

Load-bearing Capacity of Structural-Glazing Adhesives on Coated Steel Structures

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Abstract

Is it feasible to establish a structural bond between glass and anti-corrosion coatings? In the construction of segmented steel structures like gridshell roofs, connection profiles must be attached to the steel substructure. Welding or bolting the connection profiles is common, but these methods can damage the anti-corrosion coating and compromise corrosion protection. Alternatively, bonding the glazing to the substructure eliminates mechanical intervention and enables the creation of a continuous corrosion protection layer while preserving the design advantages of structural bonds. Currently, the structural bonding of glass to anti-corrosion coatings is not regulated. Anti-corrosion coating systems typically consist of a primer coat and a top coat. Designers need to consider the adhesion of the additional layers in the load path in structurally loaded bonds to anti-corrosion coatings. However, the force transfer through this multi-layer system and the durability of such bonded joints remains insufficiently investigated. To address this challenge, a series of experimental tests were conducted, including tear-off tests and tensile tests. In total, four different coating systems were examined. Additionally, the effect of accelerated aging on the load-bearing capacity of the structural bond was investigated. The combination of an epoxy-based primer coat and a polyurethane-based top coat showed the best results. The findings of the small part tests led to an application in a full-sized, double-curved steel gridshell with dimensions of 5 m x 3 m. This demonstrator was used to conduct additional tests for air permeability, resistance to driving rain, and wind load on a façade test wall, demonstrating the practical applicability of the structural sealant bond. The investigations provided the load-bearing capacity of structural bonds on anti-corrosion coated steel surfaces experimentally using both small-scale and component-scale tests.

Keywords

adhesive, glass, steel, corrosion protection, gridshell, structural sealant glazing

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1. Introduction

Skylights enhance the natural lighting and the aesthetics of buildings. They are also suitable for creating new spaces in the context of building redevelopments. Gridshell structures may span courtyards with different shapes and serve as architectural highlights. The substructure is often made of steel, when larger spans require a high load bearing capacity. Steel structures require anti-corrosion coatings to ensure durability, extend service life and maintain structural integrity.

Typically, the glazing of gridshell roofs is attached to the steel substructure using toggles or pressure caps. For these systems the connecting profiles are welded onto the steel framework to establish a structural connection. However, this method has several challenges. The necessity of specific connecting profiles increases production and assembly costs. It also limits the inclination change between the glazing units and therefore the design flexibility of double-curved skylights. The components of standard systems are only made for flat or slightly curved shapes. Moreover, on-site welding can compromise the integrity of the anti-corrosion coating, potentially reducing its protective effectiveness.

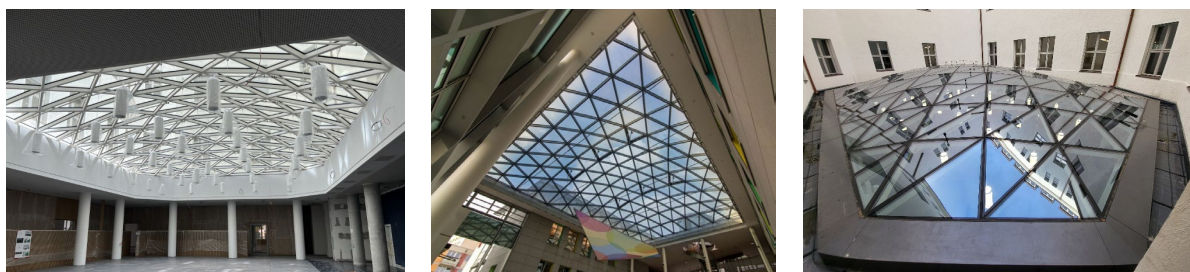


Fig. 1: Gridshell skylights realized by Metallbau Windeck GmbH in Berlin and Potsdam (Metallbau Windeck GmbH, n.d.-a) (Metallbau Windeck GmbH, n.d.-b) (Metallbau Windeck GmbH, personal communication).

