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CORRELATION BETWEEN UNIAXIAL AND BIAXIAL CREEP BEHAVIOUR OF ETFE FOILS

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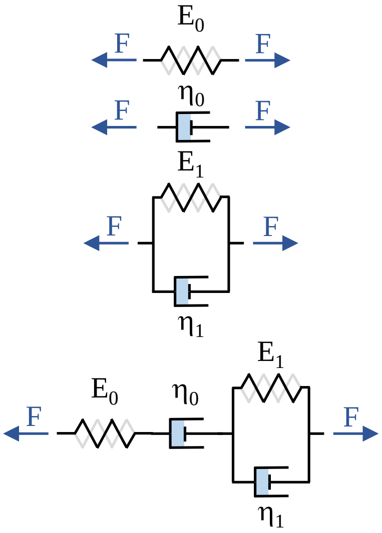
1 INTRODUCTION

With the first use of ethylene-tetrafluoroethylene (ETFE) foils as room-enclosing roof elements in the Mangrove Hall of the Burger Zoo, Arnhem, the Netherlands, ETFE foils are a fixed component in façade and roof systems of prestigious buildings and halls. Herein, ETFE foils can be applied in membrane structures independent of the building location's local climate. For instance, at the ETFE-foil roof of Khan Shatyr Entertainment Center in Astana, Kazakhstan, temperatures can reach down to -50 °C in winter and up to +40 °C in summer. All ETFE foil structures have to be designed regarding their ultimate limit state (ULS) and their serviceability limit state (SLS). In the design process, the building location's local climate must be considered. The newly developed prCEN/TS 19102 [1] defines the design process and provides recommendations for the execution of membrane structures made of technical textiles and technical foils, in particular ETFE foils. prCEN/TS 19102 requires consideration of creep effects but does not provide guidelines on how to include creep effects into the design.

The viscoelastic-plastic material behaviour of ETFE foils includes the creep behaviour which should be considered in the design of these foil structures to examine the elongation and thus deformation behaviour. To model the nonlinear time-dependent and stress-dependent creep behaviour of plastics, oftentimes Schapery's integral approach [3] is used to characterise nonlinear viscoelastic materials, see Eq. (1):

$$\varepsilon = g_0 D_0 + g_1 \int_{-\infty}^{t} \Delta D\left(\psi - \psi'\right) \frac{d g_2 \sigma}{d\tau} d\tau \tag{1}$$

Herein, D_0 and $D(\psi)$ are components of the linear viscoelastic creep compliance, g_0, g_1, and g_2 are material constants, and ψ the reduced-time. With the usage of rheological models, a combination of Hookean spring and Newtonian dashpot models, as described in [4], the nonlinear viscoelastic-plastic time- and stress-dependent material behaviour of ETFE foils under creep load can be described. Hookean spring elements describe the time-independent, instantaneous and completely reversible strain due to external loads and depend on the modulus of elasticity E. The Newtonian dashpot describes the time-dependent viscoplastic deformation and depends on the time-dependent strain $\dot{\varepsilon}(t)$ as well as a damping constant η. Parallel combinations of these springs and dashpots result in the Voigt/Kelvin model of viscoelasticity and even the Burgers model. Figure 1 illustrates the described rheological models and their corresponding equations (2) to (5).



Hookean spring
$$\sigma = E_0 \cdot \varepsilon \tag{2}$$

Newtonian dashpod
$$\sigma(t) = \eta_0 \cdot \dot{\varepsilon}(t) \tag{3}$$

Voigt/Kelvin model
$$\varepsilon(\sigma, t) = \frac{\sigma}{E_1} \cdot \left(1 - e^{-\frac{E_1}{\eta_1} \cdot t}\right) \tag{4}$$

Burgers model
$$\varepsilon(\sigma, t) = \frac{\sigma}{E_0} + \frac{\sigma}{\eta_0} \cdot t + \frac{\sigma}{E_1} \cdot \left(1 - e^{-\frac{E_1}{\eta_1} \cdot t}\right) \tag{5}$$

Figure 1: Visualization and analytical description of selected rheological models [14]

These rheological models can be combined and expended such that numerous parallel or series connections of Hookean springs, Newtonian dampers, and/or Voigt/Kelvin models can be generated.

