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STUDY OF STRENGTH PERFORMANCE, CONNECTIONS OF ETFE FILM FOR ENCLOSING STRUCTURES OF LARGE-SPAN STRUCTURES

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Abstract

Up-to-date architectural and engineering tasks require application of innovative materials, granting not only enhanced performance, but also compliance with criteria of energy efficiency, eco-and technology-friendliness. Ethylene tetrafluoroethylene (ETFE) film is one of such materials. ETFE was initially developed as a lightweight heat resistant film in the aerospace industry. However, it has been successfully applied in the construction industry for many years, including as translucent enclosing structures.

Within design development of the biosphere string tent shed the properties of ETFE film were studied, while the material enables covering over significant spans at minimal weight. Moreover, ETFE film has a whole range of unique properties, such as high strength, UV resistance, high translucency, including the light spectrum necessary for photosynthesis. That makes ETFE film an ideal candidate for creation of closed complexes with manmade manageable ecosystems.

In course of computer modelling of ETFE film serving as a roofing element of the tent shed an issue arose with regard to its properties, i. e. whether to consider the film as a linear isotropic material, thus facilitating the calculation, but it might stretch the reality of stress-strain behaviour, or whether to consider it as nonlinear anisotropic material, thus facilitating more correct description of ETFE film behaviour under different loads.

Herein, the strength parameters of ETFE film were defined in different directions. Dependency of action of temperature on strength performance, as well as influence of cyclic loads on the material was set.

The appropriate tests were conducted, which results formed the basis for the design solutions for the tent shed covering in order to choose the most effective methods to interconnect the film sheets, including the ones via welding and mechanical connections.

Keywords: polymer films, ETFE, uniaxial and biaxial testing, adhesive joints, mechanical connections.

ИССЛЕДОВАНИЕ ПРОЧНОСТНЫХ ХАРАКТЕРИСТИК, СОЕДИНЕНИЙ ПЛЁНКИ ETFE ДЛЯ ОГРАЖДАЮЩИХ КОНСТРУКЦИЙ БОЛЬШЕПРОЛЕТНЫХ СООРУЖЕНИЙ

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Реферат

Современные архитектурные и инженерные задачи требуют применения инновационных материалов, способных обеспечить не только высокие эксплуатационные характеристики, но и соответствие критериям энергоэффективности, экологичности и технологичности. Одним из таких материалов является плёнка из этилен-тетрафторэтилена (ETFE). Изначально она разрабатывалась для нужд авиационной и космической промышленности. Однако уже на протяжении многих лет она успешно применяется в строительстве – в том числе в качестве ограждающих светопрозрачных конструкций.

В рамках разработки биосферного струнного шатра было проведено исследование свойств плёнки ETFE, поскольку данный материал позволяет перекрывать значительные пролёты при минимальном весе и обладает рядом уникальных характеристик, таких как высокая прочность, устойчивость к ультрафиолетовому излучению и высокая светопропускная способность, включая спектр, необходимый для фотосинтеза. Это делает его идеальным кандидатом для создания замкнутых комплексов с контролируемой искусственной экосистемой.

В процессе численного моделирования плёнки как элемента покрытия шатра возник вопрос назначения характеристик материала – учитывать ли плёнку как линейный изотропный материал, что упрощает расчёт, но может искажать реальную картину напряжённо-деформированного состояния, или же учитывать её как нелинейный анизотропный материал, позволяющий более корректно описать работу плёнки под действием различного вида нагрузок.

В настоящем исследовании были определены прочностные характеристики плёнки ETFE в различных направлениях. Была установлена зависимость влияния температуры на прочностные характеристики, а также влияние циклических нагрузок на материал.

С целью выбора наиболее эффективных способов соединения полотен плёнки между собой, в том числе на основе сварки и механических креплений, были выполнены соответствующие испытания, результаты которых легли в основу проектных решений по формированию оболочки шатра.

Ключевые слова: полимерные плёнки, ETFE, одноосное и двухосное испытание, клеевые соединения, механические соединения.

Introduction

During design development of the biosphere tent shed with manageable inner ecosystems, large spans shall be covered over while ensuring translucency, energy efficiency, and technology friendliness while erecting [1]. Structural solutions with optimal combination of strength, weight and operational parameters are required to solve such tasks. So, application of ETFE film with unique parameters is a viable solution.

Its unique parameters enable application of ETFE film as a covering material for large-span structures with LBE (load-bearing elements) made of tightened steel strips, wire ropes or spatial trusses. So that, a string-membrane shell is created where ETFE film serves as an enclosing translucent element enabling covering of large areas and creating closed sustainable ecosystems due to enhanced translucency (including UV spectrum), weather resistance, ability to be engaged in heat exchange.

Due to low density (cca. 0.15–0.25 kg/m²) and adequate strength, the material significantly reduces loads acting on foundations and supporting systems, as well as consumption of materials, also facilitates transportation and assembly. Extra advantage of ETFE film comparing with other translucent roofing materials (PE, canvas, synthetic fabric) is that it is highly fire-resistant, chemically inert, UV-resistant and durable [2, 3].

Nevertheless, despite the obvious advantages of the material, application of ETFE film as an LBE of a roof structure shall be structurally justified with regard to actual loads, temperature conditions and operational modes.

Brief overview of fluoroplastic films

Fluoroplastic thermoelectricity polymers that undergo treatment and molding procedures are used to produce films. Basing on the applied polymer component different kinds of films with different parameters are created. For instance, ETFE film is made from fluoropolymer-40, while PVDF is from fluoropolymer-2M, etc. Let's review the most widely-spread fluoroplastic films [4–6].

ETFE film type is made from fluoropolymer-40. That is ethylene-polytetrafluoroethylene copolymer. It is characterized by high UV-resistance, tensile strength, chemical resistance, high translucency within a visible light and UV spectrum.

PVDF film type is made from fluoropolymer-2M. Its characteristics are moderate strength, enhanced UV-, chemical and radiation resistance.

