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APPLICATION OF NONLINEAR CONSTITUTIVE AND YIELD MODELS IN THE DESIGN OF ETFE CLADDING ELEMENTS

Alessandro Comitti[a], Luis M. Seixas[a], Adam Bown[b], Adrián Cabello[b], Christoph Paech[c] and Federico Bosi[a,d]

[a]Department of Mechanical Engineering, University College London, London, United Kingdom
email: fbosi@ucl.ac.uk
[b]Tensys Ltd, Bath, United Kingdom
[c]schlaich bergermann partner, Stuttgart, Germany
[d]Department of Innovative Technologies, University of Applied Sciences and Arts of Southern Switzerland, Lugano-Viganello, Switzerland

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Summary. ETFE is a stiff, ductile and recyclable polymer employed in membrane structures as a tensioned foil or shaped into inflated cushions. Although the material's mechanical properties strongly depend on both time and temperature effects the lack of a comprehensive understanding of the mutual influence of these variables prevents an optimal design and wider exploitation of ETFE in sustainable lightweight construction. In this contribution, the authors designed typical ETFE membrane applications, single tensioned foils and pneumatic cushions, comparing the results obtained with the provisions of the recent technical standard for ETFE membranes, CEN/TS 19012, with the results achieved within the LIGHTEN project. The latter includes the novel nonlinear viscoelastic constitutive model coupled with a time-temperature-dependent yield criterion, which was implemented in a User Material Subroutine for finite element analysis. The comparison contains some assumptions on the load time profiles, integrated with the load conditions identified in the CEN/TS 19012, and is necessary to make use of the LIGHTEN constitutive model: prestress, snow and wind load cases were considered, for Service Limit State only. The results showed that the LIGHTEN constitutive law predicted higher yielding values for wind load cases while being more conservative in highly time-dependent behaviours, like the snow load case and the prestress relaxation of single-tensioned foils. The dimensional changes occurring due to temperature, both simulated and measured, were found to be a decisive factor in the serviceability of single-tensioned ETFE foils. This preliminary analysis sheds light on the advantages of adopting a nonlinear viscoelastic material model for design accuracy, as well as the required prior assumptions. This work provided useful insights that could be readily integrated into current design practice.

1 INTRODUCTION

ETFE (ethylene-tetrafluoroethylene) is a semicrystalline polymer utilised in foils as a cladding material for tensioned building envelopes, either in pneumatic inflated cushions or in single-tensioned foils[1]. Over time, the popularity of this material among designers and builders has grown substantially, mostly due to ETFE architectural value and the possibility of adapting it to complex envelope design. The relevance of ETFE in the construction sector arises from its exceptional features, namely high stiffness, ductility, durability, light transmission, self-cleaning and self-extinguishing properties, and recyclability[2]. ETFE is a nonlinear viscoelastic material[3], unusual behaviour for the field of structural engineering, which often dealt with time dependencies of construction materials constitutive laws with “correcting factors”. These factors are used to modify the stiffness (assuming linear elastic behaviour) and the strength of materials depending on the load duration, as for example in timber specifications[4] . The approach of “correction factors” has been introduced for ETFE by different authors, like Moritz[5], which accounted for the influence of the temperature and the duration of loading in the material strength; these contributions are summarised in a TensiNet guideline[6]. Therein, design advice for ETFE membrane structures is provided, suggesting the use of a linear elastic model, with the stiffness values changing according to the load case, and yield values at different temperatures and loading periods. However, as Cabello and Bown[7] highlighted in their contribution, the development of a reliable thermo-viscoelastic constitutive model is needed to achieve a confident design of ETFE structures. In their work, the authors re-factored a model developed by Bosi and Pellegrino[8] to match some ETFE experimental data and applied it to common loading scenarios for membrane structures. The comparison between those results and guidelines recommendations[6] shows how the design of ETFE is currently inaccurate and often unsafe. The latest effort for standardisation, the CEN/TS 19012[9], contains additional useful information about the structural design with these foils but still does not include comprehensive detail on how to account for the time and temperature-dependent behaviour, especially for creep or relaxation conditions.

