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Minimum Load-Bearing Capacities of ETFE Area Weld Seams

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Abstract

ETFE-foils are an established building material in membrane structures and are frequently used for the realisation of prestigious buildings. The highly individual and wide-spanned membrane structures are made possible by the weldability of the thermoplastic fluoropolymer. The manufactured weld seams are categorised as area and edge weld seams. In uniaxial short-term tensile tests, these weld seam details exhibit lower load-bearing capacities than the corresponding base material. Consequently, ETFE-weld seams are the decisive points for the ultimate limit state design. This is reflected by the recently published PD CEN/TS 19102 “Design of tensioned membrane structures”, which represents the first standardised design concept for membrane structures based on the Eurocode design philosophy. PD CEN/TS 19102 provides characteristic values for the minimum weld seams strength which can be used for the preliminary design of ETFE-structures. The provided values represent minimum load-bearing capacities that have to be met or exceeded by the manufactured ETFE weld seams and correlate to the 5% fractile values according to EN 1990, derived from uniaxial short-term tensile test series with at least five individual tests. In order to ensure an economical and safe design of ETFE structures, appropriately high minimum required weld seam strengths are desirable which are achievable for all market participants .

In the frame of this contribution, results of systematic investigations into the uniaxial load-bearing capacity of different configurations of ETFE area weld seams with various test parameters are presented. Two different types of area weld seams – overlap (OV) and backstrip (BS) – of three different manufacturers and three different foil products and various foil thicknesses were investigated. The weld seam specimens were manufactured using two different welding processes – band sealing and impulse sealing – and were tested at two different test temperatures, at room temperature and at 50 °C. The results of these uniaxial short-term tensile tests provide a systematic data base for the determination of minimum characteristic weld seam strengths for ETFE area weld seams at the two investigated temperatures. The presented results will be used to improve the design concept of the future Eurocode for membrane structures.

Keywords: membrane structures, ETFE-foils, area weld seams, load-bearing capacity, PD CEN/TS 19102

1. Introduction

The fluoropolymer ethylene-tetrafluoroethylene, commonly known as ETFE, is the first and so far only homogenous plastic used as a membrane material in a wide range of architectural applications. The thermoplastic has excellent chemical, physical, optical and mechanical properties. Its high durability, recyclability as well as transparent appearance and low dead weight - when extruded as a foil - make it an attractive choice for cladding systems in structures with high span widths. ETFE structures are predominantly executed as multi-layer cushion structures which are pneumatically prestressed by internal pressure. Another construction principle involves single-layer structures which are mechanically prestressed.

Welded connections are essential details for ETFE structures. They are crucial for manufacturing the wide-spanning and commonly doubly curved foil layers from plane rolls which are only available in limited widths of about 1.5 m. Two different welding processes are commonly used to weld ETFE-foils: band sealing (HR) and impulse sealing (HI) according to DIN 1910-3 [1]. Following the heat-sealing principle, in both welding processes the weld seam is manufactured through the application of heat, pressure and time. Band sealing is a continuous welding procedure in which the joining partners are welded between two roll bands. It is the dominant welding process for joining ETFE-foils. The impulse sealing is a discontinuous welding process in which the joining partners are spontaneously welded by a movable heating bar. Both welding processes offer different advantages in the production and in the achievable geometric properties of the weld seam respectively.

ETFE-structures are premanufactured in the manufacturer´s production facilities. The extruded foils are delivered as roll goods. In the first production step, the base material is cut into smaller flat foil pieces known as cutting patterns. Following this plotting process, the cutting patterns are assembled to individual foil layers by welding. The utilized weld seams are referred to as area weld seams and can be divided into two different types: overlap seams (OV) and backstrip seams (BS). Typically, area weld seams are executed as overlap seams, where the two joining partners are positioned to overlap each other and are welded in the overlapping area, see Figure 1 (a). If the joining partners are printed, this printing on the side facing the weld seam must be removed before welding to avoid a separation layer and to ensure high weld seam strengths. Therefore, printed foils are often executed as backstrip seams, as in this type of execution, the printing does not need to be removed if the printed sides are properly arranged. For the execution of backstrip seams, the two joining partners are butted together and welded with a back strip in the butted area, see Figure 1 (b). The back strip is also made of ETFE-foil. In general, no welding additives are used when welding ETFE-foils.

