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ON TIME- AND TEMPERATURE-DEPENDENT MATERIAL BEHAVIOUR OF ETHYLENE-TETRAFLUOROETHYLENE FOILS IN BUILDING CONSTRUCTION

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Summary. Ethylene tetrafluoroethylene (ETFE) foils exhibit a non-linear viscoelastic material behaviour. For the description of such behaviour, this article proposes a model. The proposed model is based on Burgers' model which, for the purpose of this study, was enhanced by new model parameters in order to take into account the stress level and the temperature. Comparison of the experimental and the projected strain-time-curves proves the model's applicability for describing isothermal continuous load tests. All of the model's parameters can be derived directly on ETFE foils via isothermal short-time tensile and continuous load testing, which makes for the practical applicability of the model. Moreover, using a modified superposition principle, the proposed model serves to describe continuous, non-constant stress curves under constant temperatures. The influence of non-isothermal natural climatic conditions on time-dependent material behaviour was investigated in multiannual continuous load tests. Modelling of strains measured in these tests is only successful in terms of quality. As a basis for the application in static analysis, the derived equivalent temperature can be used.

1 INTRODUCTION

The requirements for modern building facades have long gone far beyond the mere external closure of the enclosed space and are to be seen in the area of tension between the aesthetic and design requirements, the structural and physical concerns and the wishes of the users for targeted transparency.

Since the 1980s, the material ethylene / tetrafluoroethylene, in short ETFE, has established itself in the field of transparent and translucent building shells as an alternative to the arvated material glass and enables the implementation of the listed, sometimes competing requirements. Furthermore, the highly transparent foils of this fluoropolymer material allow a reduction in the long-term primary energy bound in the building fabric due to their very low deadweight in connection with their design-related efficient construction as a pneumatically or mechanically prestressed membranes, cf. [1], [2].

However, in order to meet the requirements for structural stability, usability and durability, the structures made of ETFE foils require permanent pre-tensioning. In contrast, studies on the behaviour of the material under these long-term loads are only available sporadically and are more project-specific, see [3–8]. The semicrystalline structure of the thermoplastic fluoropolymer ETFE, however, causes a viscoelastic material behaviour and leads to strain due to the retardation (creep) or to the relaxation of the stresses, which must be taken into account for constructions made of ETFE foils dependent on the duration, the level of the stress as well the existing temperature.

In connection with the modified superposition principle, the model developed in [9] and presented for the first time in [10] describes the non-linear viscoelastic material behaviour of ETFE foils, thus making a contribution to the safe and at the same time economical dimensioning of ETFE foil constructions.

2 EXPERIMENTAL INVESTIGATIONS

The modelling of the non-linear viscoelastic material behaviour of ETFE foils is based on experimental, mechanical investigations. In order to enable a practical application of the method proposed, all model parameters are derived directly from the results of the most robust test setups possible and with the shortest possible test duration. Isothermal short-term tensile tests form the basis of the description of the time-independent strains and represent the starting point for material modelling.

The strains under constant loading dependent on time are modelled on the basis of the isothermal continuous load tests. In addition, the isothermal load repetition tests investigated the influence of long-lasting, non-cyclical alternating stress. The effects of the anisothermal, natural climate on the temporal development of the strains were demonstrated in continuous load tests which were conducted over several years.

2.1 Investigated ETFE foil

The experimental investigations were carried out with a 250 µm thick NOWOFLON ET 6235 Z ETFE foil. Samples based on type 1B [11] with a larger measuring range were randomly taken from the newly produced foil. In order to minimize the effects due to a thermal or hygric prehistory, all test specimens were stored at controlled temperature and humidity immediately after production and conditioned at the appropriate test temperature before the start of the test.

2.2 Experimental investigations carried out

In pre-investigations, it was possible to confirm the independence of the test results on ETFE foils from the test-related stress condition, as demonstrated by Galliot/Luchsinger [12], even for long-term stresses. For this reason, all tests in [9] were carried out in the form of robust uniaxial tensile tests. The stresses applied in the tests were determined accordingly in the form of true von-Mises equivalent stresses. A mobile system for close-range photogrammetry made it possible to record the strains occurring in the tests in true von-Mises comparison calculations.

The material behaviour of the ETFE foils, which depends on the temperature, but not on the time, was investigated in isothermal, uniaxial short-term tensile tests. For this purpose, the test specimens were tested in a universal testing machine with a temperature chamber. Fig. 1 shows the measured stress-strain curves of the single tests plotted in true von-Mises equivalent stresses over true von-Mises equivalent strains.

Fig. 1 shows the expected influence of the temperature in the uniaxial short-term tensile tests. As the temperature rises, the stiffness of the ETFE foils decreases, which is expressed in the flatter curves of the stress-strain curves. At the same time, however, the shape of the stress-strain-curves remains fundamentally unchanged.

