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TESTING OF WELDED ETFE-FOILS FOR QUALITY ASSURANCE

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Summary. DIN CEN/TS 19102 is the first European standard especially addressing the design of membrane structures made from coated fabrics and technical foils. To ensure a holistic approach to the standardisation of membrane structures, informative annexes were added, providing preliminary guidelines for the execution and testing of membrane materials. As part of the transition into a Eurocode design standard for membrane structures, these guidelines have to be extracted and incorporated into dedicated execution and testing standards for membrane structures.
Within the framework of the German WIPANO research project 03TN0011A „Area weld seams of ETFE structures: Standardisation of execution, testing and design“, a five-part German draft standard series, E DIN 18229, was developed covering the quality assurance of welded ETFE-foils. This research project was a joint project with partners from the industry including three manufacturers, two testing laboratories and an engineering office. In this collaboration, the first four parts of E DIN 18229 were completed, which cover the qualification of the welding procedure and the welding personnel. The fifth part, detailing mandatory test methods for welded ETFE-foils as required for the qualification of the welding procedure and welding personnel, was initially conceptualised.
Under the ongoing standardisation work at the Institute for Metal and Lightweight Structures at the University of Duisburg-Essen and in the context of developing an execution standard for membrane structures, E DIN 18229-5 was finalised. The standard includes test methods that can be applied during manufacturing, for internal quality control as well as for initial type testing and external inspections. These methods comprise non-destructive visual testing, peel tests with a tool, manual tensile and peel tests as well as uniaxial short-term tensile tests for welded connections of ETFE-foils. This contribution presents the various test methods in detail. In further standardisation efforts, the E DIN 18229 series is intended to be transferred into an EN standard to be referenced in the future execution standard for membrane structures.

1 INTRODUCTION

DIN CEN/TS 19102 is a technical specification representing the first outcome of national and European efforts to standardise the design, execution, and testing of membrane structures. However, further steps are required for its transformation into a Eurocode: the execution rules and test procedures contained in DIN CEN/TS 19102 must be transferred into separate standards, and additional regulations for execution and testing must be developed.

Within the German WIPANO-ETFE research project, methods and procedures for quality assurance of welded ETFE-foils were developed and standardised in the five-part German draft standard series E DIN 18229 "Welding of ETFE foils for building applications". E DIN 18229-1 to -4 govern the qualification of welding personnel and welding procedures. Testing of welded ETFE-foils is essential for welding procedure qualification, internal and external quality controls, and initial type testing of ETFE-components and is standardised in E DIN 18229-5.

The WIPANO-ETFE project was a joint research project involving six project partners: the University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Essen Laboratory for Lightweight Structures ELLF (UDE/IML, project coordinator), the Laboratory for Technical Textiles and Films of DEKRA SE (DEKRA), Vector Foiltec GmbH, Bremen (VF), se cover GmbH, Obing (SC), Taiyo Europe GmbH (TE) and formTL ingenieure für tragwerk und leichtbau GmbH (formTL), Radolfzell, all Germany. The project aimed to develop concepts and methods for the standardisation of the execution of welded ETFE-foils. Quality assurance concepts were derived both from the experience of the participating manufacturers and from established standards in structural steel welding. The resulting framework is based on three columns: qualification of the welding procedure, qualification of the welding personnel and the definition of suitable test methods for welded ETFE-foils.

Suitable test methods form the core of the quality assurance system for welded ETFE-foils since they are essential for both the qualification of welding procedures and the qualification of welding personnel. In addition, testing of welded ETFE-foils is carried out as part of the internal quality control, initial type testing and external quality control. The developed quality assurance concepts were standardised in the five-part German draft standard series E DIN 18229, see [3] to [8]. E DIN 18229-1 to E DIN 18229-4 govern the qualification of welding procedures and welding personnel, while E DIN 18229-5, covering test methods for welded ETFE-foils, was initially only conceptualised within WIPANO-ETFE. In subsequent research at UDE/IML, E DIN 18229-5 was finalised. The draft standard series E DIN 18229 was introduced as a new standardisation project within the German national standardisation committee NA 005-51-08 AA, chaired by Natalie Strannghöner, head of UDE/IML.

