Challenging Glass 5 – Conference on Architectural and Structural Applications of Glass
Belis, Bos & Louter (Eds.), Ghent University, June 2016.

ISBN 978-90-825-2680-6

Canopy for the Tram and Bus Stop "Krefeld Ostwall"

M. Kramer
IB KRAMER Structural Engineering FEM-Analysis, Germany, mk@ib-kramer.de

The „Ostwall“, one of Krefeld‘s most important public traffic intersections, is getting modernized completely for the moment. The highlight of the project is the new canopy for the tram and bus stop. It was decided to realize a steel-glass structure, to get most possible transparency. The structure has a length of 125m and a width of 12m. The main structure has 9 column brackets, that are bearing a space truss. These elements are made of steel. For the roofing, partially curved glass elements are used, that are bonded to a stainless steel frame by structural silicone. The slope of the roofing reaches to the gutter in the middle axis of the building. For each side, only one glass element is used, to guarantee a good flow of rain water. The glass elements have a developed length of 5.2m and a width of 2.2m. At the front ends of the structure, spherically curved glass elements are used. The glass roof is accessible for cleaning and inspection work. To get a smooth view of the bottom surface, the glass is bonded under the steel frame, so the silicone bonding is used to bear the self-weight of the glass elements. The pre-fabricated elements are fixed to the main structure at the bottom girder of the framework directly, and at the top girder by a suspension bar. To get a minimized cross section of the stainless steel bars, they are stabilized by the glass elements to prevent them from torsional-flexural buckling.

Keywords: silicone bonding, curved glass, FEA, structural design, glass as bracing element

1. Introduction

Krefeld's most important public traffic intersection, the "Ostwall" is going to be changed and modernized for the moment. The architectural highlight should be the canopy for the tram and bus stop "Ostwall / Rheinstrasse". Even Krefeld is well known for its textile industry, the city council decided to realize a steel-glass structure, after a long political discussion.

The architectural design was done by Stefan Schmitz Architekten, Cologne. A 125m long and 12m width structure with 9 pairs of pillars, bearing the main structure, made of a 3D-Vierendeel-girder was designed. The surface of the canopy, drafted as a hanging element, should be made of glass, with a smooth and curved shape, sloping to the center line, where the gutter was placed. Along the outer edge, a metal frame was designed to take an illumination made of LED-stripes. Additionally the suspensions for the contact wire of the tram should be fixed to the structure of the canopy (Fig. 1).

Fig. 1 Architectural design, ©Stefan Schmitz Architekten.

For the pattern of the glass elements in longitudinal direction 2.25m was chosen, the glass elements should not be fixed by point fixings, because the bottom view of the glass surface should be completely smooth ideally.

2. Load bearing system

2.1. Main steel structure

For the main steel structure, 9 pairs of columns, bearing a 3D-Vierendeel-girder was chosen. The columns had a slope in lateral direction. To brace the structure in lateral and longitudinal direction, the columns were restrained to concrete fundaments. The 3D-Vierendeel-girder on top of the columns was designed as a Gerber-girder with 7 elements. The hinged connections were done with sockets, also designed, to take the dilatation due to thermal loading (Fig. 2).

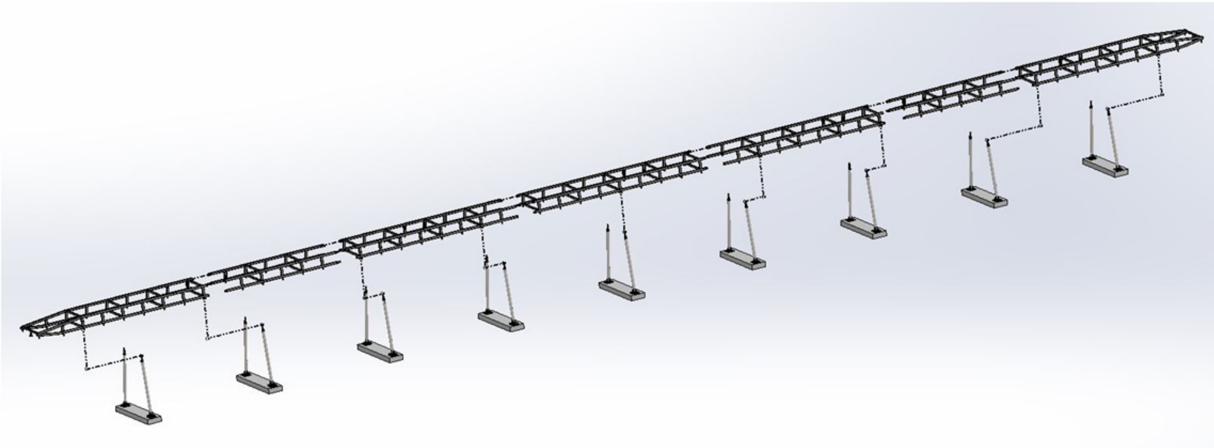


Fig. 2 Load bearing system of main steel structure.