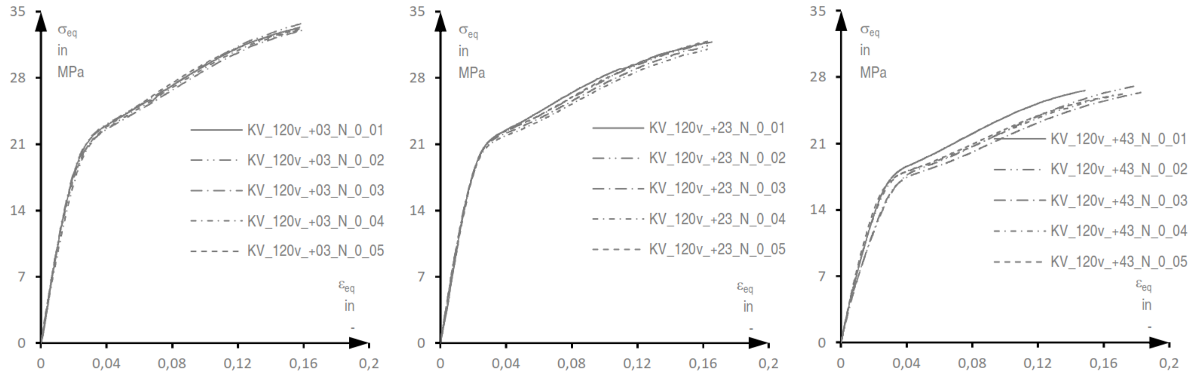

Figure 1: Stress-strain curves in single tests in short-time tensile tests at 3 °C, 23 °C and 43 °C up to the yield point

From the isothermal short-term tensile tests, the elastic limit, as the first significant change in stiffness of the stress-strain curves, and the yield point, as the second change in stiffness, were determined for each of the investigated temperatures.

The stresses of the subsequent isothermal long-term load tests were determined on the basis of the temperature-dependent elastic limit in a range of approx. 30 % to 90 %.

The isothermal long-term load tests investigate the time and temperature-dependent material behaviour of the ETFE foils. For this purpose, the test specimens were uniaxially loaded with a constant tensile force in a temperature-controlled permanent load test stand at 3 °C, 23 °C and 43 °C.

For each test temperature, four stress levels related to the temperature-dependent, but time-independent stress at the elastic limit were investigated. In order to specifically investigate the non-linearity of the viscoelasticity, high stress levels of around 30 % to 90 % of the elastic limit, which corresponds to true von-Mises equivalent stresses of around 5.1 MPa to 19.3 MPa, were applied to the test specimens.

The strains resulting from the test series with five test specimens each over the test periods of 3000 h or 4000 h were recorded photogrammetrically and are shown in Fig. 2 to 4 for the stress levels from approx. 60 % to approx. 90 % of the elastic limit (the lowest stress level is not shown here).

The measured strain-time curves in Fig. 2 to 4 were converted into the compliance-time curves for further use in material modelling, based on true von-Mises equivalent stresses and strains, see Fig. 5.

In Fig. 5, the non-linearity of the viscoelasticity of the ETFE foils in the long-term load test is clearly visible, since the compliance-time curves of the different stress levels are not congruent. Furthermore, a comparison of the compliances of the same stress level but different test temperature shows a significant dependence of the compliances on the temperature.

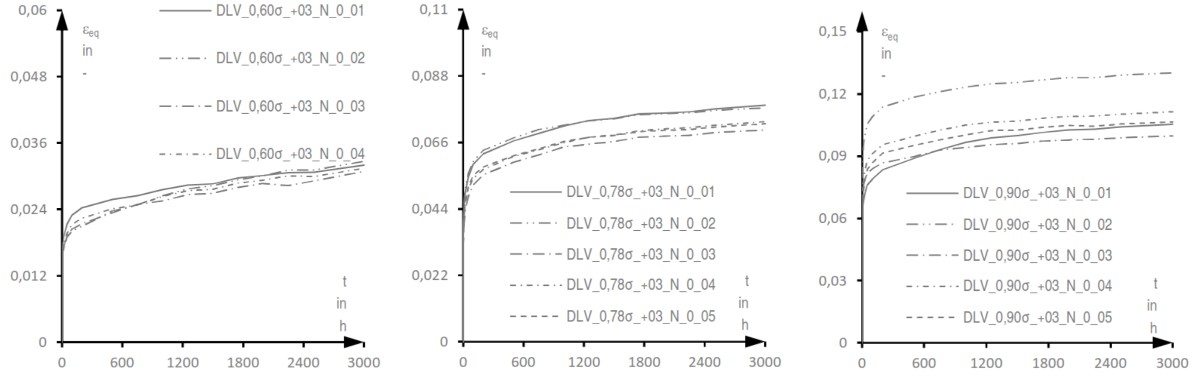

Figure 2: Strain-time curves in single tests in continuous load tests at 3 °C depending on the stress level

