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Limits of ISO 527-1 results for the simulation of environmental influences on the design with ETFE

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Abstract

The international standard ISO 527-1/-3 is used for the determination of the mechanical properties of plastics like the Young's modulus, the Poisson ratio, and the stress and strain at yield. The yield point is defined in this standard for technical reasons to have a rough estimate of the non-elastic deformation behaviour. Even though, it might be useful for materials with a well-separated linear-elastic and plastic deformation range, there is no reason to apply it for the reaction of partial crystalline thermoplastics like poly-ethylene tetrafluoroethylene (ETFE) with viscoelastic properties. ETFE always exhibits a combination of elastic, viscoelastic, and plastic deformation with only a small linear-elastic range of about 0.2% deformation at least at room temperature (23°C). This behaviour could not be deduced using the measurement as defined in the international standard. Additionally, a constant strain rate is not known in nature.

In this manuscript, the strain rate dependence of ISO 527-1/-3 measurements will be evaluated. Whereas the tensile modulus is constant, the yield point is not a reasonable concept under these conditions. Due to the viscoelastic properties of ETFE, yielding could be found in the linear region of the stress strain curve, if the measurement is interrupted at a certain stress level. In contrast, if the measurement is stopped at a certain strain level, the stress shows a strong reduction relative to the maximum value.

Keywords: membranes, uniaxial tensile test, testing speed, strain rate, natural loads, yield point.

1. Introduction

The ISO 527-1/-3 (1,2) standard is established as a fundamental tool for the experimental determination of elastic and plastic properties of plastic materials. It is used for materials characterization, quality control and design in various parts of the field of ultralightweight architecture.

However, according to the JRC report on the Prospect for European Guidance for the Structural design of Tensile Membrane Structures (3) the unquestioned use of the results of the ISO 527-1/-3, mainly the concept of the yield point, in the design of ETFE film cushion systems lead to higher static and dynamic loads and larger dimensions to higher thicknesses in the used ETFE films. This was originated by the idea, that with the application of the safety factors on the yield point, a value in the load will be reached, where no plastic deformation will occur and the film remains elastic, i.e. it acts according to Hooke's law. While this is the basic foundation of the design method of the JRC report, it was never proven experimentally, neither for fabrics nor for foils in particular.

The increase of thickness of the ETFE films lead to some unforeseen consequences for ultralightweight architecture. The area weight of the films increases with the necessity for stronger aluminium frames

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and primary steel structure. The haze of the films increases more than linear, i.e. a 500 µm thick film is more diffuse than two 250 µm thin foils. The handling of the material in the factory and on the construction-site gets more complicated. The risk for scratches, breakings at folds and, therefore, the weakening of the material is increasing. In addition, external wind loads lead to a reaction in the ETFE film with an increased plastic deformation due to the viscous properties of ETFE. In particular, the higher strain changes the funicular curve of the ETFE cushion, reducing the influence of wind gusts, increasing the amount of safety.

In this manuscript, the influence of speed on the stress-strain curve and the viscoelastic/-plastic properties of ETFE are studied by means of the uniaxial tensile test showing the limits of the concepts of the ISO 527-1 for design in architecture.

2. Experimental procedure

The tensile test experiments were conducted on a Galdabini Qasar 50kN machine with 3 kN force sensing unit to measure the low exerted forces of the ETFE foil. All experiments were conducted at temperatures of 23 ±2°C with uncontrolled humidity values in the range of 45 to 60%.

The samples were cut from a standard production foil of Nowoflon ET6235Z with a thickness of 200µm and 250 µm. The elongation was oriented in machine direction. The clamping length was chosen as 100 mm. A line clamp has been used to provide reproducible clamping forces. The testing speed with a constant strain rate according to the ISO 527-1 could be chosen between 0.125 mm/min up to 500 mm/min. For all results a comparative measurement was done at a speed of 100 mm/min to attribute them to the production samples of the Vector Foiltec Quality Lab. The samples of the measurements were chosen from a foil with a low anisotropy between machine (MD) and transverse direction (TD), i.e. the deviation between the values of tensile strength and the strength at 10% strain was less than 5% for both directions. To prevent errors in the straining of the foil due to the inertia of the tensile test machine, the experiment was started with a non-stressed foil, so that the acceleration of the test machine has a lower impact on the results. The strain was measured using the distance between the clamps, no extensometer was available. Due to this restriction the Poisson ratio could not be elucidated.