2.2. Steel-glass elements

For the glass surface two types of hybrid steel-glass elements with structural silicone bonding were used. The 104 regular glass elements in the middle had a developed length of 5290mm and a width of 2215mm. The shape was planar at a length of 3420mm, cylindrically curved at a developed length of 1677mm, and planar at the end at a length of 168mm. To "close" the structure at the front ends, four spherically curved glass elements were used, building up a semi-circle in the top view (Fig. 3).

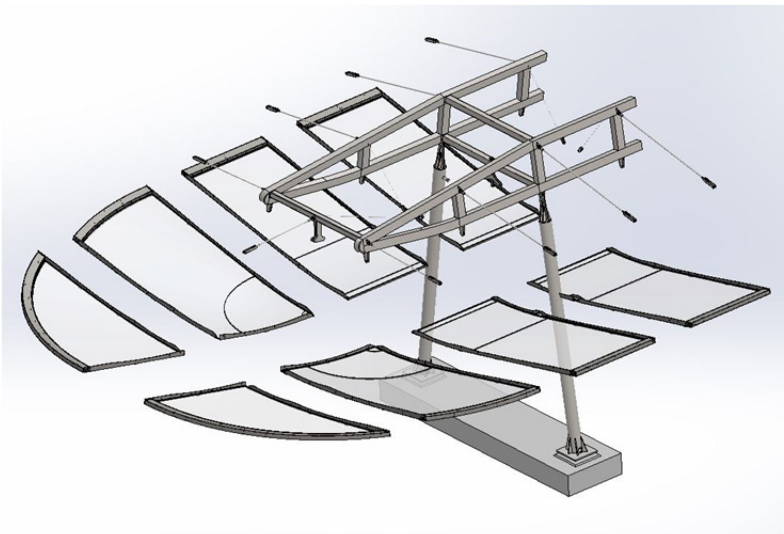


Fig. 3 Regular and front end glass elements.

The elements had a slope of 11° at the upper planar area. It was decided to use only one glass element over the developed length to guarantee a proper water flow with no gaps perpendicular to the flow direction. The use of semi-curved elements was reasonable to optical and statical aspects: The curved part of the glass helped to get a smooth and dynamical bottom view of the canopy, and from the statical point of view, it stiffened the glass element, so that the quite wide upper planar area had a quasi-four-sided support. Especially the last aspect was the reason why it was possible to realize the required pattern of 2.25m for the glass elements, and to avoid a support of the short edge at the bottom of the glass element, that would have restrained a proper water flow to the gutter. At the bottom edge the glass was designed with a step, to give the ability to fix a drip plate (Fig. 4).

