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Correlation between the uni- and biaxial tensile behaviour of ETFE-foils for rationalised modelling of multiaxial stress states

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Abstract

Membrane structures are nowadays built from technical textiles or technical foils, the latter often in form of Ethylene/Tetrafluoroethylene (ETFE)-foils. To safely design these foil structures, the mechanical behaviour has to be known or identified in experiments. Usually, uniaxial tensile tests are performed due to the ease of processing and the comparatively low costs, and the resulting tensile behaviour is taken as a basis for the design. However, foil structures experience multiaxial prestresses as well as multiaxial stresses under external loads. Knowledge about material properties and characteristic values under multiaxial – or simplified biaxial – loading conditions are crucial. Therefore, the material properties of ETFE-foils were investigated under uni- and biaxial stresses. To minimise the additional effort of biaxial or multiaxial tensile testing, a correlation between the uniaxial and biaxial tensile bearing behaviour of ETFE-foils is under development; its current state is presented in this contribution. With this correlation, the material behaviour under biaxial loading, which simplified occurs in structures, can be predicted based on uniaxial tensile tests. The generated and acquired knowledge as well as the derived correlation and material model will rationalise design and enable safer and more economical ETFE structures.

Keywords: ETFE-foils, tensile behaviour, material characterisation, uniaxial, biaxial, multiaxial, correlation, design

1. Introduction

With its first use of Ethylene/Tetrafluoroethylene (ETFE)-foils as façade and cladding materials in the 1980ies, their convention in membrane structures steadily increased. Today, the building material ETFE is applied in cladding systems of prestigious buildings, such as stadiums, atriums or market halls. They are characterised by their low dead weight and transparency. All membrane structures – both technical textiles and foils – have in common, that they are usually built in synclastic or anticlastic shapes to activate their membrane stiffness. Thus, membranes are multiaxial prestressed and are exposed to multiaxial stresses due to external loads. Herein, the prestress can be applied either mechanically or pneumatically to form the anticlastic or synclastic shapes. Mechanical prestress is used to form anticlastic, single-layer shapes. To obtain synclastic shapes, oftentimes foil envelopes are used and prestressed with an internal pressure, so that cushions are formed. Figure 1 illustrates two exemplary foil structures, which are mechanically (left) and pneumatically (right) prestressed. Comparing these two prestress application types, pneumatically prestressed multi-layer structures excel due to their capacity to compensate plastic deformations by adjusting the internal air volume while keeping the pressure constant. Plastic deformations in mechanically prestressed single-layer structures lead to a loss in pretension and therefore to a loss of structural integrity, so that plastic deformations in single-layer structures should not occur.

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Figure 1: Mechanically and pneumatically prestressed ETFE-foil structures (left: Ruhr Park Bochum, Bochum, Germany, © Taiyo Europe GmbH; right: The Avenues, Kuwait-City, Kuwait, © Nick Merrick of Hedrich Blessing provided by Vector Foiltec GmbH)

Regardless of the prestress application, all membrane structures must be designed in the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) with external loads in mind. The new technical specification PD CEN/TS 19102 [1] includes the design, execution and testing of membranes while considering the structural type using the k-factor concept. With the use of the k-factor concept, which bases on the A-factor concept developed by Minte [2], the strength characteristics of the used material are modified, usually reduced, depending on the design condition, e. g. “snow (≤ 1000 m altitude)” taking into account a slowly accumulating long-term load at T = 0 °C. For ETFE-foil structures, decisive characteristics are the Young’s Modulus E_0, the elastic limit f_{el}, the yield point f_y and the ultimate tensile strength f_u, which are all highly dependent on the strain rate and temperature due to ETFE being a thermoplastic. To derive these material characteristics, typically uniaxial tensile tests or more rarely biaxial tensile tests are performed, simplifying the multiaxial stress states in membrane structures. Uniaxial tensile tests are carried out due to the ease of processing and the comparatively low costs. However, knowledge about material properties and their characteristic values under multiaxial – or simplified biaxial – loading conditions are crucial. Therefore, the material properties of ETFE-foils were investigated under uni- and biaxial stresses in the frame of a recently completed German DFG research project. In future, also the multiaxial tensile behaviour using will be investigated on the basis of bubble inflation tests in a further DFG research project. Under multiaxial tension, ETFE-foils show a stiffer and at the same time stronger material behaviour compared to the material response under uniaxial tension. Comparing the strains in the material directions in uniaxial and biaxial stress conditions, higher forces and thus higher stresses are required for equivalent material strains in the biaxial stress state. To minimise the additional effort of biaxial or even multiaxial tensile testing, a correlation between the uniaxial and biaxial tensile stress-strain behaviour of ETFE-foils has to be developed. In this contribution, the current state of this correlation is presented. With this correlation, the material behaviour under biaxial loading, which simplified occurs in structures, can be predicted based on a uniaxial tensile test. The generated and acquired knowledge as well as the derived correlation and material model will rationalise design and enable safer and more economical ETFE structures.

