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Durability by Design: Load Carrying Silicone Bonding, Herz Jesu Church, Munich

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Abstract: The design of conventional glass façades in Germany is typically based on the extensive use of point supports that keep the glass panels in position and which provide the load transfer of the façade. Beside the optical disadvantage of discrete elements being visible in the glass façade, the application of point supports leads to highly concentrated stress regions significantly affecting sizing and durability of the façade components.

In order to overcome these limitations, a new approach has been chosen for the design of the glass façade of the Herz Jesu Church, Munich. One peculiarity of the overall glass façade of this box-shaped building consists in horizontal and vertical glass beams for support of the façade. Silicone adhesives bond steel stringers along the main edges of the horizontal and vertical glass beams in order to establish load paths between beams and façade.

The hereby-realized bonding design offers special features being favorable for the durability of the building. Load carrying capacities have been provided by line-type connections, significantly reducing stress concentrations. Major attention has been given to the geometric layout of the bonding. Thus, detailed finite element (FE) analysis has guided the careful selection of an adequate channel cross section for the stringers.

The design philosophy of the bonding is characterized by a small free surface of the silicone adhesive, offering only a very small attack area for environmental degradation. Additionally, the free surface is only stressed at a low level avoiding the critical combination of highly loaded areas exposed to aggressive environmental conditions. Furthermore, two principal load paths (tension and shear) are established leading to a fail safe design principle of the bonding. These key points contribute significantly to a high durability design of the glass façade bonding.

Keywords: Structural glazing, durability design, joint geometry, FE analysis

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Nomenclature

	Poisson's ratio
A_{front}	Effective bonding front area
A_{side}	Effective bonding side area
E	Elastic modulus
F	Tension force
G	Shear modulus
t_{front}	Adhesive thickness front area
t_{side}	Adhesive thickness side area
u	Displacement

Introduction

In contrast to German churches of the sixties and seventies, typically attributed to a multi-functional gymnasium type architecture using massive concrete structures, the newly built Lord's house Herz Jesu Church, Munich (commissioned by Erzdiözese München und Freising, Erzbischöfliches Baureferat), caused a sensation during the consecration procedures for its vanguard design. The outer structure of this spectacular monument has the timeless shape of a rectangular parallelepiped and is built almost completely with glass (Figure 1).

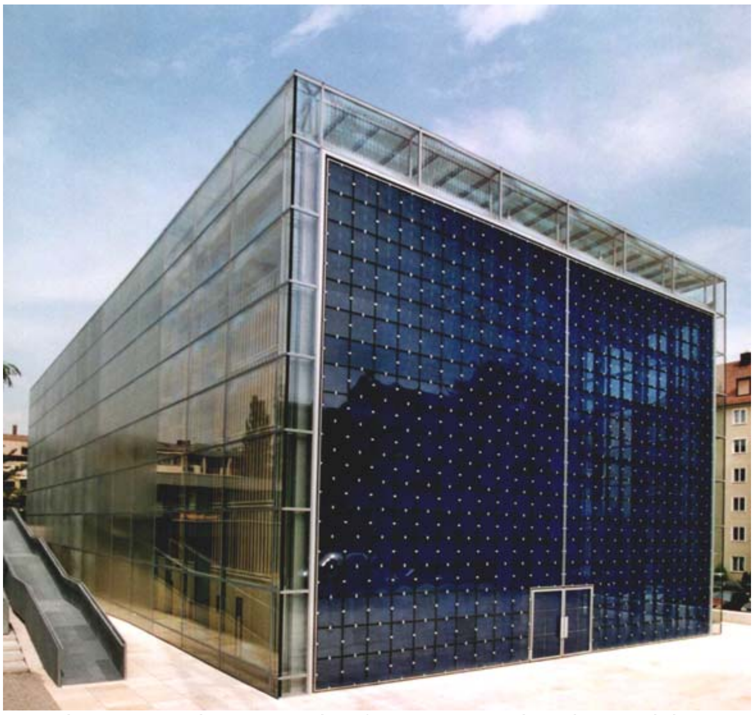

Figure 1 – *Glass Façade of Herz Jesu Church, Munich*

The innovative application of glass in the façade serves to emphasize the fundamental idea of the architecture using the style of a rock crystal. On the other hand, the glass skin plays a major role in the arrangement of the inside illumination by defined transparency gradation of the glass façade elements. Therefore, the architects asked for a glass façade with a minimum of visible load-carrying structures. In order to meet these requirements, two sophisticated technologies have been applied [1]. First, horizontally and vertically arranged glass beams serve as supporting members for the glass façade. Second, the conventional approach extensively using point supports was abandoned in favor of load-carrying line type bonding using silicone adhesives. As the functionality of these technologies guarantees the integrity of the glass façade, special emphasis was given to strength and durability of these structural elements during the design of the façade by experimental and theoretical studies. After giving a short overview concerning the peculiarities of the façade design affecting the requirements for the bonding, this paper presents design aspects including Finite Element Analysis results of the bonding geometry in order to assure adequate durability behavior of the glass façade.