Li and Wu [5] performed uniaxial creep tests at different load levels and temperatures to derive a creep and reverse creep model, based on Schapery's nonlinear constitutive equation [3]. To cover creep compliance depending on the test temperature, the time-temperature superposition principle of Williams, Landel and Ferry (W.L.F.) [6] was included by formulating a master curve. To model the uniaxial creep and reverse creep strains, a generalised Kelvin model consisting of a Hookean spring, a Newtonian dashpot and five Voigt/Kelvin models have been used. Kawabata and Moriyama [7] as well as Kawabata [8] performed uniaxial dynamic viscoelastic and uniaxial creep tests to formulate an analytical model containing a generalized maxwell element with $n+1$ Hookean springs and n Newtonian dashpots. To derive the influence of the temperature towards the viscoelastic material properties, the time-temperature superposition following the Arrhenius equation was used. Additionally, Kawabata and Moriyama [7] included a corrective function $\alpha(t, \sigma)$ to cover the nonlinear stress-dependent behaviour of the creep strains. Charbonneau et al. [9] performed uniaxial tensile tests as well as uniaxial creep tests lasting 24 hours on three different ETFE foil products (A, B, C1, C2) with foil thicknesses of 50 µm (A, B), 150 µm (C1), and 300 µm (C2), respectively. Following the principles of Liu et al. [10], they modelled the experimental results of the creep tests performed at 2 MPa, 8 MPa, 12 MPa, and 14 MPa using a viscoelastic multi-Kelvin (Hookean springs and Newtonian dashpots) as well as a viscoplastic power-law approach. They conclude a nonlinear stress-dependency on the creep behaviour of ETFE foils as well as higher elastic and creep strains in transversal direction (TD) than in extrusion direction (ED) of the analysed materials. Additional influences depending on the material producer were observed. Hu et al. [11] performed uniaxial creep tests at various test temperatures as well as various creep stresses, obtaining a nonlinear temperature- and stress-dependent material behaviour. Using the W.L.F. time-temperature superposition principle in combination with a time-stress superposition principle as described in [12], master-curves were formulated. Hanke [13] included time-stress superposition, time-temperature superposition as well as the thermal expansion of the material in his analytical model to predict the long-term behaviour of ETFE foils based on uniaxial and biaxial tensile tests, uniaxial dynamic-mechanical tests and short-term creep tests. Beck [14] derived a creep model for ETFE foils considering the material's stress- and temperature dependency. The model is based on the material's true equivalent von-Mises stress and true equivalent von-Mises strain behaviour. Saxe [16] and Li et al. [17] performed biaxial creep tests in different stress ratios (ED:TD). Saxe [16] performed the tests using cruciform specimens at room temperature with stresses in ED of 6 MPa, 9.5 MPa and 13 MPa while the stress in TD was unchanged at 4 MPa and states that even at the higher stress levels creep strains are convergent. The individual creep strains of the material directions depend on the stress ratio. Li et al. [17] performed biaxial creep tests using cruciform specimens in stress ratios 1:1, 1:0.5 and 0.5:1 with a maximum load of 6 MPa. In the uneven stress ratios, the lateral strain to the higher stressed direction were approximately 0 %, while the strains in the higher stressed direction exhibited significant creep strains. In stress ratio 1:1, ETFE foils showed an isotropic material behaviour. Based on the biaxial creep tests, Li et al. [17] derived an analytical model based on Hookean springs and Newtonian dashpots and introduced a correction function R_D based on the applied stress ratio.

Prior research towards the long-term creep behaviour of ETFE foils mainly focus on its uniaxial properties obtained from experiments performed on material from one producer, respectively. However, in membrane structures, the biaxial material behaviour of the materials is decisive. Li et al. [17] showed by using their established correction function that a mere isotropic approach considering the Poisson's ratio is insufficient. To simulate the biaxial creep behaviour of ETFE foils from different material producers and simultaneously maintain the ease of use and easy processing on uniaxial creep tests, in this contribution, an analytical correlation model between the uniaxial and biaxial creep behaviour is presented.