2. The tensile behaviour of ETFE-foils

2.1. General

In the framework of the recently completed research project, the mechanical behaviour of ETFE-foils was analysed in short-term tensile tests as well as in long-term creep and relaxation tests, both in uniaxial and biaxial stress states. To evaluate the influence of the material thickness, two commonly used foil thicknesses were examined: 100 µm and 250 µm ETFE-foils. 100 µm foils are usually applied as inner layers in synclastic structures to form multi-chamber cushion systems. 250 µm foils typically form the envelope of those structures. In the past, it was commonly agreed that ETFE foils from different producers behave in the same way, so that no do producer’s dependency had to be considered. This assumption was questioned in the research project. To investigate the producer’s influence on the material behaviour, materials from three different producers were included in the project: Fluon ETFE Film 250NJ-1550NT and 100NJ-1550NT, Nowoflon ET 6235 Z in 250 µm and 100 µm, ETFE AG

250 µm and ETFE AG 100 µm. This order does not reflect the allocation of producers I, II, and III in the following, respectively. In this contribution the uni- and biaxial material behaviour of the 250 µm foils are discussed.

2.2. Uniaxial short-term tensile behaviour

To derive the uniaxial mechanical behaviour of ETFE-foils, uniaxial tensile tests were performed according to EN ISO 527-1 [3] and -3 [4] whereby the special provisions given in PD CEN/TS 19102 [1] regarding the specimen geometry, prestress application and the strain rate have to be considered. According to PD CEN/TS 19102, uniaxial tensile tests should be performed on strip specimens with an initial measuring length of 50 mm and a width to length ratio of 1:5 with linear fixation at the top and bottom. The tensile test results included the recorded force F and elongation $\Delta L = L - L_0$ obtaining an engineering stress-engineering strain diagram (σ_{eng}-ε_{eng}-diagram) relating to the initial cross-section area A_0 and the initial measuring length L_0 with $\sigma_{eng} = F/A_0$ [MPa] and $\varepsilon_{eng} = \Delta L/L_0$ [%].

Figure 2 represents a typical σ_{eng}-ε_{eng}-diagram of 250 µm ETFE-foils at room temperature and $d\varepsilon/dt = 200$ %/min from the three different material producers I, II and III, featuring the material characterising parameters f_{ip}, f_y and f_u, respectively. In the left diagram, the overall uniaxial tensile behaviour up to the break is shown. For ETFE-foils, the ultimate tensile strength f_u occurs at the rupture of the specimens. At the inflexion point f_{ip} as well as the yield point f_y, the material stiffness significantly decreases, which is shown on the right-hand side in Figure 2. These two points are commonly called first and second yield point, $f_{y,1}$ and $f_{y,2}$, respectively. However, EN ISO 527-1 defines the yield point as the stress-strain point, where the strain increases without an increase in the stress, so that the first inflexion point cannot be called yield point according to EN ISO 527-1. Simultaneously, f_{ip} and f_y divide the material behaviour of the thermoplastic ETFE into three different stages. The first stage represents the viscoelastic stage raging up to the stress f_{ip} including elastic and viscoelastic deformations. After reaching f_y, the ETFE-foil material yields and mainly plastic, viscous deformations are present. Between f_{ip} and f_y, the material is viscoelastic-plastic with significant viscoelastic and viscoplastic deformations.

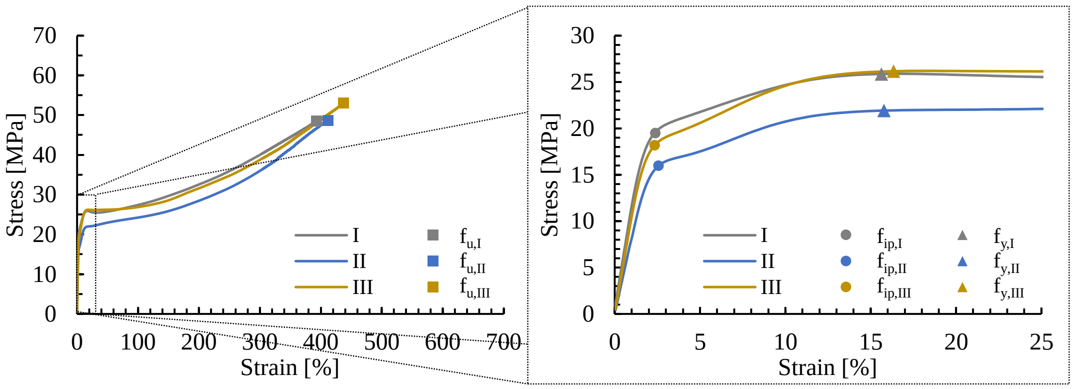

Figure 2: Engineering stress-engineering strain diagram of ETFE-foil under uniaxial tension for three different producers I, II and III ($d_0 = 250$ µm, T = 23 °C, $d\varepsilon/dt = 200$ %/min)