In the first experiment, stress-strain curves with constant strain rate were conducted for testing speeds of 100, 5, 1, and 0.1 mm/min, which could be assigned to strain rates of 100, 5, 1, and 0.1%/min to compare the influence of the speed on the mechanical properties of the ETFE foil.

To find the origin of the differences in the strain-rate dependent behaviour in the stress-strain curve of the ISO 527-1, the stress-strain curve at constant strain rate of 100 mm/min was interrupted in a second experiment at stress values of 4, 8, 12, 16, and 20 N/mm^2 for 60 min each. For all stages the stress value was kept constant and the time dependent changes in strain were detected. Thus, the creep behaviour and plastic deformation, also known as yielding, were investigated below the yielding point as determined in the first experiment.

In the next experiment the stress-strain curve of an ETFE foil was conducted at constant strain rate of 100 mm/min. The experiment was interrupted at 10 N/mm, i.e. below the yield point in the "elastic" range for 280 hrs. In contrast to the latter experiment the strain was kept constant, and the stress value was recorded.

2. Results and Discussion

2.1. Limitation of the yield point determination

According to the ISO 527-1 the stress-strain-curve has a clear deviation between the elastic or pseudoelastic part and the range of yielding. The measurement speed should be set using the appropriate standard of the material. Even though in the new technical description, the prCEN/TS 19102 (5) the test speed is defined as 100%/min, which has historical reasons instead of a material relevant background. In the ISO 527-1 for unknown materials properties a test speed of 1%/min is suggested instead. The idea to use a sufficiently low speed is to exclude the influence of time dependencies in the material properties like creeping, i.e. the stress strain curve should be measured in equilibrium conditions.

Therefore, the measurement of the stress strain curves were conducted for speeds between 0.1 mm/min up to 100 mm/min, which corresponds to strain rates of 0.1%/min and 100%/min. Figure 1 shows the stress strain curves for the different strain speeds. In the first region we have a linear behaviour, which in the case of thermal equilibrium could be attributed to the linear elastic region of the stress strain curve. However, even this low speed is not sufficient to reach thermal equilibrium, i.e. the ETFE foil does not obey Hooke's law in this region. When reducing the stress to zero, the strain is higher than zero, i.e. plastic deformation already occurred. Nonetheless, in the "pseudo"-linear region the tensile modulus of all stress strain curves is identical and could be estimated to be 750 N/mm^2.

According to ISO 527-1 the yield point is defined as the point, where the strain increases without a stress increase. In figure 1 the yield stress is reduced from 25 N/mm^2 for a strain rate of 100%/min down to 21.5 N/mm^2 for a strain rate of 0.1%/min. The yield strain is in the range of 18 to 19%. According to Annex A in ISO 527-1, the selected point should be meaningful. Only a yield point achieved under equilibrium conditions with a sufficiently low speed would be reasonable because all time dependent effects will change the yield stress in the measurement. To use the yield stress for design purposes in membrane architecture, it has to be determined for all possible strain rates and temperatures, which is indeed not reasonable.