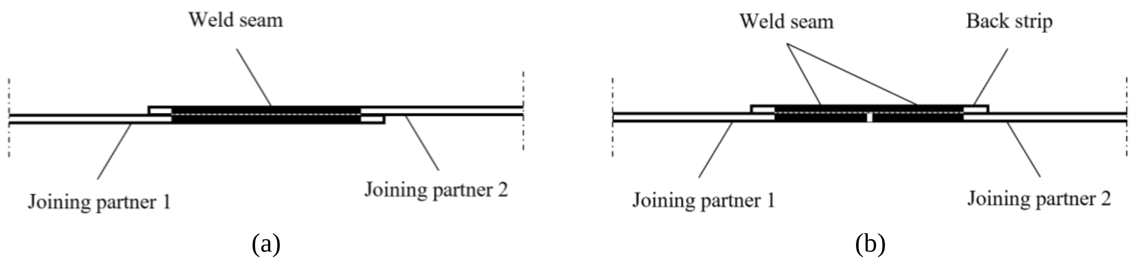

Figure 1: ETFE area weld seams (a) overlap seam (OV), (b) backstrip seam (BS)

In case of multi-layer foil elements, additionally, valve flanges have to be installed within the foil layers. Following this, the individual foil layers are fixed into a foil package using non-load-bearing constructive tack weld seams. In the final step, a keder is installed at the edges of the foil layers of a single-layer element or of the foil packages of a multi-layer element, respectively. The keder, a plastic cable, is placed in a ETFE sheet known as keder pocket. This keder pocket is folded and welded to the edges of the foil layer or foil package using an overlap seam, see Figure 2 (a). Alternatively, the keder pocket can be manufactured by folding over and welding one of the foil layers, see Figure 2 (b). The weld seam used to install the keder is called edge weld seam and serves to connect the single- or multi-layer foil element to the primary structure.

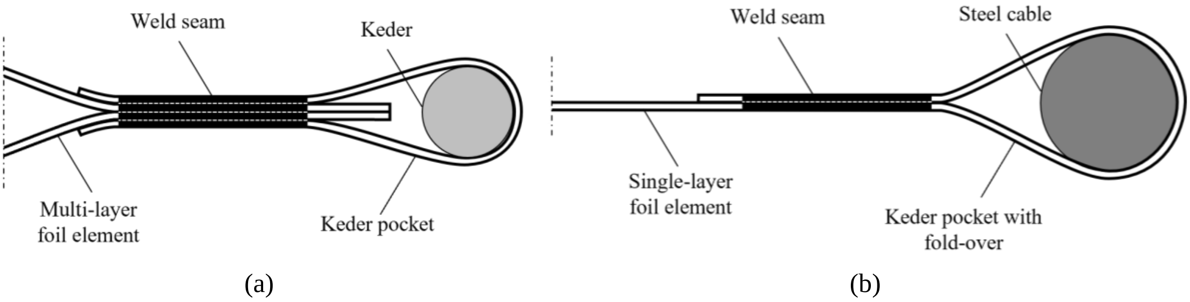

Figure 2: Examples for ETFE edge weld seams: (a) keder connection of a multi-layer foil element (OV), (b) cable connection of a single-layer foil element as an envelope

With the publication of PD CEN/TS 19102 "Design of tensioned membrane structures" [2], the first standard for the design of textile fabrics as well as plastic foils in general and ETFE-foils in particular is available. This technical specification also acts as a precursor to a future Eurocode for membrane structures. According to it, the ultimate limit state design is verified if the design membrane stress in each load case (f_{Ed}) is lower or equal to the design tensile strength of the foil or the connection ($f_{Rd,mod}$) related to the specific design situation, see equation (1).

$$f_{Ed} \leq f_{Rd,\mathrm{mod}} \tag{1}$$

where

f_{Ed} is the design membrane stress in the considered direction; and

$f_{Rd,\mathrm{mod}}$ is the design tensile strength of the foil or the connection related to the specific design situation.

