XI International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2023
C. Lázaro, R.Rossi and R. Wüchner (Eds)

TENSILE BEHAVIOUR OF ETFE FOILS WITH VARIOUS TYPES OF AREA WELD SEAMS

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Key words: ETFE foil, area weld seam, weld seam strength, prCEN/TS 19102.

Summary. ETFE foils are already an established building material in membrane construction. Many prestigious buildings have already been realised with the transparent and printable foils. The manufacturing and installation of the mostly double-curved ETFE foil structures are made possible by the weldability of the fluoropolymer. The manufactured weld seams can be divided into area and edge weld seams. Both types of ETFE weld seams provide a lower uniaxial tensile strength in comparison to the base material. Weld seams in ETFE structures are the decisive points for the limit state design, see also FprCEN/TS 19102, which for the first time provides a standardised design concept for membrane structures based on the Eurocode design philosophy. With the release of prCEN/TS 19102, a minimum tensile strength and a partial safety factor for area weld seams are given relying on the partial safety concept of the Eurocodes according to EN 1990. Nevertheless, the given values are not based on a comprehensive experimental test evaluation so far.
In the frame of this contribution, for the first time, results of investigations into the tensile strength of different configurations of area weld seams are presented. These configurations include different manufacturers, foil products, foil thicknesses, test temperatures, types of area weld seams and welding processes. Based on these results, a general minimum requirement for the tensile strength of area weld seams could be determined for future standardization processes beside that a new reliability analysis according to EN 1990 for the determination of the partial safety factor for area weld seams has been carried out. These new results will be used to improve the design concept of the future Eurocode for membrane structures which will be developed on the basis of prCEN/TS 19102. In this contribution first results of this investigations are presented.

1 INTRODUCTION

ETFE is a thermoplastic fluoropolymer with 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 as a structural membrane material. Since the first realisations of ETFE foil structures in the 1980s, the polymer foils have evolved into a widely used and well-established building material for various structures. Although ETFE foils have a lower tensile strength compared to textile membrane materials such as PVC-coated PES fabrics or PTFE-coated glass fibre fabrics, they are commonly used as air-inflated cushions with a span width of up to 6.0 m. By reinforcing ETFE cushion structures with steel cables, the span width can be increased significantly. In addition to multi-layer cushion systems, single-layer structures are also becoming increasingly popular.

ETFE foils can be produced using two different techniques, both involving melting the raw material granules at approximately 380 °C. In the blow film extrusion process, the molten ETFE is shaped to a tube-formed foil, which is later cut and unfolded to achieve a foil sheet with a width of up to 3.4 m [1]. Another method for producing ETFE foils is the casting process which produces foils with a width of up to 1.5 m. Although blown foils are more cost-effective and can be produced in larger widths, they exhibit lower optical properties and have higher thickness tolerances. Therefore, only extrusion foils are utilized in architectural applications. Due to the limited production width, a joining method is necessary for manufacturing wide-span and curved structures using ETFE foils.

As a thermoplastic, ETFE foils can be welded. For welding of ETFE foils no additives are needed. Two different welding processes are commonly used to join ETFE foils: band sealing and impulse sealing according to DIN 1910-3 [2]. Both welding methods follow the heat-sealing principle wherein the joining is accomplished through the application of heat, pressure and time. Band sealing is the dominant welding process for ETFE foils and is a continuous welding procedure in which the joining partners are welded between two roll bands. The welding parameters include the joining speed, joining pressure and joining temperature of the upper and lower roll bands as well as the range of cooling temperature.

The second welding method is the impulse sealing. It is a discontinuous welding process in which the joining partners are spontaneously welded by a movable heating bar. The welding parameters are the joining time, joining pressure, joining temperature of the upper heating bar and, if available, of the lower heating bar as well as the range of cooling temperature and cooling time. Both band sealing and impulse sealing offer different advantages in the production and in the achievable geometric properties of the weld seam respectively.