Design of the Façade of the Herz Jesu Church

The skeleton of the glass façade consists of a steel framework stretching out the box shape of the building with the dimensions 47.04 m (length), 19.00 m (width) and 16.00 m (height). The steel framework is based on constant raster units of 6.72 m in longitudinal axis and 6.39 m in lateral axis. In the vertical direction, the raster units increase from the top to the base by an arithmetic series from 2.40 m to 1.56 m for architectural reasons. The primary load-bearing members of the steel framework are eight stiff-in-bending steel frames arranged in longitudinal direction according to the raster units (Figure 2).

Two welded hollow sections compose the steel frames in order to achieve minimum cross sections for optical reasons. Furthermore, the shifting of the steel frames inside the building increases the impression of a façade almost consisting of glass. Bracings mounted on the top and on the longitudinal sides stiffen the structure and establish the load path for wind and other loads in longitudinal direction of the building. The bracings are elastically tailored in order to achieve similar deformations in lateral directions for minimum interlocking within the glass façade.

In order to realize load-bearing structures with minimum visibility, the design philosophy of a hanging system has been selected for the glass façade in order to achieve slender frame elements by avoiding destabilizing compression loads. The glass façade consists of the following major components (Figure 3):

- Insulating glass units (width 3.35 m) as core components of the glass façade grouped by two elements within one raster unit;
- Horizontal glass beams (length 6.70 m) connecting façade and suspender bars with the steel frames;
- Vertical glass beams of varying length fixed to the suspender bars for support of the horizontal glass beams;
- Vertically arranged suspender bars directly transferring the dead loads of the insulating glass units, vertical glass beams and façade stringers; and
- Horizontally arranged façade stringers for wind loading transfer from the insulating glass units to the horizontal glass beams.

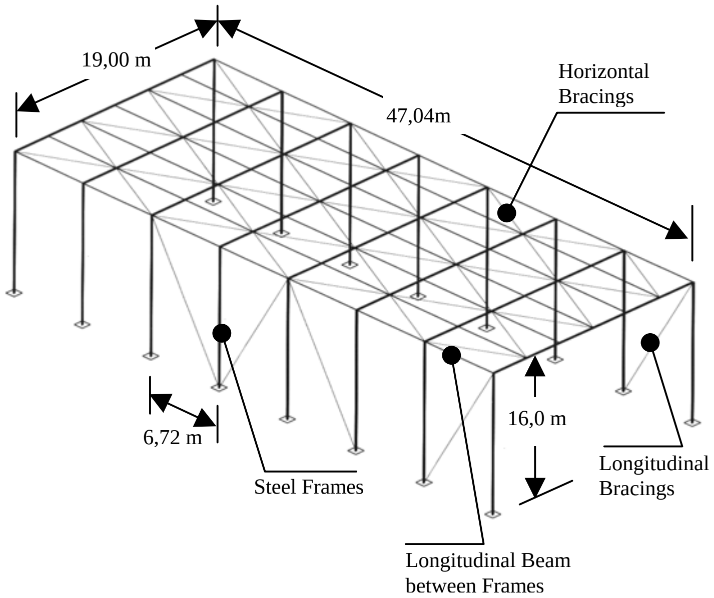

Figure 2 – *Structural System of Herz Jesu Church, Munich*

For the load-bearing connection of either the horizontal and vertical glass beams to the suspender bars, the beams were bonded by a silicone based conventional structural glazing adhesive (DOW CORNING® DC-993[2]) to steel stringers. The steel stringers are provided with discrete attachment points for connection by bolts to the façade stringers and suspender bars in order to allow easy assembly and maintenance.

The horizontal glass beams have the primary function to transfer wind pressure and wind suction loads acting on the glass façade to the steel frames. In order to establish the load path between glass façade and steel frames, each stringer bonded to a horizontal glass beam has eight attachment points for connection to the horizontal façade stringers (Figure 4). Concerning the certification of the bonding, the wind suction case is considered as critical load case because the bonding has to react tension forces. Therefore the bonding is endangered by peeling off as no positive fit is active compared to the compression load case. The wind suction load case is characterized by high peak forces (approximately 1.6 kN for the critical bolt connection) acting on the bonding during short periods.

