Challenging Glass 2 – Conference on Architectural and Structural Applications of Glass, Bos, Louter, Veer (Eds.), TU Delft, May 2010.

All Glass Enclosure with Transparently Bonded Glass Frames

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This case study describes the path to an all glass enclosure that was recently built at the Leibniz Institute for Solid State and Material Research in Dresden. The idea of a fully transparent structure without distracting metal bolts or clamps was developed from the first idea to final solution in close collaboration between the client, the design team, researchers and industrial partners. Four glass frames, joined by transparent acrylate adhesives at their edges, support the outer walls and the ceiling of the glass enclosure. Regular loading scenarios as well as different failure scenarios were analysed to evaluate redundancy of the structural system. Comprehensive testing was carried out, based on previous research on acrylate adhesives.

Keywords: Glass, Adhesive, UV- and light-curing Acrylates, Bonded glass frames

1. Introduction

A helium liquefaction unit was recently put into operation at the Leibniz Institute for Solid State and Materials Research in Dresden, which uses liquid helium for its research on superconductors and magnetic materials. Historic pressure vessels form an impressive part of this unit. It was the client's demand to display this technical object and provide an insight into the innovative and technology-dominated activities of the institution. Hence, the architectural design follows the idea of a highly transparent structure, which has been produced for the first time in Germany. The cylindrical vessels were placed in a fully glazed enclosure directly in front of the institute's main entrance. The enclosure was made of bonded glass frames and a fully glazed envelope. All components are connected without using additional metal fasteners. Adhesives offer the unique possibility to join glass in form of a substance-to-substance bond, which allows a homogenous load transfer, resulting in a significant reduction of local stress peaks in comparison to clamped or bolted connections.

2. Project Facts

The high pressure storage comprises ten steel vessels, each approximately 6 m high. The bigger part of the unit is located in a concrete trough below ground. A glass enclosure measuring approximately 7.70 x 4.40 m on plan and about 2.50 m in height covers the upper part of the unit and provides weather protection. Being transparent, it reveals the raw steel tanks and the supply circuit. Four glass frames at intervals of 1.90 m support the transparent enclosure (Figure 1).

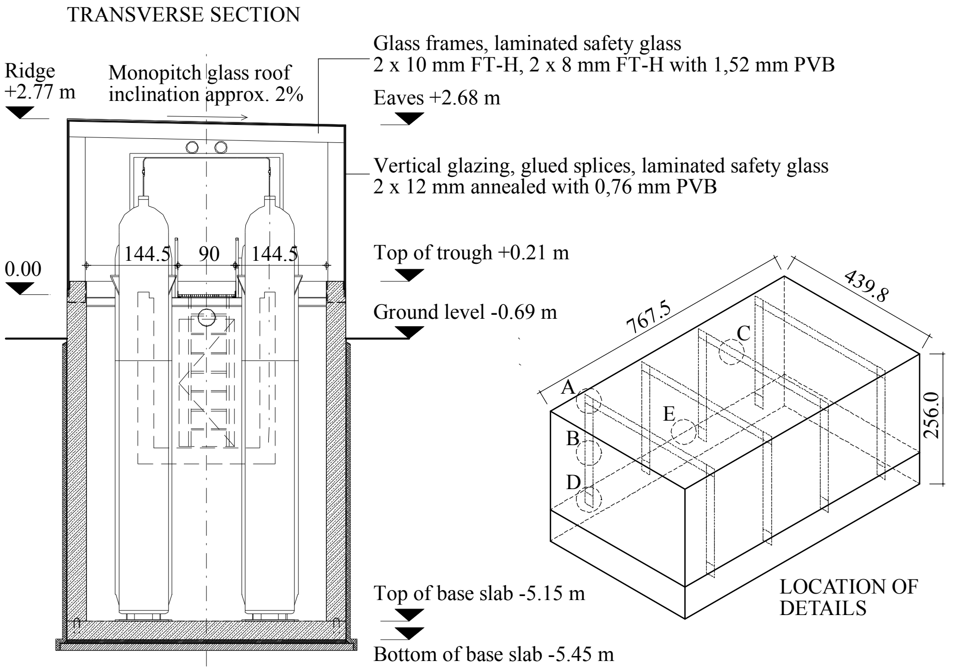


Figure 1: Fully glazed enclosure, transverse section (architects: Blum und Schultze Architekten, Dresden).