An alternative to welding is structural bonding, which presents several advantages. By eliminating the need for additional connecting profiles, structural bonding reduces the complexity of the assembly process. Furthermore, it provides greater design freedom due to the flexible geometry of the adhesive joint.

Despite its benefits, structural bonding on anti-corrosion coatings remains uncommon. The European Assessment Document for Bonded glazing kits and bonding sealants (EOTA, 2018), former ETAG 002-1, does not classify anti-corrosion coatings as suitable surfaces for adhesive bonding. This presents a scientific challenge, as the coating becomes a truly structural part of the bonded joint. Therefore, the mechanisms of force transmission and the long-term durability of these systems must be thoroughly examined before they can be widely implemented.

To address these concerns, experimental tests were carried out at TU Dresden as part of the plusROOF research project. The main goal was to evaluate the adhesive properties of various anti-corrosion coatings and assess the adhesion strength of structural adhesives applied to these coatings. Additionally, large-scale component tests were conducted using a 5.50 m x 3.10 m demonstrator on a façade test wall to simulate real-world conditions.

This paper summarizes the key findings from these investigations, offering valuable insights into the feasibility of using anti-corrosion coatings as suitable surfaces for structural bonding. The results contribute to the development of more efficient, cost-effective, and aesthetically versatile solutions for skylight construction and other steel-based architectural applications.

It is to mention that the chemical composition of anti-corrosion coatings can vary, affecting load-bearing behavior and adhesion. These changes, however, are not detectable by the user during application, posing challenges for quality assurance and performance prediction.

2. Materials

2.1. Coatings

The choice of anti-corrosion coatings was based on the experiences and reference projects of the industrial partner in the research project. The selection was further narrowed down for the presented analysis by preliminary testing (Windeck, 2021). For the experimental analysis in this study, four different anti-corrosion coatings were examined. Three of these coatings consisted of a two-coat system comprising a primer coat and a top coat. The primer coat serves as the primary layer, providing active corrosion protection. The top coat ensures high resistance to UV radiation and weathering, enhancing the long-term durability of the system. The fourth coating analyzed was just a single layer of a primer coat. In this case, the area of the bonding surface would only be coated with the primer coat and not with a top coat.

The steel sheets used in this study were pre-treated by blast-cleaning (Sa 2½) according to DIN EN ISO 8501-1 (2007) before the coating systems were applied.

Table 1: Anti-corrosion coatings investigated in the main experimental test; ¹(MIPA SE, n.d.-a), ²(MIPA SE, n.d.-b), ³(MIPA SE, n.d.-c), ⁴(MIPA SE, n.d.-d), ⁵(Axalta Coating Systems Germany GmbH & Co. KG, n.d.-a), ⁶(Axalta Coating Systems Germany GmbH & Co. KG, n.d.-b).

ID	Manufacturer	Coating-system	Primer coat	Top coat
MI-WAY	MIPA SE	Two-coat system	Acrylic resin1	Pure acrylate2
MI-PU	MIPA SE	Two-coat system	Epoxy resin3	Polyurethane4
AX-PU	Axalta Coating Systems Germany GmbH & Co. KG	Two-coat system	Epoxy resin5	Polyurethane6
MI-EP	MIPA SE	Only primer coat	Epoxy resin3	-

2.2. Adhesives

The concept of bonding the glazing directly to the steel substructure is strongly linked to structural sealant glazing (SSG) systems. Hence, silicone adhesives qualify because of their good adhesion to glass. Their flexibility also enables the compensation of different thermal elongations. Therefore, a commercially available two-component silicone adhesive was used for the tensile tests as well as in the component tests on the demonstrator. This silicone adhesive is specifically designated for application in the intended SSG system.

To assess the adhesion of the coatings on the steel surface in tear-off tests, a high strength auxiliary adhesive was necessary. Two epoxy resin adhesives were used. These epoxy resin adhesives are not intended for use in the final structural sealant glazing application.

