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Characterisation and Modelling of ETFE Membranes for Tensile Structures

Luis M. SEIXAS[*,a,b], Alessandro COMITTI[a,b], Massimo PENASA[b], Federico BOSI[a,c]

[*,a] Department of Mechanical Engineering, University College London (UCL)
Torrington Place, London, WC1E 7JE, United Kingdom
luis.seixas.20@ucl.ac.uk

[b] CAEmate SRL Innovative Startup, Bolzano, Italy
[c] Department of Innovative Technologies, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Lugano, Switzerland

Abstract

The energy transition requires the reduction of emissions in the building industry, for which new and sustainable technologies are required to overcome the environmental footprint of construction. One of the most promising materials for roofing and facades is the semi-crystalline polymer ethylene tetrafluoroethylene (ETFE), typically produced as lightweight structural membranes. However, the lack of a comprehensive viscoelastoplastic model and a reliable time and temperature-dependent yield criterion hinders its use among designers. An experimental campaign performed within the EU H2020 MSCA LIGHTEN program has enabled the mechanical characterisation of ETFE. Uniaxial properties were investigated across a range of temperatures spanning from -20 to 60°C, at different strain rates (0.01 to 1%/s). Based on Schapery's approach, a viscoelastic model was developed through the compliance master curves built using the time-temperature superposition principle. Furthermore, a time-temperature dependent yield model, integrated into the von Mises criterion, was developed to estimate ETFE's onset of plasticity, thus allowing the prediction of different yield loci under varying thermo-mechanical loading conditions. The validation of the ETFE material model and yield criterion against independently acquired data demonstrated very good agreement with experimental data, providing a solid foundation for developing safer and more efficient ETFE building designs.

Keywords: ETFE, Membrane structures, Viscoelasticity, Yield criterion, Experimental characterisation, Numerical implementation

1. Introduction

According to the United Nations, the building materials industry was responsible for 37% of global emissions in 2020 [1]. In structural design, an increasingly utilized approach in large-scale non-residential constructions to mitigate these emissions is through lightweight membrane structures. One of the most commonly used materials in these structures is the copolymer ethylene tetrafluoroethylene (ETFE) due to its excellent mechanical performance characteristics, such as high stiffness and ductility, and low environmental impact, given its ultralightweight nature and full recyclability. Despite the numerous advantages of structural membranes, there are currently no structural design standards and codes for this emerging construction technology, thereby hindering its widespread adoption [2].

ETFE is a copolymer classified as a semi-crystalline thermoplastic used in building construction characterised by its high transparency and its weather, UV, and fire resistance [3]. It is a typical replacement for glass applications since, as Charbonneau et al. [4] presented, it is lighter and has better ductile structural performance. ETFE films are mainly used in single or multiple layers in tensile membrane structures or inflated cushions. ETFE's mechanical behaviour includes nonlinearities, large plastic deformations, and strain rate and temperature dependencies, however investigations regarding its behaviour only started recently [5]. Moreover, only few standards, such as Tensinet [6] are currently in place to accurately design ETFE structures. The advantages of this material in sustainable construction and the lack of knowledge about its structural response suggest that a comprehensive thermomechanical modelling is required.

A characteristic of this material is the almost trilinear behaviour marked by two inflection points, commonly referred to in the literature as yield points [7]. This response has been the source of different interpretations, especially regarding which inflection point represents the onset of plasticity. However, it is now widely accepted that until the first inflection point, the material is viscoelastic, similarly to other polymers [8]. De Focatiis and Gubler [9] provided more insight into ETFE's two inflection points, reporting similarities between ETFE and polyethylene responses, indicating that the first inflection point is associated with the onset of plasticity of the amorphous phase within the crystalline lamellae. ETFE's nonlinear and viscous behaviour create challenges in creating a comprehensive material model that accounts for changes in thermal and loading rate conditions.