Additionally, Figure 2 shows the material producer dependency on the foil product. Material from producer II shows significantly lower strength values, even at the elastic and viscoelastic limit which is decisive for the design of ETFE-foil structures. PD CEN/TS 19102 defines the characteristic tensile strength of ETFE-foil base material to $f_{u,k} = 40$ MPa for ULS design and the elastic limit to $f_{el23} = 15$ MPa for SLS design, both values apply for T = 23 °C. With the current state of the art regarding welding procedures of ETFE-foils, the decisive strength parameter in ULS design is the tensile strength of a welded connection which is set to $f_{uw,k} = 30$ MPa (T = 23 °C) for area weld seams. With the defined parameters for uniaxial short-term tensile testing, the elastic limit of ETFE-foils ($f_{el23} = 15$ MPa) complies with all three investigated foil materials.

With an increase in the test temperature, the material shows a weaker and slightly softer tensile behaviour. An equivalent response can be observed with a decrease in the strain rate. Reports on the uniaxial temperature and strain rate dependent material behaviour are given in [5]-[15]. Only short notices regarding the impact of different ETFE-foil materials are given in Charbonneau et al. [16] and Wu [17], in which mainly the long-term creep behaviour and partial safety factors are discussed, respectively. To consider environmental effects on-site, the previously mentioned design concept in PD CEN/TS 19102 introduced the k-factor concept. k-factors modify the material behaviour at T = 23 °C to the material behaviour under the considered design condition. Recommendations and design approaches, are also given in Moritz [5] and Schiemann [6], which follow the A-factor concept already introduced by Minte [2].

2.3. Biaxial short-term tensile behaviour

As mentioned before, uniaxial stress states rarely occur in built membrane structures. The necessary prestress as well as the stresses due to external loads are carried multiaxially and transferred to the primary steel-, aluminium- or timber-structure. These multiaxial stresses can be simplified to biaxial stress states keeping in mind the principal stresses σ_I and σ_{II}. Therefore, to design membrane structures overall and ETFE-foil structures in particular, the knowledge of the load bearing behaviour in multiaxial stress states is crucial. To evaluate this material behaviour, biaxial tensile tests were performed using cruciform specimens. Herein, defined loads can be applied via arms, which transfer the uniaxial stresses to a measuring field which is thus biaxially loaded so that different biaxial stress states can be investigated.

Figure 3 presents the response of the conducted biaxial tensile tests in the stress ratios of 1:1 to 1:0.2 (ED:TD) and uniaxial tensile tests 1:0 of ETFE-foil material of the three different producers at room temperature. The tests were performed with a constant stress rate of 1.5 MPa/min which equals an average strain rate of approx. 0.33 %/min and a strain rate of approx. 2 %/min at f_{ip}. The rates refer to principal direction one, which equals the extrusion/machine direction of the material (ED). The engineering stress-strain diagrams show the stress-state dependent material behaviour of the investigated ETFE-foils. With an increasingly equalizing stress state, the three analysed materials optically stiffen, referring to the Young's modulus E_0 and the hardening modulus E_{ve}, and harden, referring to f_{ip} and f_y in comparison to an uniaxial stress state. An additional strength characteristic is introduced: f_{ve}. f_{ve} marks the beginning of the second linear part shortly after reaching f_{ip}. f_{ve} is used in the analytical model predicting the tensile behaviour of ETFE-foils which is described below. Table 1 lists the determined f_{ve} and f_y values of the performed tensile tests.

While f_y can be identified at approx. 25 % to 26 % strain in the uniaxial tensile tests, f_y does not occur in the biaxial stress states. This is due the applied specimen geometry. The specimen arms are loaded uniaxially, as mentioned above, so that the arm material yields and the biaxially loaded measuring field is not further loaded. Herewith, assessments regarding the tensile strength of ETFE-foils in biaxial stress states cannot be given. For this, bubble inflation tests must be conducted. Nevertheless, as for uniaxial tensile tests, in biaxial stress states the material response depends on the tested material (I, II, III). In all performed biaxial tensile tests, the materials from producer II shows the lowest strengths and the materials from producer I the highest strengths.