The vertical glass beam supports the horizontal glass beams in order to guarantee the integrity of the structure of the glass façade. The vertical glass beams act like mounting brackets using two attachment points of the bonded stringers for connection to the suspender bars (Figure 5). In order to generate a reacting moment for the offset of dead loads, a force couple (approximately 0.3 kN) acts on the two attachment points, one being loaded by compression, the other – critical – one by tension. This dead load case is characterized by time invariant loads (approximately 1.8 kN in vertical direction and 0.3 kN in horizontal direction for the critical bolt connection); the shorter glass beams showing larger stress levels in the bonding due to the shortened lever arm.

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[2] Dow Corning S.A., Parc Industriel, 7180 Seneffe, Belgium.

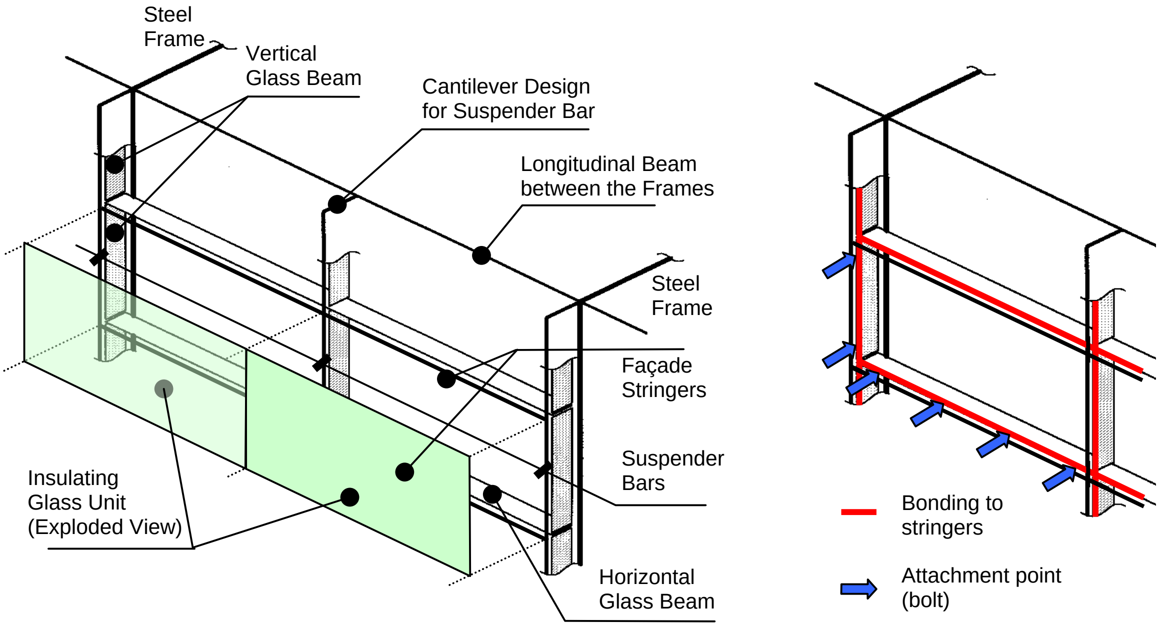

Figure 3 – *Detail of the Hanging System of the Glass Façade*

Bonding Technology for High Durability

According to Kinloch [2], observations have shown that the following parameters significantly affect joint durability.

- Environment: The presence of moisture has been identified to be the most hostile environment for structural adhesive joints, leading to significantly decreased mechanical performance.
- Temperature: High temperatures result in increased level of strength loss of the structural adhesive joint, especially in combination with moisture.
- Adhesive type: The chemical type of the structural adhesive plays a major role in joint durability due to the variety of physical or chemical attack mechanisms of the environment.
- Adherend: Structural adhesive joints to metallic adherends pose special problems due to the special surface properties of metals.
- Adherend surface pretreatment: Beside removing weakening surface contaminations by purifiers, the application of primers may help produce durable joints by stable surface layers (e.g. oxides), which are receptive to the adhesives.
- Applied stress: The presence of externally applied or internal stress increases the rate of strength loss by lowering the energy barrier from unbroken to broken state.
- Joint design: Joint designs showing relatively high stress distributions at the interface between adhesive and adherend tend to emphasize durability effects. Although unaged structural adhesive joints typically fail due to cohesive fracture, interfacial failure between adhesive and adherend is usually recorded after environmental attack.

The destructive role of the above mentioned main environmental attack mechanism – moisture in combination with increased temperature – was confirmed for silicone adhesives by experimental tests performed by the German institute FMPA [3]. The broken specimens show a significant tendency towards adhesive fractures in case of increasing immersion in water and increasing water temperature.

Glass Façade Herz Jesu Church

In order to realize a highly durable bonding technology for the glass façade of the Herz Jesu Church, the above listed key items for durability were analyzed with respect to the design of the glass façade and the bonding structures.