The frame members are made from four-ply laminated safety glass. Each ply is fully tempered and heat-soaked. At the corners the outer plies of the posts overlap with the inner plies of the rails to form what woodworkers would call a “corner bridle joint” (Figure 2). The posts and rails of each frame are connected at the corners by means of a transparent radiation-cured acrylate adhesive in double shear. The thickness of the bonded joint is governed by the PVB-interlayer, in this case 1.9 mm. The construction principle was adopted from the glazed entrance foyer to the Broadfield House Glass Museum in Kingswinford (UK) [1], which can be regarded as a pioneer of bonded glass frames. However, this early example only employs a lean-to frame. A full portal frame was used later for the entrance roof of the Buchanan Street Station in Glasgow (UK) [2].

The structure is braced by the single-glazed outer shell made from laminated safety glass. The lateral glass panes cover the whole length of the enclosure. Hence, their dimensions significantly exceed the standard-size of usual flat glass. The glazing of the monopitch roof, however, is divided into three elements. The glass panes are bonded to the frame members over their full length with a structural silicone adhesive, which is also used for joining the panes themselves.

The interior of the glass enclosure is not open to the public and can only be accessed by instructed maintenance and cleaning personnel via an underground entrance. Thus, the glass structure could be built as a quite homogeneous façade without doors and metal fittings. The enclosed room does not require heating or cooling. A venting system prevents the inner glass surfaces from fogging in case of high humidity.

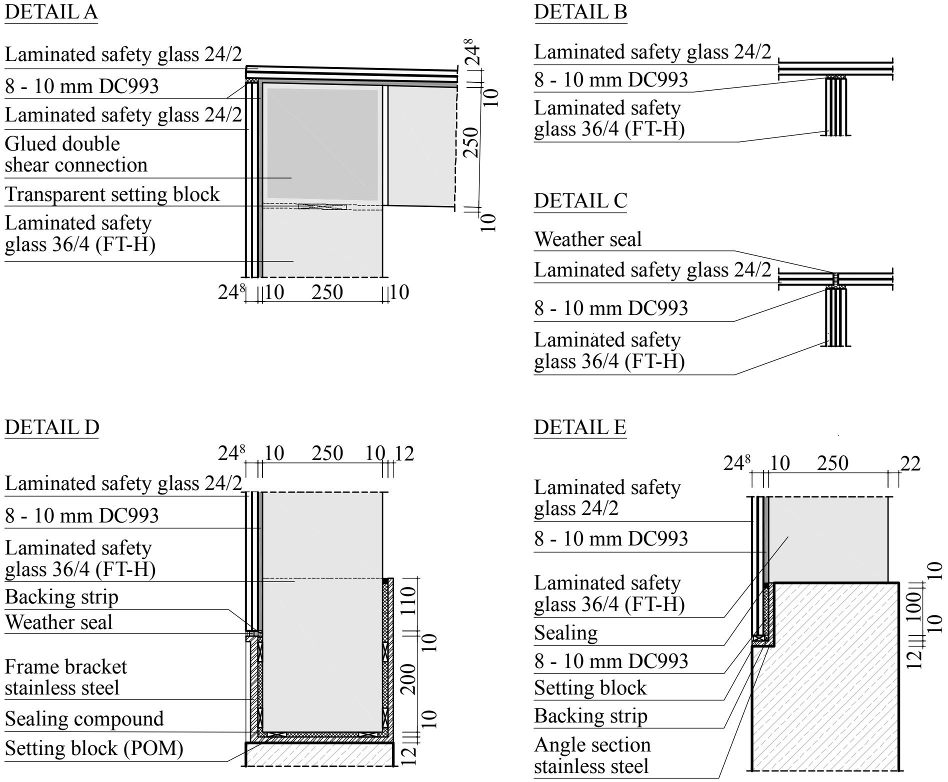


Figure 2: Details - frame corner (A), connection of vertical glazing and frame (B), connection of horizontal glazing and frame (C), base mount (D), connection of vertical glazing and concrete trough (E).