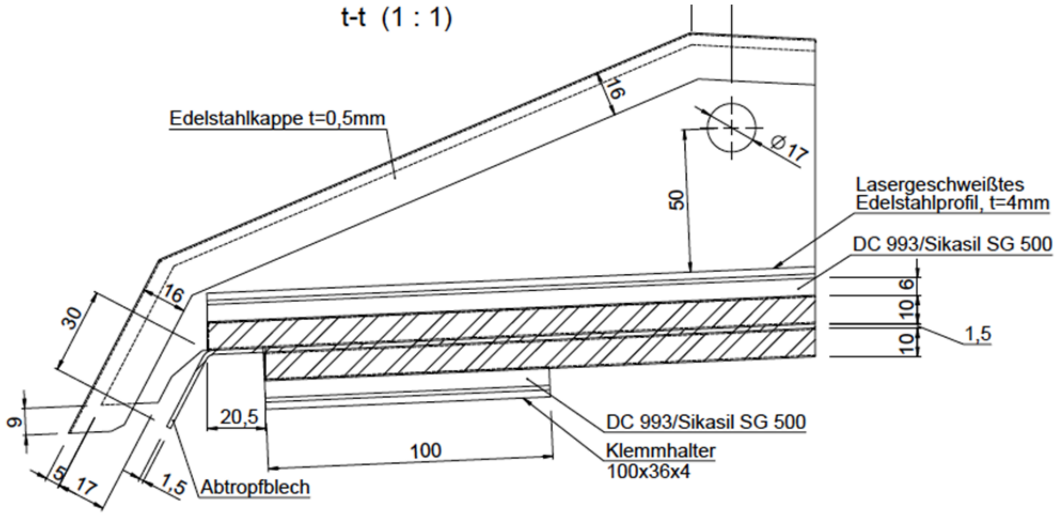
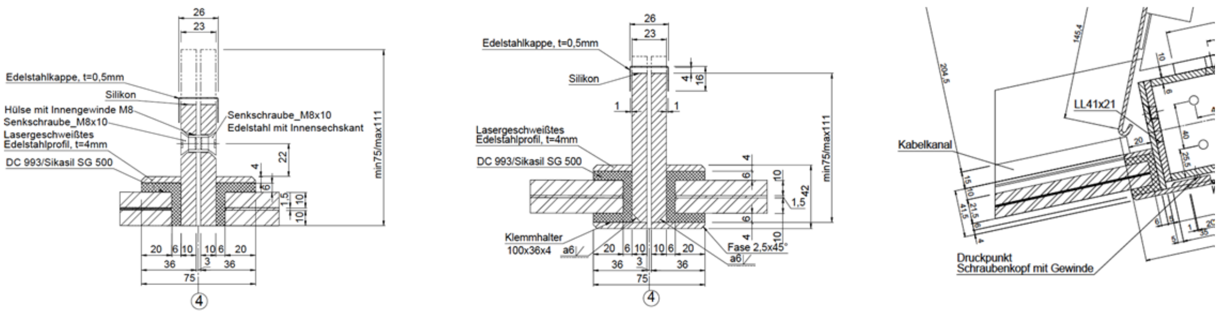


Fig. 4 Drip plate at the bottom edge.

Due to the shape and production restrictions, all glass elements were made of laminated safety glass, made of 2x10mm float glass, PVB interlayer 1.52mm.

The glass was supported at three sides. At the longitudinal sides, it was bonded below vertical stainless steel profiles with a horizontal web by the two-component structural silicone DC 993. To take the self-weight of the glass in case of failing of the bonding, four additional small supports were added at each longitudinal edge (Fig. 4 and 5a), b)). The vertical profiles had a thickness of 10mm, and a height between 75mm and 111mm following an optimized, laser cut shape to get most possible transparency. At the bottom edge a rectangular hollow section profile connected the lateral profiles, and supported the glass by a U-section profile (Fig. 5c)).



a) b) c)

Fig. 5a), b) and c) Cross sections of stainless steel frame profiles.

The three stainless steel profiles and the semi-curved glass built a hybrid steel-glass element that was put to the main structure by two suspension rods, fixed to the upper boom of the 3-D-Vierendeel girder, and directly to the lower boom by a gab (Fig. 6 and 7).