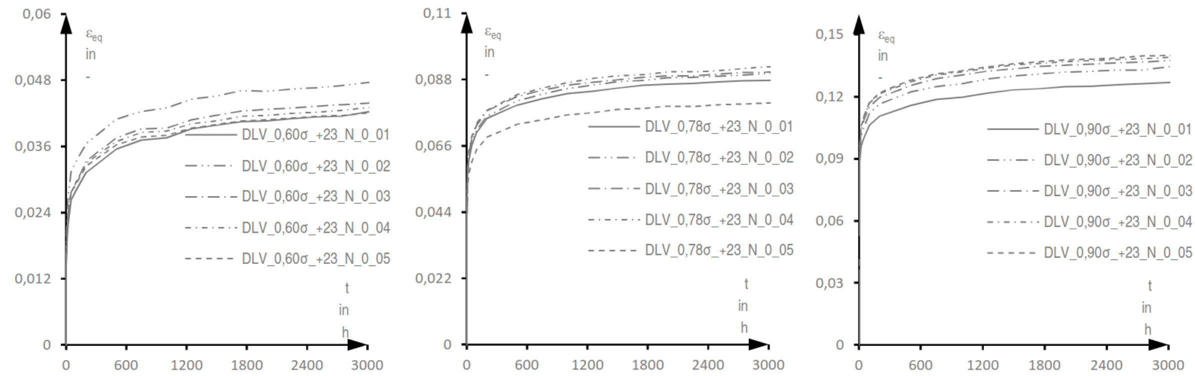

Figure 3: Strain-time curves in single tests in continuous load tests at 23 °C depending on the stress level

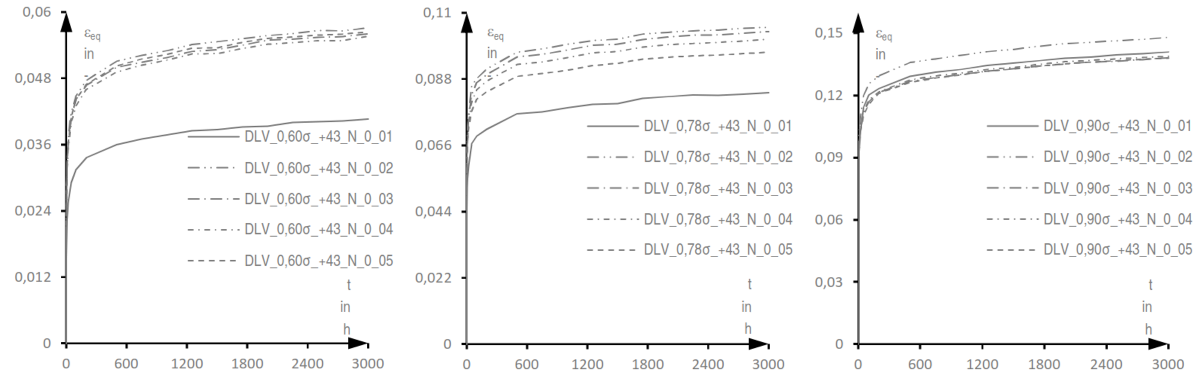

Figure 4: Strain-time curves in single tests in continuous load tests at 43 °C depending on the stress level

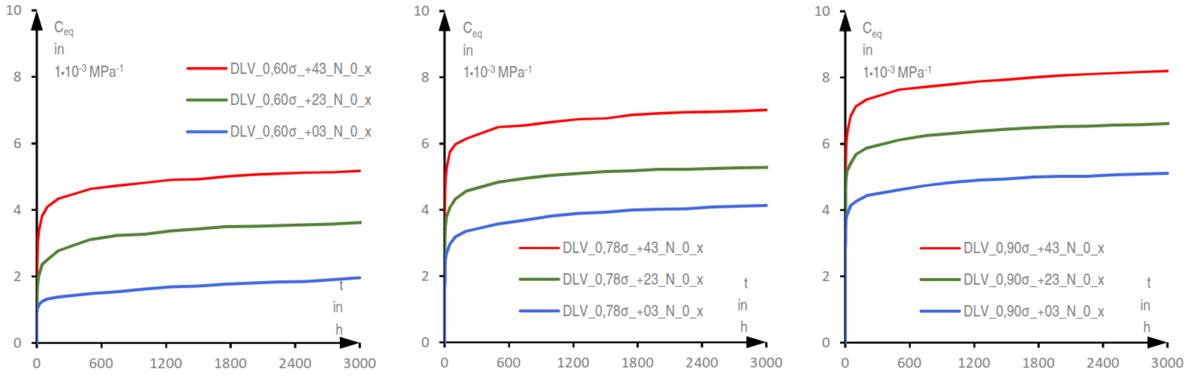

Figure 5: Compliance-time curves in mean values in continuous load tests at 3 °C, 23 °C and 43 °C depending on the stress level

Isothermally performed load repetition tests investigated the influence of repeated loading and unloading processes on the time- and temperature-dependent material behaviour of the ETFE foils. For this purpose, the test specimens were uniaxially loaded with phase-dependent constant tensile forces in the temperature-controlled continuous load test rig. The investigations were limited to the two upper, temperature-dependent stress levels of approx. 78 % and 90 % of the elastic limit, which corresponds to approx. 13.2 MPa to 19.3 MPa.

The strains occurring in the tests were also recorded photogrammetrically here and from these, the compliance-time-curves were calculated on the basis of true von-Mises equivalent stresses and strains. Fig. 6 to 8 show the strain-, time- and the resulting compliance-time curves of the isothermal load repetition tests.

The test results of the isothermal load repetition tests in Fig. 6 to 8 also show both the clearly pronounced non-linearity of the viscoelasticity due to the stress level and the dependence on the temperature.