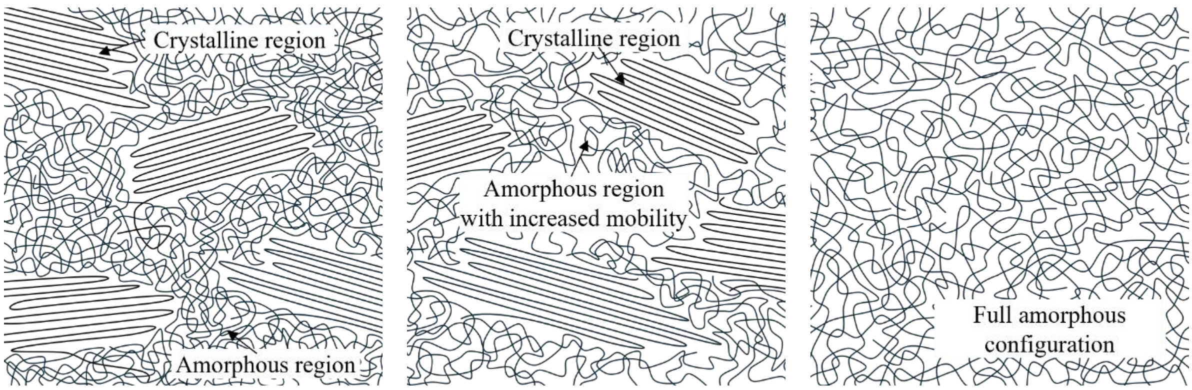
To provide a basis for understanding the mechanisms of welded ETFE connections and the corresponding quality criteria, the fundamental principles of ETFE weld seam formations are outlined first. Subsequently, the standardised test methods for welded ETFE-foils are presented, comprising both non-destructive and destructive test methods for quality assurance.

2 FORMATION OF ETFE WELD SEAMS

As a thermoplastic material, ETFE can be reversibly melted and resolidified upon cooling. This property gives thermoplastics their characteristic weldability. ETFE is a copolymer composed of two alternating monomer units: ethylene (E) and tetrafluoroethylene (($-CF_2-CH_2-$), TFE), arranged in long chain-like macromolecular structures. Within each macromolecule, primary valence bonds act between the constituent atoms. The carbon backbone of ETFE macromolecules provide one of the strongest types of primary valence bonds. Between adjacent chain segments of macromolecules, weaker secondary valence bonds are formed. Although much weaker than primary valence bonds, these secondary valence bonds are reversible and depend on the distance between the chain segments.

As a semicrystalline thermoplastic, the morphological structure of ETFE is temperature dependent. Semicrystalline thermoplastics exhibit three distinct states: the solid state, the rubbery state and the molten state. In the solid state, semicrystalline thermoplastics comprise two coexisting phases: crystalline and amorphous regions. In the crystalline regions, the macromolecules are aligned in parallel, forming tightly packed lamellae, whereas in the amorphous regions, the macromolecules adopt a random coil configuration, see Figure 1 (a). When the material is heated above the glass transition temperature T_g, the macromolecules in the amorphous region gain mobility and increased free volume, while the crystalline structures remain largely intact, see Figure 1 (b). This results in rubber-like behaviour. At temperatures above the melting temperature T_m, the crystalline structures dissolve, and the macromolecules adopt a fully random coil configuration, see Figure 1 (c). Beyond the decomposition temperature T_{dec}, the material undergoes chemical degradation. For ETFE, the melting temperature ranges from 260 °C to 280 °C depending on the foil product, see [10] to [12], while the decomposition temperature T_{dec} is reported to range from 350 °C to 360 °C [13].