The motivation of producing a unified constitutive model and yield law that can predict the behaviour and limit stress in any loading condition for ETFE gave birth to the LIGHTEN project[10], which aims to study and improve the use of sustainable lightweight structures and involves several of the authors of this work. A nonlinear viscoelastic constitutive model was built following the approach of rheological modelling through Generalised Kelvin Elements, adopting a single integral representation according to Schapery. In particular, all the nonlinear factors of the said law were included in the stress shift factor (a_σ), which is expressed according to Eyring’s law and is responsible for modifying the viscosity of each Kelvin element depending on the stress level. In other words, a_σ modifies the internal time of the material. Similarly, temperature modifies the internal time of the material through the time shift factor (a_T), a factor which follows the Arrhenius law and regulates the time-temperature superposition. The model has been fitted and validated on a wide range of experimental data: further details on this work and the full model are reported in the work published by Comitti and Bosi[11]. The time-temperature-dependent yield criterion for ETFE used in this work was presented by Seixas et al.[12] and was inspired by a yield criterion for LLDPE foils[13]. The yield stress was determined for a wide range of strain rates, temperatures and loading types. The strain rate-temperature superposition principle allowed the creation of a single master curve that was able to represent ETFE’s yield behaviour on a long time scale. Afterwards, a molecular-based yield law, known as Cooperative model, was calibrated to ETFE’s master curve and then integrated into the von Mises yield criterion. The validation of this model has shown great agreement with the experimental data and its potential to be applied to the design of structural membranes.

The two models are complementary and were combined in a User Material Subroutine for use in the finite element software Abaqus (Dassault Systèmes), allowing for accurate prediction of the behaviour of ETFE whilst it lies in the elastic domain in any loading condition. This approach allowed for a comparison between the predictions made with the LIGTHEN model and with the most updated document containing the design indications for ETFE, the CEN/TS 19012[9], a preview of the future Eurocode for membrane structures.

2 ETFE FOILS DESIGN

2.1 Shapes of ETFE cladding elements

The main structural shapes for ETFE panels, identified thanks to the expertise of LIGHTEN's industrial partners, are flat, single-skinned, pre-tensioned foils and pneumatic cushions. Both types of structure are typically used in facades and or cladding elements for inclined roofs. Both forms of structure bear the out-of-plane loads similarly, deforming to reach a curved configuration which carries tension-only loads. The cushion takes advantage of its initial curved shape to bear the applied loads in a more efficient manner, which guarantees stiffness by its geometry and internal pressure, while the flat membrane needs to deform to reach a curvature to support the same loads; however, an installation stretch is necessary to limit the out-of-plane displacement during and after the loads. Therefore, usually cushions allow for covering larger spans than flat membranes. To investigate the main differences between the two installation technologies, and to cover the vast majority of applications, these two shapes will be investigated as elements of a flat roof.

A rectangular initial geometry for both flat foils and cushions was considered, with dimensions depending on the type of analysis, but typically with a long edge equal to 5 or 10 m and a short edge between 0.5 and 3 m. The thickness was kept as a constant parameter in all geometries studied, and it was defined as 200 μm.

2.2 Load conditions for ETFE structural membranes

The load cases for a membrane element that clads a roofing area are dictated by the EN 1990[14] in Europe. The primary load types for consideration are due to wind and snow. Moreover, an additional load applied is prestress, imposed during the installation phase to provide stiffness and avoid extreme phenomena such as wind-induced flutter. The prestress load must be combined with all other load cases, as it is applied during structure installation. To focus on fewer parameters, the wind and snow pressure loads will be treated as equal, specifically 740 Pa, which was found to be the snow load in Stuttgart. These analyses were performed only considering the Service Limit State (SLS), since the LIGHTEN material model is restricted to the viscoelastic domain. Furthermore, in the case of pneumatic cushions, only an analysis of the installation pressure is presented here, since for both wind and snow load cases, the single foils are more dependent on the material model.