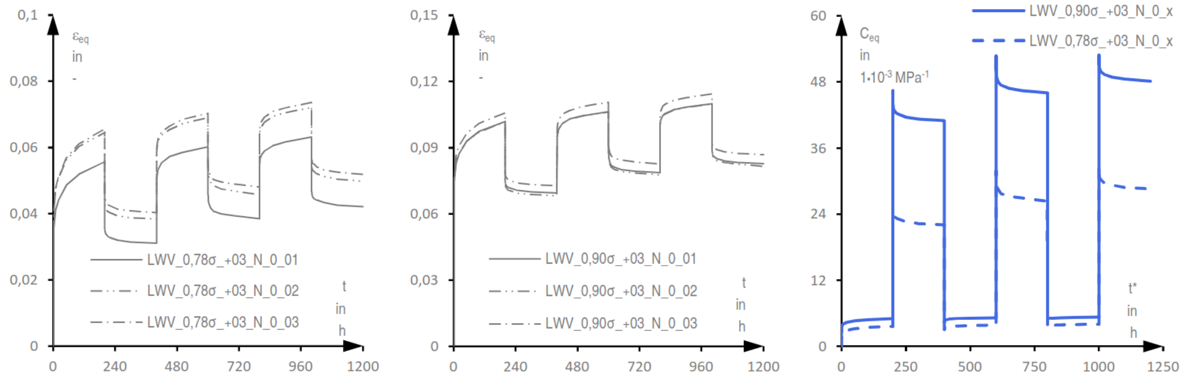

Figure 6: Strain-time curves in single tests and compliance-time curves in mean values in load repetition tests at 3 °C depending on the stress level

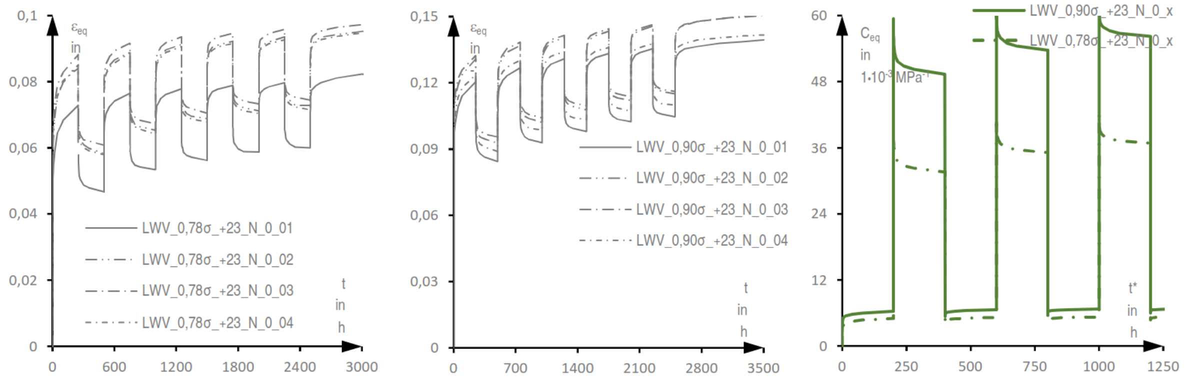

Figure 7: Strain-time curves in single tests and compliance-time curves in mean values in load repetition tests at 23 °C depending on the stress level

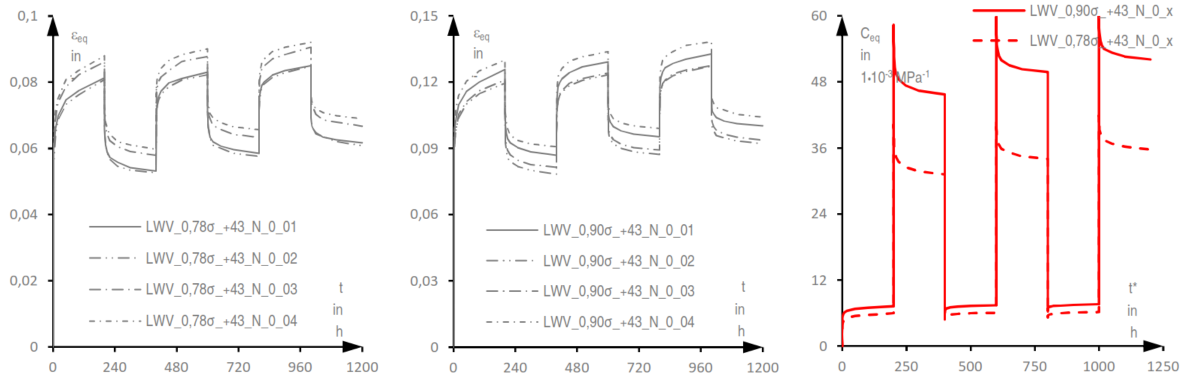

Figure 8: Strain-time curves in single tests and compliance-time curves in mean values in load repetition tests at 43 °C depending on the stress level

The influences of the natural temperature and humidity curves on the material behaviour of the ETFE foils were examined by the anisothermal continuous load tests under natural climatic conditions. For this purpose, the test specimens were uniaxially loaded by tensile stress below approx. 30 % to 90 % of the elastic limit at 23 °C and placed in a test chamber protected from wind, rain, snow and solar radiation for a test duration of approx. 56,200 h (approx. 6 a) observed in a continuous load test. The measured strain-time curves of the two high stress levels and the resulting compliance-time curves are shown in Fig. 9.