2 EXPERIMENTAL PROGRAMM AND RESULTS

2.1 Specimen and measurement methodology

To obtain the uniaxial and simultaneously biaxial creep behaviour of the investigated ETFE foils, cruciform specimens with slit arms were used. The load was applied by dead loads of hanging weights; the strains were measured optically using markers. By insertion of slits in the arms, a homogenous biaxial stress field is secured. At the same time, these slits secure a uniaxial stress field in the slits themselves. Figure 2 illustrates the dimensions of the used specimen geometry as well as the locations of the applied markers. The arm markers were applied with L_0 of 50 mm while the markers in the biaxial measuring field were applied in a 70 mm x 70 mm square. Creep tests were performed using ETFE foils from AGC Chemicals Ltd., Nowofol Kunststoffe GmbH, and TCI Europe GmbH. The material producers are numbered arbitrarily as producer I, II and III in order to maintain anonymity. The uniaxial and biaxial creep behaviour of ETFE foils of three different producers I, II, III and two foil thicknesses 100 µm and 250 µm was recorded at three different load levels 4 MPa, 8 MPa and 12 MPa and two different stress ratios ED:TD equals 1:1 and 1:0.5. All tests were performed with a load duration of 1,000 hours at T = 23 °C ± 2 °C. For each of the test options, two single tests were performed.

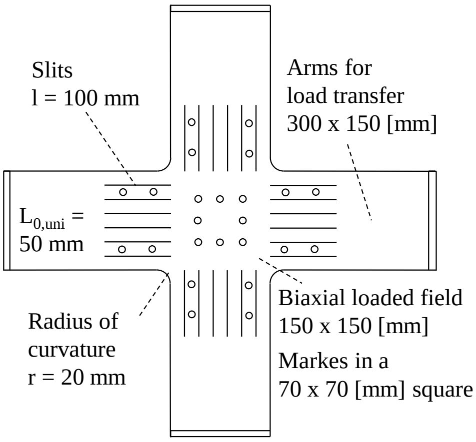


Figure 2: Cruciform specimen geometry and applied markers used in the uniaxial/biaxial creep tests.

2.2 Experimental results

As described previously, creep tests on ETFE materials from three different producers at three different load levels in uniaxial and two biaxial stress ratios were conducted. Exemplary, the measured strains, including the elastic strain due to the dead load, of the three investigated materials and two foil thicknesses of the load level $\sigma_{I,c}$ = 12 MPa in the three stress ratios (1:0, 1:1, 1:0.5) are presented in Figure 3.

The displayed creep diagrams show that the ETFE's compliance considerably depends on the material producer. Creep strains of the analysed ETFE foils from producer II exhibit the highest strains, material from producer III the second highest, and material from producer I the least strains over a period of up to 1,000 hours at $\sigma_{I,c}$ = 12 MPa. Additionally, Figure 3 shows the dependency of the applied stress ratio towards the measured strains. The least strains occur in stress ratio 1:1 due to the obstructed transversal strain, while the highest strains occur in the uniaxial stress ratio. In stress ratio 1:0.5, the transversal strain remains at approximately 0 % or is slightly negative.

Figure 4 illustrates the creep strains of three respectively two different load levels in three different stress ratios, given for material producer III as an example. It shows the nonlinearity of the creep behaviour of the thermoplastic ETFE foils. Doubling or tripling the applied stress does not result in doubling or tripling the creep strains, respectively.

Overall, the creep of ETFE depends on the applied stress level, applied stress ratio as well as on the material producer's receipt or production conditions. On the other hand, the basic shape of the creep curves is independent of the used material, or applied stress state and stress level. After the initial loading resulting in instantaneous strain, primary (starting with a high strain rate, which slows down over time) and then secondary creep (uniform creep rate) is measured in all tests.

250 µm foils exhibit slightly higher creep strain compared to 100 µm foils at an identical stress level. This follows the observations made in uniaxial tensile tests where tests on 100 µm foils show a slightly stiffer and stronger material behaviour than 250 µm ETFE foils, see [18],

[19].