3. Structural Design

3.1. General conditions

There are no regulations covering the use of load bearing adhesive joints for glass in Germany apart from [3] for structural sealant glazing (SSG) systems. However, those are limited to curtain walls with all-side linear bonded glazing units under short-term loading. Hence, this glass structure requires verification of applicability by an individual approval. The structural design bases on a redundant system and on the numerical verification of realistic failure modes. Substantial theoretical and experimental research on acrylate adhesive bonds was necessary to prove a sufficient safety level of the bonded joints.

Particularly, the restricted access to the interior of the glass enclosure simplified the effort gaining this first-time approval by the senior building authority. Accessibility limited to instructed personnel reduces the risk of accidental damaging. The glass enclosure has a slightly elevated position on top of the concrete trough for additional protection of the glass components. The well observable location in front of the main entrance provides a raised inhibition threshold against vandalism as well as a facile detectability of flaws and visible defects.

3.2. Design scenarios

The temperature-dependent material behaviour of the acrylate adhesive has a significant influence on the flexibility of the bonded corner joint. To meet the requirements of a fail-safe concept, a transparent plastic setting block carries the vertical load in the event of failure of the adhesive. Additionally, the block prevents creeping of the bonded joint under long-term loading, which otherwise may lead to large deformations and unwanted glass-glass contact.

The glass frames are clamped at their base into stainless steel brackets and fixed into position using plastic packers. Thus, the frame posts are rigidly connected to the concrete trough. The portal glass frames, which support the roof and the vertical glazing, are used for cross bracing of the structure. Longitudinal bracing is provided by the lateral glazing. The vertical glazing also prevents people from falling into the concrete trough. Hence, their impact resistance was analysed.

The redundant design of the structural system guarantees that neither the failure nor a partial damage of a single structural component result in a collapse of the whole structure. The following relevant scenarios were examined:

a) regular scenario: glass and adhesive joints intact
   temperature-dependent flexibility of the bonded corner joint
b) failure scenario no. 1: complete failure of the adhesive joint
   hinged frame corners, transfer of vertical loads from the rail to the post via the transparent setting block, horizontal loads carried by cantilevered frame posts
c) failure scenario no. 2: complete failure of horizontal glass elements (panels, rails)
   only clamped frame posts and vertical glass elements prevent people from falling into the concrete trough

3.3. Numerical analysis

Stresses and deformations were calculated using finite element analysis (Figure 3). The structural behaviour of the full glass enclosure was simulated in one global model. Submodels were used where the design requires a more detailed analysis of particular structural elements or the bonded joint.

The resulting stresses were interpreted referring to the experimentally determined and statistically evaluated strength values. Hence, global safety levels could be calculated for regular load scenarios respecting the temperature-dependent behaviour of the adhesive as well as for different failure scenarios.

Generally, verification of the impact resistance of the vertical safety barrier glazing requires pendulum impact tests. However, in this case the impact resistance was confirmed by simulation using nonlinear transient dynamic finite element analysis. Simulation of pendulum impact testing offers enormous economic advantages, because costly mock-up testing can be omitted. Additionally, the computer-aided analysis allows a more profound assessment compared to experimental testing. Numerical models were validated and verified according to [4] and [5].