PTFE film type is also a product of TFE with the properties different from that of ETFE. It was invented before ETFE, but has the advantage over ETFE at a working temperature range of –269 °C up to +260 °C and even at a higher temperature. Despite its melting point at +327°C it does not transit into a state of viscous flow. However, it has clear disadvantages, such as lower strength, much lower elasticity modulus and restricted translucency.

FEP film type is made from fluoropolymer-4MB. It is a copolymer of hexafluoropropylene and tetrafluoroethylene. The material is characterized by high resistance to UV, alkalis, and concentrated inorganic acids, dielectric properties. However, FEP ranks below in strength and rigidity comparing with ETFE, thus restricting its application in highly-loaded structures. Besides that, its lower elasticity reduces its effectiveness in flexible systems and membrane coverings.

PFA film type is made from fluoropolymer-50. It is a copolymer of tetrafluoroethylene and perfluoroether. It is UV- and corrosive-resistant, keeps stable at a wide temperature range from –196 °C to +250 °C and has superior dielectric properties.

ETFE film is characterized by the following particular properties [4–8]:

- low density: its density is 1,700 kg/m^3, which is the lesser of the counterparts;
- anti-drop property: excludes condensation formation on the surface;
- recycling: grants the opportunity to recycle the film wastes into new materials;
- translucency: it transits 90–95 % of a visible, as well as UV light spectrum;
- chemical resistance: it is resistant to alkalis, concentrated acids;
- enhanced strength: its tensile strength is up to 65 MPa;
- repair-suitable with special adhesive tapes and sheets (patches);
- fire resistance: due to its properties and structure, in case of fire the film does not create fire drops that could jeopardize people's health. Moreover, in case of big fire the membrane destroys itself and releases smoke and other combustion products, thus decreasing the indoor temperature and lessening the risk of structure failure. The film is rated G1 of flammability class under GOST 30244–94, i. e. it refers to a low-flammable material.

All these properties refer to the pluses of the material. However, the potential issues with regard to them arise. For instance, the tensile strength heavily depends on an operating temperature and could be significantly lower, than the value mentioned herein [8]. Besides that, the anti-drop property and chemical resistance hinder glueing or welding of the material.

Materials and testing procedure

200-microns-thick ETFE film with the declared tensile strength ranging from 39–65.2 MPa was tested. The film is manufactured under Technical Specifications 22 21 30-015-46708974-2022.

The following tests were conducted to check the strength values of the film

1. Uniaxial tensile test in 2 orthogonal directions at a temperature of –50 °C, –25 °C, 0 °C, +25 °C, +50 °C.
2. Cyclic uniaxial tensile test of the film;
3. Biaxial tensile test of the film.

Shear tests of the following options were conducted to study the behaviour of film connections:

1. Adhesive connection of the film;
2. Connection of the film with a special adhesive tape [9];
3. Welding film-to-film connection [10, 11];
4. Mechanical film-to-steel plate connection.

The film was tested in the Metal-Polymer Research Institute of the National Academy of Sciences of Belarus.

Strength test

Routine test schedule of the samples for uniaxial tensile tests is described in GOST 14236-81 [12]. Test bench of the uniaxial tensile test is illustrated in Figure 1. Stress-strain behaviour was defined during the uniaxial tensile test at a different temperature: –50 °C, –25 °C, 0 °C, +25 °C, +50 °C (min. 5 samples at each temperature). As tested, the stress-strain relation schedules at different temperatures were made (ref. to Figure 2–6).

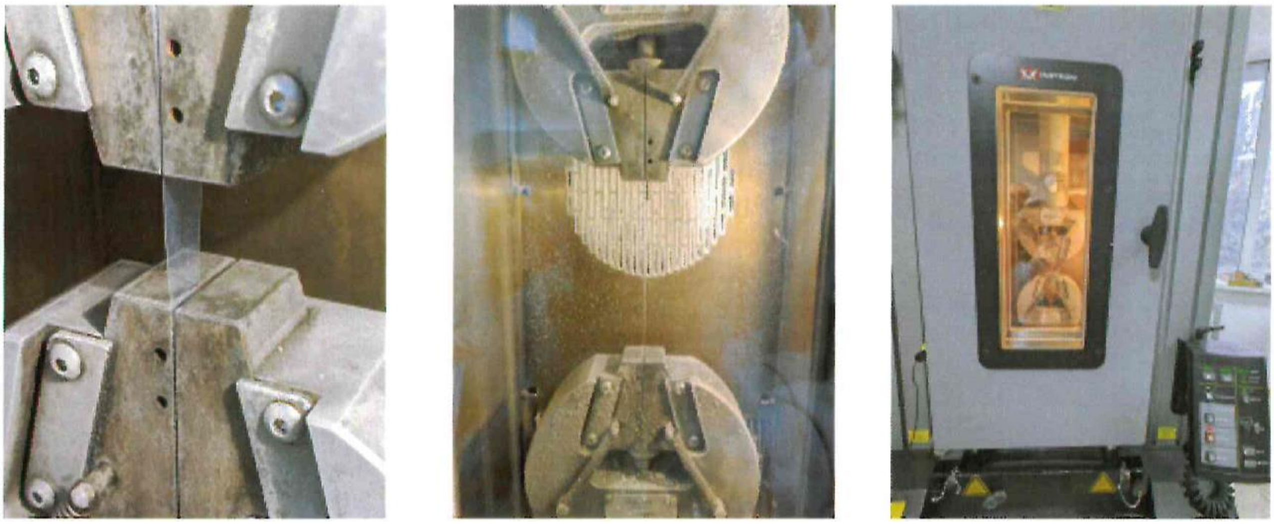

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Figure 1 – Sample placement between the grips (a), sample stretching (b) inside the Instron environmental chamber (c)