Table 1: Strength characteristics of the investigated products in the performed uni- and biaxial tensile tests, derived from the mean value σ_{eng}-ε_{eng} curves of 250 µm ETFE-foils

		Stress ratio (ED:TD)					
Strength characteristic	Prod.	1:0	1:1	1:0.5	1:0.33	1:0.25	1:0.2
f_{ve} [MPa]	I	16.7	14.7	19.0	18.1	18.9	18.2
	II	14.0	15.9	14.6	15.1	14.5	14.8
	III	15.4	15.8	15.8	16.1	15.4	15.7
f_y [MPa]	I	24.6	-	-	-	-	-
	II	22.8	-	-	-	-	-
	III	24.5	-	-	-	-	-

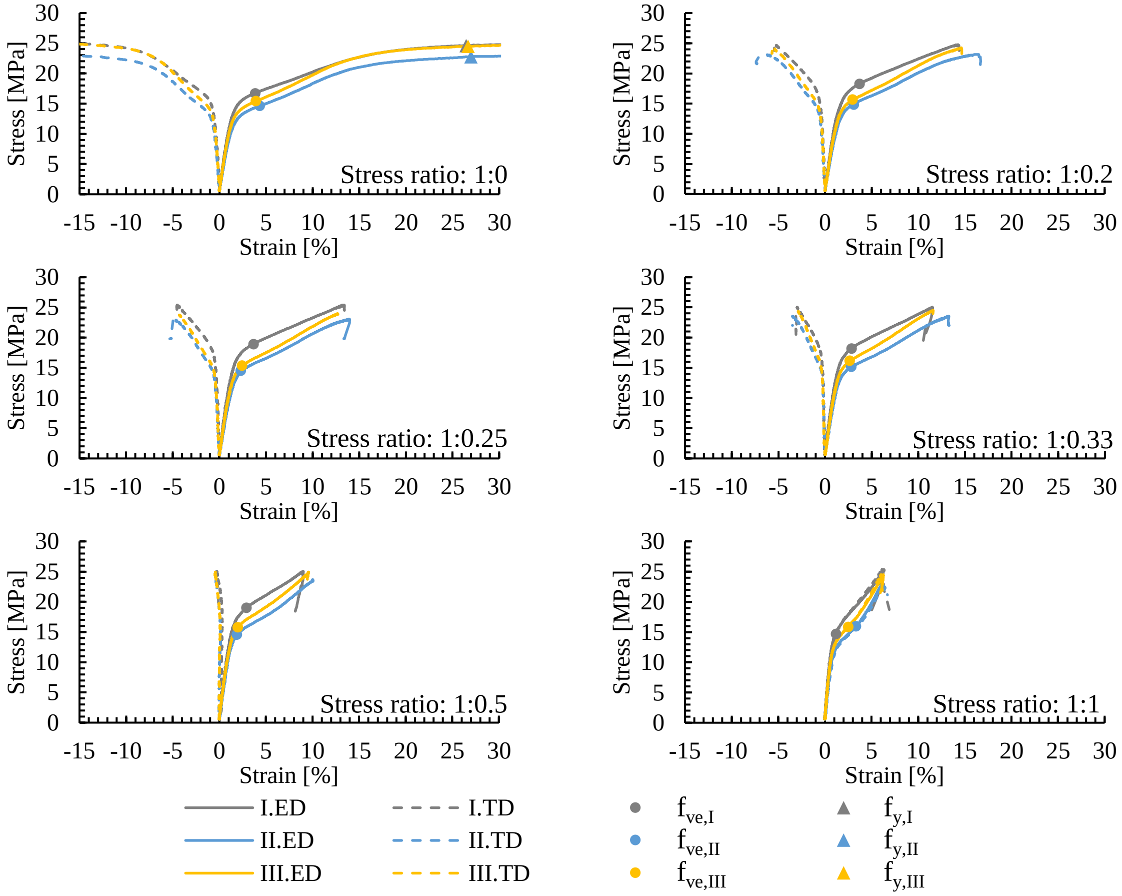

Figure 3: Comparison of the uniaxial and biaxial mechanical behaviour under tension of ETFE-foils of three different producers (mean value curves; 250 µm; dσ/dt = 1.5 MPa/min)

The derived stress-strain behaviour illustrates the need to consider the material behaviour in biaxial stress states in the limit state design (ULS and SLS) and not to base the design on uniaxially determined material characteristics, such as the elastic material strength f_{el23}. In the PhD-thesis of Moritz [5] and Schiemann [6], design approaches were already formulated considering the different material behaviour in biaxial stress states which was identified in bubble inflation tests among other tests.