The experimental campaigns to obtain the stress-strain response have primarily been based on three experimental tests: uniaxial, biaxial, and inflation tests [5]. Galliot and Luchsinger [7] studied the ETFE mechanical properties at different strain rates in the range of 0.4-200%/min and different material directions. The authours observed that the elastic modulus increased by about 20% and the yield stress by about 40% at higher strain rates. Regarding the extrusion direction, it was observed that did not significantly affect the material behaviour, leading the authors to conclude that ETFE can be considered isotropic. A recent contribution to ETFE mechanical characterisation was presented by Surholt *et al.* [8]. One novelty of their work was the impact of different ETFE manufacturers with different specimen thicknesses (250 and 100 μm) for each producer. The authors observed that the mechanical properties changed with the producers and thicknesses, which represents an increased difficulty in creating an ETFE material model that covers a wide range of applications. Sun *et al.* [10] investigated the mechanical properties of ETFE at nine different temperatures (-20, 0, 23, 40, 60, 80, 100, 120 and 140 °C) and five strain rates (5, 10, 25, 50, 100 mm/min), turning this contribution in one the most descriptive experimental campaigns in literature. The temperature and strain rate influence on the uniaxial response was visible from the stress-strain diagrams obtained. The authors proceeded to determine, for each condition, the elastic modulus through a tangent to the initial part of the elastic region and both the first and second inflection points through the geometrical method. The elastic modulus and inflection points stresses revealed a high dependence on temperature since all heavily reduced at higher temperatures. Overall these studies allowed to understand that the ETFE mechanical properties are highly dependent on temperature and strain rate.

The current research aims to characterise ETFE´s response under varying loading conditions and develop a comprehensive viscoelastic model coupled with a temperature and strain rate dependent yield criterion. This work is also conducted within the LIGHTEN project [11], which goal is to create a framework to assist the analysis, design, and implementation of novel thin films for tensioned structures with improved energy efficiency, robustness, and sustainability [12].

2. Materials and methods

An experimental campaign was conducted to determine the typical material properties of ETFE and subsequently to develop constitutive models. ETFE membranes, 200 µm thick, manufactured by Nowofol, were utilized during the testing campaign.

Initially, uniaxial tensile tests at constant strain rates were conducted on an Instron 5985, as depicted in Figure 1. Engineering stress was calculated using the force obtained from a 500N load cell and the initial specimen dimensions. Kinematic fields (displacements and strains) were measured using Digital Image Correlation (DIC) [13]. Specimens were laser-cut into a dumbbell shape for testing. In exploring the time and temperature effects on ETFE, three strain rates (0.01, 0.1, and 1% /s) and five temperatures (-20, 0, 25, 40, 60 °C) were considered in the test protocol. Additionally, both principal directions were tested according to their extrusion direction: parallel to the machine direction (MD) and transverse (TD). An inclined direction (ID) at 45°from the MD was also characterised to obtain the in-plane shear properties by rotating the stress and strain tensors. At least three samples were tested for each combination of conditions to ensure repeatability.

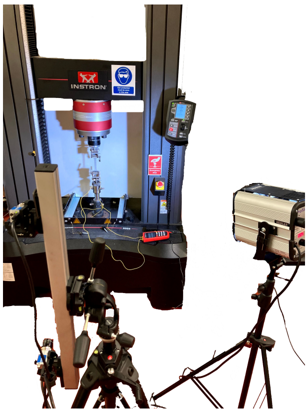


Figure 1: Uniaxial experimental setup. Tests were conducted on the tensile machine. Strains were measured using two cameras.

In addition to tensile tests, uniaxial 4-hour creep tests at 1.5MPa were performed on a Dynamic Mechanical Analyser. Creep behaviour was analysed at different temperatures, ranging from -20 to 65°C, with intervals of 5°C above 0°C and 10°C below. Three directions of the material were considered: MD, TD, and ID.

3. Experimental results

In Figure 2, it is possible to observe the stress-strain curves for the same temperature (strain rate variation) and the same strain rate (temperature variation) with three samples for each condition obtained from the uniaxial tensile tests. It is evident from these plots that the material response varies significantly with temperature and slightly with strain rate. Regarding the load direction (MD and TD), the results show a small degree of anisotropy, primarily noticeable after the viscoelastic phase.