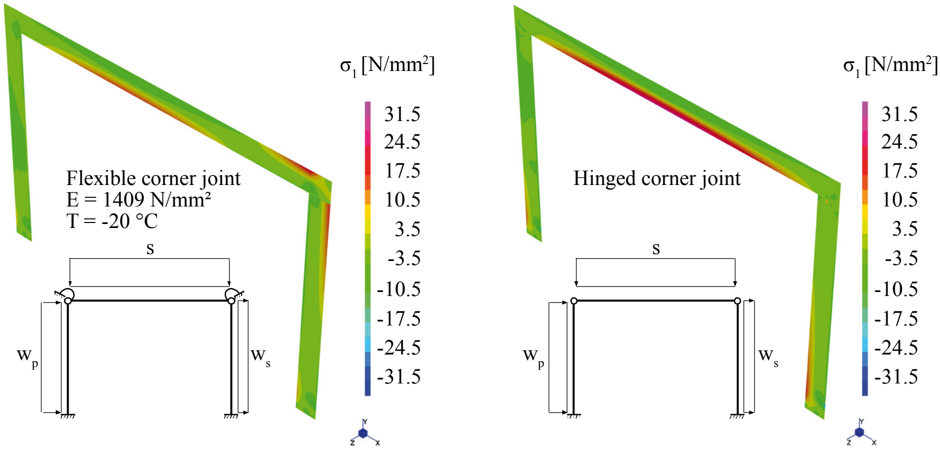


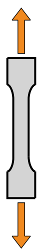
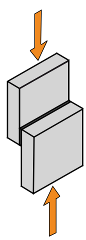
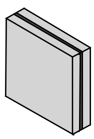
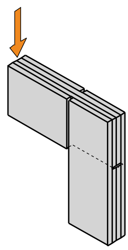
Figure 3: Stress distribution for different states of the structural system.

4. Experimental Analysis

4.1. Programme of tests

A complex programme of tests for the approval procedure for the bonded frames was drawn up jointly by the design team, the senior building authority and the testing centre appointed. The experimental analysis comprised studies of the material behaviour, the adhesion of aged and non-aged specimens, the load-bearing capacity and the production method. Table 1 gives an overview of the tests conducted. Time-consuming ageing test could be minimised due to comprehensive knowledge from previous research on glass-metal bonds with acrylate adhesives [6], [7]. First tests on glued frame corners supplied promising results: the adhesive joints remained intact while the glass failed [8].

Table 1: Programme of tests

	 Standard dumb-bell specimen	 Compression shear specimen	 Glass-glass bond sample	 Specimen component
Material properties Load bearing capacity	30 tests	30 tests	-	6 tests
Ageing	-	20 tests	-	-
Application Curing	-	-	20 tests	16 tests

4.2. Material behaviour

The numerical analysis required an explicit description of the adhesive's material behaviour at different temperature and strain levels. A maximum value of +60 °C was specified by expertise. Hence, the adhesive material was indentified by means of tensile tests on standard dumb-bell specimens at temperatures of –20 °C, +23 °C and +60 °C. The shallower curve in the stress-strain diagram (Figure 4) clearly reveals the low material stiffness at higher temperatures. The data from the tensile tests with contactless biaxial deformation measurement enabled direct calculation of the elastic modulus and Poisson’s ratio. The elastic modulus is determined according to [10] using the average values of the stress-strain-relation.

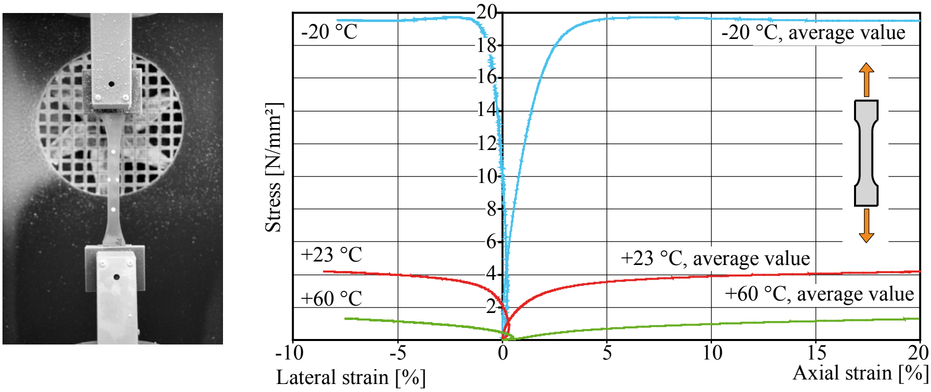


Figure 4: Tensile test for determining the material parameters, test set-up and stress-strain-diagram.