The design tensile strength $f_{Rd,mod}$ is calculated based on the design strength f_{Rd}, which in turn is determined as the minimum of the short-term tensile strength of the base material f_{u23} and the welded connections f_{uw23}, respectively, as shown in equation (2). These two values represent the characteristic strengths in the ultimate limit state (ULS). They correspond to the 5 % fractile value of the tensile strength derived from uniaxial short-term tensile tests of the ETFE base material and welded connections at room temperature (T = 23 °C $\pm$ 2 K). The base material and the welded connections have to be tested in the relevant material direction, either the extrusion direction (ED) or transversal direction (TD), conducted in a separate test series with at least five individual tests. The uniaxial short-term tensile tests are conducted in accordance with EN ISO 527-1 [5] and -3 [6], considering the special provisions according to PD CEN/TS 19102, Annex I.

$$f_{Rd} = \min \begin{cases} f_{1Rd} = f_{u23}/\gamma_{M0} \\ f_{2Rd} = f_{uw23}/\gamma_{M1} \end{cases} \tag{2}$$

where

f_{u23} is the short-term tensile strength of the base material derived from uniaxial material tests at T=23°C,

f_{uw23} is the short-term tensile strength of a weld seam or edge connection derived from uniaxial tests at T=23°C,

$\gamma_{M0} = 1.1$ partial safety factor for the resistance of ETFE foils,

$\gamma_{M1} = 1.15$ partial safety factor for the resistance of ETFE connections.

The 5 % fractile value has to be calculated according to EN 1990 [3], D.7.2, using the mean value of the test series as well as the coefficient of variation (COV) and the fractile factor k_n, as given in equation (3). PD CEN/TS 19102 also provides recommended values for the characteristic strengths of the base material and welded connections, referred to as the material strength (f_{u23}) and the seam strength (f_{uw23}), respectively. These values have to be validated by experiments. Additionally, PD CEN/TS 19102 provides values for the minimum required weld seam strength at room temperature (T = 23 °C $\pm$ 2 K) and at elevated temperature of 50 °C $\pm$ 2 K, serving as nominal values for the characteristic strength of welded connections. The minimum required weld seam strength at room temperature aligns with the seam strength f_{uw23}. Therefore, the minimum required weld seam strength at elevated temperature is referred to as f_{uw50} in this paper.

$$f_{u/uw} = \sigma_x \cdot (1 - k_n \cdot V_x) \quad (3)$$

where

$f_{u/uw}$	is the short-term tensile strength of the base of a weld seam or edge connection,
σ_x	mean value of the tensile strength of the base material or of the weld seam strength of welded connections least 5 individual tests,
V_x	coeffitient of variation of the load-bearing capacity,
$k_n = 2.33$	for a test series with 5 individual tests.

These two temperature dependent minimum required weld seam strengths are the minimum load-bearing capacities for welded ETFE-foils, implying that the 5 % fractile values of the weld seam strengths determined by uniaxial short-term tensile tests have to meet or exceed these values. The following characteristic values are specified in PD CEN/TS 19102:

- f_{u23} = 40 MPa,
- f_{uw23} = 30 MPa,
- f_{uw50} = 24 MPa.

This brief overview of the manufacturing process and the ultimate limit state design of ETFE structures highlights the crucial role of a high weld seam quality and thus the importance of high standards in the execution of welded ETFE-foils. Furthermore, ensuring appropriately high characteristic values for the weld seam strength is essential to guarantee a safe and economical ultimate limit state design of ETFE structures. Furthermore, currently, no standards neither guidelines exist for the quality assurance of welded ETFE-foils which includes methods for the qualification of the welding procedure and the welding personnel as well as a standardised test method for ETFE weld seams. Moreover, the values for the minimum required weld seam strength provided in PD CEN/TS 19102 are based on the experience of numerous tests carried out by the manufacturers and independent testing laboratories but systematic investigations into the load bearing capacities of various weld seams were still missing during the time of preparing PD CEN/TS 19102. Within the frame of the German research project 03TN0011A „Welded connections of ETFE structures: Standardisation of execution, testing and design“ [4] (short: WIPANO-ETFE), under the WIPANO initiative of the German Federal Ministry for Economic Affairs and Climate Action, for the first time, the load-bearing behaviour of ETFE area weld seams was systematically investigated. Furthermore, methods and standards for the quality assurance of the execution of ETFE structures were developed. The project was a joint project with industrial and scientific partners involved in the planning, testing and execution of ETFE structures. Some results of the investigations into the minimum load-bearing capacity of ETFE area weld seams are presented in this contribution. The tests underlying the data presented in this paper were carried out at the Essen Laboratory for Lightweight Structures (ELLF) of the University Duisburg-Essen and by the laboratory for technical textiles and films at DEKRA Automobile GmbH, Stuttgart. The welded samples were provided by Vector Foiltec GmbH, se cover GmbH and Taiyo Europe GmbH. Furthermore, formTL, ingenieure für tragwerk und leichtbau gmbh, Radolfzell accompanied the investigations. All mentioned companies/organizations were partners of the WIPANO-ETFE research project.