2.2.1 Installation of single tensioned foils

The installation phase for single flat foils employs an initial stretch of the membrane to avoid wrinkles and defects, and to provide additional stiffness. It is usually performed slowly: a time frame of 1 hour was believed to be representative. Usually, designers assume an equibiaxial prestress state; in this work, it was assumed to be achieved simultaneously in both directions of the foil. The stretch provided to ETFE single-tensioned flat foils during the installation phase causes stress relaxation due to ETFE's viscous features. Usually, the designer assumes a level of prestress as a permanent load on the foil for its service life: the technical report CEN/TS 19012[9] suggests 4 MPa. However, because ETFE undergoes stress relaxation, the material needs to be overstretched during installation to achieve the desired prestress once it becomes practically constant. For the analyses of wind and snow, a 48-hour interval was defined as sufficient to reach a relaxed configuration before applying any external load to the material.

2.2.2 Installation of cushions

The installation phase for cushions is a quicker process than for single foils, as the two layers of the cushions are installed slack between the aluminium frame and the air is pumped into the cavity. Towards the end of the inflation, the ETFE cushion forms, even though there is still no stress in the material; only the last few minutes of inflation will build up to reach the desired pressure and stresses. After installation, some viscous effects will manifest on the cushion, though they differ from those on a flat membrane. The cushion will continue to deform, increasing its strain and slightly increasing its depth, thereby reducing its radius. As a result, the stress will also decrease by a negligible amount. A study on the permanent installation pressure on the yield stress was performed at 23°C

2.2.3 Snow

In order for the LIGHTEN model to be used, it is necessary to provide a time profile of the snow load, and particularly, the two main parameters are the rate of snow accumulation and the time of snow permanence. Regarding the former, several resources have been consulted in order to establish realistic boundaries for a snowfall rate and an extreme rate was chosen as 0.0185 m/h[15]. To make use of this accumulation rate, the bulk weight density of snow was defined as 1 kN/m^3, which corresponds to fresh snow according to the Eurocode[14]. A 40-hour time period was determined to accumulate the snow quantity corresponding to the established final pressure of 740 Pa. With regards to the standing time on the envelope of the snow load on average, for non-mountainous land, a time of 30 days was considered representative of the data found[16].

2.2.4 Wind

For what concerns the wind, the idea was to consider the typical gust velocity in order to assign the fastest wind load on the cladding. Several standards are based on averaging the velocity of wind during different periods, usually referring to a common 3-second gust[17]. However, this was recognized as a technical construct, not representing the reality of the load on a structure. Wind gust peak velocities adopted in the most recent standards have a lower gust duration, around 0.1 - 0.3 seconds[18]. This work is an initial study aiming to evaluate the effects of fast loading on a cladding element. Therefore, a 1-second gust, starting from a zero-wind pressure condition, was assumed to represent this load case. This gust is slower than the 0.1 seconds mentioned; however, as it can be observed in ETFE experimental results[19], the stiffness of the foils is mainly dependent on temperature, as it is the yield value, leaving the general considerations of these examples still valid.

2.3 Modelling approach

All analyses were performed using the finite element (FE) software Abaqus (Dassault Systèmes). LIGHTEN's material model was implemented using a User Material Subroutine (UMAT), whereas CEN/TS 19012[9] was used with a linear elastic material model available in Abaqus. The geometry was discretised using quadrilateral membrane elements (Abaqus M3D4) with an approximate edge length of 50 mm, a mesh density confirmed sufficient to avoid inaccuracies through a convergence study. Loads were applied either as imposed displacements at the edges for prestress of single foils, or as surface pressures perpendicular to the membrane surface for wind and snow loads.

The installation phase of the cushion required the inflation of the space between the two foils. It was not useful to model the whole inflation process, however, there was a need to have an unstressed initial state in the FE model. Flat membranes of the same base sizes as the cushions were inflated in Abaqus to reach the target depths. The shapes obtained with this operation were used to define the morphology of each layer of the cushion, in the initial configuration. This was possible thanks to a custom Abaqus-Python code, which allowed to merge both meshes into one, representing the shape of the cushion. Finally, Abaqus fluid cavity elements were introduced between the two membranes to simulate the inflation of the cushion.