The shear strength values were determined using small test specimens [9]. Single-shear glass to glass bonded connections were tested in a compression shear test. Some of the test specimens were subjected to accelerated ageing and subsequently tested at room temperature. Climatic cycle tests and immersion in cleaning agent have proved to be relevant ageing scenarios for acrylate adhesive joints [6]. The results of the shear tests also indicated a temperature-dependent behaviour. Therefore, limit value considerations reflecting different stiffnesses are included in the structural calculations.

Tests on specimen components were carried out at room temperature to establish the load-carrying capacity of the bonded glass frame corner. The dimensions and glass build-up of the test specimen reflected those of the actual corner detail of the original component. In the test setup, the glass post was clamped in a frame. The critical moment at the corner was used as the characteristic load and applied in form of an equivalent load at the outer end of the rail segment. The test programme provided for an incremental increase in the loading up to three times the characteristic design load. Vertical forces were directly transferred via the plastic setting block.

All six specimen components tested within the scope of the approval procedure withstood the specified load without any failure of the adhesive joint or the glass. This constitutes verification of applicability in the meaning of building legislation. The production of the frames and their installation on site could therefore be initiated and successfully completed.

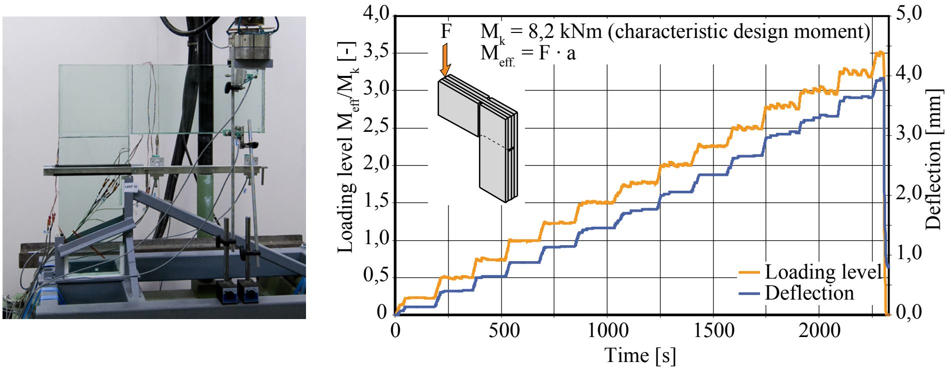


Figure 5: Verification of load bearing capacity: test set-up and results.

4.3. Studies of the production and curing of the adhesive joint

Acrylate adhesives are frequently used for point or linear joints. Building a "patch" connection in double shear, the challenge was to introduce the adhesive into the planar joint, barely 2 mm wide, without any bubbles. Furthermore the aim was to achieve homogenous curing of a relatively large amount of adhesive. The final design parameters were determined on the basis of a series of curing tests [9]. These have an influence on both the visual (Figure 6) and the structural properties of the joint.

The one-part, solvent-free acrylate adhesive cures very quickly upon being exposed to visible light or UV radiation. The full strength of the adhesive and all other material properties relevant for the adhesive joint are achieved as soon as curing is complete. Subsequent curing or additional fasteners at the joints are not necessary, which enables a fast production. With a viscosity of 50,000 mPas, the adhesive exhibits highly viscous flow characteristics. In order to apply the adhesive, a suitable flat nozzle was developed that could be attached directly to the cartridge of the adhesive (Figure 7).

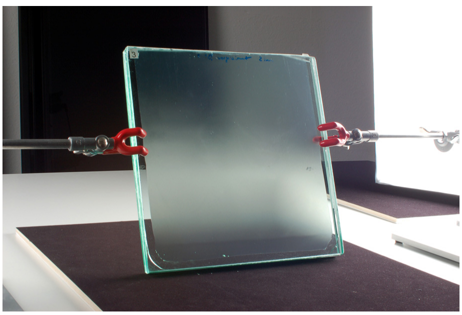


Figure 6: Studies of curing parameters - haze of the adhesive after curing with intense radiation power.