3. Analytical modelling of the uniaxial tensile behaviour of ETFE-foils

For design purposes, the nonlinear material behaviour of ETFE-foils up to the yield is important. In SLS design, stress limitations are defined in PD CEN/TS 19102 [1] to minimise plastic deformations. For example, the (visco-)elastic limit is set to f_{el23} = 15 MPa. Anyway, in an analytical model, the nonlinear viscoelastic material behaviour has to be considered in detail. To model the nonlinear material behaviour of ETFE-foils, a modified Ramberg-Osgood-Material model has been introduced by the authors. The original model was developed by W. Ramberg and W.R. Osgood [18] and was further developed by Rasmussen [19], Arrayago, Real and Gardner [20] to describe the nonlinear stress-strain behaviour of stainless steel, see also SCI [21]. To model the material behaviour of stainless steel, the parameters K, n and m were introduced to fit the nonlinearities. Figure 4 shows the modified model parameters for the description of ETFE-foils which are drawn to a stylized uniaxial engineering stress-strain curve.

The model divides the nonlinear engineering stress-strain curves into two separate parts by applying two equations. The first equation models the response up to the second linear material behaviour of ETFE-foils shortly after reaching f_{ip}, see Eq. (1). This transition point is called f_{ve}. The second equation starts above f_{ve} and models the response up to f_y, see Eq. (2). Doing so, both nonlinearities in the engineering stress-strain behaviour are covered. With the two equations (1) and (2), the uniaxial tensile material behaviour of ETFE-foils can be described using the stiffness parameters E_0 and E_{ve}, the strength values of f_{ve} and f_y as well as the parameters n, m, K and $\Delta\varepsilon_y$ to model the nonlinearities:

$$\varepsilon_{uni} = \frac{\sigma}{E_0} + K\left(\frac{\sigma}{f_{ve}}\right)^n \qquad \text{for } \sigma \leq f_{ve} \tag{1}$$

$$\varepsilon_{uni} = K + \frac{f_{ve}}{E_0} + \frac{\sigma - f_{ve}}{E_{ve}} + \Delta\varepsilon_y\left(\frac{\sigma - f_{ve}}{f_y - f_{ve}}\right)^m \qquad \text{for } f_{ve} < \sigma \leq f_y \tag{2}$$

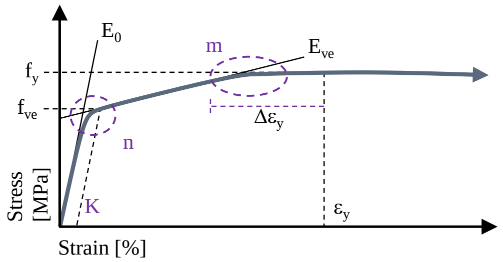

Figure 4: Stylized engineering stress-strain curves with modified Ramberg-Osgood parameters to describe the nonlinear material behaviour of ETFE-foils in short-term tensile tests

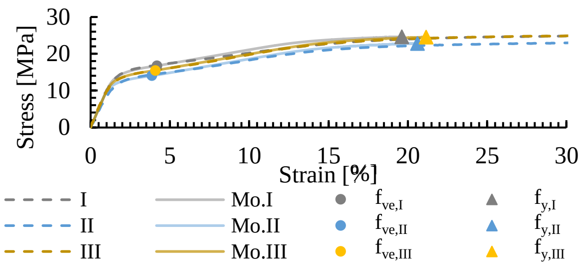

Figure 5: Comparison of mean value engineering stress-strain curves and the analytical model (Mo.) in uniaxial stress states

With the derived model parameters, see Surholt et al. [15], the uniaxial engineering stress-strain curves can be modelled. With the previously determined characteristic strength values f_{ve} and f_y (cf. Table 1) and the parameters defined in [15] for n, m, K, $\Delta\varepsilon_y$, E_0 and E_{ve}, the uniaxial tensile behaviour can be modelled, see Figure 5.

4. Correlation for modelling the biaxial tensile behaviour based on uniaxial material parameters

The investigated ETFE-foils show a homogeneous and nearly-isotropic tensile material behaviour. This is confirmed on the basis of the performed biaxial tensile tests in a 1:1 stress ratio. Both material directions (ED and TD) show similar engineering stress-strain curves. Due to this material behaviour, a biaxial analytical model can be formulated based on a plane stress state approach, see Eq.(3):