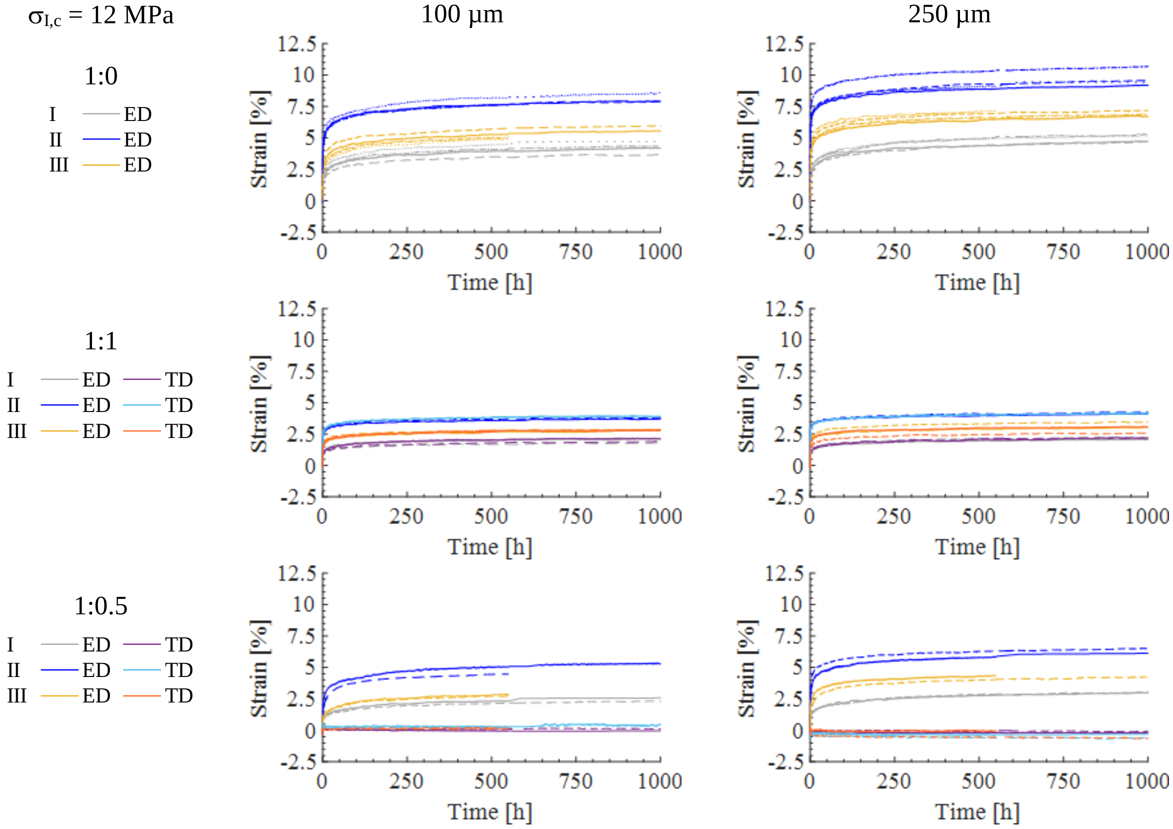


Figure 3: Strains of ETFE foils under long-term loading depending on the stress ratio, foil thickness and producer for $\sigma_{I,c}$ = 12 MPa, mean value curves.

3 MODELLING THE NONLINEAR CREEP BEHAVIOUR

3.1 General

To model the creep behaviour of the investigated ETFE foils, the creep strains $\Delta\varepsilon_c$ of the tests were identified, isolated, and then extracted, see Eq. (6):

$$\Delta\varepsilon_c(t) = \varepsilon_{total}(t) - \varepsilon_{initial} \tag{6}$$

Following the principles described in section 1, and by using the described Hookean springs as well as the Newtonian dashpots, the extracted creep strains $\Delta\varepsilon_c(t)$ are modelled analytically. Here, five Voigt/Kelvin models in a series connection are used:

$$\Delta\varepsilon_{c,uni}(t) = \sigma_c \cdot \left[\sum_{i=1}^{5} D_i \left(1 - e^{\frac{-t}{0.01\cdot 10^i}}\right)\right] \tag{7}$$

where D_i resembles the compliance at specific times t [h].