Here, too, the pronounced non-linearity of the viscoelasticity is clearly evident. Furthermore, seasonally recurring, very strong increases in strains can be seen, which correlate with the seasonal increase in temperature in spring and summer.

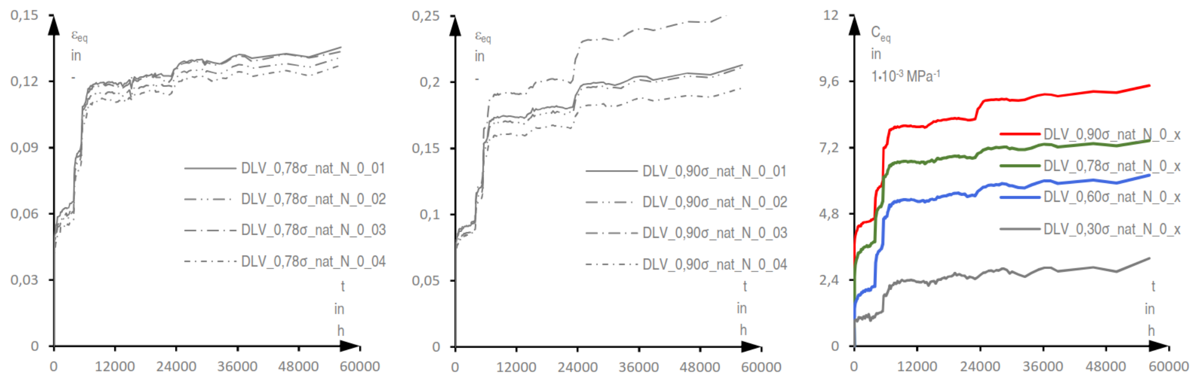

Figure 9: Strain-time curves in single tests and compliance-time curves in mean values in continuous load tests under natural climatic conditions depending on the stress level

3 MATERIAL MODELING

The rheological model according to Burgers, Fig. 10, forms the basis for the development of the time- and temperature-dependent material model of the ETFE foils.

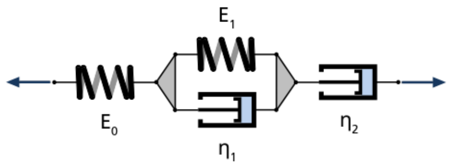

Figure 10: Rheological model according to Burgers for the description of viscoelastic material behaviour

In its original formulation according to Eq. (1), it enables the modelling of spontaneously elastic, delayed elastic and viscous deformations and thus the modelling of time-dependent retardation and relaxation processes. The description of the pronounced non-linearity of the viscoelasticity of the ETFE foils due to the partially crystalline polymer structure, however, requires a further development of the Burgers model.

$$\varepsilon(\sigma,t) = \frac{\sigma}{E_{el}} + \frac{\sigma}{E_{vel}} \cdot \left(1 - e^{-\frac{E_{vel}}{\eta_{vel}} \cdot t}\right) + \frac{\sigma}{\eta_v} \cdot t \tag{1}$$

For the non-linear expansion, Eq. (1) is initially formulated in compliance $C_0(\sigma, T)$, $C_{vel}(\sigma,T,t)$ and $C_v(\sigma,T,t)$ according to Eq. (2), which enables the identification of compliances solely on the basis of the previously presented test results.

$$\varepsilon(t) = \frac{\sigma}{E_e l} + \frac{\sigma}{E_{vel}} \cdot \left[1 - e^{-\frac{E_{vel}}{\eta_{vel}} \cdot t}\right] + \frac{\sigma}{\eta_v} \cdot t = [C_0(\sigma,T) + C_{vel}(\sigma,T,t) + C_v(\sigma,T,t)] \cdot \tag{2}$$

3.1 Modell component of the time-independent material behaviour

The time-independent compliance $C_0(\sigma, T)$ of the material modelling according to Eq. (2) is described on the basis of the model according to Ramberg/Osgood [13].

$$\varepsilon(\sigma) = \frac{\sigma}{E_0} + K \cdot \left[\frac{\sigma}{E_0}\right]^n \tag{3}$$

To model the influence of temperature, the original formulation according to Eq. (3) is modified and formulated in compliances according to Eq. (4).

$$C_0(\sigma, T) = \frac{1}{E_0(T)} + \frac{k_{01}}{f_{el}(T)} \cdot \left[\frac{\sigma}{f_{el}(T)}\right]^{k_{02}(T)-1} \tag{4}$$

3.2 Model component of the time-dependent material behaviour

The non-linear dependence of the compliances on the stress level and the temperature, which is evident from experimental investigations, requires non-linear extensions of the viscous and viscoelastic component of the underlying Burgers model.