Environment – The arrangement of the bonded structures inside the glass façade lead to favorable effects with respect to humidity and temperature, both of them dominated by the climate inside the building (forced air convection). Nevertheless, this type of arrangement of the glass beams was guided by architectural requirements, not by durability considerations.

Adhesive Type – The selection of an adhesive for the glass façade was dominated by structural glazing requirements for this kind of application. Adhesives based on silicone are first choice due to their special mechanical and chemical properties. Using glass as adherend, chemical bonds as primary interfacial forces increase interfacial stability with beneficial effects on durability.

Adherends – The adherends, glass beams on the one hand and stainless steel channel on the other hand, result from the special glass façade design and are therefore not to be substituted.

Adherend Surface Pretreatment – Concerning the pretreatment of the bonding surfaces, technical instructions from the adhesive manufacturer were taken into account aiming on strong and durable bonding. The glass surfaces needed a purification treatment with a special cleaning agent whereas the corresponding channel surfaces required an additional coating with a primer.

Moisture / Stress / Temperature – The effects of moisture, stress and temperature on the bonding are mainly determined by the bonding geometry. Therefore, the designer of the bonding has to focus on the following aspects in order to increase the durability of the bonding significantly.

- How to diminish attack of moisture (e.g., cleaning agents) acting on the bonding
- How to obtain a favorable stress distribution in the adhesive evoked by external loads
- How to consider changing temperatures leading to thermal stresses and other effects

Design of the Load-Bearing Bonding between Glass Beam and Stainless Steel Channel

The bonding design answering favorably the above listed topics should show the following unique features:

- Small surfaces for minimizing exposure of bonding to environment,
- Low loading of adhesive and interfacial regions exposed to environment, and
- Low shear stiffness for low thermal loading.

A conventional approach for bonding a steel stringer to the glass beam consists of a steel band attached at one side to the glass abutting face. Nevertheless, this design shows significant disadvantages with respect to the above mentioned key items. Under tension loading, the adhesive is especially stressed at the interfacial regions on the bonding surface as the silicone has a nearly incompressible behavior leading to significant lateral contractions [7]. Due to the differences in the flexibility of silicone, steel and glass (Table 1), the contraction tendency under axial deformations of the adhesive results in regions of high strains at the edges of the structural joint (Figure 4). In this case, a combination of critical aspects leads to the assumption that this type of joint does show only limited performance with respect to durability and fracture mechanics:

- Tension loaded surface exposed to environmental attacks,
- Peak loading of interface at regions exposed to environment being the worst condition with respect to durability, and
- Unstable fracture mechanics behavior as crack growth leads to increasing stresses due to diminished load-carrying cross section area.

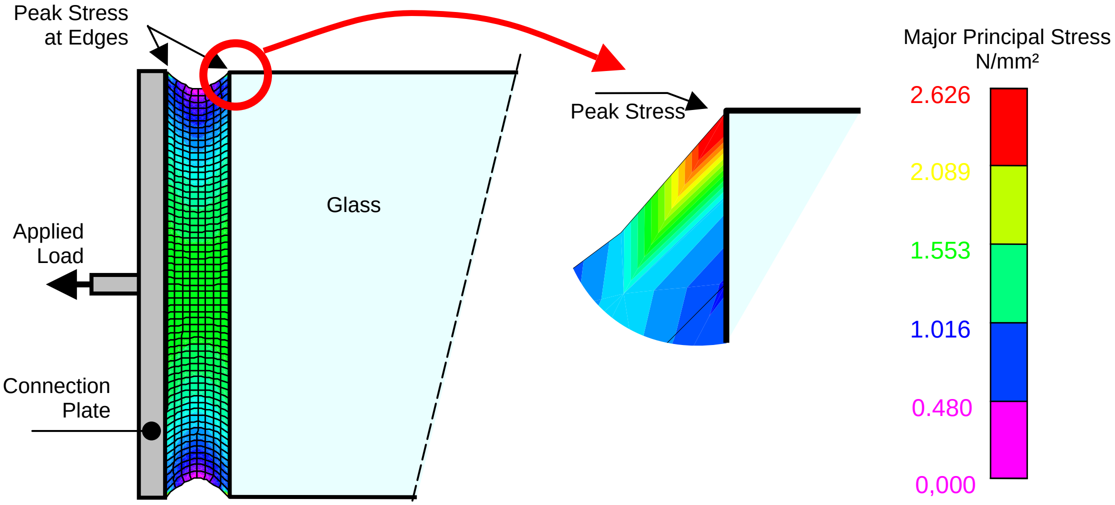

Figure 4 – *Stress Distribution of Conventional Structural Joint (One-Sided Bonding)*

Table 1 – *Physical Properties*

	Young Modulus, N/mm^2	Shear Modulus, N/mm^2	Poisson's Ratio, –	Thermal Expansion, 1/K	Reference
Steel	210 000	81 000	0.3	12e-6	[4]
Glass	70 000	28 000	0.23	9e-6	[5]
Silicone	1.4	0.47	> 0.495	≅ 9e-6[3]	[6], [7]

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[3] Sitte, S., Dow Corning GmbH, Germany, personal communication with A. Hagl, A. Hagl Ingenieurgesellschaft mbH, Graefelfing, Germany, November 2002.