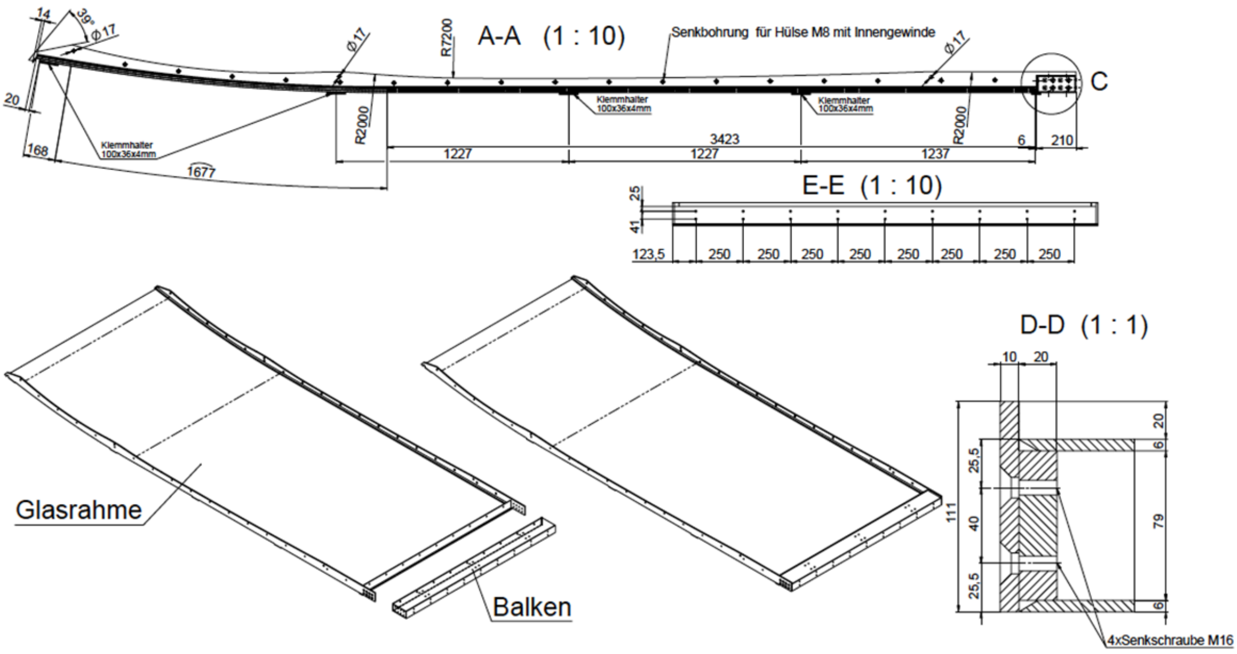


Fig. 6 Steel-glass frame.

Normally the statical system of the suspended steel-glass frame would cause severe stability problems to the lateral steel profiles, because the normal force is quite high, due to the small slope of the forward suspension rod (Fig. 7).

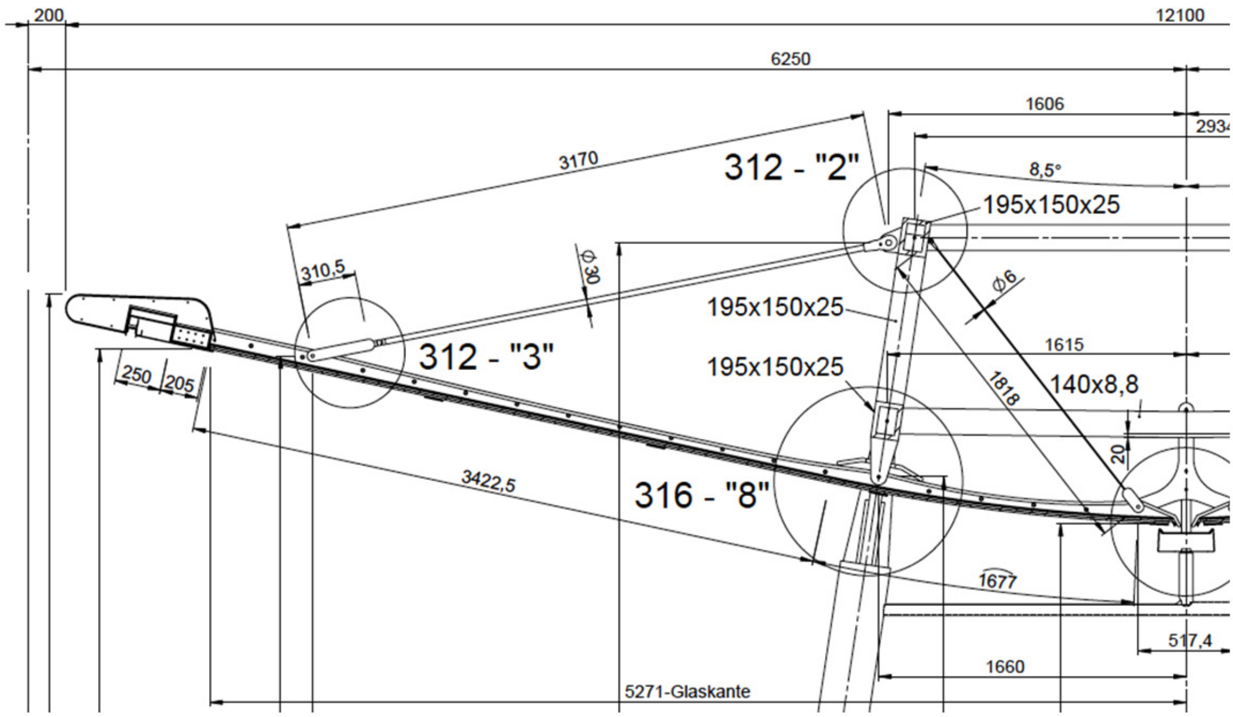


Fig. 7 Cross section of installed regular steel-glass element.

But by creating a hybrid load-bearing element, bonding the steel and glass elements together, it was possible to avoid any problem of lateral torsional buckling. The glass elements acted as a bracing element, preventing the very slender steel profiles from lateral spreading, and the bonding was sufficient to generate an elastic rotating support. So the steel profiles could be designed very slender and small to get most possible transparency (Fig. 8).