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{pmatrix} = \frac{1}{E_0}\begin{pmatrix} 1 & -\nu & 0 \\ -\nu & 1 & 0 \\ 0 & 0 & 2(1+\nu) \end{pmatrix}\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{pmatrix} \tag{3}$$

with ν being the Poisson’s ratio. Assuming that stresses σ_{xy} do not occur in biaxial tensile tests, a plane stress formulation covering the linear elastic material behaviour can be simplified to Eq. (4) and (5):

$$\varepsilon_x = \frac{\sigma_x}{E_0} - \nu\frac{\sigma_y}{E_0} \tag{4}$$

$$\varepsilon_y = -\nu\frac{\sigma_x}{E_0} + \frac{\sigma_y}{E_0} \tag{5}$$

By implementing Eq. (1) into Eq. (4) and (5) for the x- and y-directions or principal directions I and II, respectively, a nonlinear material model covering the nonlinear viscoelastic material properties of ETFE-foils can be derived. To consider the stress state dependent material behaviour, Eq. (4) and (5) are modified with factors R_I and R_{II}, respectively. By calculating the nonlinear tensile response using Eq. (1) and (2) for the viscoelastic and viscoelastic-plastic material behaviour and combining these parts depending on the Poisson’s ratio, the total strains in principal directions I and II can be derived as follows:

$$\varepsilon_{biax,I} = \varepsilon_{uni}\left(R_I - \nu R_{II}\right) \tag{6}$$

$$\varepsilon_{biax,I} = \varepsilon_{uni}\left(-\nu R_I + R_{II}\right) \tag{7}$$

R_I and R_{II} resemble the influence of the effective stress ratio. Stress ratios are always expressed as 1:*, with * as a variable for the principal stress σ_{II}. Herewith, R_I becomes 1.0 for each stress ratio and R_{II} = {1.0; 0.5; 0.33; 0.25; 0.2; 0} depending on the stress ratio. For instance, for the stress ratio 1:0.5, it follows: R_I = 1.0 and R_{II} = 0.5 and for the stress ratio 1:1: R_I = 1.0 and R_{II} = 1.0. Additionally, to cover the strengthening effect in biaxial stress states, the modelling point f_{ve}, which marks the beginning of the second linear/proportional material behaviour, is modified using the S_{ve}-factor. This factor is shown in Eq. (8) and (9):

$$\varepsilon_{uni} = \frac{\sigma}{E_0} + K\left(\frac{\sigma}{f_{ve}S_{ve}}\right)^n \qquad \text{for } \sigma \leq f_{ve}\cdot S_{ve} \tag{8}$$

$$\varepsilon_{uni} = K + \frac{f_{ve}S_{ve}}{E_0} + \frac{\sigma - f_{ve}S_{ve}}{E_{ve}} + \Delta\varepsilon_y\left(\frac{\sigma - f_{ve}S_{ve}}{\left(f_y - f_{ve}\right)S_{ve}}\right)^m \qquad \text{for } f_{ve}\cdot S_{ve} < \sigma \leq f_y\cdot S_{ve} \tag{9}$$

S_{ve} depends on the effective stress ratio as well. For stress ratios 1:1 and 1:0, S_{ve} equals 1.0, for the stress ratio 1:0.5, S_{ve} equals 1.15 and for the remaining investigated stress ratios, S_{ve} is set to 1.1. Other stress ratios, such as 1:0.75, still need to be investigated. The upper limit of the model has to be confirmed in bubble inflation tests since f_y cannot be determined in biaxial short-term tensile tests using cruciform specimens, as mentioned above.

Following the proposed material model and derived correlation between the uni- and biaxial short-term tensile behaviour of ETFE-foils, the biaxial material behaviour can be calculated on the basis of parameters, which are determined in uniaxial short-term tensile tests. Figure 6 illustrates the measured and calculated material behaviour up to f_{ve} in both principle directions I and II which equal the material directions ED and TD, respectively. In Figure 6, all strains are plotted against the stresses in principle direction I in order to visualise the strains in the lower stressed direction, especially in a stress ratio of 1:0. The modelled stress-strain curves were calculated using the generalized model parameters E_0, E_{ve}, K, n as described in [15]. The strength characteristics f_{ve} were taken from the uniaxial tensile tests, see Table 1, stress ratio 1:0. The material's strains including the transversal, negative strains can be mapped well up to f_{ve}.