In order to overcome these limitations in bond design, a new philosophy has been applied for the layout of the adhesive joint. The special idea consists in encapsulating the structural adhesive by appropriate selection of steel cross sections in order to protect the adhesive against environmental influences. Therefore, a channel type section is first choice for this objective leading to a three-sided bonding design (Figure 5). Finite Element Analysis for this kind of structural joint demonstrated the following unique characteristics of this design (Figure 6).

- The highly loaded face surface of the silicone adhesive is totally encapsulated.
- The adhesive surfaces at the end of the side surfaces are nearly unloaded.
- In case of failure or fracture in the face surface region, the side surfaces establish a second load path by shear.

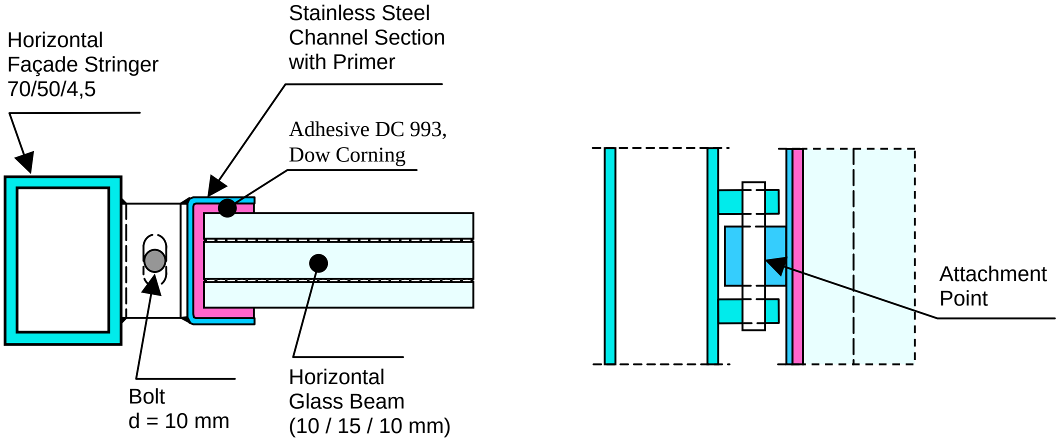

Figure 5 – *Bonding Design Glass Façade Herz Jesu Church*

In this context, it is very interesting to note that due to the high level of incompressibility of the silicone adhesive, almost 90% of the total load is transferred by tension stresses in the front region and the remaining 10% by shear stresses in the side regions. If lateral contraction is not considered by using simple engineering formula (constant tension stress in the front region, constant shear stress in the side regions), only 60% of the total tension load would be transferred by the front region. For this case the load is shared between front and side regions according to the following formula

$$F = F_{front} + F_{side} = \left(\frac{EA_{front}}{t_{front}} + \frac{2GA_{side}}{t_{side}} \right) u \qquad (1)$$

This load rearrangement is evoked by the dramatically increased stiffness of the front region by preventing the lateral contraction of the adhesive due to the three-sided design
and its encapsulating capabilities (2). Please note that if a perfectly incompressible material (Poisson's ratio ν=0.5) is totally encapsulated by rigid boundaries, tension or compression stiffness is infinite (3)

$$F = \left(\frac{EA_{front}}{t_{front}} \left(\frac{1}{1+v} + \frac{v}{(1+v)(1-2v)} \right) + \frac{2GA_{side}}{t_{side}} \right) u \tag{2}$$

$$\frac{EA_{front}}{t_{front}} \left(\frac{1}{1+v} + \frac{v}{(1+v)(1-2v)} \right) \rightarrow \infty \text{ for } v \rightarrow 0.5 \tag{3}$$

These graduated stiffness and loading properties of front and side regions lead to a remarkable behavior concerning fracture mechanics. If the bonding is overloaded, the front region will partially or totally fail due to the high stresses under normal operating conditions. In this case, the stiffness of the entire bonding will drop leading to a relaxation of the structure as the damaged front region results in increased flexibility. In case of the load still being present, the side regions whose load carrying capabilities are not damaged will establish the load transfer in a more flexible manner.

