stress at 3600 seconds

Figure 2. Viscoplastic-forming process in S-2

To distinguish the effect of two factors in S-1 and S-2, the unrecoverable deformation in the loading and unloading processes is called plastic deformation in this section, and the unrecoverable deformation in the creep process and recovery process is called viscoplastic deformation. These two deformations compose the total unrecoverable deformation, which is used to form the final cushion shape of ETFE foil. Unrecoverable deformation in S-1 and S-2 are listed in Table 1.

Table 1. Unrecoverable deformation in test

	S-1			S-2			
	6 %	9 %	12 %	300 s	900 s	1800 s	3600 s
Plastic Deformation	3.38	5.81	8.07	5.81	5.85	6.16	5.93
Viscoplastic Deformation	2.11	2.27	3.32	2.27	3.98	4.53	6.09
Unrecoverable Deformation	5.49	8.08	11.39	8.08	9.83	10.69	12.02

As listed in Table 1, with the increase of the objective strain in S-1, viscoplastic deformation increases slightly, and plastic deformation rises in a rapid speed. Also, most increase parts in the objective strain are reserved in the final unrecoverable deformation. For example, when the objective strain increases 3 %, from 6 % to 9 %, unrecoverable deformation increases more than 2.5 %. Moreover, in S-1, plastic deformation counts about 60 % to 70 % of the total unrecoverable deformation, and this percentage increases with the growth of the objective strain.

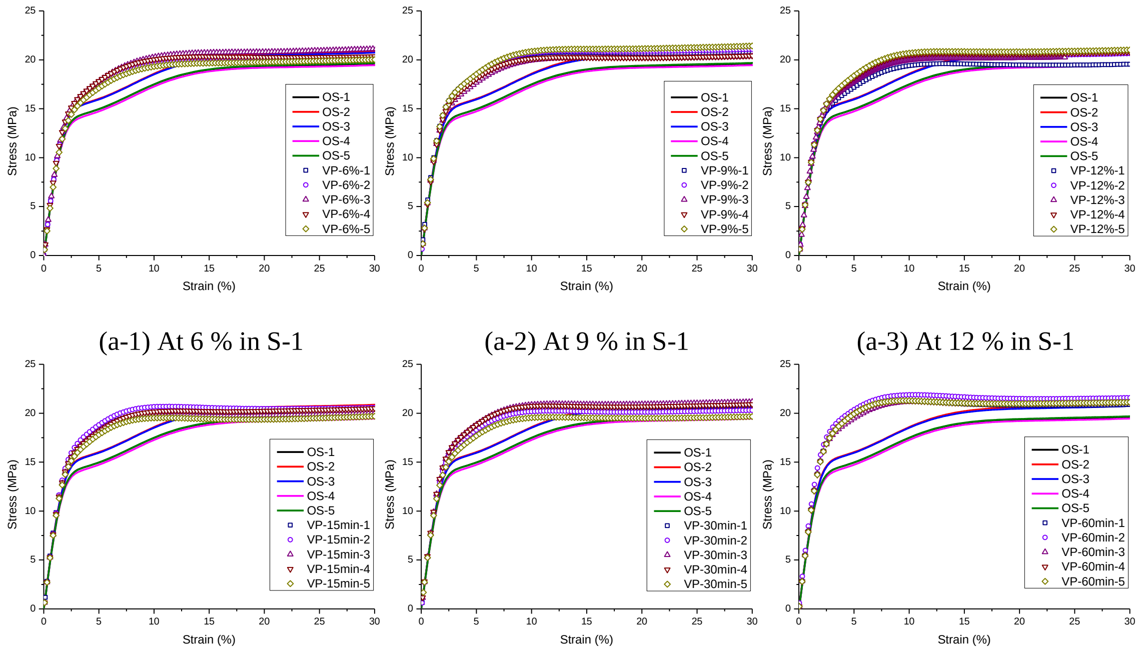
While in S-2, total unrecoverable deformation increases when more time lasts in creep process. Even though plastic deformation changed little in this part, it counts more than half of the unrecoverable deformation in most cases. Meanwhile, the time in creep process major affects the viscoplastic deformation. When the time increases from 300 seconds to 1800 seconds, viscoplastic deformation doubled in creep process, and it is closed to the plastic deformation when creep time reaches 3600 seconds.

That is to say, the objective strain in loading process and the time in creep process are two major factors that affect the final unrecoverable deformation. With the enhancement of two factors, unrecoverable deformation increases. Meanwhile, in most cases, the objective strain contributes more than the time in creep process to the final unrecoverable deformation.

3. Uniaxial tensile test

To investigate the mechanical property of ETFE foil after viscoplastic-forming process, uniaxial tensile tests were performed in this section. Strain rate in uniaxial tensile tests was set as 100 %/min. Temperature in these tests was 20±1 ^{0}C.

Uniaxial tensile tests of original specimen (OS) and specimen of ETFE foil after viscoplastic-forming process (VP) in S-1 and S-2 were carried out. Results of these tests are shown in Fig. 3.



(a-1) At 6 % in S-1 (a-2) At 9 % in S-1 (a-3) At 12 % in S-1

(b-1) At 900 seconds in S-2 (b-2) At 1800 seconds in S-2 (b-3) At 3600 seconds in S-2

Figure 3. Uniaxial tensile tests of ETFE foil

As illustrated in Fig. 3, after the viscoplastic-forming process, mechanical property of ETFE foil is different with that of original material. The two yield points become unclear. The deformation between the first yield and the second yield points become smaller. Because the objective strain in the loading process is above the first yield point, new yield point appears at a higher stress. This stress is identical to that of the objective strain in viscoplastic-forming process. As shown in Fig. 3, strain and stress of the first yield point both increase.

On the other hand, because the objective strain is less than the strain of the second yield point of original material, the second yield stress of ETFE foil has not changed. Because the viscoplastic deformation generates in the viscoplastic-forming process, strain of the second yield point decreases in tensile tests. Yet, stress of the second yield point keeps the same as that in original material.

The first tangent modulus, from zero to the first yield point, changes little. Material in this stage keeps in elasticity. However, modulus between the first yield point and the second yield point increases. Specifically, with the growth of unrecoverable deformation, modulus between two yield points increases.

4. Conclusions

This paper studied viscoplastic-forming process of ETFE foil and tensile property of the material after this process.

Two series of viscoplastic-forming process were performed to investigate the effect of the objective strain and the time in creep process. These two factors both have a significant effect on the final unrecoverable deformation. With the enhancement of the objective strain and the time in creep process, the unrecoverable deformation increased. And, the objective strain contributed more than the time increep process to the final unrecoverable deformation in most cases.

Uniaxial tensile tests of ETFE foil after viscoplastic-forming process showed that strain and stress of the first yield point increased. The deformation between the first and the second yield points become smaller. Yet, the stress of the second yield point kept the same as original material. Also, the initial tangent modulus of ETFE foil after the viscoplastic-forming process changed little, but the modulus between two yield points increased.

Acknowledgement

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