2. Minimum load-bearing capacity of ETFE area weld seams

2.1 General and scope of testing

In order to ensure a systematic and representative investigation into the minimum load-bearing capacity of ETFE area weld seams, foil products from three different foil producers (referred to as 1, 2 and 3) with various foil thicknesses were investigated, as shown in Table 1. The weld seam samples were produced by three different manufacturers (referred to as A, B and C) to ensure a diverse representation of weld seams across the industry. The investigation covered area weld seams executed as overlap seams (OV) as well as backstrip seams (BS) using both aforementioned welding processes (HR and HI).

Table 1: Investigated foil products and foil thicknesses

Foil product	Foil thickness [µm]
1	80, 100, 150, 200, 250, 300
2	100, 150, 200, 250, 300
3	100, 150, 200, 250, 300, 500

Additionally, for reference, the tensile strength of the investigated foil products was determined at room temperature (T = 23 °C ± 2 K) and elevated temperature (T = 50 °C ± 2 K). The weld seam samples for each foil product were produced using the same foil production batch.

2.2 Uniaxial short-term tensile test

The load-bearing capacity of ETFE area weld seams is determined by uniaxial short-term tensile tests according to EN ISO 527-1 and -3 which are designed for the determination of tensile properties of homogenous and composite polymer films and sheets, focusing on the determination of the material properties. In contrast, welded ETFE-foils are components with an inhomogeneous cross-section and material behaviour, making the application of EN ISO 527-1 and -3 for welded connections off-labelled. For this reason, PD CEN/TS 19102, Annex I gives special provisions in regard to the determination of tensile properties of structural foils and their connections under uniaxial stress states which have to be considered additionally.

Furthermore, the test parameters specified in EN ISO 527-1 and -3 are provided within broad ranges to represent the diverse group of polymer materials and composites. For instance, the recommended test speeds range from 0.125 mm/min to 500 mm/min. It is well known that varying test speeds, and consequently different strain rates, lead to different test outcomes for polymer materials, see [7], [8] and [9]. As a result, the repeatability and comparability of test results across different laboratories may be compromised due to differently chosen test parameters. To overcome this issue, within the WIPANO-ETFE research project, a uniform test method was developed for the determination of the uniaxial load-bearing capacity of ETFE area weld seams. For this purpose, the effect of various test parameters on the results of ETFE base material and area weld seams was studied. In this frame, in the first step, the project partners established a preliminary, uniform test specification as a base line and in the second step, subsequently varied the individual test parameters. On this basis, the test parameters could be optimised including the specimen geometry, the specimen preparation, the test speed and the clamping configuration. Table 2 presents the optimised test parameters for the newly developed standardised test method, while Figure 3 illustrates the optimised specimen geometry.

The investigations into the minimum load-bearing capacities of ETFE area weld seams as well as the base material tests were conducted using this uniform test method. For each test series five individual tests were conducted. It is well known that ETFE foils exhibit low anisotropy. As a result, in this investigation, tests on the base material were conducted in both material directions, the extrusion direction (ED) and the transversal direction (TD). Due to limitations in the extrusion process of the foils, the width of the base material in TD is restricted to approximately 1.5 m. Consequently, ETFE area weld seams are executed parallel to ED to extend the span width in TD, making ETFE area weld seams predominantly loaded in TD. Therefore, the welded samples were executed according to practical standards and tested exclusively in TD.