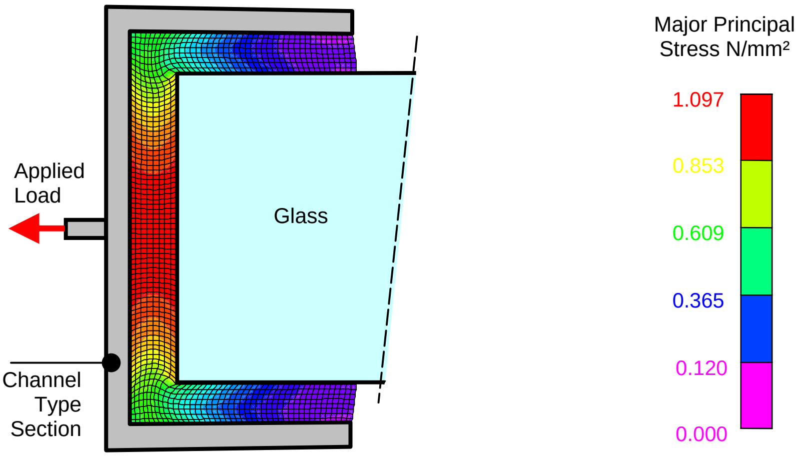

Figure 6 – *Stress Distribution of Three-Sided Bonding*

Although this bonding design shows a high stiffness under tension, shear flexibility in the stringer direction is governed by the high flexibility of the silicone adhesive.

Therefore, thermal loading by differing expansion characteristics of the materials, steel and glass, under altering temperature does not lead to high thermal stresses also being favorable for durability of the bond design.

A critical issue for this kind of bond design is the selection of an adequate geometry (side lengths, adhesive thickness). Increasing side lengths lead to favorable encapsulating effects of the highly loaded front region with respect to diffusion of aggressive environmental media and to beneficial load carrying capabilities in case of failure of the front region. The disadvantages of large side lengths are seen in optical drawbacks due to increased visibility of the steel channels and in high consumption of material (steel, adhesive). Therefore, compromises have been worked out leading to the selected bonding design with a flank length of 30 mm overall. The thickness selection of the bonding in the front and side regions is governed by minimum thickness requirements of the adhesive and by tolerances of the components. The thickness of the adhesive is adjusted by the usage of positioning devices to 5 mm in the front and side regions.

As a drawback with respect to the encapsulating properties of the bonding design, a two-component silicone adhesive has to be applied as the desired decrease of diffusion in the adhesive prevents the application of one-component silicone adhesives.

Three-dimensional finite element analysis, taking into account the hyper-elastic and almost incompressible nature of silicone by appropriate material and element definition, showed that the design of the bonding is in accordance with the requirements posed by load and strength analysis (Figure 7). Therefore, stress distributions within the horizontal and vertical glass beam bonding have been compared with maximum loads obtained by experimental results with respect to material and design tests.