There are basically two main types of ETFE weld seams: area weld seams and edge weld seams. Area weld seams are used to manufacture the different foil layers of the ETFE structures. This type of weld seams can often be observed in the field of ETFE structures. Edge weld seams are implemented to attach the foil system to the primary structure. In the case of a multilayer systems, they also serve to join the different foil layers to an air-tight cushion. ETFE weld seams are usually executed by overlapping the joining partners and welding these parts together. These types of weld seams are known as overlap weld seams (OV), as shown in Figure 1(a). When joining printed foil layers, the printing on the side facing the other joining partner within the weld seam area has to be removed to ensure a sufficient quality of the weld seam. Alternatively, an area weld seam can be executed as a back strip weld seam (BS). It is executed by welding an ETFE foil strip onto the butted joining partners, see Figure 1 (b).

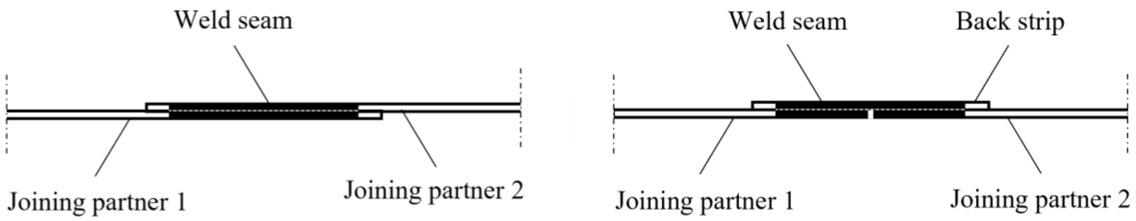


Figure 1: ETFE area weld seams (a) Overlap weld seam (OV), (b) Backstrip weld seam (BS)

It is commonly known that ETFE weld seams have a lower uniaxial tensile strength than the corresponding base material. The mechanical properties of ETFE weld seams depend on the chosen base material and its pretreatments as well as on the weld seam preparation and the chosen welding parameters. Therefore, qualified welding personnel and execution are mandatory for ETFE weld seams with a sufficient load-bearing capacity.

Currently, there are still no standards neither guidelines available for the design of ETFE structures and the execution of weld seams. Moreover, no harmonized product standard for ETFE foils exists. Within the framework of the technical specification FprCEN/TS 19102 [1], design concepts for textile fabrics as well as for plastic foils in general and ETFE foils in particular were developed. This document also acts as a precursor to a future Eurocode for membrane structures. According to it, the ultimate limit state design is verified if the acting design load in each load case (f_{Ed}) is lower or equal to the modified design tensile strength of the material or the weld seam ($f_{Rd,mod}$), see equation (1).

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

where

f_{Ed} is the design principle foil 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 modified design tensile strength ($f_{Rd,mod}$) is derived from the design strength (f_{Rd}), which is determined using the 5 % fractile value of the tensile strength obtained from a uniaxial short-term tensile test at room temperature for both the ETFE base material (f_{u23}) and welded connection (f_{uw23}), see equation (2). The test series have to contain five individual tests, which results are used to determine the 5 % fractile value according to EN 1990 [4], D.7.2. Hereby, it is essential to take into account the material direction when determining these strength values.

Depending on the tested detail, the 5 % fractile value is the short-term tensile strength of the base material f_{u23} or the short-term tensile strength of the weld seam f_{uw23}, which is the load-bearing capacity of welded ETFE foil. These two values represent the characteristic resistance in the ultimate limit state (ULS) of FprCEN/TS 19102, see equation (2).

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

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,

$\gamma_{M1} = 1.5$; partial safety factor for the resistance of ETFE connections.

The uniaxial short-term tensile tests are conducted in accordance with EN ISO 527-1 [5] and -3 [6] as well as the provisions according to FprCEN/TS 19102, Annex I. According to Annex I the coefficient of variation (COV) of the tensile strengths of the base material as well as the load-bearing capacity of the weld seams shall not exceed 0.08.