Table 2 Test parameters of the uniform test method for the determination of the uniaxial load-bearing capacity of ETFE area weld seams

Test specimen	Specimen type 2, modified according to 6.1.1 of EN ISO 527-3
Gauge length L_0	50 mm
Gauge width b	10 mm
Test speed	100 mm/min
Test temperature	23 °C ± 2.0 K
Cutting	By knife
Prestress	0.2 MPa
Clamps	Pneumatic clamps, convex against plain, one-sided PET-PVC coated
Number of specimens per series	5

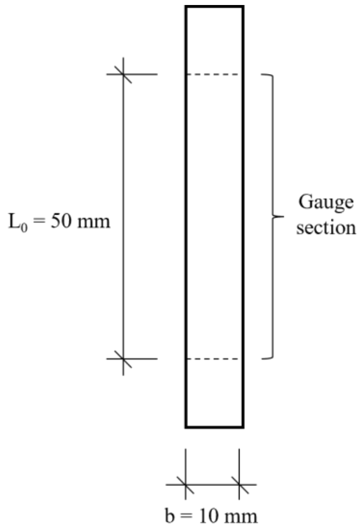

Figure 3 Optimised tensile test specimen type (modified specimen type 2 acc. to EN ISO 527-3, 6.1.1)

2.3. Tensile strength of the investigated foil products

In addition to the investigations into the minimum load-bearing capacity of ETFE area weld seams, uniaxial short-term tensile tests were conducted for the investigated foil products for reference. The 5 % fractile value of each test series was calculated according to EN 1990, D.7.2, representing the experimentally determined characteristic strength of the material. In PD CEN/TS 19102 this value is referred to as short-term tensile strength of the base material f_{u23}. Figure 4 illustrates the short-term tensile strengths of the different foil products and thicknesses in both material directions at room temperature.

Test series of uniaxial short-term tensile tests for ETFE base material typically exhibit a wide range of tensile strengths within each series, leading to a high variability and an elevated upper limit of the COV of the test series. This observation is consistent with the findings of the present investigation shown in Figure 4, where the 5 % fractile values range from 41.9 MPa to 62.3 MPa, while the COVs range from 0.3 % to 14.0 %. The wide range of results makes it challenging to evaluate the performance of the different foil products relative to each other. Similarly, the evaluation of the influence of the material direction on the tensile strength becomes also difficult.

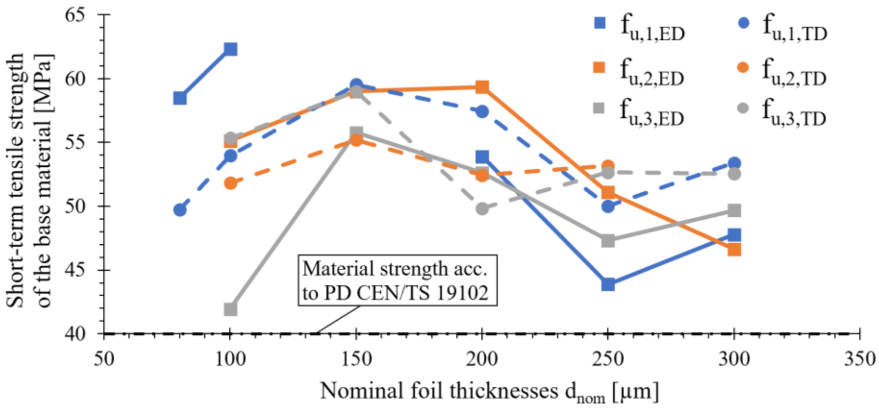

Figure 4: 5 % fractile values of the tensile strength of three foil products (1, 2 and 3) and various foil thicknesses in both material directions (ED and TD) at room temperature

Overall, a trend can be observed, where the short-term tensile strengths of the 150 µm and 200 µm foils are slightly higher than those of the thinner and thicker foils. Excluding the 80 µm and 100 µm foils, the short-term tensile strength decreases with increasing foil thickness. The dash-dot line in Figure 5 represents the nominal value of the characteristic strength of ETFE-foils with 40 MPa as given by PD CEN/TS 19102. This value is considered conservative and safe sided as the 5 % fractile values across all investigated parameters, reflecting the experimentally determined characteristic strength, consistently exceed it.