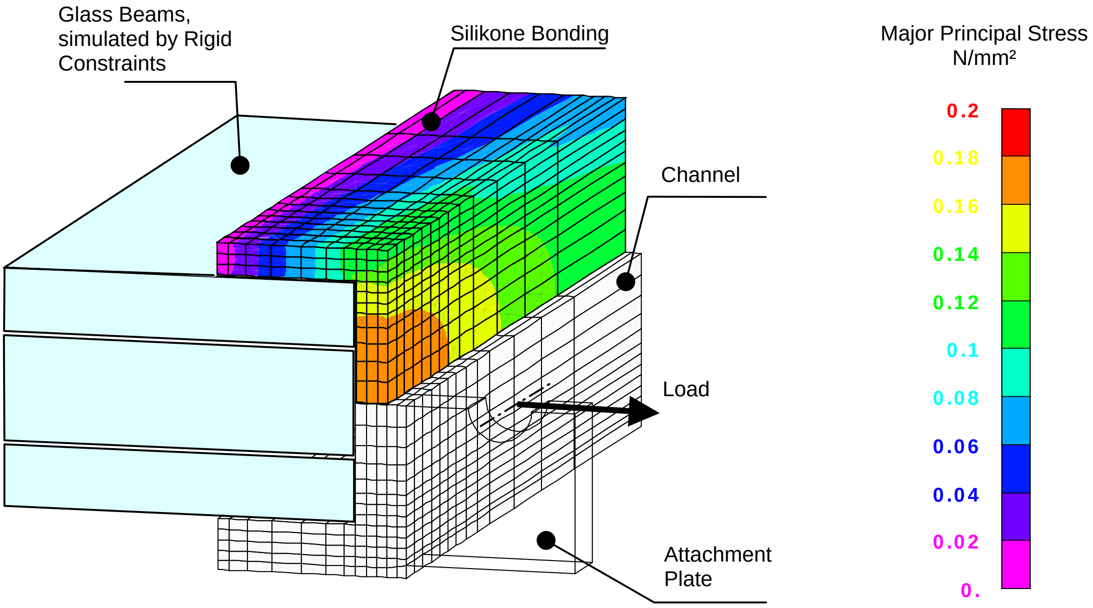

Figure 7 – *Peak Stress Distribution in Horizontal Glass Beam*

Experimental Tests for Material and Design

Due to the innovative design of the bonding, an integral part of the glass façade certification is dedicated to experimental tests resulting from a lack of adequate standards. The European Organization for Technical Approvals (EOTA) has established rules for the application of structural sealant glazing systems. According to the 'Guideline for European Technical Approval for Structural Sealant Glazing Systems (ETAG Nº 002)', samples were mechanically tested under various conditions by the German Institut fuer Fenstertechnik (ift), Rosenheim (Figure 8). Regarding the selected material combination for the glass façade, related tests have been successfully performed for tension and shear strength in a temperature range from –20° C to +80° C. Furthermore, tension strength behavior has been analyzed with respect to environmental influences by artificial ageing or conditioning. Therefore, samples were exposed to:

- Ultraviolet (UV) radiation combined with immersion in water at high temperature,
- Humidity and sodium chloride (NaCl) atmosphere,
- Humidity and sulfur dioxide (SO_2) atmosphere, and
- Façade cleaning products.

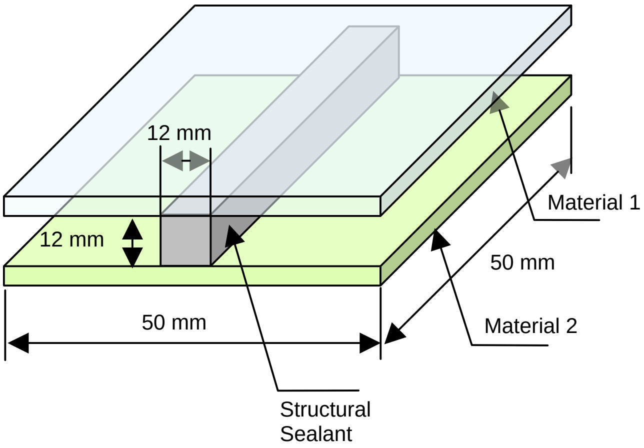

Figure 8 – *ETAG Nº 002 Test Specimen*

Regarding all investigated test conditions, the samples did not show any significant decrease in mechanical strength. As the bonding design of the glass façade differs significantly by the three-sided design from these samples (only one-sided bonding), special specimens of the envisaged design with 50 mm width were tested in order to investigate the influence of design on bonding strength (Figure 9). The samples were loaded by tension according to the critical loads encountered by the bonding in the glass façade. Figure 10 shows the mechanical behavior of a sample under a prescribed deformation velocity of 5 mm/min. At a deflection of about 2 mm, the stiffness of the sample decreases significantly although the load-carrying maximum is still not reached. Based on the FE analysis results, it is assumed that at 2 mm deflection, the bonding reaches its strength limits in the front region. The failure in the tension stressed area leads to increased flexibility of the bonding and the load is increasingly transferred to the still intact side regions, which establish the load path by shear. The deflection at maximum load (approximately 8 mm) confirms this hypothesis as the related strain corresponds to those experienced with ETAG specimen under maximum shear force.