To ensure a safe-sided design of ETFE structures, FprCEN/TS 19102 establishes nominal reference values for the characteristic resistances. This paper indicates the nominal reference value for the characteristic resistance of the base material as $f_{u23,nom}$, and similar, the nominal reference value for the characteristic resistance of ETFE weld seams is indicated as $f_{uw23,nom}$. The nominal reference values given in FprCEN/TS 19102 are: $f_{u23,nom} = 40$ MPa and $f_{uw23,nom} = 30$ MPa. These values represent the minimum load-bearing capacity of ETFE base material and weld seams, respectively. Therefore, they have to be lower than the experimentally determined characteristic resistances which are indicated in this paper as $f_{u23,exp}$ for the base material and $f_{uw23,exp}$ for weld seams.

In the frame of the German research project “Welded connections of ETFE foils in building construction: Standardisation of execution, testing and design” (WIPANO-ETFE for short), under the WIPANO initiative of the German Federal Ministry for Economic Affairs and Energy, the primary objective was to determine a minimum load-bearing capacity of ETFE area weld seams. The WIPANO-ETFE project involved six project partners which are: University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen Laboratory of Lightweight structures ELLF (UDE, project coordinator), Laboratory for Technical Textiles and Films of DEKRA SE (DEKRA), Vector Foiltec GmbH, Bremen (VF), se cover GmbH, Obing (SC), Taiyo Europe GmbH (TE), formTL ingenieure für tragwerk und leichtbau GmbH (formTL), Radolfzell, all Germany.

The minimum load-bearing capacity refers to the characteristic resistance of ETFE area weld seams and therefore to the 5 % fractile value of the uniaxial short-term load-bearing capacity of ETFE area weld seams.

For the determination of the minimum load-bearing capacity of ETFE area weld seams, different configurations of welded ETFE foils produced by three manufactures were investigated. These configurations involved overlap and backstrip weld seams manufactured by different welding processes. Furthermore, different foil thicknesses and foil products were investigated to generate a systematic and statistically significant database for the determination of a minimum load-bearing capacity of ETFE area weld seams.

In this contribution, initial results of the investigation into the minimum load-bearing capacity of ETFE area weld seams of the WIPANO-ETFE research project are presented. The results give a first insight on the influence of the manufacturer on the outcomes of uniaxial short-term tensile tests of ETFE area weld seams. Furthermore, the determined 5 % fractile values of the uniaxial short-term tensile strength of the investigated ETFE area weld seams ($\sigma_{uw,5\%} \triangleq f_{uw23,exp}$) and the corresponding base material ($\sigma_{u,5\%} \triangleq f_{u23,exp}$) at room temperature were used for the validation of nominal reference values ($f_{u23,nom}$ and $f_{uw23,nom}$) given in FprCEN/TS 19102.

2 SPECIMEN MANUFACTURING AND EXPERIMENTAL PROGRAMM

The different investigated configurations of ETFE area weld seams in the WIPANO research program include OV and BS area weld seams of different foil thicknesses, foil products manufactured by both welding processes band and impulse sealing. In this paper, the results for two different foil thicknesses – 100 µm and 250 µm – and only one foil product tested at room temperature is presented. The weld seam specimens were provided by three different manufacturers and were manufactured using the band sealing welding process. The production batch used for all weld seams specimens and base material specimens was identical. The backstrip material was identical to that of the base material to be welded together.

The manufacturers involved meet the requirements of the highest inspection level (high execution quality level) according to FprCEN/TS 19102. Therefore, the investigated area weld seams are expected to represent weld seams of high quality.

Area weld seams are usually manufactured in the machine direction. To determine the uniaxial load-bearing capacity, the uniaxial short-term tensile tests were performed perpendicular to the weld seam, the so-called transversal direction (TD).

To evaluate the load-bearing capacity of ETFE area weld seams, the tensile strength of the corresponding base material was determined as well. The test matrix is provided in Table 1.