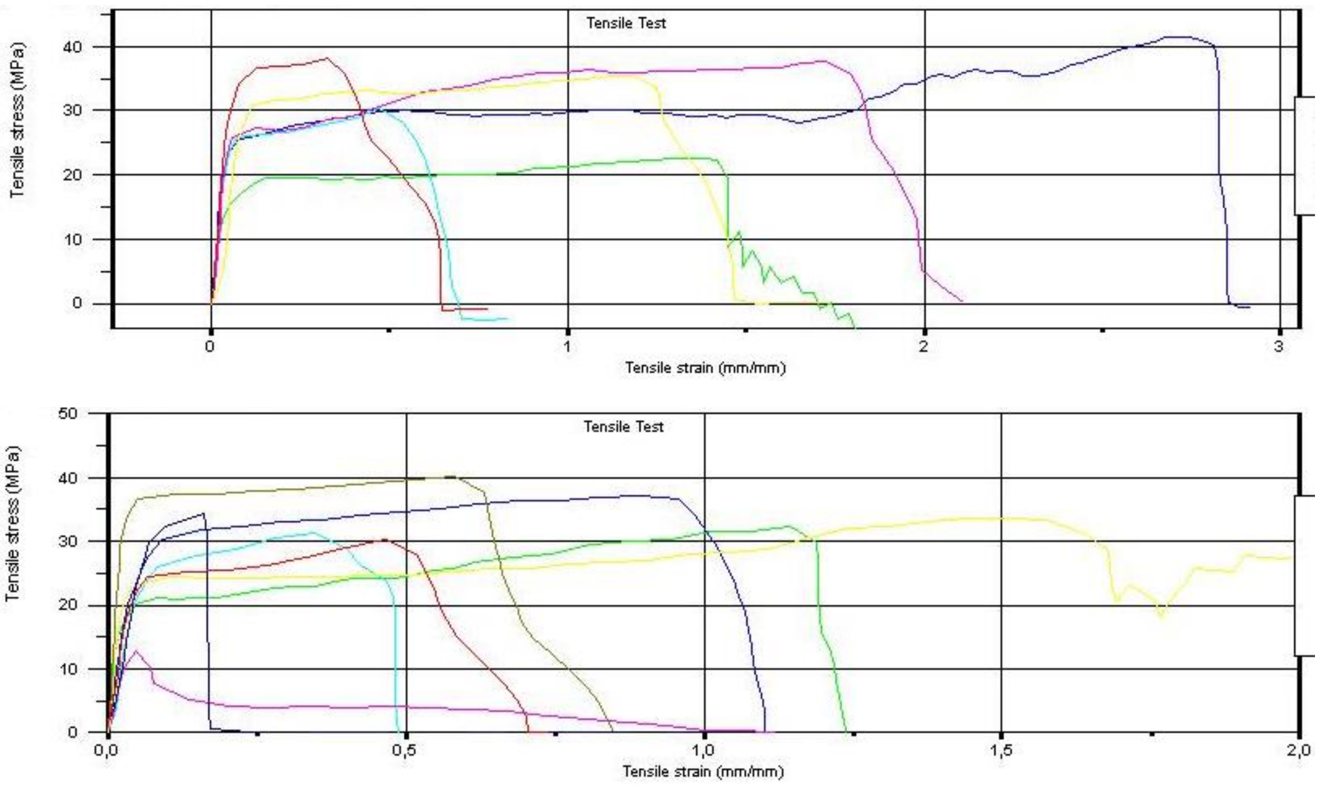


Figure 2 – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of –50 °C

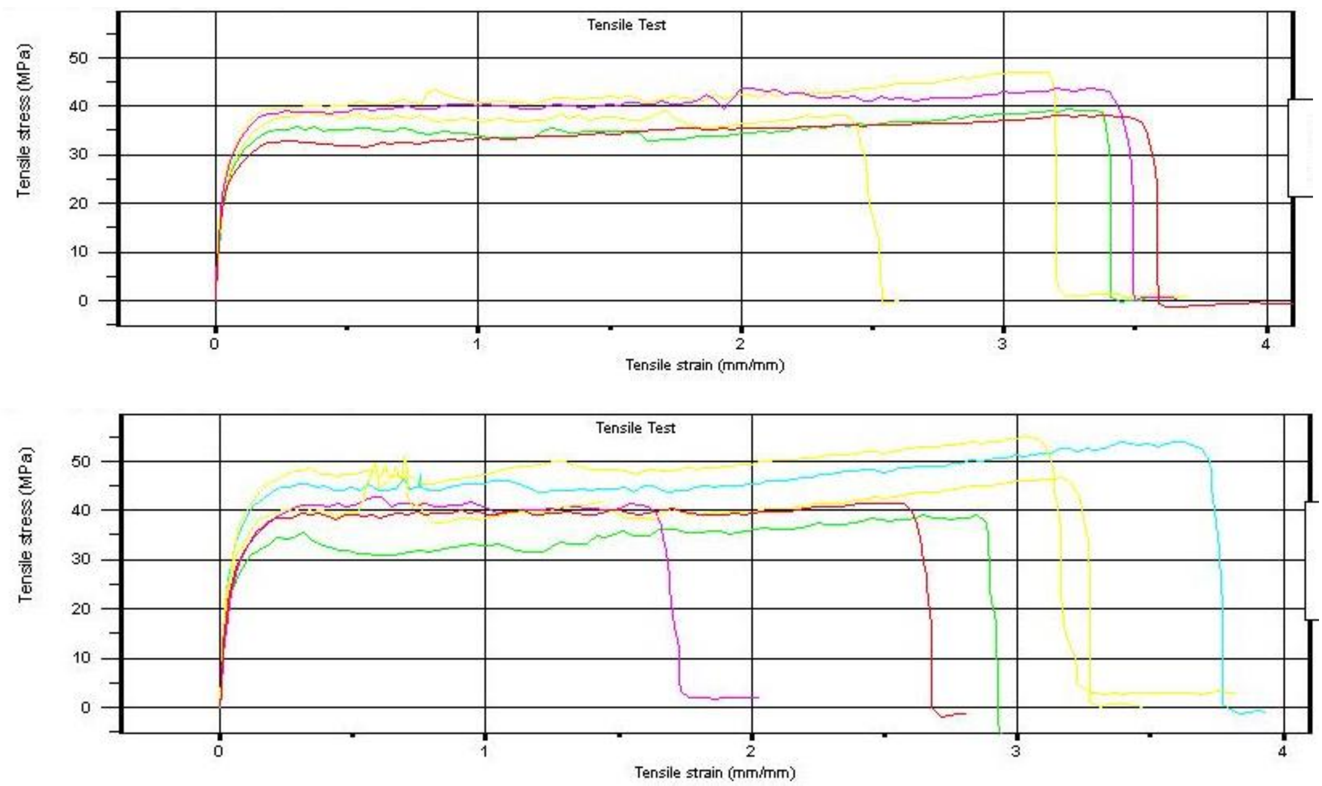


Figure 3 – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of –25 °C

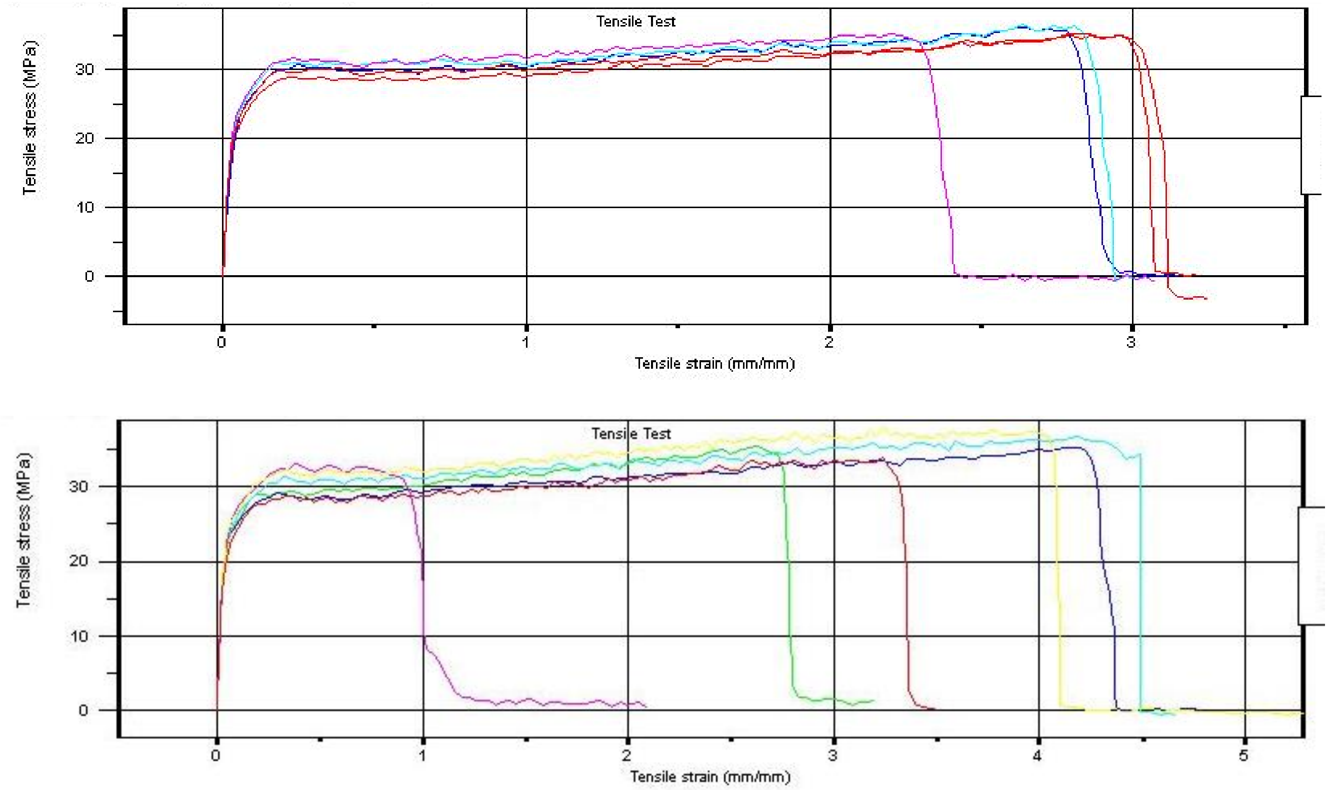


Figure 4 – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of 0 °C

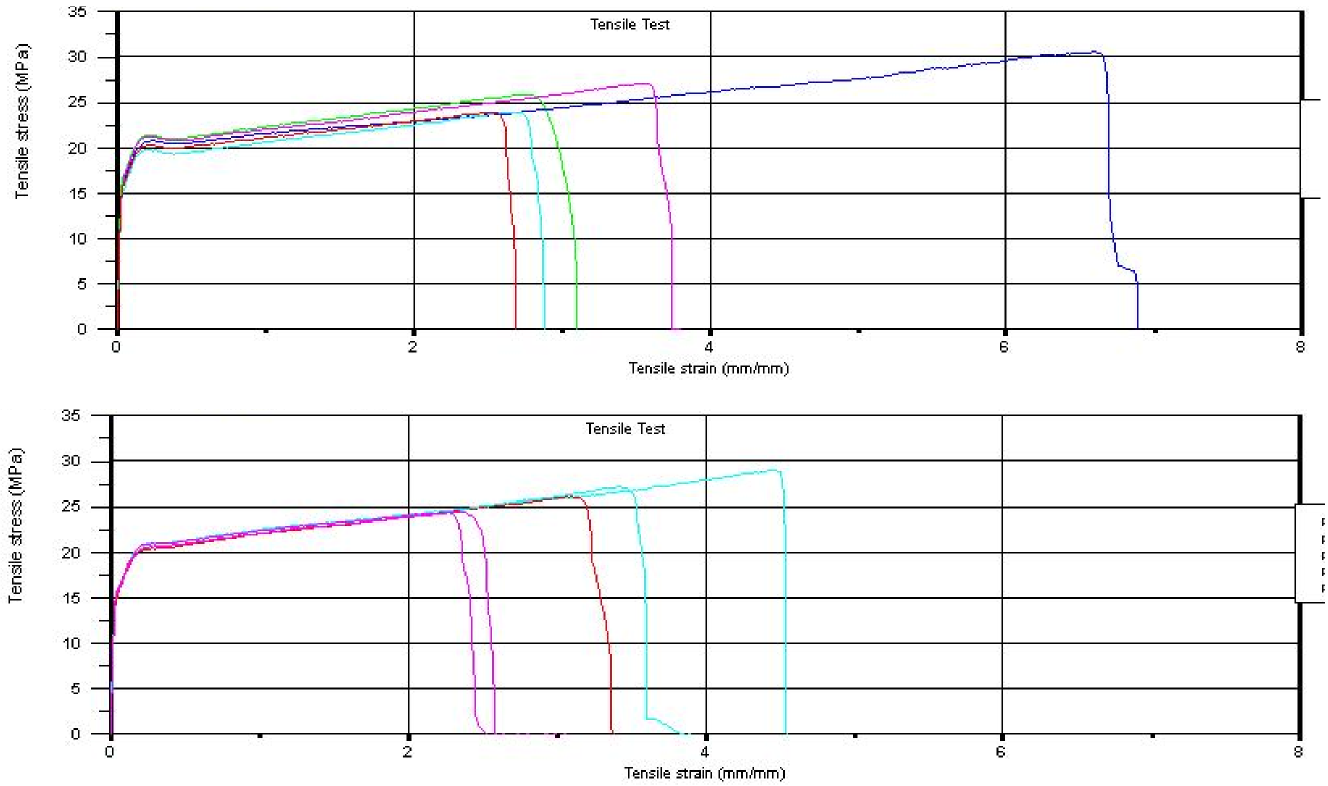


Figure 5 – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of +25 °C

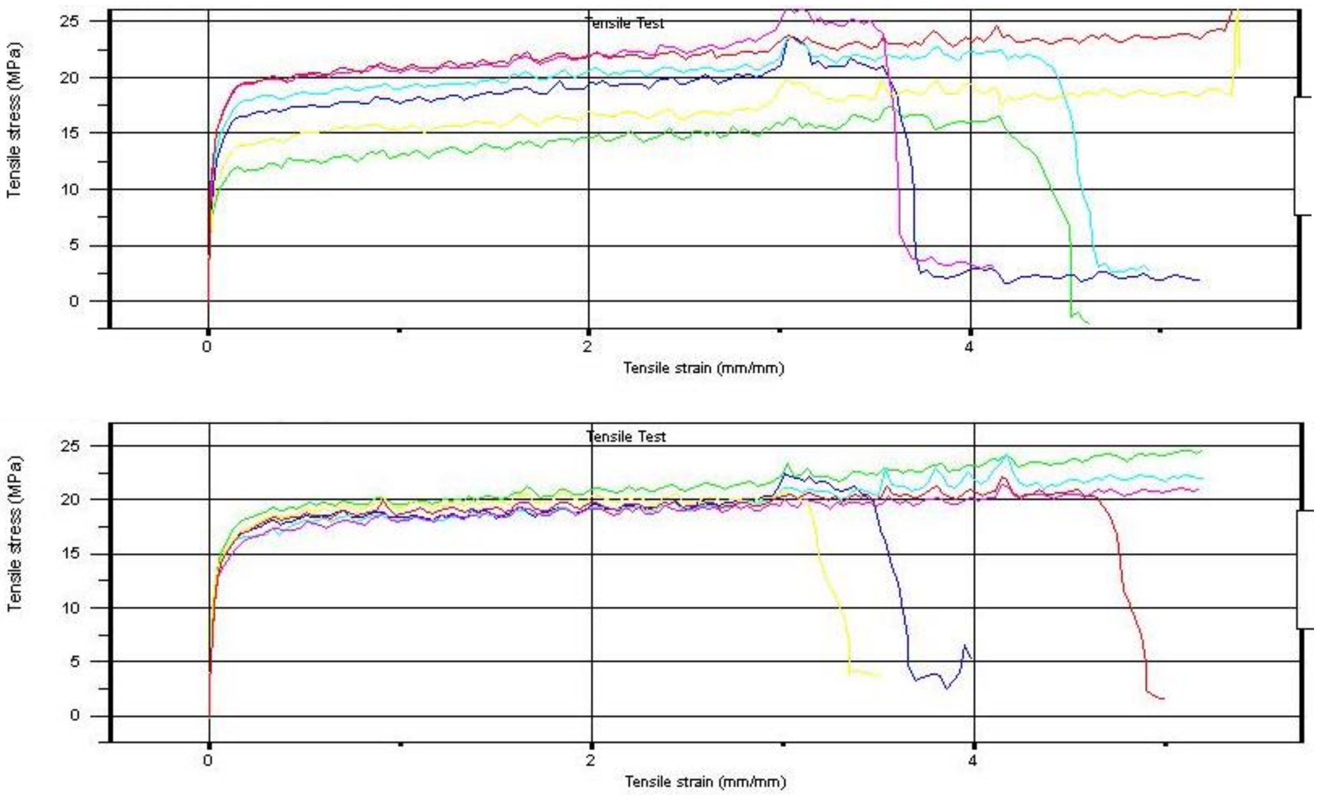


Figure 6 – Stress-strain relation for the samples in direction 1 (top) and 2 (bottom) at a temperature of +50 °C

Table 1 – Characteristics and main use of fluoroplastic films [4–6]

Parameters	PVDF	ETFE	PTFE	FEP	PFA
Density, kg/m^3	1,750	1,700	2,120	2,150	2,150
Tensile modulus, MPa	2,350	1,000	410	550	550
Break elongation, %	200–420	200–510	250–500	200–300	250–340
Working temperature, °C	from –50 to +130	from –200 to +180	from –269 to 260	from –150 to +200	from –196 to +250
Tensile strength, MPa	44.1–55.0	40–65	14–34	17.0–35.0	17.0–24.0
Translucency, %	80–90	90–95	50–80	94–96	90
Self-cleaning ability (anti-adhesive properties)	High	High	High	Average	High
UV resistance	Excellent	Excellent	Excellent	Excellent	Excellent
Main use	Facades, protective coatings	Architecture, roofs, green houses	Non-stick coatings, medical industry	Electronics, solar panels	Chemical and medical industry

Refer to Figure 7 for the test results in 2 orthogonal directions as the mean values of UTS (ultimate tensile strength) σ_p and relative break elongation ε at different temperatures. By comparing the test results, it is apparent that the higher the temperature is, the lower the strength of the sample and the strain increases. Direction of the sample testing did not significantly influence the test results.