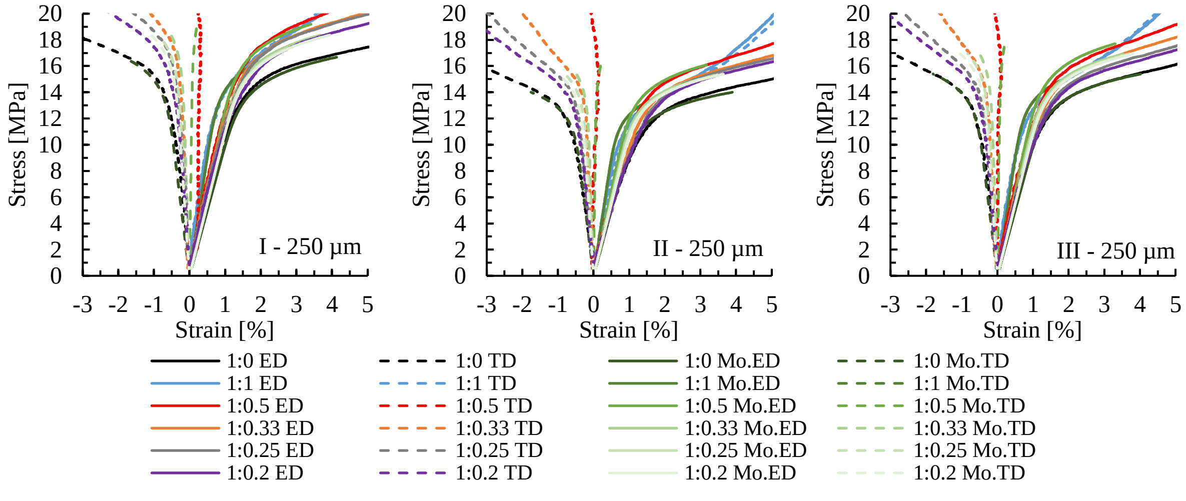

Figure 6: Cut-out of the biaxial stress-strain behaviour of ETFE-foils of three different producers at 23 °C, 1.5 MPa/min in comparison to the analytical model; plotted against the stresses in principle direction I

Furthermore, with the use of generalised parameters, the temperature and strain rate dependent but material independent characteristic strength value $f_{k,ve}$ can be calculated according to Surholt et al. [15], see Eq. (10):

$$f_{k,ve} = \left(\exp\left(a + \frac{b}{c+v} \right) \right) \left(d\left(T - T_{ref} \right) + f \right) \tag{10}$$

with a, b, c, d and f being model parameters. T_{ref} is the reference temperature of 296.15 K = 23 °C. T [K] is the test temperature and v [mm/min] the test speed. For the implementation of v in [%/min], a factor of 2.0 has to be applied ($\dot{\varepsilon}$ [%/min] = 2.0 v [mm/min]). Following the parameters given in Surholt et al. [15], a safe-sided characteristic modelling parameter $f_{k,ve}$ was calculated to $f_{k,ve}$ = 14.0 MPa as the lowest one of all investigated materials, which complies with the determined strength value of producer II listed in Table 1. Of course, using the 5 % fractile value and neglecting material dependencies, the model predicts the weakest material behaviour leading to a save design of ETFE-foils in building application regardless of the used foil material.

To cover the impact of different material producers, analytical models to predict the material, temperature and time dependent strength values f_{ve} were defined. As illustrated in Figure 5, the uni- and biaxial short-term tensile behaviour depends not only on the commonly known influencing factors of test temperatures and strain rates, but also on the ETFE-foil material itself, which is offered by different material producers. This can be observed in the stiffnesses of the materials, strain behaviour and strength values. Consequently, one set of model parameters for each material producer independent of the material thickness could be defined with which the strength characteristic f_{ve} can be calculated with Eq. (10) for any state (material, temperature, strain rate). Inserting the test conditions of the performed biaxial short-term tensile tests of T ≈ 23 °C =296.15 K and v ≈ 1.15 mm/min into Eq. (10) and using the derived parameters from Table 2, the strength parameters f_{ve} in the uniaxial stress state for each material become $f_{ve,I}$ = 17.2 MPa, $f_{ve,II}$ = 14.1 MPa, and $f_{ve,III}$ = 15.6 MPa, respectively. Using the parameters shown in Table 2 and the generalised parameters for ETFE-materials dependent on the producer and independent on the foil thickness, the biaxial material behaviour is calculated with Eqs. (6) and (7) depending on the test temperature, strain rate, and stress ratio. Stress-strain paths modelled in this way compared to measured ones are shown in Figure 7 as an example for the stress ratios 1:1, 1:0.5 and 1:0.33.

With the definition of the derived equations, structural engineers can base their design of ETFE-foil structures depending on the environmental condition considering temperatures on site as well as load speeds in form of strain rates. By defining material dependent model parameters, structural engineers do not have to rely on the elastic limit of f_{el23} = 15 MPa given in PD CEN/TS 19102 but can rely on the modelled strength and stress-strain capabilities of the used material. For economic reasons, ETFE-foils of different producers should not be treated equally. Additionally, the conducted biaxial short-term tensile tests with very low strain rates show, that f_{ve} for producer II can be lower than the elastic limit f_{el23} = 15 MPa. This indicates that using f_{el23} according to PD CEN/TS 19102 is not a safe-sided approach in all design situations. This highlights the strain rate dependency of the material as f_{el23} is determined with a strain rate of 200 %/min.