Solid state **Rubbery state** **Molten state**



(a) (b) (c)

Figure 1: Morphological structure of semicrystalline thermoplastics [16]: (a) solid state, (b) rubbery state, (c) molten state

Weld seams of thermoplastics are typically formed through a combination of heat, pressure, time and cooling. In the case of ETFE-foils, the heated tool welding process according to DIN EN ISO 4063 [14] is applied, with band welding (German: Heizelement-Rollbandschweißen, HR) and impulse welding (German: Heizelement-Impulsschweißen, HI) according to DIN EN 1910-3 [15] being the commonly used process variants [16]. The corresponding welding units are the traverse welding machine and beam welding machine, respectively. For semicrystalline thermoplastics, weld seam formation proceeds in three stages:

- stage 1: wetting and contact establishment,
- stage 2: interfacial chain diffusion and entanglement,
- stage 3: recrystallisation.

In stage 1, the surfaces of the joining partners get into molecular contact, which is a fundamental requirement for chain diffusion in stage 2 [17]. In order to enable a molecular contact between the two joining partners, the distance between the macromolecules at their surfaces has to be sufficiently small to allow secondary valence forces to act. Initially, a surface contact can only occur at small portions of the interface due to the natural surface roughness [17], see Figure 2 (a). When the joining partners are heated above the melting temperature, both surfaces soften and the effective contact areas increase, see Figure 2 (b). The application of pressure further enlarges the contact area. This process, known as wetting, is characteristic by the progressive growth of molecular contact areas from the initial points of contact, often referred to as “pools” [19]. Therefore, wetting is both a time- and location-dependent process.

Wetting is considered to be complete once the surface structure of both joining partners have been sufficiently deformed to establish full molecular contact across the joining interface, see Figure 2 (c). Herewith, the key factors for achieving molecular contact are the initial surface roughness, the applied heat and pressure as well as the contact time. The overall welding process is considered to be pressure-dependent only due to the stage of contact establishment as the subsequent diffusion and recrystallisation stages are pressure-independent.