ETFE's stress-strain response exhibits a trilinear curve with two inflection points, as reported in the literature [7]. During the current investigation, residual strains were measured on specimens that were loaded until a stress level close to the first inflection point and subsequently unloaded for a long period. It was found that permanent deformations were developed when the material was loaded after the first inflection point indicating that this location must be considered the yield point. The region before the yield point is defined as the viscoelastic phase, while after there are two viscoplastic phases with different material properties separated by the second inflection point. The geometrical method [14] was used to obtain the value of the yield point for each stress-strain curve, allowing the association of a yield value with a temperature and strain rate combination.

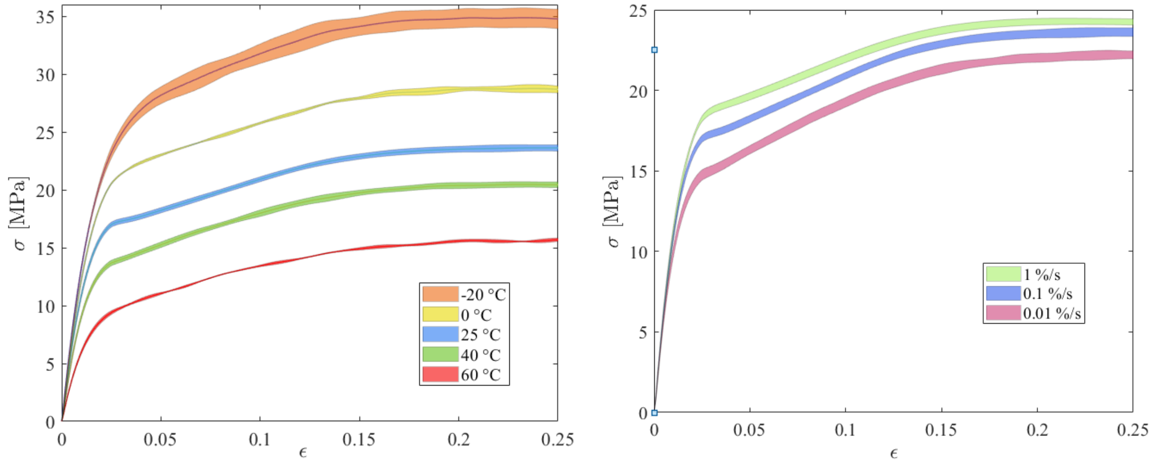


Figure 2: Stress-strain curves obtained from uniaxial tests are illustrated. On the left, test at various temperatures are plotted at a strain rate of 0.1%/s. On the right, there are tests at different strain rates at 25°C.

The uniaxial creep tests described earlier allowed for the characterisation of the viscoelastic regime and the construction of a creep-compliance master curve by applying the time-temperature superposition principle (TTSP) to each test, as illustrated in Figure 3.

4. Material modelling

As observed in previous sections, both time and temperature have significant influence on ETFE behaviour, requiring its modelling as a viscous material. Therefore, a viscoelastic material model coupled with a strain rate-temperature-dependent yield criterion, based on the experimental data obtained, was developed to accurately predict ETFE's response under various loading conditions, including multiaxial tension, creep, and relaxation.