3. Experimental tests

3.1. Overview

The experimental investigations were divided into three phases. First, preliminary tests were conducted to select suitable coating systems. These tests (Windeck 2021) are not discussed further in this paper. In the second phase, small-scale tests evaluated the adhesion of structural glazing adhesives to various coatings. Tear-off tests according to DIN EN ISO 4624 (2016) were conducted to examine the adhesive strength of the coatings on steel surfaces. Tensile tests according to EOTA (2018) were carried out to investigate the bond strength of the structural glazing silicone adhesive on the anti-corrosion coatings. In the third phase, the structural glazing system was analyzed at the component level. A demonstrator was fabricated and tested.

3.2. Tear-off tests

The tear-off tests focused on evaluating the adhesive strength of the coating on the steel surface and the adhesive strength between the primer coat and top coat. In the tear-off tests, a stainless-steel test stamp (\varnothing 24 mm) was bonded to a coated steel sheet (75 mm x 75 mm). The auxiliary adhesive was used to minimize the risk of cohesive failure within the adhesive layer. The coating was scored around the stainless-steel test stamp down to the substrate surface to prevent the surrounding coating from affecting the test results. This results in a bonded contact area of 452 mm². A tensile force according to DIN EN ISO 4624 (2016) procedure B was applied to the stamp while simultaneously measuring the load. A test speed of 1 mm/min was used. To evaluate the adhesive strength of the coatings on the steel surface, the failure loads and failure patterns of the test specimens were analyzed. The failure loads provided quantitative values of adhesive strength, while the failure patterns helped assess the reliability and significance of these values. A cohesive failure within the individual layers of the coating or an adhesive failure either between the coating layers or between the primer coating and the steel sheet was desired.

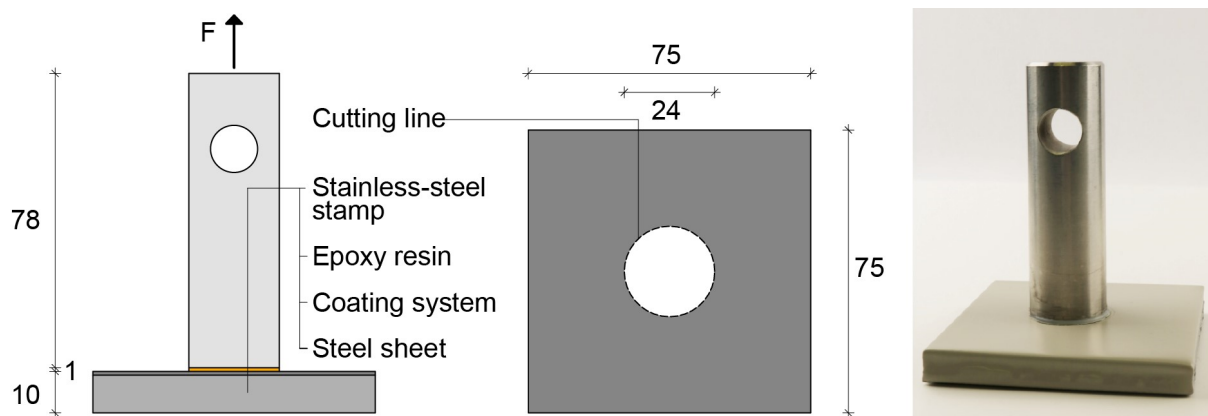


Fig. 2: Test specimen for tear-off tests.

3.3. Tensile tests

The tensile tests focused on evaluating the adhesive strength of the silicone adhesive on various corrosion protection coatings. In this test, a coated steel sheet (40 mm x 50 mm) was bonded to a glass plate using the silicone adhesive. Both the glass plate and the coated steel sheet were pre-treated with an adhesion promoter. The silicone bond measured 50 mm in length and 12 mm in width, resulting in a bonded contact area of 600 mm². The specimen configuration followed design as specified in EOTA (2018), figure 2.2.14.3.2.1. A tensile force was applied at a test speed of 5 mm/min until failure.