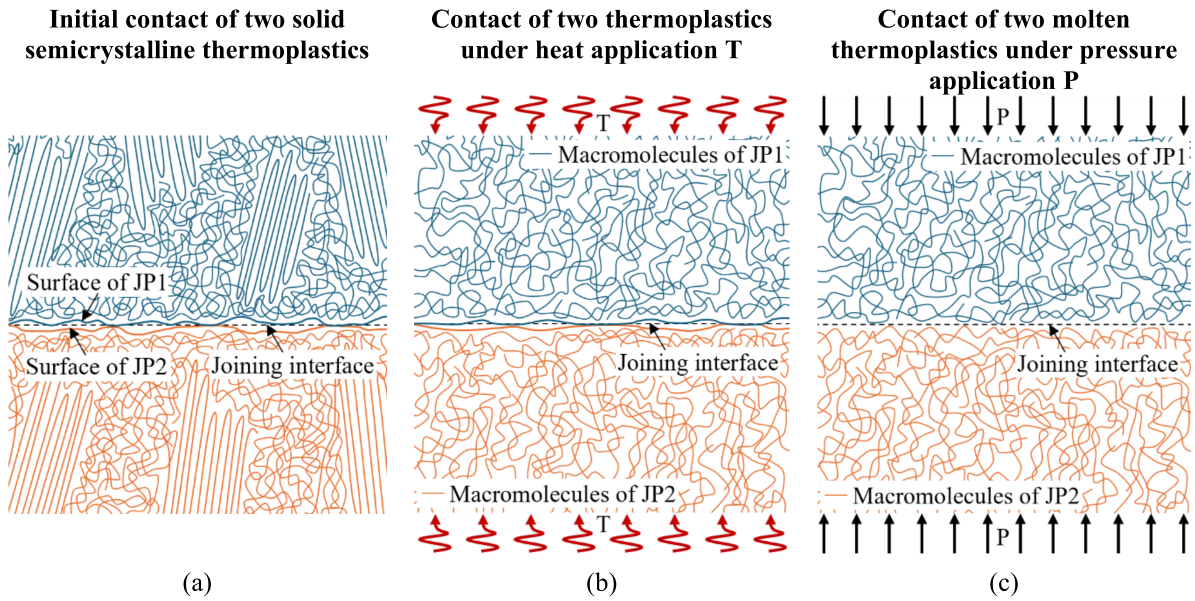
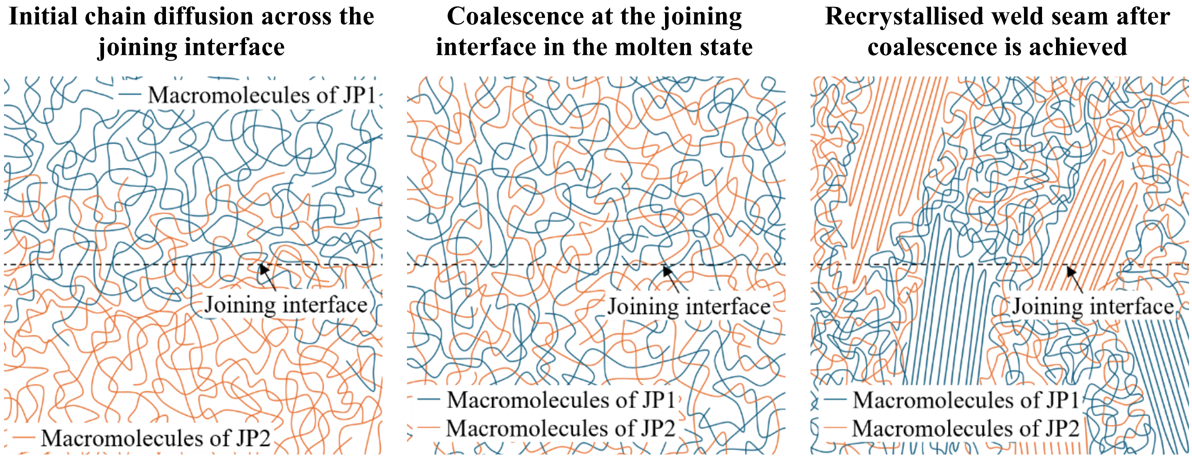


Figure 2: Schematical illustration of contact establishment of two joining partners JP1 and JP2 [16]; (a) initial contact, (b) increased contact under heat application, (c) full molecular contact under pressure application

When two polymer surfaces are brought into molecular contact in the molten state, chain diffusion across the joining interface begins [17]. Consequently, the diffusion stage is also both a location- and time-dependent process. During the diffusion stage, macromolecules from the opposing joining partners interpenetrate the opposite surface, leading to the formation of macromolecular entanglement across the joining surface [19], see Figure 3 (a). Over time, the macromolecular structure at the joining interface progressively approaches a homogenous random coil configuration, a process referred to as coalescence [19], see Figure 3 (b). As a result, the joining interface disappears and a uniform material is formed in the weld seam area, exhibiting mechanical properties comparable to the base material [19]. The first model to accurately describe the motion of the macromolecules in an entangled melt was the reptation model by De Gennes [20].

In the final stage, the homogenous polymer melt cools down and recrystallises, forming crystalline structures across the former joining interface, see Figure 3 (c). Since the degree of crystallisation strongly depends on the cooling rate of the polymer melt [21], the mechanical properties of the weld seam area may differ slightly from those of the base material. The influence of crystalline structures spanning the initial joining interface on the weld seam strength is described by the *Nexus Hypothesis* proposed by Bonten [22].