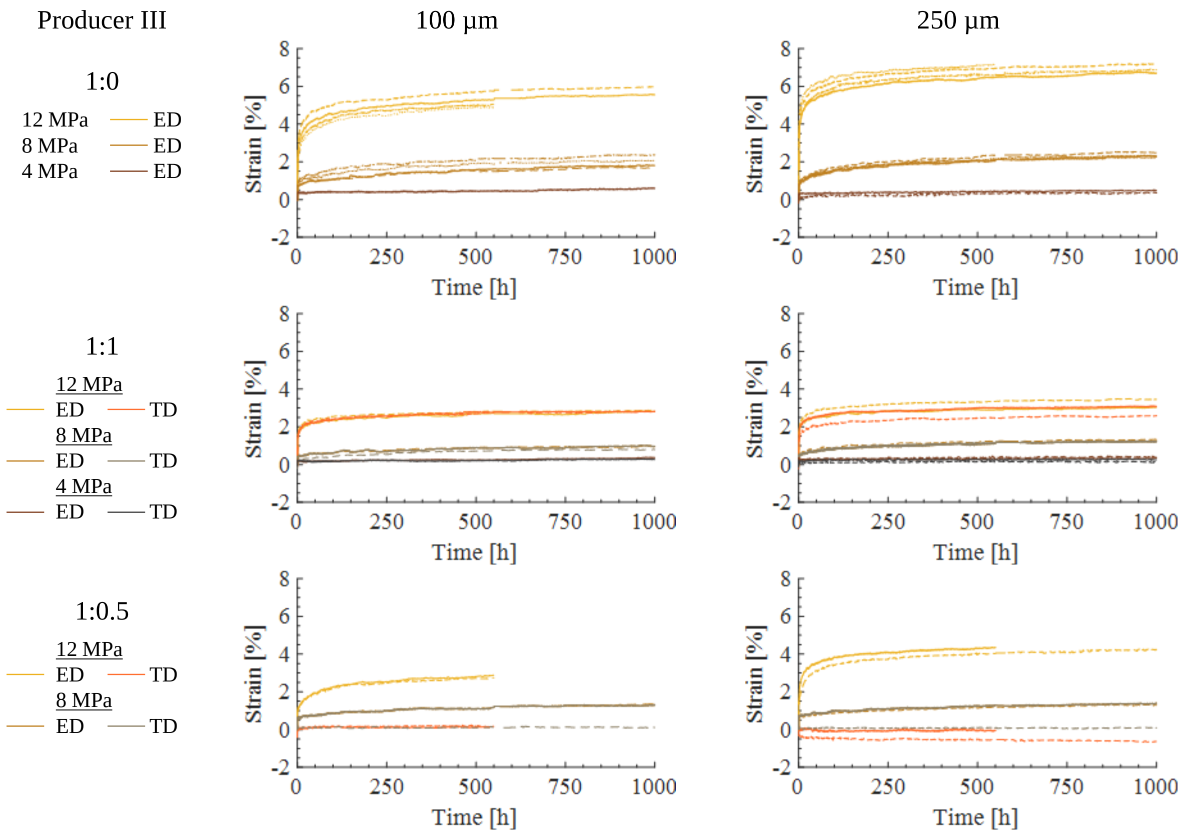


Figure 4: Strains of ETFE foils under long-term loading depending on the stress ratio, foil thickness and load level for producer II, mean value curves.

3.2 Modelling the uniaxial creep behaviour

Using Eq. (7), the uniaxial creep curves are fitted and the parameters are identified. Due to the compliance-dependency on the material producer I, II, or III, and the nonlinearity of creep strain caused by the applied load level, in a first step, each creep curve is modelled separately. Exemplary, Figure 5 illustrates the fitted model as well as the raw data creep curves of the ETFE foils investigated at the load level of σ_c = 12 MPa for 100 µm and 250 µm foils of the three material producers.