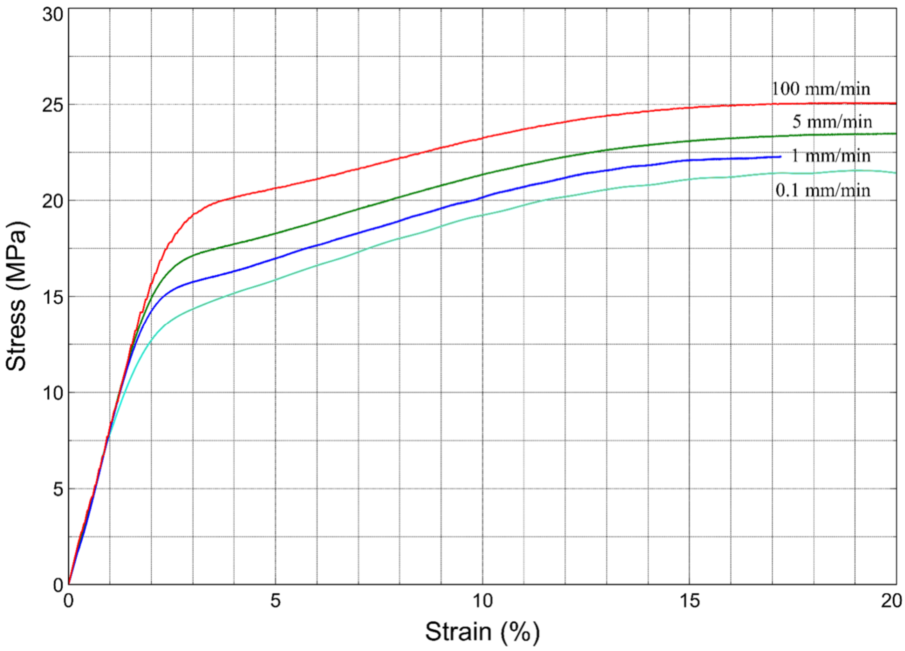

Figure 1 Uniaxial stress-strain measurements according to ISO 527-1/-3 of an ETFE foil (Nowoflon ET6235Z) with a thickness of 200 µm in dependence of the applied speed from 100 mm/min to 0.1 mm/min, corresponding to strain rates between 0.1%/min and 100%/min.

If ETFE foil structures would be handled like other building materials, e.g. steel, and it should only be used in the linear elastic range without plastic deformation, only the yield point under equilibrium conditions would be allowed. Under these conditions only the stress strain curve could be used for the yield point, which would lead to the lowest possible yield point without change by lower speeds. Taking into account that the curve with the strain rate of 0.1%/min already took 200 min to reach 20% strain, it becomes clear, that in a standard measurement this strain rate is not feasible.

2.3. Plastic deformation and creeping behaviour below the "yielding" point

According to ISO527-1 in the linear region the mechanical properties should be defined by Hooke's law. Thus, it should be possible to interrupt the measurement at a certain stress level well below the yield point and no changes in the strain should occur.

In figure 2 the results of the experiments are shown for stopping the increase of stress for 60 min at a stress level of 4, 8, 12, 16 and 20 N/mm^2. According to what is defined as yield point in ISO 527-1, all values are below the stress level of the yield point. This behaviour of the foil is known as creeping, i.e.

the time dependent elongation of the foil under constant stress with a saturation after more than 1000 hrs (4). The development of the strain in time for a constant applied stress was thoroughly investigated by Li and Wu (6), showing the development of viscoelastic and viscoplastic deformation of the ETFE foil.

For the stress level of 4 N/mm^2 the increase in strain after 60 mins was 0.08%, which is contrary to elastic behaviour. However, this value corresponds to the stress in the foils of an ETFE cushion, with a foil thickness of 200 µm and an internal pressure of about 250 Pa. From our results in the uniaxial tensile test experiment it is possible to deduce, that even for this low stress level a plastic deformation of the cushion is identified. Even after 12 hrs. of relaxation at a stress level of 0 N/mm^2 the original strain level of 0% could not be reached. Thus, the elastic region of the ETFE-foil is estimated to be much lower (approx. 0.2%) than what is defined as elastic within the linear region of the measured stress strain curve shown in figure 1.

Stopping of the stress has been repeated at increased stress levels leading to an increased strain during the stopping time of 60 min of 0.1% at 8 N/mm^2, 0.24% at 12 N/mm^2, 1.26% at 16 N/mm^2, and 2.67% at 20 N/mm^2.