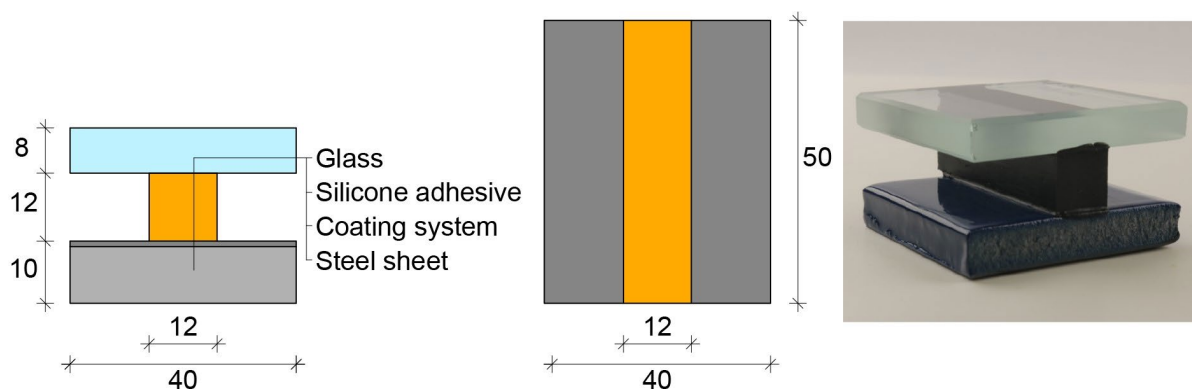


Fig. 3: Test specimen for tensile tests.

To evaluate the adhesive strength of the silicone adhesive on the coated steel surface, the failure loads and failure patterns of the test specimens were analyzed. The failure loads provided quantitative values of adhesive strength, while the failure patterns helped assess the reliability and significance of these values. According to EOTA (2018) the validation criteria is a rupture of minimum 90 % cohesive within the adhesive bond.

3.4. Material aging

To evaluate the effects of artificial aging, both unaged reference samples (REF) and artificially aged samples were tested. The aging process followed standardized procedures to simulate real-world environmental conditions. For the tear-off tests, only the steel sheets were artificially aged. After aging and a reconditioning phase, the stainless-steel test stamps were bonded to the steel sheets. In contrast, the specimens for the tensile tests were fully assembled before undergoing the aging process, ensuring that the silicone bond was also subjected to the aging process. The samples underwent the following aging programs:

Table 2: Artificial aging programs.

ID	Exposure	Value	Standard / Guideline
UV500 / UV1000	Ultraviolet radiation	500 h / 1000 h	EOTA (2018) clause 2.2.14.4.1
NSS	Humidity and sodium chloride	480 h	EOTA (2018) clause 2.2.14.4.2 DIN EN ISO 9227 (2017) DIN EN ISO 12944-6 (2018)
SO ₂	Humidity and sulphur dioxide	20 cycles, 24 h each	EOTA (2018) clause 2.2.14.4.3 DIN EN ISO 3231 (1998)
REI	Detergent solution	500 h	EOTA (2018) clause 2.2.15.1.6
CH	Water condensation	240 h	DIN EN ISO 6270-1 (2018) DIN EN ISO 12944-6 (2018)

DIN EN ISO 12944-6 (2018) defines minimum values for residual tear-off-strength of exposed coatings. Generally, all specimens have to exceed the limit of 2.5 N/mm². This limit value increases to 5.0 N/mm² if adhesion loss of the coating occurs.

Besides aging, the specimens for the tensile tests were tested under extreme temperatures:

- Low temperature: - 20 °C (TLO)
- High temperature: + 80 °C (THI)

In the tensile tests the average strength must not fall below 75 % of the initial strength (REF) both under increased temperatures (THI) and after artificial aging, according to EOTA (2018). In addition, the adhesive layer must fail cohesively by more than 90 %.