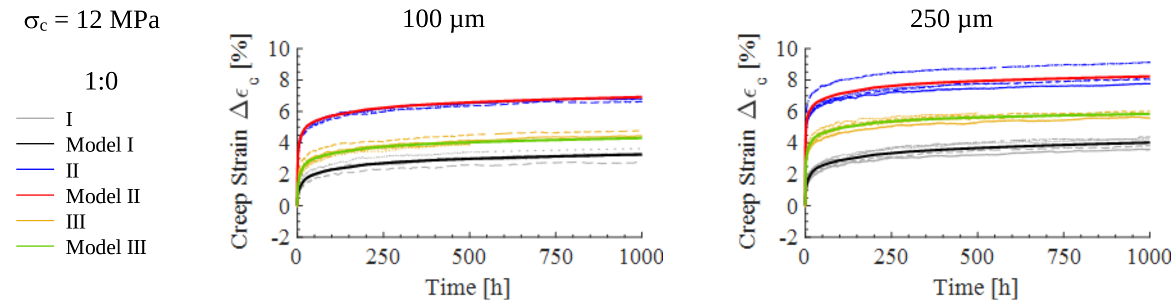


Figure 5: Comparison of recorded average creep strains of ETFE foils and the creep models at the uniaxial stress level σ_c = 12 MPa depending on the foil thickness.

As illustrated in Figure 5, the general approach modelling the creep strains of ETFE foils using rheological models is justified. Table 1 lists the average values of the determined compliances D_i. Here, a first approach modelling the creep behaviour of different ETFE foils is presented. In future, a stress dependency towards the compliances will be formulated, considering the nonlinear material dependency towards the creep behaviour depending on the applied stress level as well as the material differences caused by the producer. Nevertheless, in membrane structures, the biaxial material behaviour is decisive in the design.

Using the derived compliances, the decisive biaxial creep behaviour of ETFE foils can be modelled in the next step.

Table 1: Average values of the calculated compliances D_i in dependency of the applied stress level, foil thickness and material producer.

Producer	Foil thickness [μm]	Stress level σ_c [MPa]	Compliance D_i [1/MPa]				
			D_1	D_2	D_3	D_4	D_5
I	100	12	0.0094	0.0354	0.0870	0.0807	0.0948
		8	0.0092	0.0044	0.0073	0.0309	0.0921
	250	12	0.0185	0.0566	0.1006	0.0852	0.1177
		8	0.0085	0.0042	0.0107	0.0395	0.0893
II	100	12	0.0710	0.2002	0.1318	0.1000	0.1165
		8	0.0149	0.0090	0.0361	0.1320	0.1789
	250	12	0.2428	0.1753	0.1011	0.1037	0.0998
		8	0.0177	0.0068	0.0780	0.1564	0.1312
III	100	12	0.0216	0.0723	0.1184	0.0890	0.0912
		8	0.0188	0.0038	0.0191	0.0495	0.1351
	250	12	0.0633	0.1661	0.1158	0.0939	0.0766
		8	0.0165	0.0026	0.0291	0.0863	0.1225

3.3 Modelling the biaxial creep response based on the uniaxial creep behaviour

To model the biaxial creep behaviour, the approach in Surholt et al. [20] was used modelling the biaxial material behaviour in a short-term tensile test using the plane stress state and assumption of isotropic material behaviour. Eq. (7) is extended by the influence of the transverse strain to formulate a biaxial correlation term. Li et al. [17] conducted a similar approach by integrated functions to modify the uniaxial creep behaviour to a biaxial creep behaviour.

Following the principles of a plane stress state and by ignoring stresses σ_{xy}, the creep strains in ED and TD can be calculated individually for the principle directions I and II as follows:

$$\Delta\varepsilon_{c,I,biax}(t) = \Delta\varepsilon_{c,uni}(t)\cdot(1-\nu\cdot r) \tag{8}$$

$$\Delta\varepsilon_{c,II,biax}(t) = \Delta\varepsilon_{c,uni}(t)\cdot(-\nu+r) \tag{9}$$

Here, ν is the Poisson’s ratio with ν = 0.45 = const. and r is a modification factor considering the applied stress ratio. For example, in a stress state 1:1, r equals 1.0, and in a stress state 1:0.5, r equals 0.5. Additional modification factors R_i have to be integrated to accurately model the biaxial creep behaviour, due to the limitation of the plane stress state to elastic materials as well as the assumption of an isotropic material behaviour. By shifting the individual compliances