Figure 5 illustrates box plots representing the tensile strength of the three foil products and the two foil thicknesses in both material directions at elevated temperature. Additionally, it shows the 5 % fractile value as well as the COV. As observed with the short-term tensile strength at room temperature, the 5 % fractile values of the test series at elevated temperature show significant variation, ranging from 33.2 MPa to 54.6 MPa. Correspondingly, the COVs also demonstrate considerable deviation, ranging from 3.3 % to 12.4 %. Despite the considerable variation in tensile strength at elevated temperature, it can be observed that foil product 2 shows a higher anisotropy compared to foil products 1 and 3. It can also be noted that there is a trend in TD, where foil product 3 shows slightly higher tensile strengths, whereas in ED, both foil products 2 and 3 exhibit slightly higher tensile strengths than foil product 1.

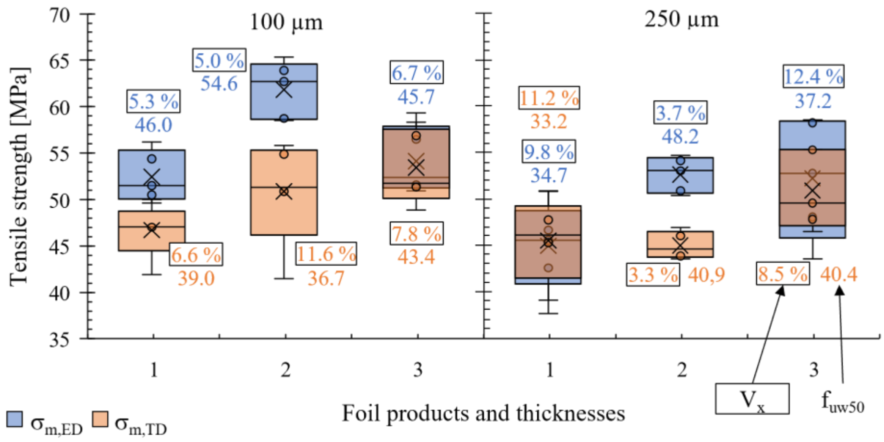

Figure 5: Box plot of the tensile strength of the three foil products (1, 2 and 3) and two foil thicknesses 100 µm and 250 µm for both material directions (ED and TD) at elevated temperature of 50 °C ± 2 K, additional information: boxed is the COV and below the 5 % fractile value of the tensile strength in MPa

PD CEN/TS 19102 does not provide the characteristic strength of the base material at elevated temperature of 50 °C. However, it provides a k-factor for temperature effects of 50 °C ($k_{temp,50}$), ranging from 1.3 to 1.7. Considering the smaller k-factor and the characteristic material strength at room temperature (f_{u23} = 40 MPa), the nominal characteristic strength of the base material at elevated temperature of 50 °C can be calculated to be 30.8 MPa, which is still far below the experimentally determined characteristic strengths across the investigated foil products and thicknesses at elevated temperatures. Consequently, the lower limit of the k-factor, taking into account the influence of the temperature effect of 50 °C ($k_{temp,50}$), seems to be conservative and safe sided considering the investigated parameters.

2.4. Load-bearing capacity of ETFE area weld seams

To conduct a representative and systematic study into the minimum load-bearing capacity of ETFE area weld seams, welded samples from three different manufacturers (A, B and C) and three foil products (1, 2 and 3) were investigated. The corresponding uniaxial short-term tensile tests were carried out at both room and elevated temperature using the within the WIPANO-ETFE research project developed standardised test method described above. In the following, the results for the two different types of ETFE area weld seams (OV and BS) manufactured using band sealing and impulse sealing are presented.

Figure 6 shows the 5 % fractile values of the weld seam strengths of overlap seams (OV) for the investigated foil products at room temperature, across the various foil thicknesses produced by different manufacturers using band sealing. The results indicate a trend that with higher foil thicknesses the weld seam strength decrease. This is in line with observations made for the base material.