As described above, a polymer weld seam is not formed instantaneously at a single point but develops progressively through a complex, multi-stage process. Both the formation of the weld seam and the development of the interfacial strength are location- and time-dependent. As the surfaces of the joining partners approach full molecular contact, the interfacial strength approaches the yield strength of the base material, since only secondary valence forces act between the joining partners at this stage [23]. Because no true material fusion has yet occurred, such connections typically fail by separation without that one of the joining partners fails by fracture. In literature [17], these thermally adhesive connections are referred to as seal seams. According to DIN EN ISO 472 [24], in some countries, the term sealing is used for processes in which only the surfaces of plastics are joined. The time required to achieve full molecular contact depends on the applied heat and pressure as well as on the material and surface structure and is typically in the order of a few seconds [19]. The yield strength of ETFE varies depending on the foil product but generally lies between 20 MPa to 25 MPa [25].



(a) (b) (c)

Figure 3: Schematical illustration of weld seam formation of two joining partners; (a) initial chain diffusion across the joining interface, (b) coalescence at the joining interface, (c) recrystallised weld seam

Upon chain diffusion, the interfacial strength progressively increases beyond the yield strength and reaches its maximum once coalescence is achieved [19]. Due to the material fusion, those types of connections are referred to as cohesive bonds. As the interfacial strength approaches the mechanical properties of the base material, the failure mode shifts from interfacial separation to fracture at the weld seam edge. The lower load-bearing capacity of the component "weld seam" compared to the base material can be attributed to both the external geometrical notch at the weld seam edge and the alternated mechanical properties within the weld seam area, which can be interpretated as an internal structural notch [26].

The quality of welded connections is determined by their mechanical properties – primarily its load-bearing capacity – as well as by the failure mode and its visual appearance. In destructive tests such as uniaxial short-term tensile, the load-bearing capacity can be directly quantified. Peel tests can only reveal the principal constitution of the weld seam. High-quality weld seams exhibit load-bearing capacities significantly higher than the yield strength of the base material and typically fail at high plastic strains by fracture at the weld seam edge. In contrast, low-quality connections fail at load-bearing capacities around or below the yield strength of the base material. Such connections usually fail by interfacial separation and are referred to as seal seams.

In non-destructive tests, weld seam quality can only be assessed indirectly. During visual inspection, the weld is examined for its distinguishability from the surrounding base material and for possible irregularities. Vector Foiltec GmbH, Bremen developed a non-destructive test method in which a low peel moment is applied at the weld seam edge to determine whether the connection represents a cohesive or an adhesive bond. It should be emphasised, however, as stated in the introduction to DIN EN ISO 3834-1 [27]: “Quality cannot be inspected into a product: quality needs to be built in. Even the most extensive and sophisticated non-destructive testing does not improve the quality of the product”.

3 NON-DESTRUCTIVE TEST METHODS

3.1 General

Manufacturers currently employ various non-standardised tests for the internal quality control of ETFE-structures. These include, in particular, visual testing (VT) before (VT1), during (VT2), and after welding (VT3), as well as peel testing with tools (PT). All of these tests are considered non-destructive and have been standardised within the framework of E DIN 18229-5. Visual testing of the finished weld seam (VT3) as well as during welding (VT2) are already required in E DIN 18229-4 as the initial step of the welding procedure testing developed for welded ETFE-foils [28]. However, since the other tests – VT1 and PT – are also applied for quality assurance of project welds in ETFE-structure manufacturing, they had to be included and standardised in E DIN 18229-5.

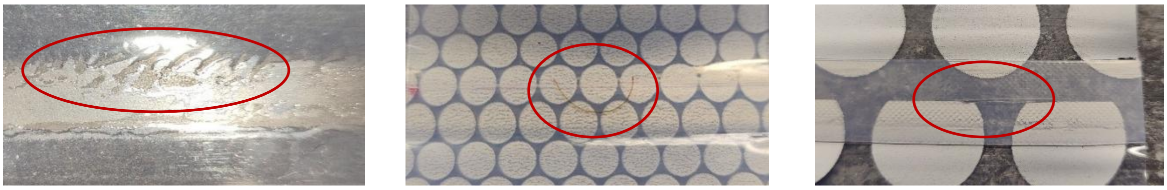
3.2 Visual testing (VT)

Visual inspection of both the base material and the weld seams is of central importance in the construction of ETFE-structures. Upon delivery, many manufacturers conduct incoming goods inspection, during which the delivered rolls are unwound and examined for defects such as foreign inclusions or local damage. To the authors knowledge, at present, non-standardised visual inspections are performed for the cutting patterns after the cutting process and for the weld seams during/after the welding process.