D_i, the biaxial creep behaviour can be modelled precisely using Eq. (10) and Eq. (11):

$$\Delta\varepsilon_{c,I,biax}(t) = \sigma_c \cdot \left[\sum_{i=1}^{5} D_i R_i \left(1 - e^{\frac{-t}{0.01\cdot 10^i}}\right)\right] \cdot (1 - \nu \cdot r) \tag{10}$$

$$\Delta\varepsilon_{c,II,biax}(t) = \sigma_c \cdot \left[\sum_{i=1}^{5} D_i R_i \left(1 - e^{\frac{-t}{0.01\cdot 10^i}}\right)\right] \cdot (-\nu + r) \tag{11}$$

However, to maintain the simplicity of the plane stress state approach, the modification factors R_i are extracted from the compliances D_i and applied to the biaxial correlation term, see Eq. (12) and Eq. (13). This approach is at the expense of accuracy.

$$\Delta\varepsilon_{c,I,biax}(t) = \Delta\varepsilon_{c,uni}(t) \cdot (R_I - \nu \cdot r \cdot R_{II}) = \sigma_{c,I} \cdot \left[\sum_{i=1}^{5} D_i \left(1 - e^{\frac{-t}{0.01\cdot 10^i}}\right)\right] \cdot (R_I - \nu \cdot r \cdot R_{II}) \tag{12}$$

$$\Delta\varepsilon_{c,II,biax}(t) = \Delta\varepsilon_{c,uni}(t) \cdot (-\nu \cdot R_I + r \cdot R_{II}) = \sigma_{c,I} \cdot \left[\sum_{i=1}^{5} D_i \left(1 - e^{\frac{-t}{0.01\cdot 10^i}}\right)\right] \cdot (-\nu \cdot R_I + r \cdot R_{II}) \tag{13}$$

For a uniaxial stress state, both R-factors equal 1.0. In a 1:1 strass ratio, both R-factors are equal with $R_I = R_{II}$. Figure 6 illustrates the calculated creep curves, that base on the creep compliance parameters D_i determined in the uniaxial creep tests, which are then modified by the R-factors described above. The determined R-factors are listed in Table 2.