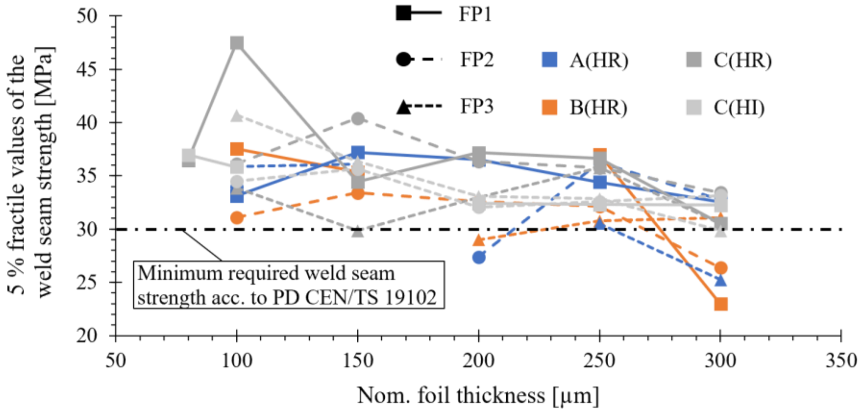

Figure 6: 5 % fractile values of the weld seam strength (OV) of three foil products (1, 2 and 3) and various foil thicknesses of the three manufacturers (A, B and C) and two welding processes (HR and HI) at room temperature

Furthermore, within one foil thickness and product, significant differences between the weld seam strengths can be observed, as exemplary shown in Table 3. This indicates that the execution of the weld seam has a significantly higher impact on the weld seam strength than the choice of the foil product. This becomes particular evident when looking at the 5 % fractile values of the weld seam strengths of manufacturer C for both welding processes. The deviation between them is 32.7 %. Not surprisingly, this underlines the hypothesis that the welding procedure, including the applied welding parameter, the welding equipment, the condition of the heat beams and the heating bands as well as the welding personnel significantly influence the weld seam quality.

Table 3: Statistical values of the weld seam strength of the 100 µm foil of foil product 1 for the three manufacturers A, B and C and two welding processes HR and HI

Manufacturer (Welding process)	**Short-term tensile strength of weld seam f_{uw23}**	**COV of the weld seam strength V_x**
A(HR	33.1 MPa	4.6 %
B(HR)	37.5 MPa	2.3 %
C(HR)	47.5 MPa	4.8 %
C(HI)	35.8 MPa	1.5 %

In Figure 6, the minimum required weld seam strength according to PD CEN/TS 19102 is illustrated as a dash-dot line. The trend of decreasing 5 % fractile values with increasing foil thickness results in some individual weld seams strengths falling below the minimum required weld seam strength of 30 MPa. This is especially valid for weld seams of larger foil thicknesses of 200 µm and 300 µm, observed for both manufactures A and B. However, it should be noted that this applies to individual weld seams only. In case of manufacturer C, the weld seams provide 5 % fractile values which meet and exceed the minimum required weld seam strength. This indicates that the provided values for the minimum required weld seam strength at room temperature of 30 MPa in PD CEN/TS 19102 is – in principle - achievable by the participating manufacturers considering the investigated parameters.

Table 4 presents the average weld seam strength σ_x and the 5 % fractile f_{uw23} as well as the COV for ETFE overlap and backstrip seams, produced by the three manufacturers considering the 100 µm and 250 µm foil of foil product 1. Across all manufacturers and foil thicknesses, the weld seam strength of backstrip seams tends to be slightly lower compared to that achieved for overlap seams. The difference is particularly notable for the 100 µm backstrip seams. For instance, the 100 µm backstrip seam from manufacturer B exhibits a comparably high COV of 7.1 %, resulting in low 5 % fractile value that falls below the minimum required weld seam strength of 30 MPa. Overall, the currently provided value for the minimum required weld seam strength at room temperature is also considered appropriate in the context of backstrip seams.