Table 1 Test matrix for uniaxial short-term tensile tests

Type of specimen	Material direction	Foil thickness	Manufacturer	Number of individual tests per series
Base material (MA)	TD	100 µm, 250 µm	-	5
Overlap seam (OV)	TD	100 µm, 250 µm	A, B, C	5
Backstrip seam (BS)	TD	100 µm, 250 µm	A, B, C	5

The tensile tests were conducted in accordance with EN ISO 527-1 and -3. The test parameters are provided in Table 2, the specimen geometry is displayed in Figure 2. The uniaxial short-term tensile tests of the 100 µm foil were carried out in the Essen Laboratory for Lightweight Structures of Essen (ELLF) and the tests of the 250 µm foil in the DEKRA Laboratory for Technical Textiles and Films. The tensile tests involved in this investigation were performed at room temperature (23,0 °C ± 2,0 K).

Table 2 Test parameters

Test specimen	Specimen type 2, modified according to 6.1.1 of EN ISO 527-3
Gauge length	50 mm
Gauge width	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

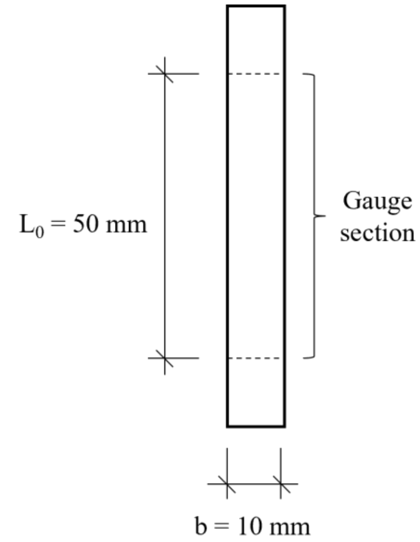


Figure 2 Specimen type 2 modified according to 6.1.1 of EN ISO 527-3

3 RESULTS AND DISCUSSION

For the evaluation of the load-bearing capacity of the ETFE area weld seams, the tensile strength of the corresponding base material has to be determined first. Figure 3 shows the boxplots of the tensile strength (σ_u) of the investigated foil products. Additionally, the mean value ($\sigma_{u,x}$), the 5 % fractile value ($\sigma_{u,5\%} \triangleq f_{u23,exp}$) as well as the COV ($V_x$) of the tensile strengths are given for both foil thicknesses.

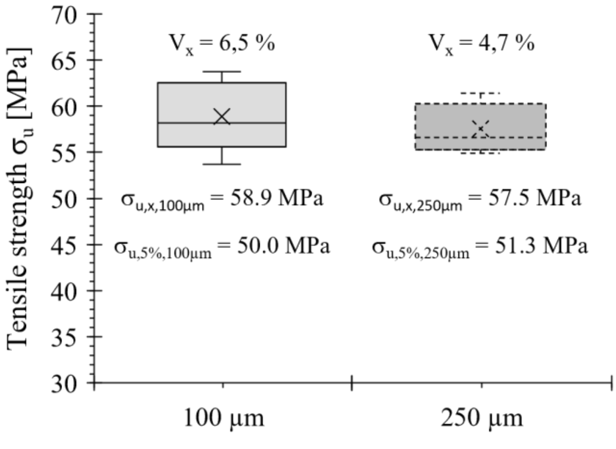


Figure 3 Boxplots, mean values, COV and 5 % fractile value of the uniaxial short-term tensile strengths of 100 µm and 250 µm base materials, TD

The mean tensile strength of the 100 µm foil is slightly higher than the mean value of the 250 µm foil. However, due to the higher COV, the 5 % fractile value of the 100 µm foil is slightly lower compared to that of the 250 µm foil. These deviations lay within the range of the standard deviation and are therefore not significant.

For both foil thicknesses, the 5 % fractile values of tensile strength were determined. As previously mentioned, this value represents the characteristic resistance ($f_{u23,exp}$) of the base material in the ULS according to FprCEN/TS 19102. The determined values are significantly higher than the given reference value for the characteristic tensile strength ($f_{u23,nom}$ = 40 MPa), exhibiting a 25.0 % exceedance for the 100 µm foil and a 28.3 % exceedance for the 250 µm foil. These findings confirm that the reference value is conservatively determined and can be used for a safe-sided design of ETFE structures at least for the two tested foil thicknesses of the investigated foil products.