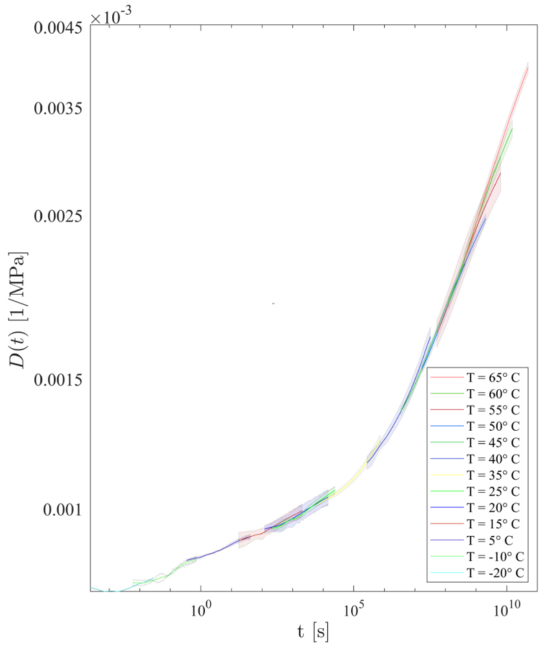


Figure 3: Creep compliance master curve along MD at Tref = 20°C

4.1. Linear viscoelastic model

As mentioned in Section 3. and shown in Figure 3, the time-temperature superposition principle (TTSP) was applied to build a creep-compliance master curve. This was done for the directions MD, TD and ID, choosing a reference temperature T_{ref} = 20°C. The shifting operation of each curve around the one at T_{ref}, expressed by the shift factor a_T, was fitted to an Arrhenius law [15]. This allowed to express the time-temperature relationship for linear viscoelasticity by the single parameter E_a, the activation energy, according to the equation

$$\log_{10} a_T = -\frac{E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right), \tag{1}$$

where R is the universal gas constant. The average value determined for the three master curves is $E_a = 260.7$ kJ/mol.

The viscoelastic modelling proposed adopted a Generalized Kelvin element, expressed by means of Prony series, to incorporate the time and temperature effects on the material constitutive model. The constitutive law was formulated in the framework of the Boltzmann superposition principle [16] as

$$\varepsilon(t', T) = \int\limits_0^{t'} \left[D_0 + \sum_{i=1}^{N} D_i\left(1 - e^{-\frac{t'-s}{\tau_i}}\right)\right]\frac{d\sigma}{ds}ds, \tag{2}$$

where D_0 is the compliance of the isolated the spring of the Generalized Kelvin model and D_i are the compliances of the springs of each of the N Kelvin elements whose relaxation times are τ_i. t' is the internal time of the material, that takes into account the temperature variation from T_{ref} according to the TTSP. Twenty-one τ_i were defined between 10^{-12} and 10^{11} s. Using Equation 2 in the case of creep loading, the twenty-two resulting free compliance parameters, D_0 and D_i, could be fitted on each mastercurve.

The results of the fitting operation are the in-plane compliances values, for each direction tested, which were used to build a plane stress orthotropic constitutive model: D_{MD} and D_{TD} were used as the two principal material direction, D_{ID} as the in-plane shear. The Poisson coefficient ν = 0.43 was determined in the experimental campaign and used in the model to describe the transverse components of the compliance matrix.

In order to provide this model as a useful tool for the application, and to validate its prediction, the integral viscoelastic relation of Equation 2 was discretised with a recursive integration algorithm [17, 18, 19] and implemented in a MATLAB code. A thorough description and validation of the experimental campaign and linear viscoelastic constitutive law of ETFE is presented in Comitti and Bosi[20]. The model has been proven to be a useful tool in predicting loading, creep and relaxation conditions on ETFE foils until 1% of equivalent engineering strain.

The additional efforts happening in the framework of LIGHTEN research consist of extending the discussed linear viscoelastic model into the complete nonlinear viscoelastic domain, adopting a further modification of the internal time of the material to account for the stress level [21]. In particular, the Eyring stress shift factor a_σ [22], formulated as

$$a_\sigma = \frac{\sigma_{ey}}{\sigma_0 \sinh\left(\frac{\sigma_{ey}}{\sigma_0}\right)}, \tag{3}$$

is in consideration. Here $\sigma_0 = \frac{RT_0}{V}$, σ_{ey} is the effective stress on the material and V is the activation volume. A preliminary result of this model is shown in Figure 4, compared to the prediction of the linear viscoelastic model, for a uniaxial tensile test and a creep test.