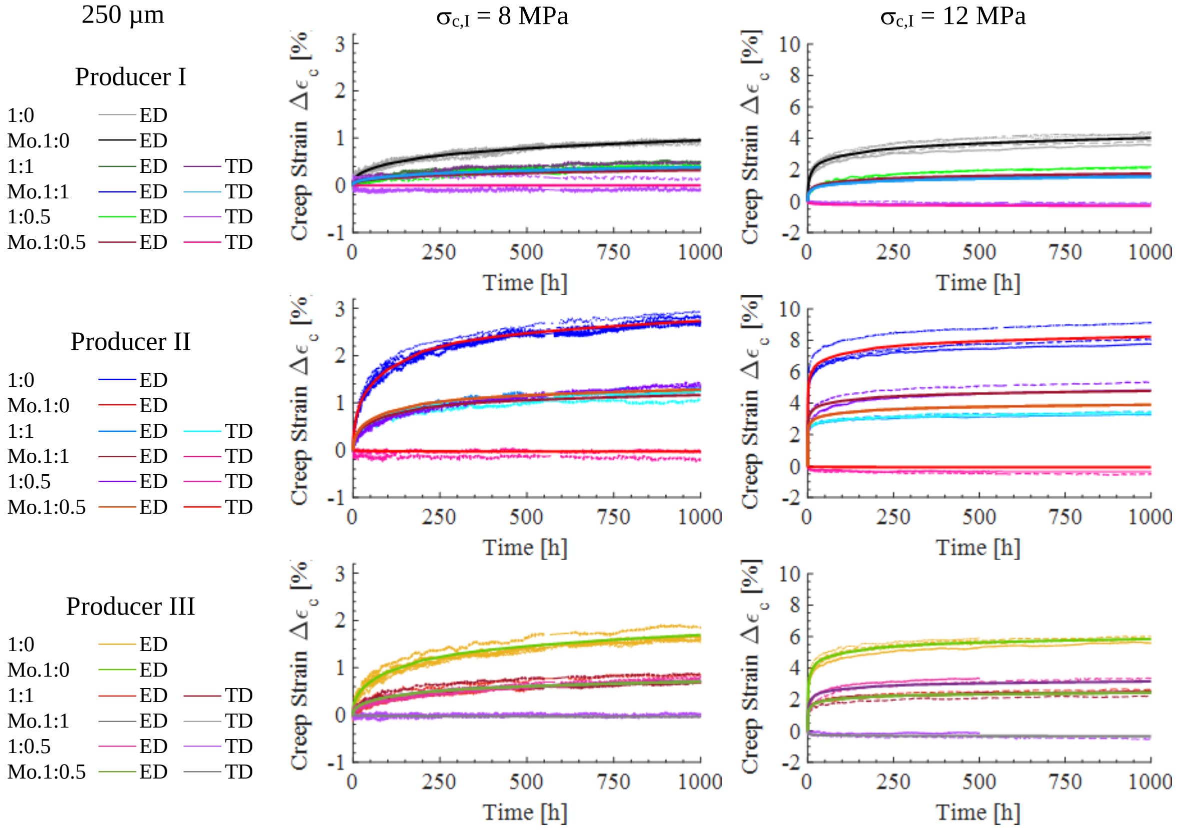


Figure 6: Comparison of the average creep strains of ETFE foils and the creep model (Mo.) depending on the applied load level and the stress ratio, given for 250 µm foils as an example.

Table 2: Average values of the calculated modification factors R_I and R_{II} in dependency of the applied stress level, foil thickness and material producer.

Producer	Foil thickness [μm]	Stress level σ_c [MPa]	Stress ratio	Modification factors R_i	
				R_I	R_{II}
I	100	12	1:1	0.7486	
			1:0.5	0.4848	0.3236
		8	1:1	0.7476	
			1:0.5	0.6750	0.1726
	250	12	1:1	0.7081	
			1:0.5	0.5083	0.3097
		8	1:1	0.7338	
			1:0.5	0.4245	0.3842
II	100	12	1:1	0.9532	
			1:0.5	0.7180	0.7571
		8	1:1	1.0000	
			1:0.5	0.5990	0.6102
	250	12	1:1	0.8623	
			1:0.5	0.7242	0.6343
		8	1:1	0.8529	
			1:0.5	0.5300	0.4556
III	100	12	1:1	0.8992	
			1:0.5	0.6093	0.6276
		8	1:1	0.9591	
			1:0.5	0.6287	0.7674
	250	12	1:1	0.7542	
			1:0.5	0.6418	0.4627
		8	1:1	0.7578	
			1:0.5	0.5181	0.4265

4 CONCLUSION

In the design process of membrane structures including ETFE foil structures, the biaxial material behaviour under short-term tension as well as under long-term loading is decisive. In this contribution, the creep behaviour of different ETFE foils from three different producers with two foil thicknesses each was analysed. Tests were performed over a period of 1,000 hours at room temperature in three different stress ratios, a uniaxial stress state and two biaxial stress states. To maintain the simplicity of uniaxial creep tests and simultaneously derive the biaxial creep behaviour, a correlation approach to model the biaxial creep behaviour of ETFE is presented. Up to now, this correlation bases on compliances determined in uniaxial creep tests which is of course not sufficient for application in practice. Following a plane stress state approach, the correlation was formulated including two modification factors related to the biaxial creep behaviour in comparison to the uniaxial creep behaviour.

In future, the determined compliances D_i as well as the determined modification factors R_i have to be transferred into an equation in dependency of the stress ratio, foil thickness, and material producer in order to achieve a generalized procedure. Furthermore, additional information will be included based on creep tests at temperatures different from room temperature.

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AGC Chemicals Europe Ltd., Amsterdam, Netherlands (Fluon ETFE Film 250NJ-1550NT, Fluon ETFE Film 100NJ-1550NT), Nowofol GmbH & Co. KG, Siegsdorf, Germany (Nowoflon ET 6235 Z in 250 µm and 100 µm) and Textiles Coated Europe GmbH (TCI), Kaarst, Germany (ETFE AG 250 µm, ETFE AG 100 µm), provided the investigated 100 µm and 250 µm ETFE foil materials. The materials provided by AGC were shipped from Japan, the materials from Nowofol came from Germany, and the materials from TCI were shipped from USA.

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