The time-dependent viscous sub-model is first formulated as temperature- and stress-dependent according to Eq. (5).

$$C_v(\sigma, T, t) = k_{11}(\sigma, T) \cdot t \tag{5}$$

The influence of the viscous compliances on the modelling of the strain-time curves of the isothermal long-term load tests was determined to be negligible in model calculations, which is why the viscosity $k_{11}(\sigma, T)$ according to Eq. (6) can be accepted.

$$k_{11}(\sigma, T) = k_{11} = 0 \tag{6}$$

The viscoelastic sub-model in its original form according to Eq. (1) describes the curvature of the measured strain-time curves only inadequately due to the constant model stiffness and viscosity. By introducing the stress- and temperature-dependent model functions $k_{13}(\sigma,T)$ and $k_{14}(\sigma,T)$ instead of constant model parameters as well as the three stress- and temperature-dependent nonlinearity functions $g_1(\sigma,T)$, $g_2(\sigma,T)$ and $k_{12}(\sigma,T)$, following Schapery [14], the nonlinear viscoelastic compliance $C_{vel}(\sigma,T,t)$ results according to Eq. (7).

$$C_{vel}(\sigma, T, t) = g_1(\sigma, T) \cdot g_2(\sigma, T) \cdot k_{12}(\sigma, T) \cdot \left[1 - e^{-k_{13}(\sigma,T) \cdot t^{k_{14}(T)}}\right] \tag{7}$$

Eq. (7) can be simplified to Eq. (8) for the description of isothermal continuous load tests via the non-linearity function $G^*(\sigma,T)$.

$$G^*(\sigma, T) = g_1(\sigma, T) \cdot g_2(\sigma, T) \cdot k_{12}(\sigma, T) \tag{8}$$

The model functions $G^*(\sigma,T)$, $k_{13}(T)$ and $k_{14}(\sigma,T)$ are determined on the basis of the test results of the continuous load tests via the minimisation of the sum of the deviation squares. The result is an exponential dependence of the model function $G^*(\sigma,T)$ on temperature and stress in Eq. (9) and an exponential temperature dependence of $k_{13}(T)$ in Eq. (10).

$$G^*(\sigma,T) = G_0^* \cdot e^{-E_{G^*}/T} \cdot \left[\frac{\sigma}{f_{el}(T)}\right]^{k_{G^*}} = 0{,}2247\frac{1}{MPa} \cdot e^{-1035K/T} \cdot \left[\frac{\sigma}{f_{el}(T)}\right]^{1{,}558} \quad (9)$$

$$k_{13}(T) = k_{13,0} \cdot e^{-E_{k_{13}}/T} = 35{,}926\frac{1}{h} \cdot e^{-1324{,}6K/T} \quad (10)$$

The model function $k_{14}(\sigma,T)$, which transforms the physical time into a material time, can be regarded as independent of the temperature as well as the voltage with sufficient accuracy according to Eq. (11).

$$k_{14}(\sigma,T) = k_{14} = 0{,}2444 \quad (11)$$

The now completely determined material model allows the description of isothermal continuous load tests, but requires the use of a superposition principle for the representation of non-constant stresses in the isothermal load repetition tests.

The classical formulation of the superposition principle according to Boltzmann in Eq. (12) is limited to linear viscoelastic material behaviour and must be extended to non-linear behaviour for modelling ETFE foils.

$$\varepsilon(\sigma,T,t) = C_0(\sigma,T) \cdot \sigma(t) + \int_{-\infty}^{t} \Delta C(\sigma,T,t-\tau)\frac{d\sigma(t)}{d\tau}d\tau \quad (12)$$

Following Schapery [14], the total compliance is divided into the time-independent compliance $C_0(\sigma,T)$, the time-dependent compliance $\Delta C(\sigma,T,t-\tau)$ and the non-linearity functions $g_1(\sigma,T)$, $g_2(\sigma,T)$ and $k_{12}(\sigma,T)$ are introduced. This results in the modified superposition principle according to Eq. (13), which enables the differentiation of the different non-linear influences in the loading and unloading phases and thus the modelling of non-constant, long-lasting stress conditions.

$$\varepsilon(\sigma,T,t) = C_0(\sigma,T) \cdot \sigma(t) + g_1(\sigma,T) \cdot \int_{-\infty}^{t} \Delta C(\sigma,T,t-\tau)\frac{dg_2(\sigma,T) \cdot \sigma(t)}{d\tau}d\tau \quad (13)$$

For a detailed presentation of the sub-models, the modified superposition principle, the assumptions made as well as for the calculation of the sub-models, please refer to [9].

3.3 Comparison of the modelled and experimentally determined strain-time curves

The approximation quality of the material model presented in the previous section is evident from the comparison of the experimentally determined strain-time curves and those predicted by the model.

The isothermally conducted continuous load tests are very well approximated according to Fig. 11 to 13. The description of the strains of the continuous load tests at 3 °C and a stress of approx. 60 % of the elastic limit unfortunately only succeeds qualitatively, without any experimental or model-related deficiencies being detected.