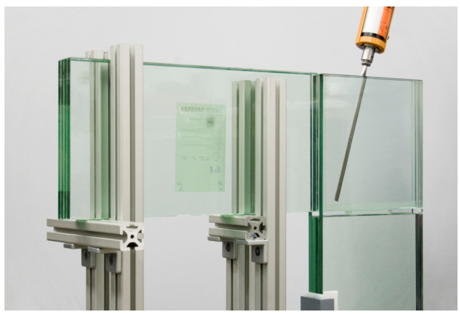


Figure 7: Production studies - application of adhesive to the test specimen with a flat nozzle.

Particular attention has to be paid to the shrinkage behaviour of the adhesive. Contraction is prevented by the stiff members at the joint. A decrease in volume whilst curing leads to air being sucked into the joint and hence to imperfections and bubbles in the adhesive. Significant impairments as a result of this phenomenon are judged critically in terms of both, the appearance and the load-carrying capacity of the joint. In the course of the technology testing it was discovered that this behaviour could be counteracted by applying an additional reservoir of adhesive along the side and top of the adhesion surfaces and by exposing the joint to the radiation intermittently. At the end of the test phase it was possible to produce specimen components with a high optical quality and without any serious flaws.

5. Construction of the Glass Enclosure

5.1. Frame assembly

The adhesive connections of the frames were manufactured in a workshop under controlled ambient conditions. A centring was used for precise alignment and fixation of the individual glass elements. The corners of the frame were enclosed before commencing with the application of the adhesive to prevent uncontrolled curing by ambient daylight. Both gaps of each joint were filled consecutively via the developed flat nozzle. Heating of the glass elements improved the fluidity of the adhesive. The adhesive was cured with intermittent radiation using ultraviolet fluorescent lamps. After complete curing the frames could be delivered to the construction site (Figure 8).

5.2. Final installation

The glass frames were lifted into the stainless steel brackets which were encased in the concrete trough. Each frame post was fixed by several setting blocks at its base and sealed subsequently. The outer glass panes were installed after the erection of all four frames and connected to them by structural silicon. The handling of the lateral panels was quite challenging because of their dimensions which exceeded significantly the standard-size of usual flat glass (Figure 9).

Figure 8: Glass frame erection.

Figure 9: Installation of the large-sized lateral glazing.

Along the joints, the glazing of the outer shell was coated with a thin linear film made from silicon. This enables a high optical quality and substantial adhesion of the bonded joints. The on-site fabrication of the structural sealant silicon bonds was supervised by external quality control. The glass enclosure was completed in autumn 2009 well-timed before the first snow (Figure 10).

Figure 10: Glass construction after completion.

6. Conclusion

After years of comprehensive studies on bonded glass connections in general and acrylate adhesives in particular, the knowledge attained could be successfully transferred to an innovative project. Glued glass frame corners are one promising application for acrylate adhesives. Further studies are planned within the scope of a research project that is exclusively devoted to transparent bonded glass frame corners. The aim of this project is to provide further momentum for the gluing of glass and such corner details.

7. Acknowledgements

The realisation of this project was only possible through the exemplary dedication of the client, the Leibniz Institute for Solid State and Materials Research, Dresden and the close collaboration among the design and research teams.

Participating companies and institutions:

Architects:	Blum & Schultze Architekten, Dresden
Structural engineer glass:	GSK - Glas Statik Konstruktion GmbH, Dresden
Excecutive company glass:	Glasbau Gipser GmbH, Halle (Saale)
Testing and scientific assistance:	Institute of Building Construction, Technische Universität Dresden
Adhesive manufacturer:	DELO Industrial Adhesives, Windach
Glass manufacturer:	Thiele Glas Werk GmbH, Wermsdorf

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