As already mentioned, in ETFE-structure manufacturing, visual testing is carried out before (VT1), during (VT2), and after welding (VT3), depending on the welding process employed. Prior to welding, VT1 must confirm that the geometry and dimensions of the seam preparation comply with the predefined specifications. Manufacturers typically document the characteristics and required parameters for the execution of each specific weld seam detail in – up to now – non-standardised Welding Procedure Specification (WPS). Now, within WIPANO-ETFE, two WPS templates – one for band welding and one for impulse welding were developed and subsequently standardised in E DIN 18229-3. Furthermore, a weld seam preparation typically involves that the surfaces to be joined are clean and free of markings or printing that could form a separation layer within the weld seam. Herewith, it must also be checked whether the cutting patterns are free of defects from the cutting process. If the joining partners have been pre-tacked, their arrangement must likewise be verified for compliance with the WPS.

Visual inspection during welding using VT2 is applied exclusively to band welding (HR), see [12], as this is a continuous welding process. VT2 is particularly recommended for complex and heavily curved weld seams, where continuous monitoring is advantageous. During band welding, the welding personnel inspect the finished weld directly behind the welding head of the traverse welding machine and report any deviations to the personnel positioned in front of the welding head, who are responsible for threading the joining partners into the welding head. Typical deviations include, for example, weld seams outside the predefined range for overlap welds or back strips not centred above the joint in butt weld.

Following the welding process, a more detailed visual inspection (VT3) is performed to detect unwelded areas or major inclusions. In addition, the weld seam edges are examined. The weld seam should be clearly distinguishable from the base material with straight and parallel weld seam edges. The weld seam width, specified in E DIN 18229-3, must also be measured on a random basis and should be at least 6 mm ± 1 mm.



(a) (b) (c)

Figure 4: Detected irregularities in visual tests; (a) irregular weld seam edge, (b) small inclusion, (c) gap between butted joining partners

3.3 Peel test with a tool (PT)

The peel test with a tool (PT) is carried out after the weld seam has been manufactured and, where applicable, before removal of excess material. Although the peel test with a tool is not part of the qualification of a welding procedure, it may be used for quality control of project weld seams during execution. Consequently, the peel test with a tool, developed by Vector Foiltec GmbH, Bremen, was standardised in E DIN 18229-5. For the execution of the peel test with a tool, a rod-shaped and flat tool with a rounded tip is guided with minimal force along the weld seam edge, either between the joining partners or between the joining partner and the back strip, see Figure 5 (a). The foil material must not be damaged in the process. The test is considered passed if the weld seam remains intact. If, however, the joining partners separate, the connection is considered to be insufficient for load-bearing and the test fails. A so-called folding bone, commonly used in upholstery and bookbinding and particularly suitable for sensitive materials, has proven to be an effective tool for this purpose.