Figure 2 Plastic and creeping behaviour below the yielding point of an ETFE foil (Nowoflon ET6235Z) with 200 µm thickness

Following the yield-point concept of ISO 527-1 and JRC report (3) no yielding/creeping are allowed below the yield point.However, natural environmental loads , e.g. wind loads, water ponding, or snow loads do not create a constant strain rate but always both a elastic and a plastic deformation

2.4. Viscoelastic behaviour in the one-dimensional simulation of a single layer profile after pre-stress

According to ISO 527-1 the stress strain curve follows Hook's law in the linear range, i.e. between 0 N/mm² and 10 N/mm². This behaviour was analysed by pretressing an ETFE foil to 10 N/mm². After achieving the stress level of 10 N/mm², the strain was kept constant. Figure 3 shows the results for the time behaviour of the stress for 280 hours. The stress decreases to 4.9 N/mm² after 10^6 seconds (280 hours).

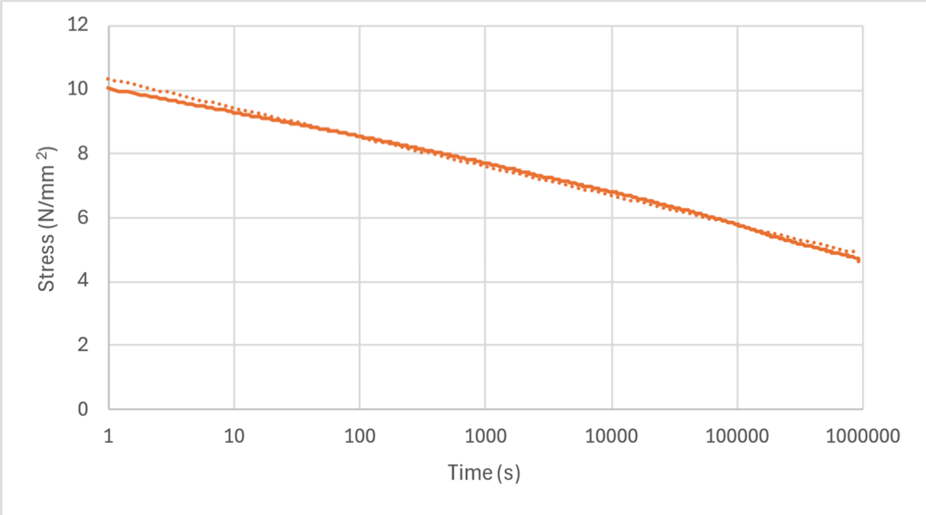

Figure 3 Experimental results of the uniaxial simulation of single layer assembly after a pre-tension of the foil (Nowoflon ET6235Z) at 10 N/mm^2 and keeping it under constant strain.

The relaxation of the stress follows a logarithmic law. This is the stress, which could be found as a pre-stress in the cushion originated by the internal pressure of about 250 Pa. Extrapolating the logarithmic decrease of the stress in the uniaxial load, the time with no stress in the strained layer would be more than 6000 years. Thus, this relaxation is not critical for the stability of the single layer foil system under this temperature. Assuming a relaxation process based on an activation energy of the reorientation of the polymer chain and the associated time behavior according to Aarhenius (7), the time constant of this process could be reduced by an increase in temperature depending on the activation energy. Further investigations will be necessary to elucidate this behaviour.

4. Conclusion

In summary, limitations of the measurement technique according to ISO 527-1/-3 are shown for the design of ETFE in the case of different strain rates, for the viscoelastic and viscoplastic behaviour in the case of a constant stress, and a constant strain. Contrary to materialsshowing a well-separated linear-elastic and plastic deformation region in the stress strain curve like steel, ETFE always shows a mixture of elastic, viscoelastic and plastic deformation. Thus, results from measurements according to ISO 527-1/-3 which are based on a defined yield point and a linear-elastic behaviour with no plastic deformation below the yield point cannot be used for the determination of the mechanical characteristics of ETFE foils for the application in architecture. . In particular, the constant strain rate could not be found in any load situation in nature. Using the pseudolinear range in the stress strain curve, especially the assumption, that there is no plastic or viscoelastic behaviour below the yield point, lead to a neglection of plastic deformation. Even at loads caused by the static inner pressure of the cushion a plastic deformation occurs.

However, given a constant strain rate the results of a single foil can be compared, making it an indispensable tool for test of potential changes of the properties. This is the basis for all quality control not only of the material (incoming goods tests) but also of the welding properties of ETFE films and their connections.

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