The following figures show the boxplots illustrating the load-bearing capacity of both OV and BS weld seams σ_{uw} for both the 100 µm foil (Figure 4) and the 250 µm foil (Figure 5), manufactured by A, B and C. Additionally, the mean load-bearing capacity $\sigma_{uw,x}$ and the deviation between it and the mean tensile strength of the corresponding base material are given as $\Delta_{uw-u} = (\sigma_{uw,x} - \sigma_{u,x})/\sigma_{u,x}$ [%].

Table 3 provides the COV (V_x) as well as the 5 % fractile value $\sigma_{uw,5\%}$ and the average load-bearing capacity $\sigma_{uw,x}$ of the investigated area weld seams. This table also presents the deviation of the experimentally determined characteristic resistance of each investigated ETFE area weld seam from the reference value, calculated by $\Delta_{uw} = (f_{uw23,exp} - f_{uw23,nom})/f_{uw23,nom}$ [%]. This deviation is calculated as the ratio of the experimentally determined characteristic resistance to the reference value and given in [%].

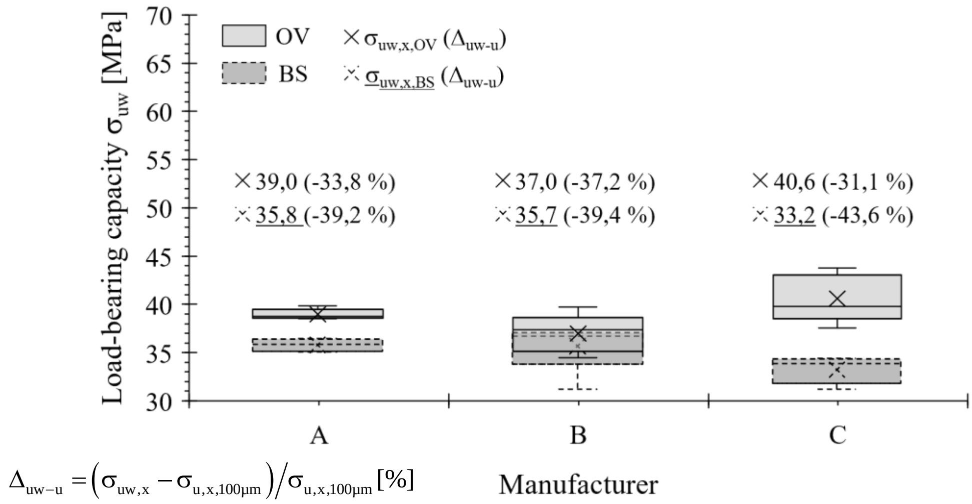
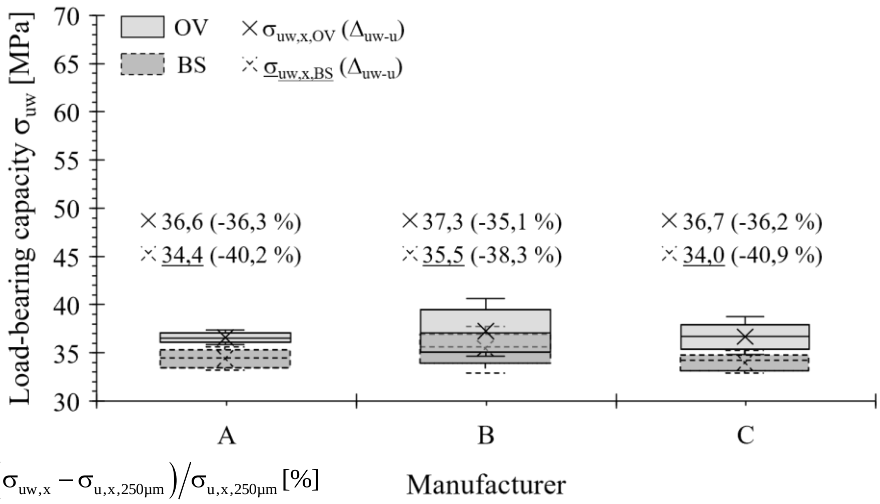