(a) (b)

Figure 5: Peel test with tool; (a) conduction at an edge weld seam; (b) recommended tool: folding bone

4 DESTRUCTIVE TESTS

4.1 General

Destructive testing of welded ETFE-foils comprises both manual and machine-based tensile and peel tests. In current ETFE-structure manufacturing, non-standardised manual tensile and peel tests are conducted prior to machine-based testing to assess the weld seam quality. This practice enables to identify low-quality weld seams without the need for time- and therefore cost-intensive machine-based tensile tests. For the same reason, manual tensile and peel tests have been integrated in E DIN 18229-4 [28] for the WPS for welded ETFE-foils. For the quality assurance of welded ETFE-Foils, machine-based tests are mandatory for documenting and qualifying the load-bearing capacity of welded ETFE-foils. Machine-based tests mainly involve uniaxial short-term tensile tests, currently performed according to DIN EN ISO 527-1 [29] and -3 [30]. However, the authors strongly recommend to consider the additional provisions of DIN CEN/TS 19102, Annex I, to achieve comparable fully test results. Since welded ETFE-foils do not exhibit homogeneous material behaviour but rather complex component behaviour, the relevant property to be determined is not the stress-strain behaviour of the material, but the load-bearing capacity of the joint. According to DIN CEN/TS 19102, this corresponds to the 5 %-fractile value of the ultimate tensile stress σ_b as defined in DIN EN 1990 [31].

4.2 Manual tensile and peel tests

Manual tensile and peel tests are classified as destructive tests and, in accordance with E DIN 18229-4, form a part of the welding procedure qualification for ETFE weld seams. The welding procedure qualification concept developed within WIPANO-ETFE defines a two-stage system in which manual tensile and peel tests are required in both stages, see [28]. In stage 1, applicable to ETFE-structures with low consequence classes (CC), they serve as the final assessment of the weld seam quality. In stage 2, applicable to ETFE-structures of all CC, manual tensile and peel tests are conducted prior to the machine-based weld seam test. This allows to identify load-bearing joints with insufficient load-bearing capacity at an early stage without the need of time- and cost-intensive machine-based tests. Therefore, manual tensile and peel tests were standardised in E DIN 18229-5.

The test specimens to be used for such a testing are strip specimens with a width of 15 mm ± 5 mm, see Figure 4 (a), with the specimen length depending on the weld seam detail to be tested. Manual tensile tests are primarily applied to area weld seams and are performed by manually pulling the foil layers on opposite sides of the welded connection, see Figure 4 (b). Manual peel tests are applied to edge weld seams and are performed by manually pulling different foil layers at the same weld seam edge. For manual tensile tests, specimens should have a minimum length of 600 mm, whereas specimens for manual peel tests require only a minimum length of 320 mm. During testing, the test specimen may be fixed to the ground. In manual tensile tests, the weld seam is subjected mainly to tensile stress, while in peel tests it is subjected to a combination of tensile and peel stress. Passing manual peel tests demonstrate high tensile and peel strength without quantifying the actual load-bearing capacity, so manual tensile tests are not necessary.

According to DIN CEN/TS 19102, Table H.10, manual tensile and peel tests are considered as passed if the base material yields either before the joining partners separate or the specimen fails at the weld seam edge, see Figure 6 (c). This criterion verifies whether the load-bearing capacity of the weld seam exceeds the yield strength of the base material, which at room temperature typically ranges between 20 MPa and 25 MPa, depending on the foil product, see for example [25]. Since this stress range lies below the characteristic weld seam strength of f_{uw23} of 30 MPa required by DIN CEN/TS 19102, additional mechanical testing – specifically uniaxial short-term tensile tests – is required within the framework of stage 2 of the welding procedure qualification in order to quantify the load-bearing capacity of the weld seam.

(a) (b) (c)

Figure 6: Manual tensile test of an overlap weld; (a) specimen before testing; (b) manual pulling of the specimen, (c) specimen after successful testing