2.4 Material models

The CEN/TS 19012[9] provides stiffness and yield stresses design values in order to deal with SLS and ULS design, depending on the load type. As a general overview, the standard suggests nonlinear geometric analysis to account for the relevant deformation that this type of structure will experience. Concerning the material properties, despite acknowledging the influence of time and temperature on them, only the yield value is modified with factors to account for, namely, the temperature influence, the long-term effects and redundancy (single foils are treated more carefully), while the stiffness is considered linear and constant. Summarising the indications of the technical report for single foils and cushions, Table 1 was produced, reporting the design values from the various load cases deriving from the characteristic value of 15 MPa.

Regarding the LIGHTEN model, the specific strain rate at each point in the analysed geometry and the temperature variation would lead to different yield stresses and stiffnesses, so it is not possible to produce a similar table. Since the yield stresses measured during the experimental campaign[12] were found from the average stress/strain curves of ETFE, an additional factor was provided to transform the average yield domain into a design one. The approach adopted by the

Table 1: CEN/TS 19012[9] design values for ETFE.

Design Load Cases	T [°C]	E [MPa]	Yield Stress [MPa]		k factors	
			Cushion	Single foil	Cushion $k_{temp} \times k_{dur}$	Single foil $k_{temp} \times k_{dur} \times k_{single}$
Snow	0	1000	13.4	12.2	0.8×1.4	0.8×1.4×1.1
Wind	0		18.8	17.0	0.8×1	0.8×1×1.1
	23		15.0	13.6	1×1	1×1×1.1
	40		12.5	11.4	1.2×1	1.2×1×1.1
	50		10.7	9.7	1.4×1	1.4×1×1.1

Eurocode and related documents is to offer characteristic values (5% fractile value) as limit stress, then further divide them by a "material and model safety factor for SLS", which is defined as $\gamma_{M,sr} = 1.0$ for ETFE according with CEN/TS 19012[9]. For the LIGHTEN material model, a more conservative factor was defined based on thickness variability and the coefficient of variation in the experimental data, resulting in a safety factor of $\gamma_{LIGHTEN} = 1.14$. Therefore, all yield stress values determined by the time-temperature-dependent yield law are divided by this value.

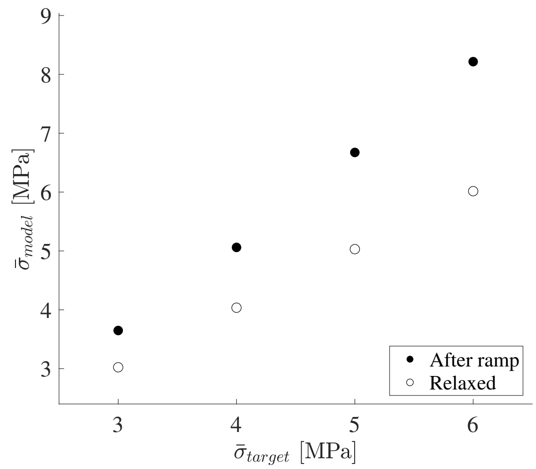
3 RESULTS

3.1 Installation of single foils

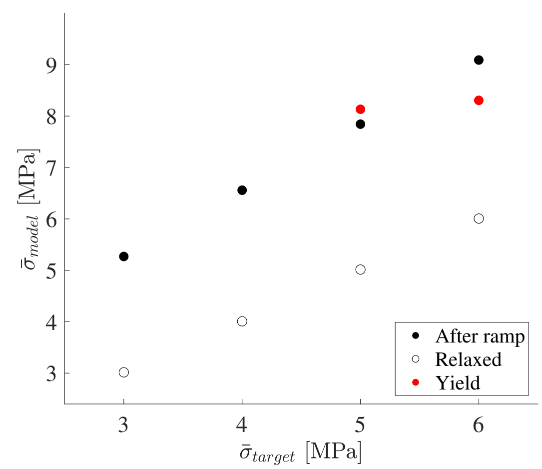
The installation stretch of the membrane, once retained at fixed positions, causes a stress relaxation due to ETFE viscous features. Therefore, the hypothesis of a constant and immutable prestress is inaccurate, and needs some precautions in order to be verified. In this installation study, the aim was to achieve different target stress levels after a period of relaxation, thereby bringing the relaxation phenomenon to a marginal level, so that the prestress could be considered constant over time. An iterative algorithm was written to determine the appropriate strain to apply to the membrane to achieve the desired target prestresses of 3, 4, 5, and 6 MPa after 48 hours of relaxation at -10, 0, 20, 30, 40, 50, and 60 °C. In some cases, due to high stress relaxation, ETFE yielded when trying to achieve higher stress values. This phenomenon was observed at 40°C and 50°C at 6 MPa, and at 60°C for prestresses higher than 4 MPa. The results are shown in Figure 1 for the representative cases at 20°C and 50°C.