4. Results

4.1. Tear-off strength of the coating systems

To evaluate the strength of the anti-corrosions systems as part of the structural loaded bond, tear-off tests were analyzed. Figure 5 shows mean tensile strength values as well as the range of results for each coating system and aging scenario. Each test series consisted of five individual test specimens. In the majority of the tear-off tests, the specimens failed within the coating or between the coating and the metal surface of the steel sheets. Hence, the results allow a clear evaluation of the coating's tensile strength.



Fig. 4: Failure patterns of tear-off test specimens (cohesive failure within primer coat; adhesive failure on metal surface, mixed failure).

Comparing the reference (unaged) series (REF), the AX-PU coating system has the highest tensile strength value (14.4 N/mm²). Followed by the MI-PU and MI-EP coating systems with a strength level of 7.2 N/mm² - 8.4 N/mm². The acrylic resin-based coating system MI-WAY showed the lowest tensile strength value with 4.3 N/mm².

The artificial aging UV500, UV1000, NSS, and SO₂ generally led to an increase in tensile strength for the MI-EP, MI-PU, and MI-WAY coating systems. An exception was observed in the MI-EP system and SO₂, where tensile strength remained nearly unchanged. For the AX-PU coating system, these artificial aging resulted in almost no change in tensile strength. REI and CH caused a significant reduction in tensile strength for the MI-EP, MI-PU, and AX-PU coating systems. For the AX-PU coating system, REI caused a decrease in tensile strength by 77 %.

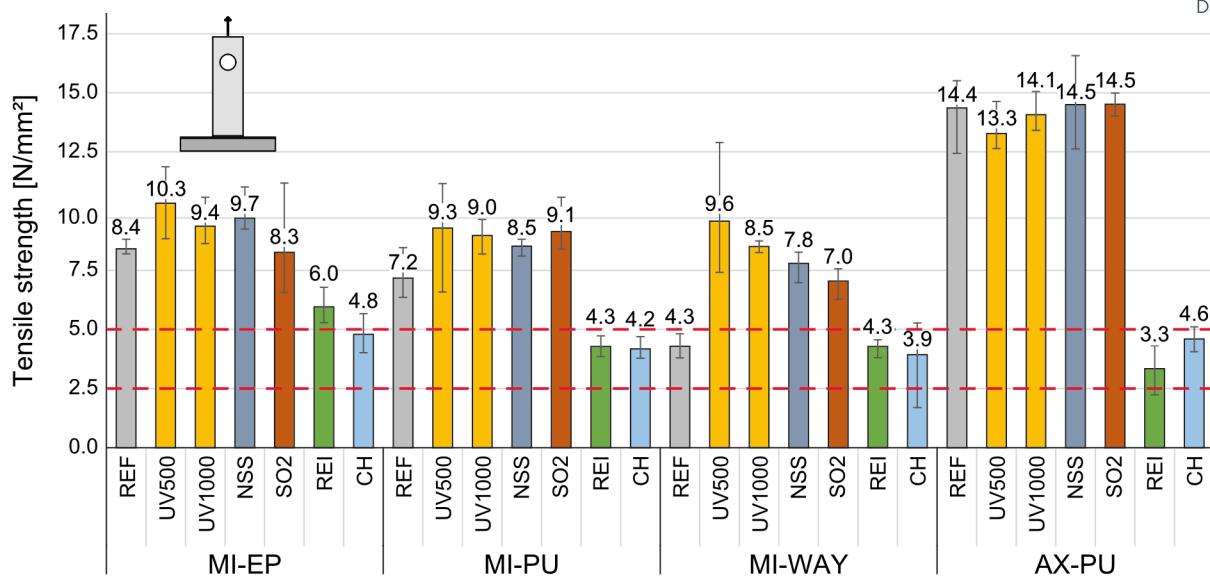


Fig. 5: Results of the tear-off tests as a bar chart, showing the mean tensile strength values (bars) and the range of values of each test series; dashed lines mark limits according to DIN EN ISO 12944-6 (2018).