4.2. Yield criterion

From the mechanical characterisation of ETFE, it was possible to understand that the yield strength (first inflection point) depends on temperature and strain rate. To define a yield criterion that predicts these dependencies, it is necessary to create a yield model in the form of a mathematical expression that relates the yield strength with both independent variables. From the results obtained, it was observed that the yield point follows a linear relation both with temperature and the logarithm of the strain rate. Therefore, the following expression is proposed to model ETFE yield strength:

$$\sigma^{y}(\dot{\varepsilon}, T) = A + B\,\log_{10}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{0}}\right) + C\,T, \tag{4}$$

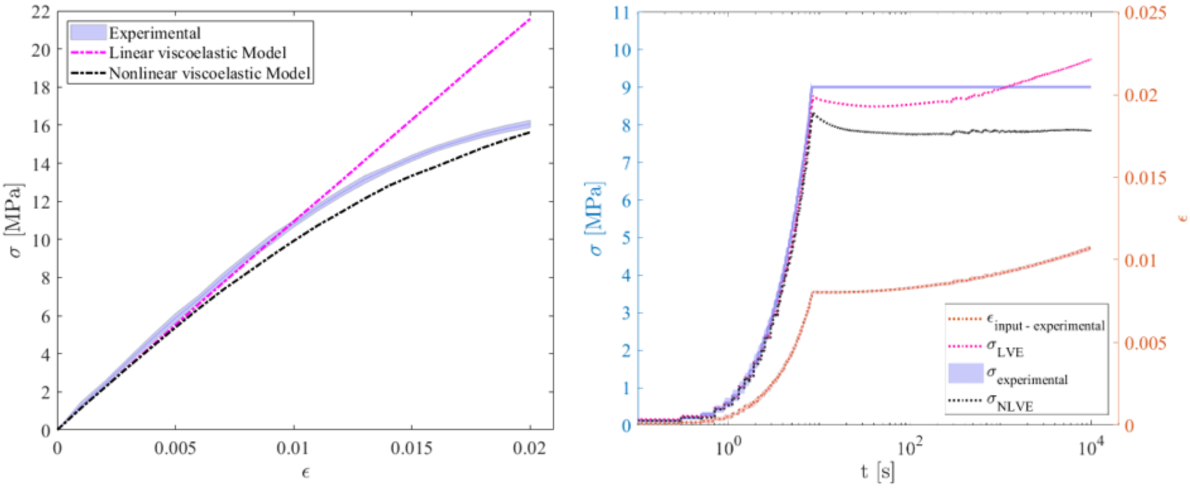
where $\dot{\varepsilon}$ and T are the strain rate and temperature, in s^{-1} and °C, respectively. A, B, and C are parameters that need to be identified and $\dot{\varepsilon}^{0}$ is a reference strain rate chosen in this investigation to be 1s^{-1}. The parameter values obtained after fitting the model to the experimental results can be observed in Table 1.

Table 1: Yield model parameters.

Parameter	Value	Unit
A	78.85	MPa
B	1.88	MPa
C	-0.19	MPa K^{-1}

Figure 5 illustrates how the model compares with yield stress values for some conditions tested during the experimental campaign. The goodness of the model fitting can be evaluated with the quality measures R^{2} and mean absolute percentage error, which are 0.993 and 2.28%, respectively. These values indicate that the model can predict the onset of plasticity at different temperatures and strain rates with good accuracy.

The model described in Equation 4 allows obtaining the yield value. However, to correctly describe the



(a) MD, T_{amb}=25°C, $\dot{\varepsilon}$ = 0.1%/s (b) MD, T_{amb}=25°C, σ_{creep} = 9 MPa, t_{creep} = 4 h

Figure 4: LVE and NLVE models prediction of (a) uniaxial tensile test and (b) creep test

onset of plasticity in a multiaxial stress state, a yield criterion is necessary. The von Mises yield criterion has been applied to some ductile polymers, including ETFE, as demonstrated in the works of Coelho and Roehl [23] and Galliot and Luchsinger [7]. During ETFE's modelling, this criterion was implemented in conjunction with the yield model, enabling the capture of time-temperature dependencies in multiaxial cases. The yield function ($\mathcal{F}$) that represents the time-temperature-dependent von Mises yield criterion can be written as

$$\mathcal{F}(\bar{\sigma}, \dot{\varepsilon}, T) = \bar{\sigma} - \sigma^y(\dot{\varepsilon}, T) = 0 \tag{5}$$

where $\bar{\sigma}$ is the equivalent von Mises stress. By incorporating the effects of temperature or strain rate on the yield function, it implies that the yield surface will expand or shrink due to the viscous effects.