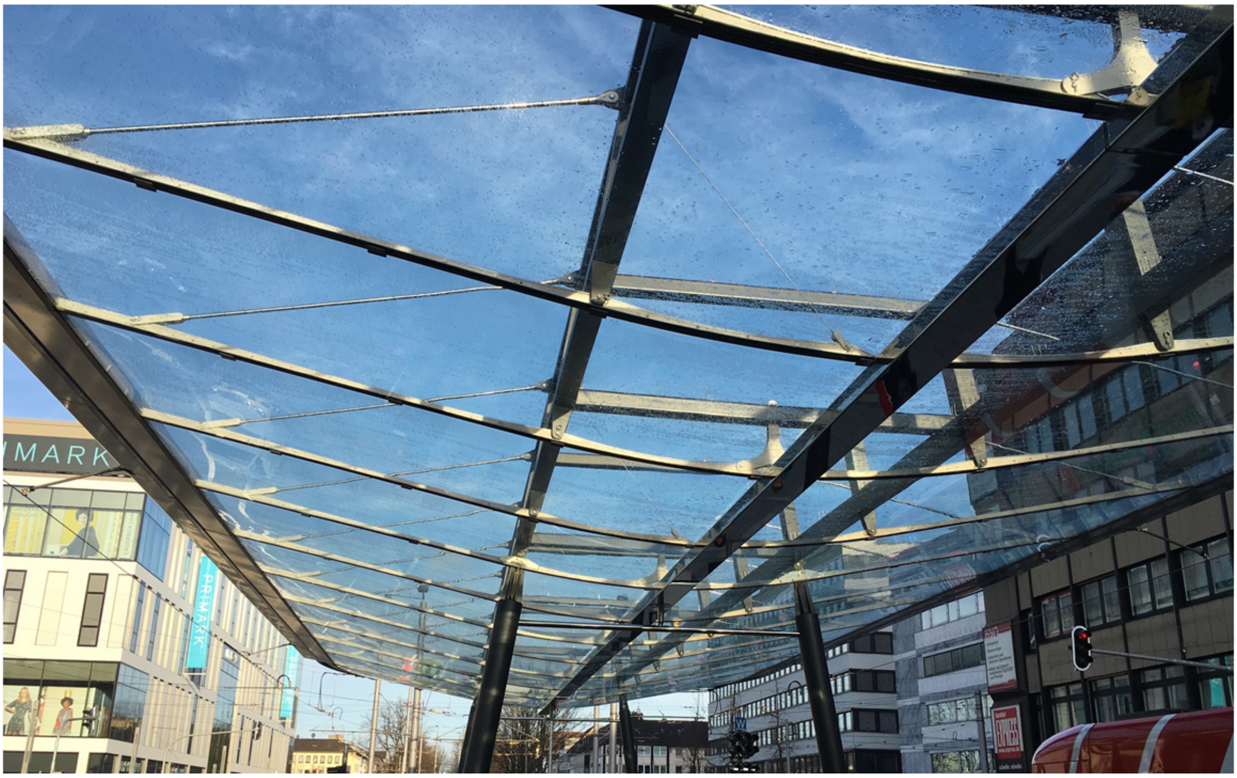


Fig. 8 Bottom view finished canopy.

The frames were fixed to each other by a row of countersunk bolts, so that in case of failing of one glass element, the stabilization of the steel profile could be taken by the steel-glass elements next to it. To enable a proper installation, even in case of changing an element, and to take tolerances and dilatation from thermal loading, a gap of 3mm was designed between the elements, assured by using sleeves for the countersunk bolts.

For the spherically curved steel-glass elements at the front ends, the same structure was chosen principally, but there was no gap designed (Fig. 9).

Fig. 9 Front end.

The metal frame around the outer edge is made of a load bearing, welded U-section profile, containing the LED-stripes, and covered by an aluminum cap. To avoid dismounting the LED-lights and the aluminum cap in case of changing one of the steel-glass elements, the U-section profile was designed to bridge the gap of a missing glass element. Also the supports for the contact wire were fixed to the surrounding frame (Fig. 10).