Analysis of failure patterns showed that the specimens predominantly failed either within the coating itself or at the interface between the coating and the steel substrate. The observed reduction in tensile strength after exposure to REI and NSS correlates with partial adhesive failure at the steel substrate in MI-EP, MI-PU, and AX-PU. Initial signs of corrosion were visible on the metal surfaces of the failed specimens.

In the shown tear-off tests according to DIN EN ISO 12944-6 (2018), coating systems have to achieve a minimum tensile strength of 2.5 N/mm² after aging. All test results exceeded this level. If adhesive failure occurs between the steel surface and the primer coat, the minimum tensile strength increases to 5 N/mm² (DIN EN ISO 12944-6, Tab. 5 and 6, 2018). The MI-EP, MI-PU, and AX-PU coating systems showed such a failure pattern (Fig. 4 middle) after being aged under REI and CH exposure. The failure strength reaches values close to 5 N/mm² but did not fulfill the criteria of DIN EN ISO 12944-6 (2018).

4.2. Performance of the SSG system under tensile force

To evaluate the tensile strength of the SSG system, tensile tests were analyzed. Figure 5 shows mean engineering stress for each coating system and aging scenario. Each test series consisted of ten individual test specimens.

All coating systems showed similar tensile strength values of ~1,1 N/mm² in the reference series (REF). For all coating systems, the tensile strength increased when tested at low temperatures (TLO) and decreased when tested at high temperatures (THI). The MI-WAY coating system showed a tensile strength of 71 % of the reference value at high-temperature conditions (THI). With a few exceptions in the case of UV500 and UV1000 exposure, all artificial aging scenarios resulted in a reduction in the tensile strength of all coating systems.