The time-temperature-dependent yield criterion presented here is purely phenomenological, and its accuracy is reliable only within the range of conditions studied. Another possible approach that will be pursued in future research is to implement yield models based on molecular theory, such as the co-operative yield model [24], where the obtained parameters have a physical meaning. This model also enables the extension to much lower strain rates using the strain rate temperature superposition principle (SRTSP) [25].

To achieve a comprehensive description of ETFE's behaviour after the onset of plasticity, it is necessary to develop a viscoplastic model that incorporates the yield criterion just described. This final step of the research will enable the prediction of the influence of viscous effects on the hardening behaviour, as well as on the second inflection point.

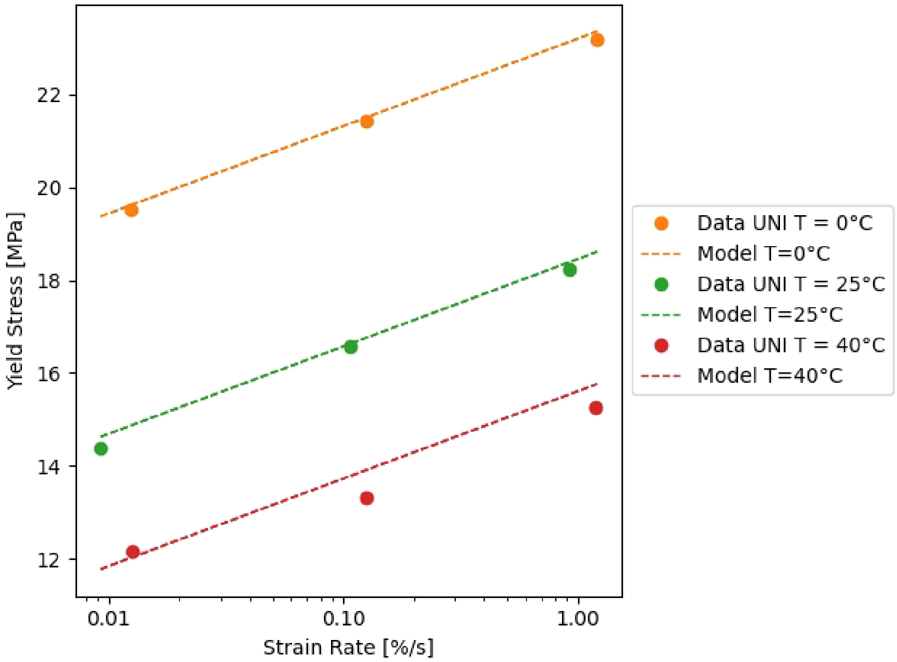


Figure 5: Comparison between yield stress experimental values at different temperatures and strain rates with values predicted by yield model.

5. Conclusions

The uniaxial thermomechanical characterisation of ETFE has clearly demonstrated the influence of time and temperature on the material properties. Creep compliance curves allowed for the construction of a master curve, which was subsequently used to define a linear viscoelastic model. Validation and comparison with experimental results, either from uniaxial or creep tests, have shown the model's good accuracy. Viscous effects were also considered in the yield behaviour, for which a time-temperature-dependent yield criterion is proposed. The discrepancy between the values predicted by the yield law and experimental results is minor, confirming the capabilities of using the proposed criterion. The proposed constitutive models can serve as a good approximation for typical applications. However, nonlinearities were also observed at higher stress levels that need to be addressed in the viscoelastic model. Similarly, to obtain a full description of ETFE's response, it is necessary to develop a viscoplastic model that includes a time-temperature-dependent yield criterion. Once such a model is completed, complex loading situations can be accurately predicted, promoting safer and more efficient designs.

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