3.2 Installation of pneumatic cushions

To study the effect of creep during the installation phase of cushions, an analysis was conducted on a membrane measuring 4x10 m and 1/8 the short edge in depth. The pressure was selected within the range of 150-500 Pa, and the effects of this constant pressure were investigated until yielding at 23°C. While the creep produces a slight relaxation of the cushion and a general increase in strain, it also leads the material towards the onset of plasticity. In fact, the inflation study has shown that a constant installation pressure can result in yielding after a particular creep time, depending on the pressure amount. For high installation pressures, resulting in high stresses, the yielding will occur at an initial stage of the creep phase. The creep strain rate decreases at lower



(a) $T = 20°C$

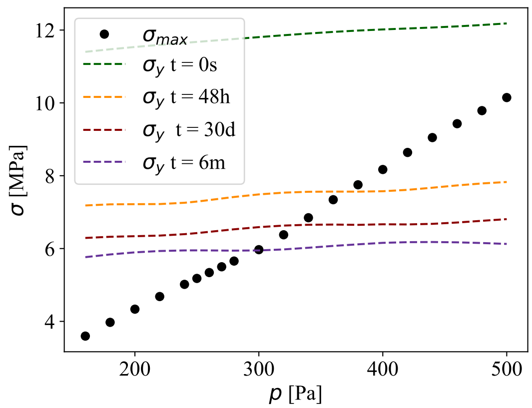


(b) $T = 50°C$

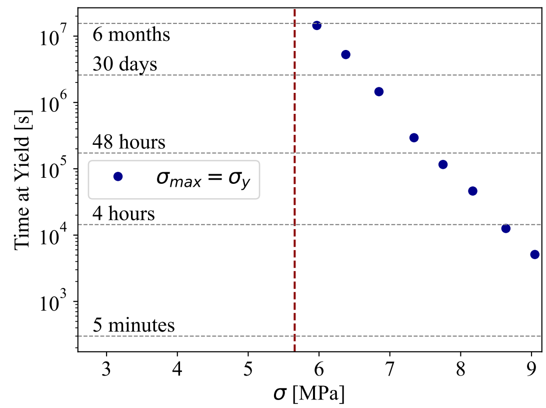
Figure 1: Installation peak stresses (filled black dots) necessary to reach the target prestress in flat tensioned membranes, equally stretched in the two directions. The installation stretch, which caused the peak stress, was reached in one hour, while the relaxation time considered was 48 hours, at 20°C (a) and 50°C (b). In the case of 50°C, the additional stretch necessary to achieve the aimed prestress was higher than the yield stress (red dots).

pressures, as the stress in the membrane does, resulting in a delayed onset of plasticity. Figure 2(a) shows the value of stress when plasticity was achieved for each installation pressure (blue dots). These values are compared with the yield stress calculated using the time-temperature-dependent yield law developed for ETFE[12] at selected time points for each installation pressure (dashed lines). The steepness of these lines is not particularly high, and qualitatively they approach zero: it is possible to conclude that the internal pressure, or the creep stress, does not influence the yield stress value significantly and is only dependent on the time period and temperature of installation. A clear takeaway from Figure 2(a) is the timing of yielding as a function of installation pressure. This can also be observed in Figure 2(b), where the time at yield associated with some of the pressures analysed is reported together with the yield stress value. The yield stresses plotted correspond to each installation pressure of Figure 2(a). The use of a logarithmic scale helps to visualize that by decreasing the installation pressure, the time to yield will increase exponentially. For example, the time to yield at 340 Pa was approximately 48 hours, whereas at 300 Pa it increased to 6 months. Although this study was conducted at 23°C, it can be concluded that, at higher temperatures, ETFE cushions are at a higher risk of yielding during installation. The peak stresses obtained with the same inflation pressure would be similar, since they are shape-dependent. However, the yield limit decreases significantly due to temperature effects.