Table 4: Average weld seam strength and 5 % fractile value of OV and BS area weld seams of 100 µm and 250 µm foils of foil product 1 produced by the three manufacturer A, B and C using band sealing at room temperature

		A		B		C	
		100 µm	250 µm	100 µm	250 µm	100 µm	250 µm
OV	σ_x [MPa]	39.0	36.6	37.0	37.2	40.6	36.7
	V_x	1.4%	1.5%	5.4%	6.4%	6.1%	3.9%
	f_{uw23} [MPa]	**37.7**	**35.3**	**32.4**	**31.7**	**34.9**	**33.3**
BS	σ_x [MPa]	35.8	34.4	35.7	35.5	33.2	34.0
	V_x	1.8%	2.8%	7.1%	5.0%	4.2%	2.7%
	f_{uw23} [MPa]	**34.3**	**32.1**	**29.8**	**31.4**	**30.0**	**31.9**

In Figure 7, box plots showing the load-bearing capacity of ETFE area weld seams are presented for the three foil products and the two foil thicknesses 100 µm and 250 µm at elevated temperature. The overlap seams were produced by the three manufacturers using band sealing and impulse sealing. Additionally, the 5 % fractile values of the weld seam strengths are provided as numbers above or below the box plots.

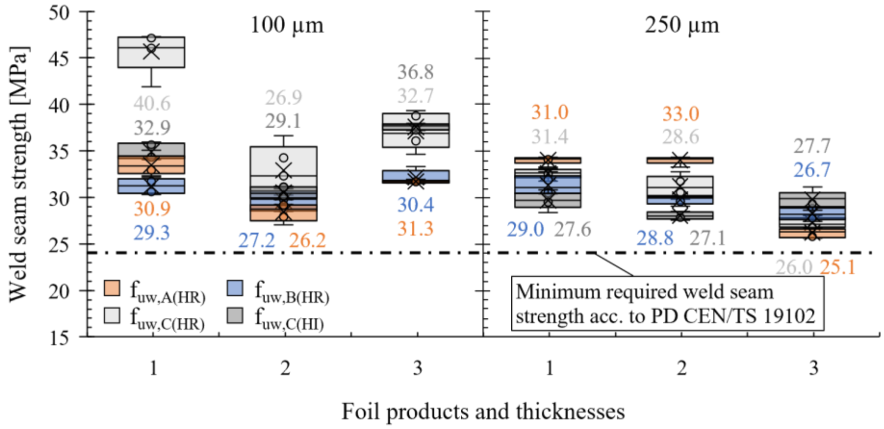

Figure 7: Box plot of the weld seam strength (OV) of the three foil products (1, 2 and 3) and two foil thicknesses 100 µm and 250 µm of the three manufacturers (A, B and C) and two welding processes (HR and HI) at elevated temperature of 50 °C ± 2 K, additional information: 5 % fractile value of the weld seam strength as numbers above or below the box plots

The minimum required weld seam strength of 24 MPa at elevated temperature of 50 °C is indicated by a dash-dot line. Consistent with the results observed for the tests at room temperature, there are significant differences in weld seam strength among the three manufacturers, highlighting the significant influence of the execution process on the weld seam quality. Despite this variability, the 5 % fractile values for all manufacturers, foil products and foil thicknesses exceed the minimum required weld seam strength at elevated temperatures. Thus, the provided value for the minimum required weld seam strength at 50 °C is to be considered conservative and safe sided.

3. Conclusion and outlook

The representative and systematic investigation into the load-bearing capacity of ETFE area weld seams has provided detailed insights into their performance across various factors such as manufacturer, foil products and thickness as well as weld seam type. These results highlight the significant influence of the execution process on the weld seam quality, along with the observed trend of decreasing weld seam strengths with increasing foil thickness. Despite this variability in the weld seam strength, all tested weld seams consistently meet or exceed the minimum required weld seam strength at both room and elevated temperature of 50 °C. Consequently, the values for the minimum required weld seam strength at room temperature and elevated temperature stated in PD CEN/TS 19102 can be considered to be appropriately high but achievable for market participants for area weld seams within the scope of the investigated parameters. This ensures an economic and safe design of ETFE structures. Further research into the load-bearing capacity of edge weld seams is recommended to validate the stated requirements for these specific details.

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