Table 2: Model parameters for the determination of strength characteristics f_{ve} depending on the test temperature, strain rate and material producer

Strength characteristic	Producer	a [-]	b [(mm/min)$^{-1}$]	c [mm/min]	d [MPa/K]	f [MPa]
	I	2.1975	-6.3531	20.0191	-0.02588	2.5732
f_{ve} [MPa]	II	2.1243	-7.1514	29.6585	-0.03017	2.1223
	III	2.0988	-1.5719	5.4521	-0.03518	2.4290

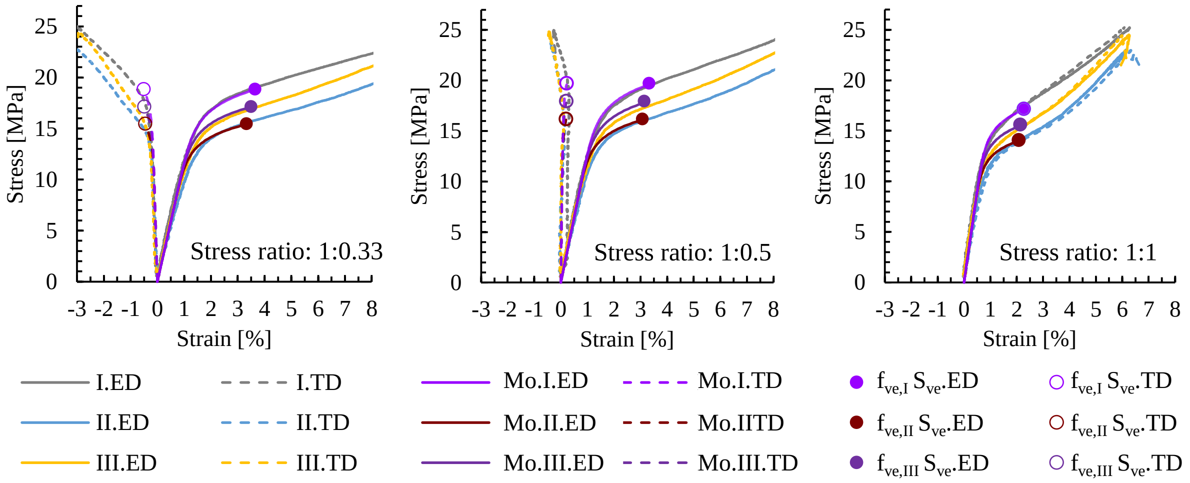

Figure 7: Comparison between the biaxial short-term tensile behaviour for 250 µm ETFE-foil of three different material producers and the analytical model based on the test temperature, strain rate and material producer dependent strength value f_{ve}

5. Conclusion and Outlook

Following the design specifications of PD CEN/TS 19102 [1], membrane structures including technical textiles and technical foils have to be designed in the ultimate limit state (ULS) and serviceability limit state (SLS). In both states, stress checks have to be carried out for the used material. For ETFE-foils in particular, in ULS design the load-bearing capacities of the base material f_u and the welded connections f_{uw} are modified using k-factors depending on the design condition which both have to be equal or higher than the tensile stresses in the foil. Special provisions are defined in the SLS. Additional stress checks have to be performed in order to limit the possibility of plastic strains which can lead to a loss of prestress or lead to contacts to parts of the primary structure which can result in material defects. Here, the k-factor concept applies as well. In both cases, characteristic material strength values are typically determined in uniaxial short-term tensile tests. However, tensile bearing membrane structures exhibit biaxial stress states so that for the design process the biaxial material behaviour is decisive. Accordingly, strength characteristics should be determined in biaxial tensile tests. In order to still rely the design of ETFE-foil structures on uniaxial short-term tensile tests, to minimise the effort of preparing biaxial specimens and to minimise the test evaluation procedure of biaxial short-term tensile tests, an analytical model to predict the uniaxial short-term tensile behaviour as well as an analytical correlation between the uni- and biaxial short-term tensile behaviour of ETFE-foils has been developed and could be presented. Using the derived analytical model and analytical correlations, designers can predict the biaxial material behaviour in ETFE-foil structures based on simple uniaxial short-term tensile tests.

The derived material model and analytical correlation have to be modified to assess the increased strength of f_y in biaxial stress states which cannot be identified using cruciform specimens. In an upcoming DFG research project, bubble inflation tests are going to be conducted to identify the temperature, strain rate and material class dependent strength value f_y in different multiaxial stress states. Herewith, the presented analytical model and analytical correlation are going to be extended.

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