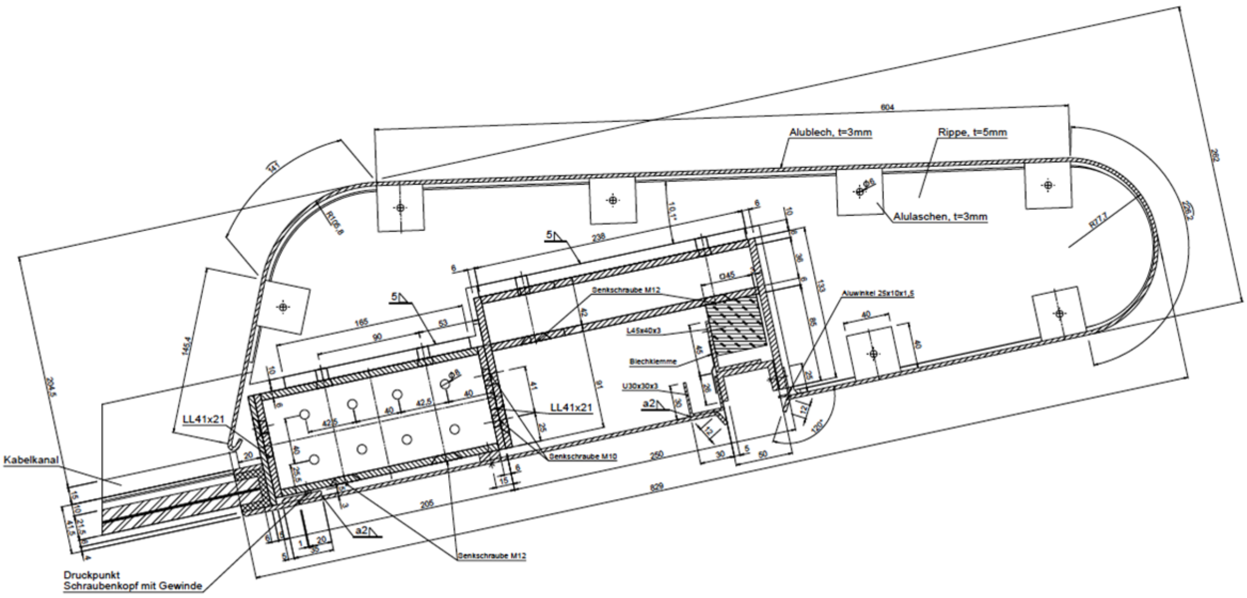


Fig. 10 Surrounding frame with aluminum cap and LED.

2.3. Fabrication

The columns, the seven parts of the 3-D-Vierendeel girder and all steel-glass elements were pre-fabricated. So all structural bonding were done in factory under defined temperature and defined humidity conditions.

3. Proofs

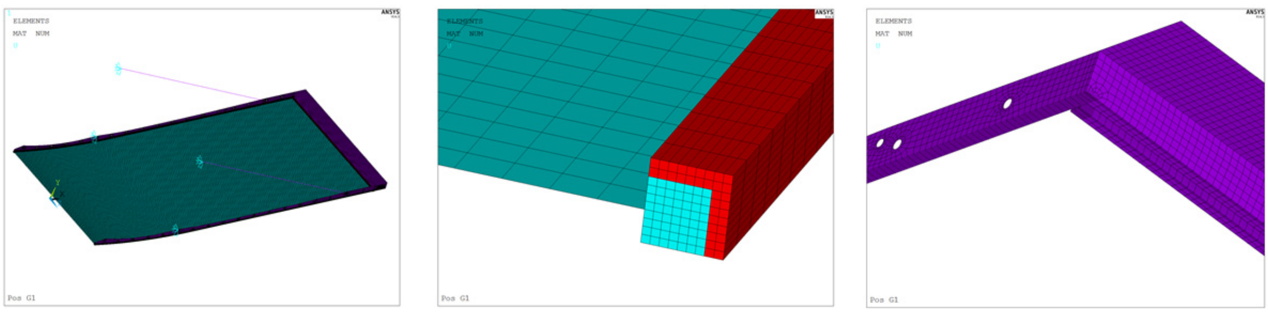
3.1. Analytical proofs

The main steel structure was proofed according to DIN 18800 for steel structures in combination with the German national technical approval "Allgemeine bauaufsichtliche Zulassung Nr.: Z-30.3-6 Erzeugnisse, Verbindungsmittel und Bauteile aus nichtrostenden Stählen", which is the basic to proof stainless steel elements in Germany. This approval refers to DIN 18800, so this code was chosen to proof the complete steel structure instead of using DIN EN 1993.

Loads and load combinations were assumed according to DIN 1055-100. In detail dead weight, wind loads, and snow loads were used to analyze the main structure with a standard 3D-framework software.