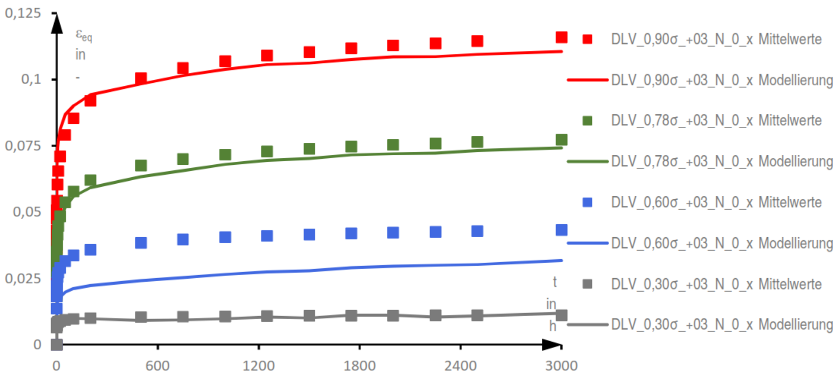

Figure 11: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal continuous load tests at 3 °C depending on the stress level

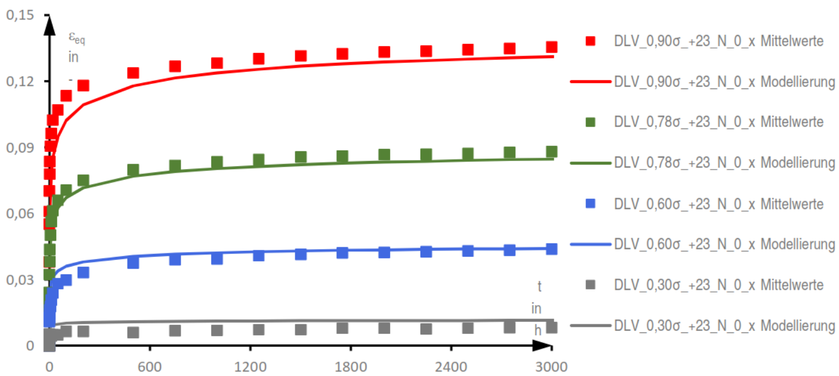

Figure 12: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal continuous load tests at 23 °C depending on the stress level

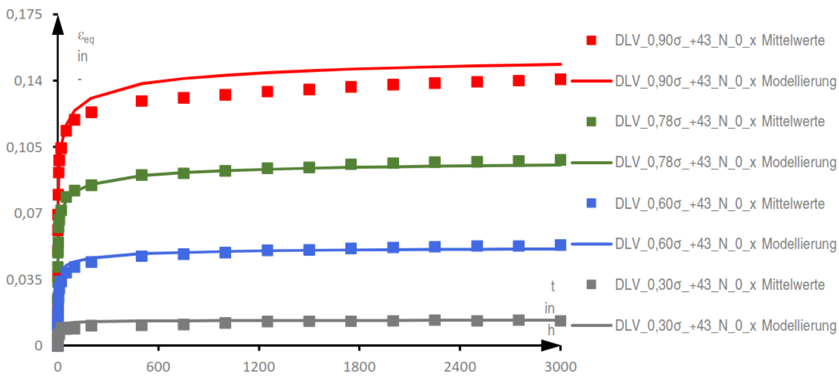

Figure 13: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal continuous load tests at 43 °C depending on the stress level

Similarly, the test results and the modelling of the isothermal load repetition tests at temperatures of 3 °C and 23 °C agree well, see Fig. 14 and 15. However, the description of the strain-time curves at 43 °C in Fig. 16 shows a qualitative rather than quantitative character.

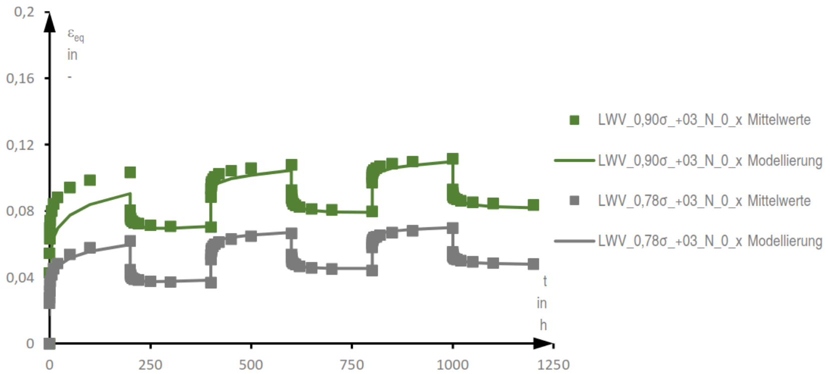

Figure 14: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal load repetition tests at 3 °C depending on the stress level

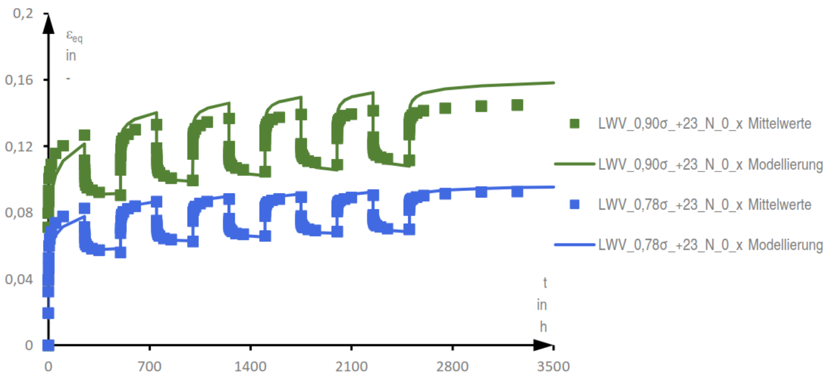

Figure 15: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal load repetition tests at 23 °C depending on the stress level