Due to the fact that the uniaxial tensile test results of the samples cut in different directions appeared to be close in their values, the biaxial tensile tests were conducted to compare the strength values.

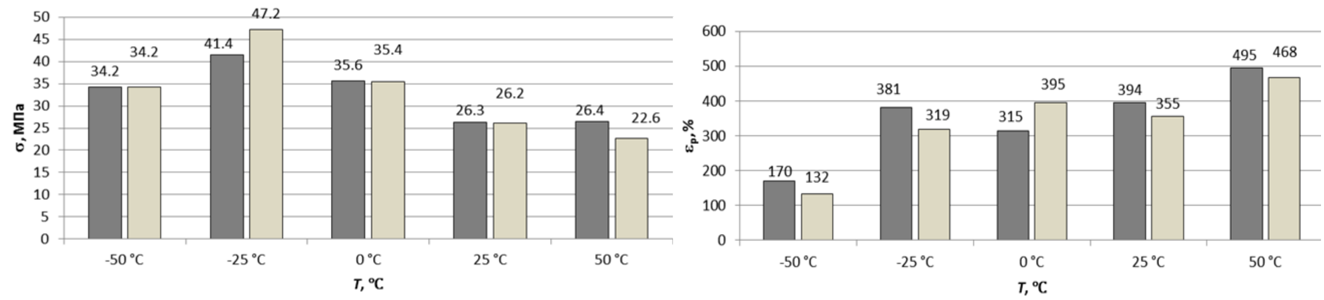


Figure 7 – Histograms of UTS σ_p (from the left) and relative break elongation ε (from the right) in direction 1 and 2 at different temperatures

Bubble inflation test was conducted to define the tensile modulus and strength of ETFE film at biaxial stretching. The principle of the test lies in gradual pressurization of the film sample with air or liquid accompanied with simultaneous record keeping of created bending (buckling) of the film [13–17]. In particular, effectiveness of the method is stated in the paper [16] using SiO_2/Si_3N_4 films as an example. The tests were conducted at a temperature of +25 C on 5 square-shaped samples 250×250 mm.

At biaxial tensile test the film sample was fixed with a steel ring flange to the air pressurization chamber. A sensitive distance gauge was installed at an arbitrary distance from the sample. The gauge was directed on the non-transparent mark on the sample (Figure 8). The distance between the mark on the sample and the sensitive distance gauge was measured before pressurization. Such a value (the distance) served as the reference of vertical displacements that were caused by biaxial deformation of the film in course of gradual pressurization.

In course of testing the air was supplied into the chamber and, simultaneously, the pressure, as well as displacement of the film were measured and recorded. On a rather small initial area under pressure ETFE film deformed elastically without any significant plastic deformation. The bigger the "bubble" was, the more irreversibly (plastically) deformed the film: noticeable reduction in its thickness at an increasing speed. That caused a fast growth of the "bubble" volume and growth slowdown of the pressure at permanent air supply (pump capacity). The sample was pressurized until it failed.

Figure 8 – Test bench for the bubble inflation test of the film sample

Table 2 illustrates vertical displacements, w of 5 film samples and mean values of displacements at pressure varying, p in increments of 40 mmHg. It is apparent that the test results are highly stable.

Table 2 – Results of vertical displacements of the mark on the samples at pressure increase in the chamber

Pressure, p		Vertical displacement w, m					
p, mmHg	p, MPa	№ 1	№ 2	№ 3	№ 4	№ 5	Mean value
40	0.0053	0.008	0.008	0.008	0.008	0.008	0.008
80	0.0107	0.011	0.011	0.011	0.011	0.011	0.011
120	0.0160	0.016	0.014	0.014	0.014	0.014	0.014
160	0.0213	0.020	0.019	0.019	0.019	0.018	0.019
200	0.0267	0.023	0.022	0.023	0.022	0.022	0.022
240	0.0320	0.027	0.026	0.025	0.025	0.025	0.026
280	0.0373	0.030	0.029	0.029	0.028	0.029	0.029
320	0.0427	0.033	0.032	0.032	0.033	0.032	0.032
360	0.0480	0.043	0.044	0.044	0.082	0.081	0.059

The relation between of the biaxial modulus of elasticity and pressure was calculated from the obtained values (ref. to Table 3). The modulus of elasticity under biaxial tension was determined based on the relation (1) between the bending of a thin membrane, w and the excess pressure P, given in the paper [18]:

$$P = C_1 \frac{\sigma_0 hw}{a^2} + C_2 \frac{Ehw^3}{(1-\mu)a^4}, \quad (1)$$

where P – pressure, MPa;

σ_0 – residual stress in the film, where P = 0, MPa;

h – membrane thickness, m;

w – membrane bending, m;

a – membrane radius, m;

E – Young's module, MPa;

μ – Poison's ration.

Table 3 – Results of displacements at pressure increase in the chamber

Pressure, p		Module E, MPa					
mmHg	MPa	№ 1	№ 2	№ 3	№ 4	№ 5	Mean value
40	0.0053	2,182	2,182	2,182	2,182	2,182	2,182
80	0.0107	1,695	1,695	1,695	1,695	1,695	1,695
120	0.0160	823	1,229	1,229	1,229	1,229	1,148
160	0.0213	561	655	655	655	770	659
200	0.0267	463	529	463	529	529	503
240	0.0320	343	384	432	432	432	405
280	0.0373	291	322	322	358	322	323
320	0.0427	250	275	275	250	275	265
360	0.0480	127	119	119	18	19	80

Values of ratio C_1 and C_2 depend on a membrane shape. For round membranes C_1 = 4 and C_2 = 8/3 could be set. The relation $P(w)$ consists of 2 sections that differ in inclination. Steep section corresponds to small bendings (the first addend of the relation (1) is much greater than the second one).