For the steel-glass elements a complete 3-D-finite element model was generated and analyzed with ANSYS 14.5. In addition to the loads assumed for the calculation of the main steel structure, a man load according to GS BAU 18 in context to DIN 4426 was set to the structure, because the glass elements had to be entered by cleaning service staff.

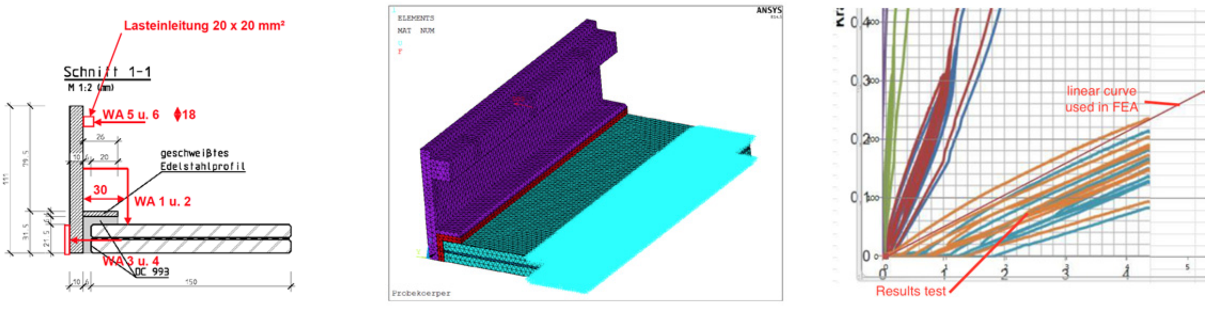
The glass and the profiles at the longitudinal edge were generated with shell elements, the stainless steel and glass elements at the edges, and the silicone bonding were generated with volumes, and the suspension rods with beam elements (Fig. 11). For the glass no composite action of the PVB-interlayer was assumed.



a) b) c)

Fig. 11 a) Complete model. b) Glass and silicone. c) Stainless steel.

Because the expected strain of the silicone bonding is very small, and is even not allowed to be high, due to the needed elastic supporting effect for stiffening the slight steel profiles, a linear elastic material law is defined to generate the silicone in the FEA-model, instead of using a hyper-elastic material law. To get the Young's modulus for the silicone, five small specimen with a length of 300mm and original dimensions of the silicone bonding, and the stainless steel profile, were tested at the Labor für Stahl- und Leichtmetallbau, Munich. The glass panel was restrained, and the steel profile was loaded by a single load. At six points, the displacements were measured. To verify the Young's modulus of the silicone, a FEA-model of the specimen was generated, and the load-displacement-curve of the FEA was compared with the curves from the tests. A sufficient conformity was obtained with a Young's Modulus of 1.2 N/mm2 (Fig. 12).



a) b) c)

Fig. 12 a) Specimen. b) FEA model. c) Comparison load-displacement-curves.

The verified Young's modulus was applied to the complete FEA-model. To proof stability of the slight steel profiles, a pre-deformation following the ideal lateral-torsional-buckling figure, was put to the FEA-model, and the total deformation and stresses for all materials were calculated for the loads given above. The stainless steel elements were proofed according to DIN 18800 in combination with the national technical approval for stainless steel. Needed results from the FEA were the von-Mises-stress.

To proof the glass the first principle stresses were decisive. Proofs were done according to DIN 18008 "Glas im Bauwesen". For the characteristic resistance of the curved float glass, values according to BF Bulletin 009/2011 "Guideline for thermally-curved glass in the building industry" were used, with fk=40N/mm2.

Directional stresses were used to proof the silicone bonding according to ETA-01/0005 "DC 993 and DC 895", and ETA-03/0038 "Sikasil SG 500". The minimum allowable design stress was used for the proofs, because the type of silicone bonding should be open before contracting.

For the spherically curved elements only a shell model of the glass was generated, because the loading to the steel elements was lower than at the regular elements, due to the smaller width of influence.

3.2. Proofs based on tests

Proofs based on tests at an original mockup were needed to check the post breakage behavior of the glass elements, and to check safety to prevent from falling thru the glass element in case of cleaning staff falling onto the glass.

For both tests three original steel-glass-frames had been produced and installed at a test structure in original position.

First the test to simulate a falling person according to GS BAU 18 was done. Therefor a bag filled with 50kg of glass beads was dropped from a height of 1.2m onto the pre-damaged glass unit at two different positions (Only the upper glass of the laminated glass unit was destroyed). After this a weight of 100kg was put to the place, the bag laid, at an area of 200x200mm. The test was fine, when the glass elements resisted the loading more than 15min. This target was reached without any problem. Even the lower pane of the laminated glass unit did not show any damage. The same result was getting for the second element, so this test was fulfilled.