Figure 4 Boxplots and mean values of the uniaxial short-term load-bearing capacity of 100 µm ETFE area weld seams of the three manufacturers A, B and C and their deviations from the tensile strength of the base material Δ_{uw-u}



$\Delta_{uw-u} = \left(\sigma_{uw,x} - \sigma_{u,x,250\mu m}\right) / \sigma_{u,x,250\mu m}$ [%]

Figure 5 Boxplots and mean values of the uniaxial short-term load-bearing capacity of 250 µm ETFE area weld seams of the three manufacturers A, B and C and their deviations from the tensile strength of the base material $\Delta_{uw\text{-}u}$

Table 3 Average and characteristic load-bearing capacity of OV and BS area weld seams of the three manufacturers A, B and C and validation of the refernce value f_{uw23}

		A				B				C			
		OV		BS		OV		BS		OV		BS	
		100 µm	250 µm	100 µm	250 µm	100 µm	250 µm	100 µm	250 µm	100 µm	250 µm	100 µm	250 µm
$\sigma_{uw,x}$	[MPa]	39,0	36,6	**35,8**	34,4	37,0	**37,3**	35,7	**35,5**	**40,6**	36,7	33,2	34,0
V_x	[%]	**1,40**	**1,53**	**1,80**	2,84	5,36	6,37	7,10	4,96	6,07	3,94	4,20	**2,68**
$f_{uw23,exp}$	[MPa]	**37,7**	**35,3**	**34,3**	**32,1**	32,4	31,7	29,8	31,4	34,9	33,3	30,0	31,9
$f_{uw23,nom}$	[MPa]	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0
Δ_{uw}*	[%]	25,7	17,6	14,3	7,1	7,9	5,7	**-0,7**	4,6	16,2	11,0	**0,0**	6,2
*: $\Delta_{uw} = \left(f_{uw23,exp} - f_{uw23,nom}\right) / f_{uw23,nom}$ [%]													

The mean load-bearing capacities of the investigated ETFE area weld seams ranges from 33.2 MPa to 40.6 MPa and are – as expected - significantly lower than the mean tensile strength of the corresponding base material. The load-bearing capacities of ETFE area weld seams are 56.4 % to 69.0 % of the tensile strength of the corresponding base materials, see Figure 4 and Figure 5. For the investigated foil products, the results confirm the general opinion that the load-bearing capacities of ETFE area weld seams are significantly lower than the tensile strengths of the corresponding base materials.

Additionally, the results reveal a slight discrepancy in the load-bearing capacity for BS and OV seams. The deviation ranges from 3.5 % for the 100 µm foil weld seams of manufacturer B to 18.2 % for the 100 µm foil weld seams of manufacturer C, with the OV seams being stronger than those made with a backstrip. The differences between both do not seem to be dependent on the foil thickness.

It has to be mentioned that these results reflect only the current state-of-the-art of the execution of ETFE weld seams. Previous optimisations of the execution have already shown that the load-bearing capacity of ETFE weld seams can be increased by improved technical progresses and knowledge about the load-bearing behaviour of welded ETFE foils.

The relation between the load-bearing capacity of ETFE area weld seams and their execution can be confirmed by the presented results as well. Although the weld seams were manufactured from the same production batch, the results of the different manufacturers can differ significantly. This becomes particularly evident for the results of the 100 µm foil, where the load-bearing capacities of the BS seams manufactured by A and C show clearly distinguishable scattering ranges, see Figure 4.