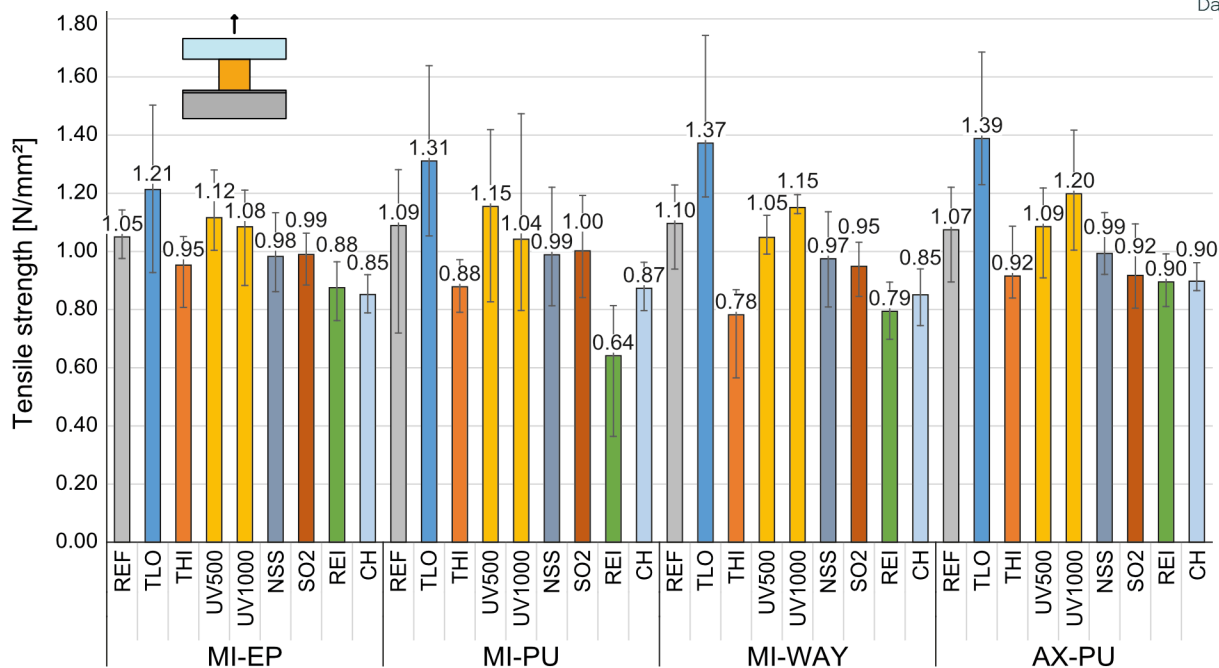


Fig. 6: Results of the tensile tests as a bar chart, showing the mean tensile strength values (bars) and the range of values of each test series.

In the REF series, all samples failed cohesively within the adhesive layer. At high temperatures (THI), MI-WAY showed overstressing in the failure pattern with excessive cohesive failure of the top coat or primer coat or adhesive failure between the top coat and primer coat. An exact classification was not possible due to similar color of top coat and primer coat. Adhesive bonds failed cohesively under all other aging conditions except for MI-PU under REI exposure, where failure was largely adhesive on the steel substrate.

The mean tensile strength of the silicone adhesive in the reference series in this study is 1.1 N/mm² and is therefore below the tensile strengths determined in the tear-off tests. Furthermore, the maximum permissible stress of the silicone adhesive is only 0.14 N/mm² (DIBt, 2014), which is significantly lower than the required minimum tensile strength in the tear-off tests.

The MI-EP and AX-PU coating systems fulfill the requirements of EOTA (2018). All tested specimens failed cohesively. The strength did not decrease below 75 % of the initial value of the REF series after artificial aging. The other two coating systems do not meet the requirements. The mean tensile strength of MI-WAY at high temperatures (THI) achieves only 71 % of the initial value at ambient temperature. The MI-PU system fails adhesively on the steel substrate after REI exposure and the residual tensile strength is only 59 %.

5. Discussion

Silicone adhesives have a pronounced resistance to temperature and environmental exposure. In addition, silicones can develop very good and resistant adhesive properties on many technical surfaces. Different manufacturers supply adhesives approved for load-bearing applications in SSG-facades. According to the related European Technical Assessments e.g. ETA 01/0005 (UBAtc, 2017), ETA 03/0038 (DIBt, 2014), ETA 08/0286 (CSTB, 2013) suitable substrates for those adhesives are uncoated and coated soda-lime glass, stainless steel and anodized aluminum. The presented test series reveals that the requirements such as failure pattern and residual strength after aging could also be met by wet coated steel. However, the criteria are only met by one out of three coating systems tested within the study. To emphasize it again, the chemical composition of anti-corrosion coatings can vary, which affects durability, load-bearing behavior and adhesion. Therefore, further experimental investigations are recommended.

Additional testing of the tear-off-strength showed an onset of corrosion and significant strength decrease for all selected coating system after being exposed to high humidity (CH) and immersion in cleaning agent (REI). This also applies to the coating (AX-PU) which has passed the requirements of the EOTA (2018). Although the tear-off-strength is still far beyond the expected loading in glass roofs and typical SSG applications it may become critical with further progression of the corrosion. On the other hand, the level of corrosive exposure was set quite high to be on the safe side. Hence, future studies should also address a more detailed evaluation of realistic exposure levels for the bond and the coating of the steel structure for glass roofs. It is expected that a lower level of corrosive exposure could lead to results that achieve the tear-off-strength limits stated in DIN EN ISO 12944-6 (2018). The determined values were rather close to the limit. Alternatively, a sufficient safety margin could be applied to expected load-bearing capacity of the joint as described in Momber (2020) for the subsequent mounting of metal brackets onto coated steel substrates.