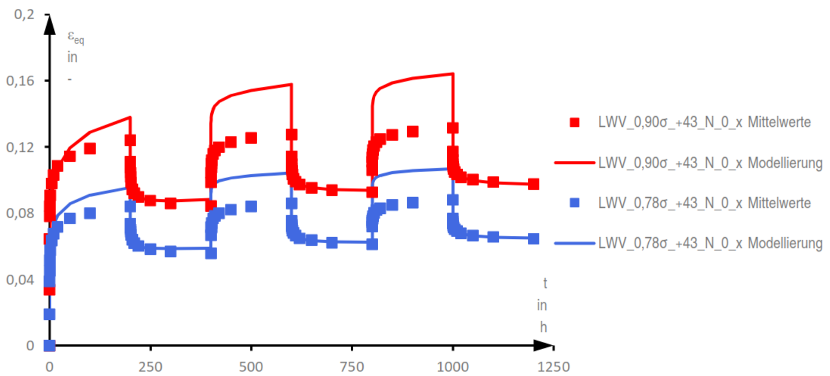

Figure 16: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in isothermal load repetition tests at 43 °C depending on the stress level

While the modelling of non-constant stress conditions under isothermal conditions is still well achieved with the developed material model, the continuous load tests carried out anisothermally under a natural climate can only be described qualitatively. Fig. 17 illustrates this by comparing the test results with the strain-time curves projected by the material model, taking monthly temperature data into account.

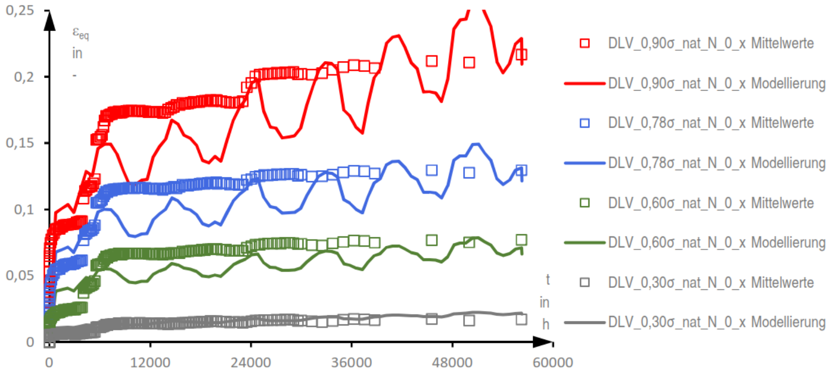

Figure 17: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) in non-isothermal continuous load tests under natural climatic conditions depending on the stress level

At the same time, however, the developed material model enables the basic modelling of the strain-time curves for long test periods if the meteorological temperatures are replaced by an equivalent temperature. Fig. 18 shows this site-specific equivalent temperature to be around 33 °C and thus offers the possibility to take this into account for dimensioning safe and durable constructions made of ETFE foils.

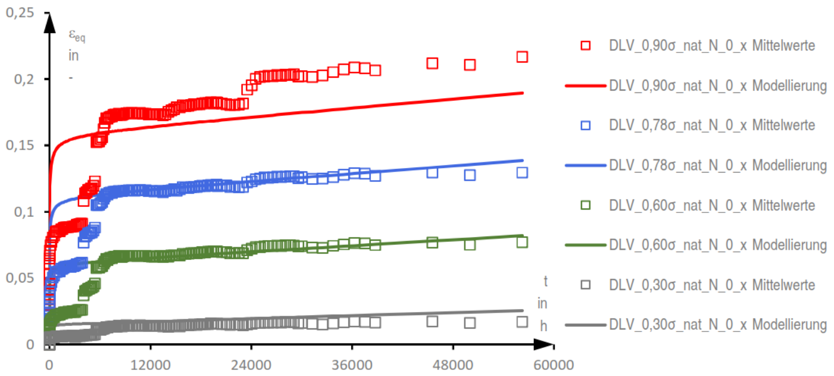

Figure 18: Comparison of the measured strain-time curves (dotted line) and the strain-time curves projected by the model (continuous line) using der equivalent temperature in non-isothermal continuous load tests under natural climatic conditions depending on the stress level

4 SUMMARY

The material behaviour of ETFE foils under long-term stress differs significantly from that under short-term stress. The foils of the semi-crystalline fluoropolymer show a pronounced non-linearity of the viscoelastic material behaviour in the experimental investigations. For safe and durable constructions made of ETFE foils, knowledge and prediction of this behaviour are indispensable, especially for single-layer, mechanically prestressed constructions.

The model presented is based on the rheological model by Burgers in conjunction with approaches by Ramberg/Osgood and Schapery. It allows the description of the non-linear viscoelastic behaviour of ETFE foils and at the same time the determination of the model parameters and functions solely from the results of isothermal short-term, long-term load and load repetition tests with maximum test durations of 4000 h.

The approximation accuracy of the model is demonstrated by comparing the experimentally determined strain-time curves with those projected by the model. If the isothermal continuous load tests are modelled very well and the isothermal load repetition tests are modelled well, the approximation accuracy of the anisothermal continuous load tests must be considered to be of a more qualitative nature. By introducing the equivalent temperature to model the natural, variable temperature processes through a site-specific, constant model temperature, the developed material modelling can be successfully applied to design tasks in structural engineering.

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