The influence of the manufacturer becomes particularly clear when looking at the COV of the load-bearing capacity of the different manufacturers. The COV of the load-bearing capacities of the weld seams of manufacturer A ranges from 1.40 % to 2.84 % and is significantly lower than those of manufacturers B (4.96 % to 7.10 %) and C (2.68 % to 6.07 %), see Table 3. The only exception is the 250 µm BS seams for which the COV of the weld seams of manufacturer C is slightly lower.

As previously stated, the 5 % fractile value of the load-bearing capacity represents the experimentally determined characteristic resistance ($f_{uw23,exp}$) for the ultimate limit state design according to [3]. Manufacturer A provides with 37.7 MPa for OV seams and 34.3 MPa for BS seams the highest characteristic resistances for every tested type of weld seams and foil thickness. This is due to the low COV of the results.

For the validation of the reference value for ETFE weld seams ($f_{uw23,nom}$ = 30 MPa) given in FprCEN/TS 19102, the experimentally determined characteristic resistances are compared to the reference value of 30 MPa. The ratios between these values are indicated as Δ_{uw}, see Table 3. The investigated OV seams provide higher characteristic resistances than the given reference value. The exceedance of the strength ranges from 5.7 % for the 250 µm welds of manufacturer B to 25.7 % for the 100 µm welds of manufacturer A. Therefore, the given reference value is safe sided for the investigated OV seams. When looking at Δ_{uw}, it becomes evident that the experimentally determined values for the 100 µm BS seams of manufacturer B and C provide equal or lower resistances than the reference value. The undercut is mainly the result of a comparably high COV (V_x = 7,1 %) of this test series. This reveals that the nominal reference value for the characteristic resistance of welded ETFE foils ($f_{uw23,nom}$) for the ULS represents a strict limit which is not met by all investigated manufacturers although they all have high quality levels.

4 CONCLUSIONS AND OUTLOOK

Within the framework of the WIPANO-ETFE research project different configurations of ETFE area weld seams were investigated to determine a minimum load-bearing capacity which can be used as a nominal reference value for the ultimate limit state design of ETFE structures according to the technical specification FprCEN/TS 19102. This paper presents initial results of these investigations including OV and BS seams in two foil thicknesses of one foil product. The weld seams were provided by three manufacturers A, B and C and executed using the band sealing welding process.

The results show that the currently applied nominal reference value for the characteristic resistance of the tensile strength of ETFE base material ($f_{u23,nom}$ = 40 MPa) is very conservative and can be applied as a safe-sided value for the ULS considering the investigated foil product and foil thicknesses.

The results of the ETFE area weld seams confirm the general knowledge that the load-bearing capacity of welded ETFE foils are significantly lower than the ultimate tensile strength of the corresponding base material. Furthermore, the results show that the experimentally determined characteristic resistances are highly dependent on the execution quality of the weld seam and hence from the manufacturer. Additionally, the investigations indicate that the load-bearing capacity of BS seams is slightly lower compared to the load-bearing capacity of OV seams.

The investigation also showed that the nominal reference value for the characteristic resistance of ETFE weld seams ($f_{u23,nom}$ = 30 MPa) for the ULS as provided in FprCEN/TS 19102 reflects the current performance of the industry. The required nominal value was slightly undercut in one test series and exactly met in another one. This shows that it can be reached in principle, but it sometimes demands special efforts from the manufacturers to reach it. Particularly a uniform welding is important which leads to small scattering of the load-bearing capacities.

Within the framework of the WIPANO-ETFE research project, further foil thicknesses and foil products as well as different welding processes were investigated which will be published in future contributions. Based on the achieved results, the minimum value for the load-bearing capacity of ETFE area weld seams will be reassessed and implemented in the future Eurocode for membrane structures based on FprCEN/TS 19102.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the funding of this research by the German Federal Ministry for Economic Affairs and Energy within the framework of the research project "Welded connections of ETFE structures: Standardisation of execution, testing and design" (funding code: 03TN0011A). Additionally, the authors would like to extend their appreciation to the project partners for their valuable collaboration as well as NOWOFOL for providing the base material.

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