Biaxial modulus of elasticity $E/(1–μ)$ is calculated on a flat section of the relation (1) at large values of membrane bending, w, when the value of the first addend could be neglected. The following formula (2) shall be used in such a case:

$$\frac{E}{1-\mu} = \frac{Pa^4}{C_2 hw^3}. \quad (2)$$

By applying the formulae of stress-strain calculation under the article [14], the stresses could be determined at biaxial tension for the mean result (Table 4). Stress is determined from the formula:

$$\sigma_x = \sigma_y = \frac{p \cdot R}{2 \cdot t_p}; \quad (3)$$

$$R = \frac{a^2 + h^2}{2 \cdot h}; \quad (4)$$

$$\varepsilon_x = \varepsilon_y = -\frac{1}{2} \cdot \varepsilon_z = -\frac{1}{2} \cdot \ln\left(\frac{t_p}{t_0}\right) = \ln\left(1 + \frac{h^2}{a^2}\right); \quad (5)$$

$$\varepsilon_x = \varepsilon_y = \ln\left(1 + \frac{h^2}{a^2}\right); \quad (6)$$

$$t_p = t_0 \cdot \left(1 + \frac{h^2}{a^2}\right)^{-2}, \quad (7)$$

R – "bubble" radius (from the point on its surface up to its theoretical center), m;

h – height from the fixation plane up to the top of the "bubble", m;

a – distance from the center up to the start point of fixation (circle radius, in case of fixation with a ring flange – use the inner radius of the ring flange), m;

ε_x, ε_y – relative deformation of the sheet;

t_0, t_p – thickness of the initial and deformed sample, m;

Calculation results under formulae 3–7 are presented in Table 4.

Table 4 – Results of biaxial stretching

Formula	Value of the indicator for the sample					Mean value
	№ 1	№ 2	№ 3	№ 4	№ 5	
$\sigma_x = \sigma_y = \dfrac{p \cdot R}{2 \cdot t_p}$, MPa	27.93	27.76	27.76	33.21	32.82	27.47
$R = \dfrac{a^2 + h^2}{2 \cdot h}$, m	0.180	0.178	0.178	0.124	0.125	0.145
$\varepsilon_x = \varepsilon_y = \ln\left(1 + \dfrac{h^2}{a^2}\right)$	0.127	0.132	0.132	0.400	0.391	0.227
$t_p = t_0 \cdot \left(1 + \dfrac{h^2}{a^2}\right)^{-2}$, m	0.00016	0.00015	0.00015	0.00009	0.000091	0.00013

Refer to Table 5 for the results of uniaxial and biaxial tensile tests at a temperature of +25 °C.

Table 5 – Results of displacements at pressure increase in the chamber

Indicator at break	Mean value of the indicators for direction 1 and 2 at uniaxial tension	Indicators at biaxial tension	Divergence of the results, %
Tensile strength, MPa	26.3	27.47	Cca. 5 %

Cyclic uniaxial tension of the 200-micron-thick film in 2 orthogonal directions at a temperature of +25 °C (2 sets of 5 samples per each., total Qnty is 10 samples) was conducted under GOST 14236 [12]. Maximum stress per cycle was set equal to the yield limit at static tension which mean value under the diagram "stress-strain" is 15 MPa (Figure 5). The samples were subject to 10 cycles of loading. Refer to Figure 9 for the test results of one of the samples.

As illustrated in Figure 9, each load relief of the material was accompanied with increase of residual strain. Maximum value of the residual deformations (5 samples) upon completion of the 10th loading cycle was 3.95 %.

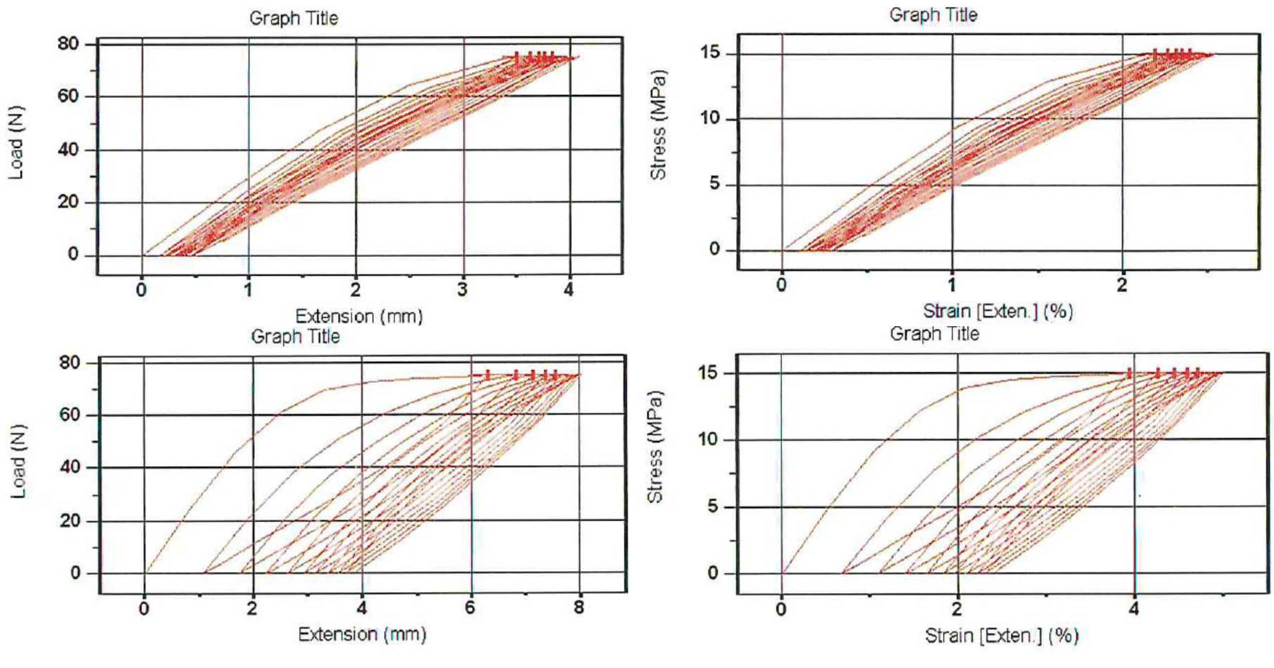


Figure 9 – Cyclogram "force-displacement" (from the left) and "stress-strain" (from the right). From the top into direction 1 of the film, from the bottom into direction 2