It is fundamental to be aware of this effect during design, as exceeding the onset of plasticity would lead to permanent strains and, consequently, increase the depth of the cushion. However, it is also acknowledged that this increase can be minimal and not expected to compromise its safety if properly accounted for. Therefore, the analysis of the effect of installation pressure would greatly benefit from the integration of a viscoplastic model that can determine strains after yield during a creep load case, which is currently under development by the authors of this study.



(a) Yield stress (σ_{max}) at each installation pressure (dots) compared with the yield loci at different times (dashed lines)



(b) Time at yield for each installation pressure's yield stress

Figure 2: Results from inflation study at installation pressures in the range 150-500 Pa, at 23°C.

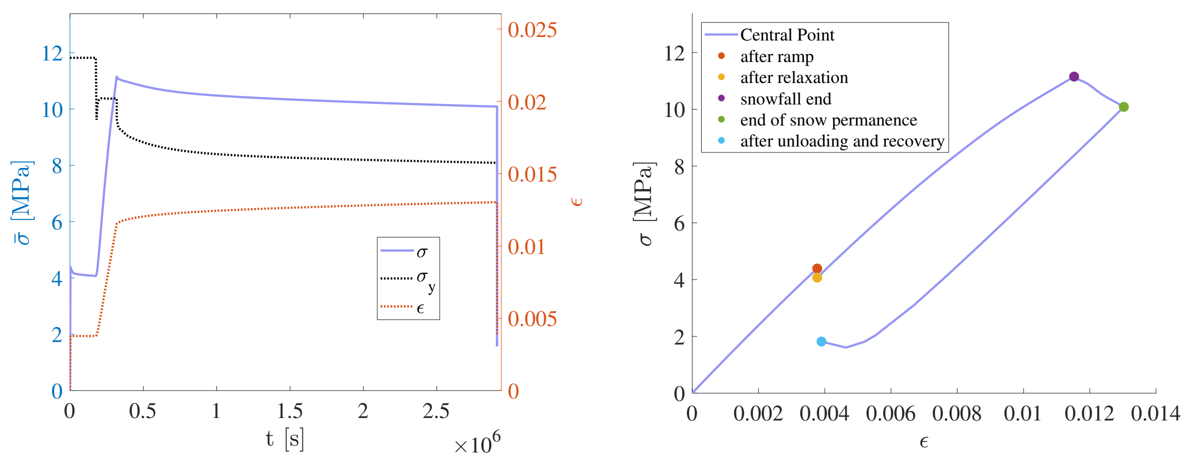
3.3 Snow in single foils

The snow load time profile consists of a snowfall period, during which the load ramps to the maximum amount defined, followed by a permanent load condition due to snow accumulation on the membrane, and a final unloading phase. Figure 3 displays the typical evolution of strains and stresses for the central point of the membrane. After the installation stretch on the membrane, and the consequent stress relaxation, the strains and stresses increase due to the application of the snow load. Subsequently, when the load reaches its final value, a creep phase ensues, causing the strain to further increase; however, at a reduced rate. In fact, the additional strains cause a shape change, particularly increasing the curvature and therefore causing a stress decrease. As shown in the validation of the material models, creep phases are associated with a shrinkage of the yield surface due to the reduced strain rate, as observed in Figure 3(a).

Two geometries (1x10 and 0.5x5 m) were studied under a snow load of 740 Pa, first ramped during 40 hours and followed by 30 days of creep. The 0.5x5 m membrane was both verified with the LIGHTEN model and CEN/TS 19012[9], even though the yield stress values between the two models are significantly different (≈35% variation). On the other hand, the geometry with a span of 1 m entered plasticity during the creep phase due to reduced strain rate, which is accounted for only by the LIGHTEN model. The results are reported in Figure 4. Since the yield value of the LIGHTEN model changes, both the value at the peak of the loading ramp and the final one during the creep phase are reported, respectively as σ_{y} and σ_{creep}. Finally, it is important to note that after removing the snow load, the LIGHTEN material model predicted that the material would not return to its original prestress value. The reason for this behaviour is the material model's nonlinearity during loading and unloading.