To check post breakage behavior, both pre-damaged glass units were used. The second layer was destroyed, too, and then a simulated snow load of 0.5kN/m2 was put onto the glass. Both units were able to take the load more than 24h (Fig. 13). To check the effect of the bonding, at one unit the silicone sealant was cut completely. Even this additionally damaged element did not fail.

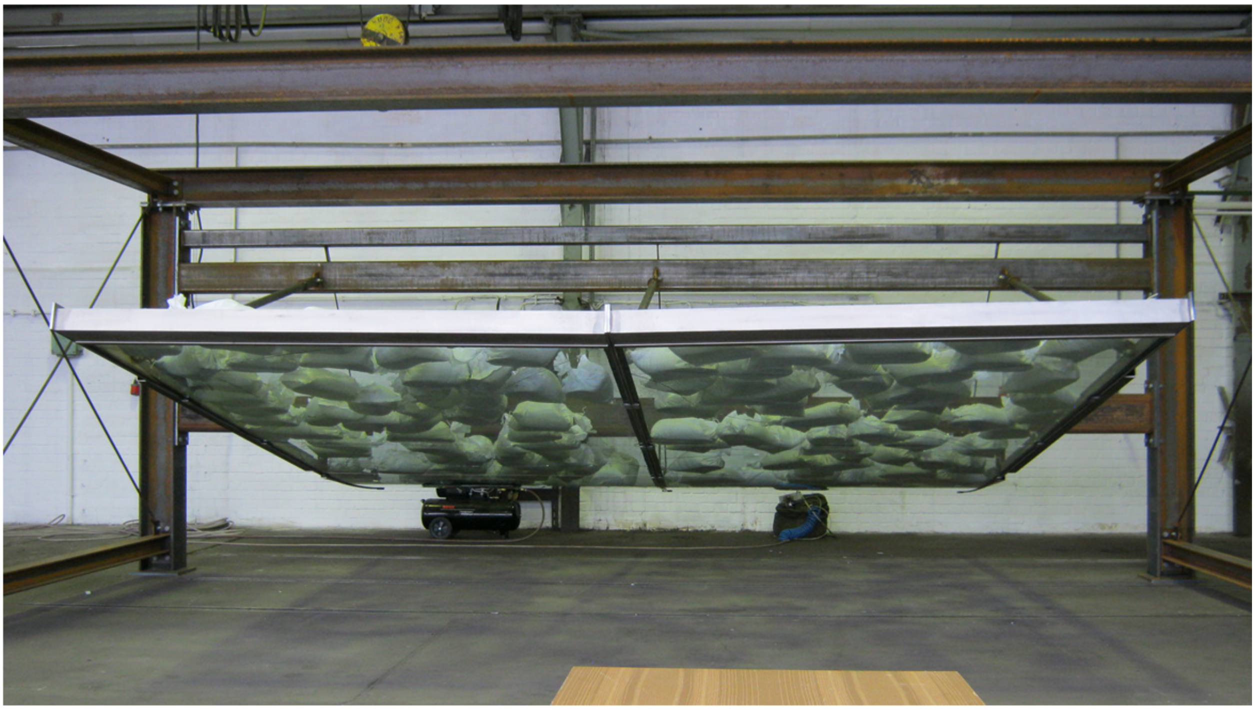


Fig. 13 Test for post breakage behavior.

The very positive post breakage behavior is reasonable for the cylindrically curved part of the glass. Normally a two, or three side supported flat glass pane would not had have any chance to confirm this test, having a width of more than 2.2m. But due to the high stiffness of the curved part of the glass element, the plane part of the glass element shows a behavior similar to a four side supported pane, so the curved part of the glass is acting like an additional supporting for the large plane area of the element.

4. Conclusions

For the canopy of the tram and bus stop "Krefeld Ostwall", a high transparent steel-glass structure could be realized. The consequent use of glass as a stiffening and load bearing element helped, to minimize the steel elements of the steel-glass frames, because stability failure could be avoided. Also the silicone bonding, connecting the stainless steel and the glass elements was suitable for this kind of fixing, because it was elastically enough for the brittle material glass, but stiff enough to generate an elastic supporting for the steel profiles to prevent them from lateral torsional buckling.

All in all, the realized structure is not so far away from the first architectural design (Fig. 14).

Fig. 14 Realized project.