Film connection testing

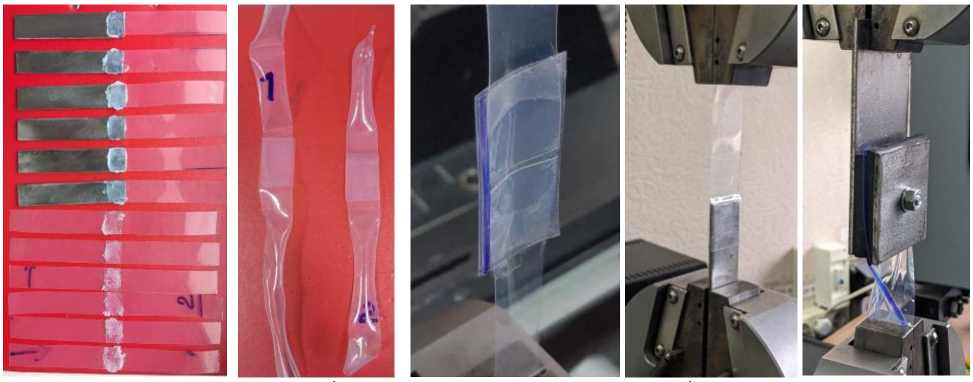
Essence of the shear tests of adhesive, mechanical, welded connections of the film and the connections with an adhesive tape lay in determination of stress limits that caused sample failure. Samples were tested like during uniaxial tensile tests at a temperature of +25 °C under GOST 14759 [19]. One set of 8 samples designated for mechanical connection and 6 samples each for the rest connection types were tested.

Bolted connection complete with a washer and rubber gasket served for testing of a mechanical film-to-steel plate connection.

Partite 7400 [20] glue served for testing of an adhesive connection. The glue was applied on the cleaned surfaces without corona discharge or plasma treatment of the film. CMC 77700 adhesive tape was used for a connection via a special adhesive tape. Test samples are illustrated in Figure 10.

Refer to Table 6 and Figure 11 for the test results of all the connections as the values of ultimate shear stress τ.

As tested, the best results belong to the adhesive connection, however, complexity, labour input and adherengce to the surface preparation requirements, as well as keeping of the glued sample during the closed assembly time for such a connection type is impossible to perform on-site. Welding unit could be used while assembling rather small areas or low-rise buildings/facilities. Use of the adhesive tape is a too costly solution. Moreover, it is recommended to be applied as a repair material. Bolted connection is easily assembled on any areas, does not require any special equipment. However, the surface of a bolted connection could accumulate snow, icing, dirt. The choice of one or another film connection type is prompted by the quantity and area of a connection.



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a) adhesive film-to-film and metal-to-film; b) welded film-to-film; c) with an adhesive tape film-to-film; d) with an adhesive tape metal-to-film; e) bolted metal-to-film

Figure 10 – Connection samples

Table 6 – Results of the tests of different connections

Sample No.	Connections					
	Adhesive with metal	Adhesive	Welded	Adhesive with an adhesive tape	Adhesive with an adhesive tape with metal	Bolted
	Ultimate shear stress τ, kPa					
1	300	–	125	85.5	77.5	109
2	205	95	127	83.2	76.3	100
3	277	179	134	85.5	80.9	100
4	101	122	–	85.7	90.7	123
5	114	130	–	88.3	83.7	127
6	105	63	–	85.9	82.0	113
7	–	–	–	–	–	122
8	–	–	–	–	–	106
Mean	184	118	128	85.7	81.9	112
MD (mean deviation)	90.1	42.8	4.4	1.6	5.1	10.6

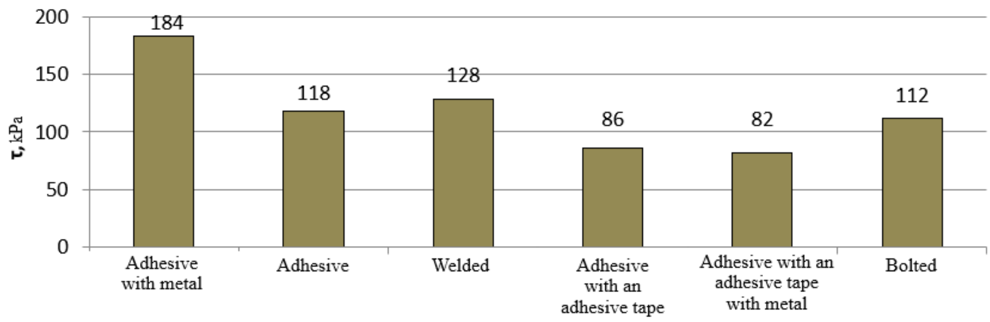

Figure 11 – Comparison of strength of connections

Conclusion

The conducted experimental study of the 200-micron-thick ETFE film provides a rather comprehensive description of its mechanical properties at static and cyclic loading within a rather wide temperature range (–50 °C…+50 °C) that covers its possible application in construction and architecture.

The paper illustrates uniaxial and biaxial tensile tests of ETFE film to determine its strength and yield limits. The relation between the temperature and strength of the film, as well as the influence of cyclic loads on the material was defined. In particular, it was found that ETFE film has sufficiently high strength at uniaxial and biaxial tension that remains in the tested wide enough temperature range.

The paper states different options of film connection and their subsequent shear testing to check their viability in application for large-span structures. Strength limits of different connection types were defined. The highest shear strength τ = 128 kPa belongs to the welded film-to-film connection, while the adhesive connection τ = 184 kPa – to the film-to-metal adhesive connection.

The scientific merit hereof lies in reception of new test data about stress-strain behaviour of ETFE film and about the shear strength of its mechanical, adhesive and welded connections.

The practical relevance hereof lies in consideration of real-life behaviour of ETFE film at calculation and design development of enclosing structures. It is advisable to specify the film as a nonlinear material via diagrams of materials with regard to operating temperature of the film.

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