3.4 Wind in single foils

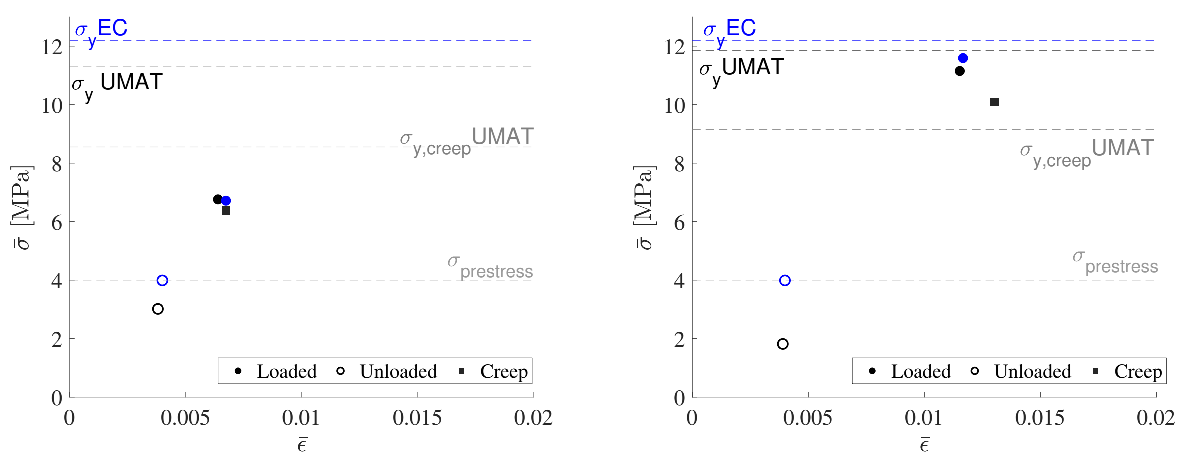
The one-second gust was applied to a 1x10 m flat membrane. In general, the LIGHTEN material model predicts a steep stress and strain increase, followed by an unloading phase. The stress/strain behaviour would be similar to the one shown for the snow load in Figure 3, excluding the creep phase. In the following Figure 5, the points of peak stress and unloading are reported in a stress-



(a) Time evolution of the quantity of interest

(b) Stress-strain plot, marking the different phases the membrane undergoes

Figure 3: Strain and stress evolution caused by a snow load on a flat membrane.