Direct bonds on the base coat (MI-EP) showed also promising results. However, the additional effort for masking the adhesive zone for the second coating process and expected tolerances (substructure, glazing, bonding geometry) lead to the decision to recommend the coating system AX-PU for further testing in component size.

6. Demonstrator

The aim of this component size tests was to evaluate the adhesive strength of the structural sealant bond under realistic manufacturing quality and loads. For this purpose, a demonstrator with dimensions of 5.50 m x 3.10 m was fabricated, featuring a double-curved gridshell roof with a total area of approximately 17 m². The structure consisted of a coated steel substructure (AX-PU) and triangular insulating glazing units (IGU). The triple IGUs were bonded using the silicone adhesive. To enhance adhesion, both the coated steel substructure and the glass were pre-treated with adhesion promoter. The adhesive joint had a continuous width of 15 mm and a height of 10 mm.

The demonstrator was installed vertically in a window and façade test wall, and the test procedure was conducted in accordance with the product standard for curtain walls DIN EN 13830 (2020) (Seidel, 2023). The investigations included air permeability testing, driving rain tightness assessment, and resistance to wind load evaluation. Additionally, an increased load beyond the permissible limit was applied to analyze the structural behavior under extreme conditions.

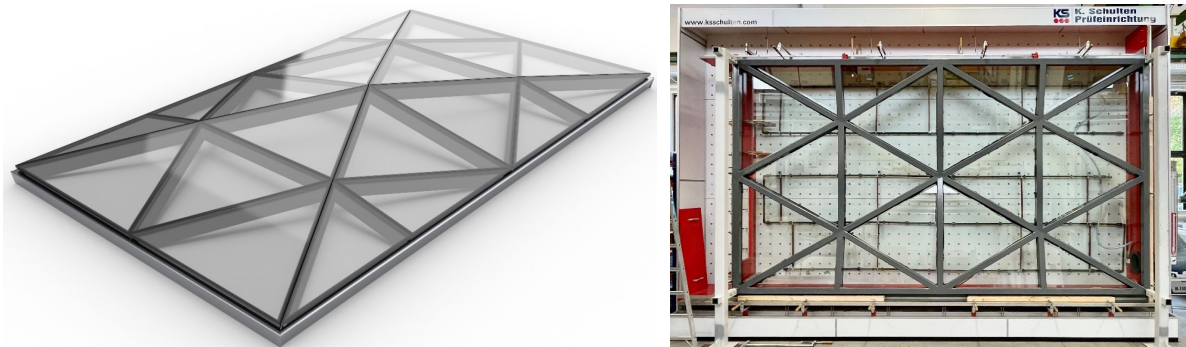


Fig. 7: Gridshell demonstrator for experimental tests in component size; render image (left), installed in a façade test wall (right).

The demonstrator exhibited excellent performance across all tests. It achieved an exceptional air permeability class (AE) according to DIN EN 12152 (2002) and a driving rain tightness class RE₁₀₅₀ in accordance with DIN EN 12154 (2000). Even under increased load conditions, the observed deformations remained below the limit values according to DIN EN 13116 (2001) and no damage to the construction was detected. These results confirm the practical applicability of the structural sealant bond, demonstrating its suitability for SSG applications.

7. Conclusions

Steel-glass-roofs are still on demand for new and existing buildings. Individual requirements of clients and the unique character of many buildings govern the architectural design and realization of such projects. The direct bonding of the glazing onto the substructure offers multiple advantages, a broad geometric freedom in particular. Therefore, the study assesses the bonding properties and aging stability of silicone bonds on anti-corrosion coatings for steel. The results are promising since the requirements of the EOTA (2018) are achieved by at least one of the selected coatings in combination with a structural sealant. Still, the influence of the coating composition on the whole bond and realistic corrosion exposure requires further research and in-depth analysis. A life-size demonstrator proves applicability and load-bearing capacity under realistic conditions.

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