4.3 Short-term tensile test of ETFE area weld seams

Within WIPANO-ETFE, a standardised test method was developed for determining the short-term tensile load-bearing capacity of ETFE area weld seams. The standardised area weld seam test was developed on the basis of uniaxial short-term tensile tests in accordance with DIN EN ISO 527-1 and -3 and DIN CEN/TS 19102, Annex I. The test parameters were defined by systematic investigations into their influence on the ultimate tensile stress of area weld seams, see [2], [16], [32] and [33]. The standardised area weld seam tests consist of uniaxial short-term tensile tests using the modified test specimen type 2 according to DIN EN ISO 527-3, 6.1.1, with a gauge length L_0 of 50 mm and a width b of 10 mm (MT2-50), see Figure 7 (a). The suitability of a strip specimen with a gauge length of 100 mm and a width of 20 mm is currently under investigation. The standardised test speed is defined such that the resulting initial strain rate corresponds to 200 %/min. Specimens should be cut using a cutter knife with a new blade or a lever cutter. The use of a punch must be verified on a case-by-case basis. Clamping should be carried out with a smeared line pressure with a single-sided Vulkollan coating, see Figure 7 (b). The standardised test method has been verified by tests in the participating test laboratories, see [2] and [16]. The test setup is shown in Figure 7 (c). The resulting standardised area weld seam test ensures consistent comparability and reproducibility of the test results, which are indispensable for a test-based design concept.

(a) (b) (c)

Figure 7: Uniaxial short-term tensile test of ETFE area weld seams; (a) modified strip specimen according to DIN EN ISO 527-3, 6.1.1, (b) smeared line pressure clamping with a single-sided Vulkollan coating, (c) test setup of the Essener Laboratory for Lightweight Structures of the University of Duisburg Essen (ELLF)

4.4 Short-term tensile test of ETFE edge weld seams

The testing of ETFE edge weld seams is also carried out as a destructive test in the form of a uniaxial short-term tensile test following DIN EN ISO 527-1 and -3. The edge weld seam test is applied both by manufacturers as part of internal quality control and by external testing laboratories for external monitoring and initial type testing. The objective of both internal quality control and external monitoring is to determine the characteristic load-bearing capacity of edge weld seams, which is defined as the 5 %-fractile value of the ultimate tensile stress σ_b, analogous to the load-bearing capacity of ETFE area weld seams in accordance with DIN CEN/TS 19102. For this purpose, strip specimens are prepared in which the keder pocket is held in place using a profile defined in DIN CEN/TS 19102, Annex I, see Figure 8 (a). Typically, all foil layers of the tested edge weld seam are pulled during testing. Depending on the foil thicknesses and the number of pulled foil layers, specimens generally fail either in the keder pocket or at the weld seam edges opposite the keder pocket.

In contrast, during initial type tests, the decisive failure mode and the corresponding load-bearing capacity of the entire edge detail are determined. In this case, the complete edge detail is tested, including the keder profile, its sealing and cover, the keder rail and the actual edge weld seam specimen, see example in Figure 8 (b). The width of the edge weld seam specimen should correspond to the width of the cut-to-size keder profile.

Up to now, no standardised test methods for ETFE edge welds exist. Although the planned E DIN 18229-5 specifies test parameter ranges currently in use, there remains urgent need to establish a standardised test method for ETFE edge weld seams. Such a method is essential to ensure the reproducibility and comparability required for an experimental design concept. On this basis, further studies on the minimum load-bearing capacity of edge welds should be conducted, analogous to the investigations conducted within WIPANO-ETFE project for ETFE area weld seam.

(a) (b)

Figure 8: Testing of ETFE edge weld seams; (a) test setup in accordance with DIN CEN/TS 19102, Annex I, for external and internal quality control, (b) test setup of the for initial type testing using the project specific keder profile, here TensoSky® profile system by Taiyo Europe

5 CONCLUSIONS

In the frame of this contribution, various test methods for welded ETFE-foils have been presented, including non-destructive tests such as visual testing before (VT1), during (VT2) and after (VT3) welding as well as the peel test with a tool (PT). In addition, destructive test methods were discussed, comprising manual tensile and peel tests alongside machine-based test methods. For edge weld seams, however, further systematic investigations into the minimum load-bearing capacity and the optimisation of test parameters for machine-based testing remain necessary. These test methods were standardised in the newly developed German draft standard E DIN 18229-5.

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