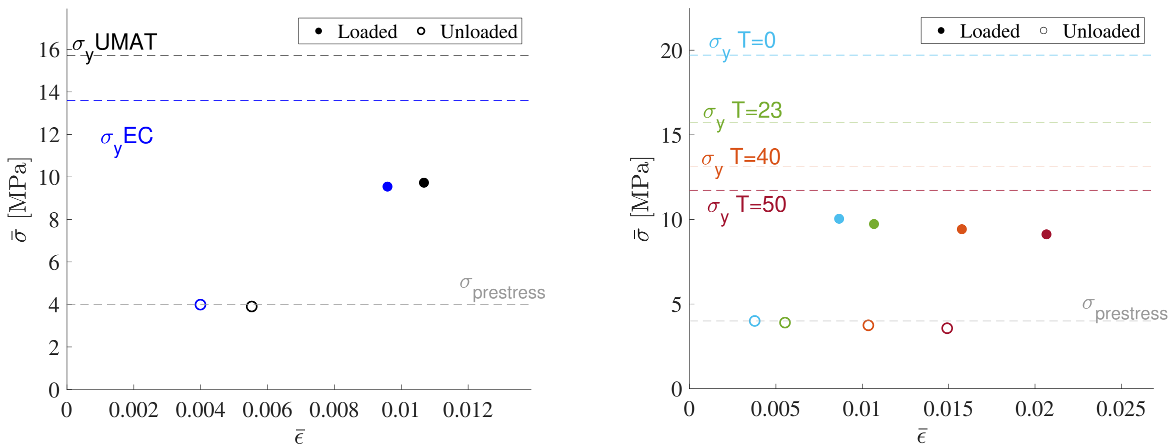


(a) 0.5x5 m

(b) 1x10 m

Figure 4: Comparison between the use of the nonlinear LIGHTEN model (black symbols) and the CEN/TS 19012[9] linear elastic material (blue symbols) on the results of a snow load on flat membranes, using different initial geometries. Since the yield value of the LIGHTEN model changes, both the value at the peak of the loading ramp and the final one during the creep phase are reported, respectively as σ_y and σ_{creep}.

strain plot, together with the yield point and the prestress level, for both the LIGHTEN and the CEN/TS 19012[9] for the size 1x10 m.



(a) $T = 23$°C

(b) $T = [0,\ 23,\ 40,\ 50]$°C

Figure 5: Comparison between the maximum stresses and strains achieved by the most loaded point of a 1x10 m flat membrane during a 1 s wind gust. Figure 5(a) compares the use of the LIGHTEN model (black dots) and the CEN/TS 19012[9] linear elastic material (blue dots), where the prestress level for both analyses and the respective yield stress are also reported with dashed lines. Figure 5(b) compares the results at all temperatures for only the LIGHTEN model.

In this analysis, it was possible to observe the effects of the different stiffness that the LIGHTEN model assumes as the temperature changes, which is not captured by the CEN/TS 19012 since it assumes constant stiffness. It is also evident that the high dependence of the elastic limit on temperature, which in the LIGHTEN model is accounted for by a physical model, while CEN/TS 19012 uses the correction factors presented in Table 1.

4 DISCUSSION

The design of ETFE flat membranes and pneumatic cushions has been extensively studied in the previous section, analysing the installation process and the response to wind and snow loads. In general, whenever the applied load has a relevant time duration, its effects become increasingly impactful on the foil, which can only be highlighted with the use of a refined viscoelastic model such as the one developed in the LIGHTEN project. The installation section for flat foils showed the magnitude of the stress relaxation required to achieve the target prestress, which needs to be taken into account during design. In the case of cushions, the installation section showed the possibility of reaching the yield stress due to the installation pressure only.

The study on the snow demonstrated the relevance of creep and its permanent effects on the material. On the other hand, the load case of wind showed a limited influence of the time-dependent effects on ETFE. The comparison with the design performed according to CEN/TS 19012[9] showed that the LIGHTEN model was more conservative when time effects were relevant, for installation and snow loads, while for wind loads the LIGHTEN approach provided a more efficient use of the material. The results between the LIGHTEN model and CEN/TS 19012 differ most in Young's modulus, since the Eurocode proposal's values do not include any temperature or time effects, resulting in a stiffer response at higher temperatures. Regarding the yield stress, minor differences exist. Still, the values obtained with the LIGHTEN model are very similar to those in CEN/TS 19012 until the loading phase is considered. In the snow load case, the creep effect is not adequately accounted for in CEN/TS 19012; therefore, during creep, the LIGHTEN model exhibits a lower elastic limit.

5 CONCLUSIONS

A preliminary study on the use of the LIGHTEN constitutive model in the design process of ETFE was presented in this paper. The two most common shapes, pneumatic cushions and single-tensioned foils were analysed as members of the cladding of a roof, varying their dimensions. The load cases investigated —prestress, snow, and wind loads —were assigned time profiles that were deemed reasonable according to the literature and the suggestions of the industrial partners. The results were compared with the most recent design document available, which anticipates the publication of a Eurocode for the structural design of membranes. In general, the use of the LIGHTEN model provided more information on the behaviour of the two shapes, being more conservative in the allowable state under prolonged time effects and more efficient under fast loading. It was observed that using a nonlinear viscoelastic model integrated with a time-temperature-dependent yield law can offer advantages in the analysis of complex load behaviour under varying time and temperature profiles, leading to safer and more efficient membrane structures.

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