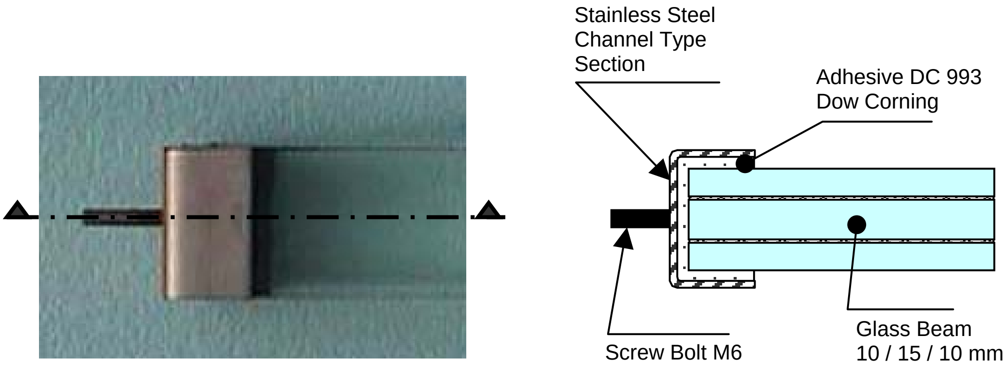

Figure 9 – *Specimen Design Herz Jesu Church*

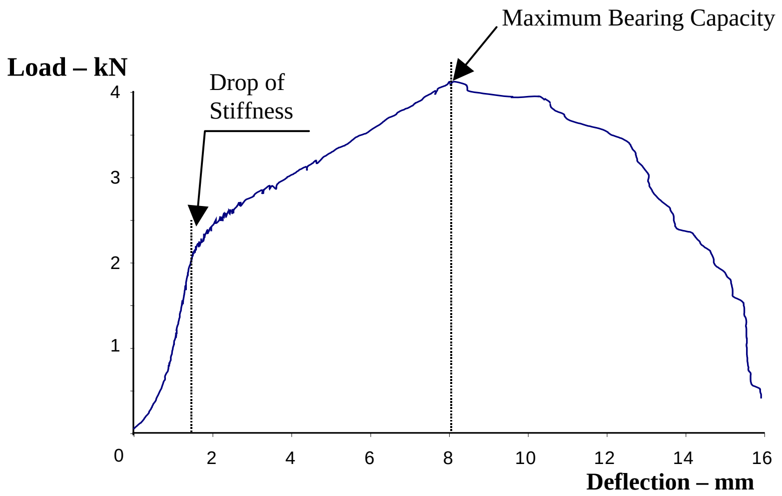

Figure 10 – *Load versus Deflection for Baseline Test Case (Initial Strength, Silicone DC 993, 23° C)*

Corresponding to the ETAG tests, the samples with the three-sided bonding show similar performance with respect to the investigated temperature range (–20° C to +80° C). Furthermore, strength tests were conducted after continuous loading of 500 h and 1000 h duration with six times the maximum design load. According to Figure 11, no degradation of maximum strength could be observed.

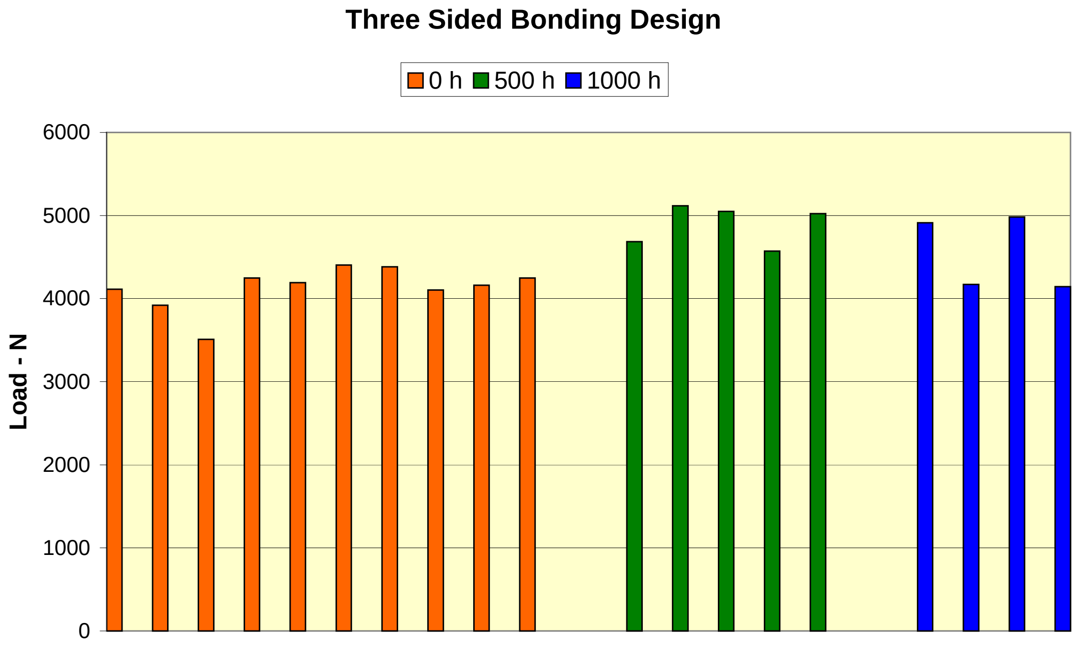

Figure 11 – *Maximum Strength with and without Continuous Loading*

Concerning environmental attacks, no additional tests were performed for the three- sided bonding design. The critical medium with respect to the glass façade is the application of cleaning agents inside the building. Due to the design of the bonding, it is assumed that the behavior of the three-sided bonding is superior to the ETAG sample with respect to environmental conditions as the highly stressed region is encapsulated. Regarding the ETAG sample, load peaks are generated at edges and corners of the adhesive similar to the one side bonding design presented in Figure 4. Therefore, the load peaks are totally exposed to environmental attack mechanisms.

Summary and Conclusions

For the glass façade of the Herz Jesu Church, Munich, horizontal and vertical glass beams build major structural components with respect to wind and dead loads. The glass beams are bonded to stainless steel sections using a silicone adhesive for load transfer. For an adequate design of the bonding, a short review is presented with respect to parameters significantly affecting structural joint durability. This review is discussed in the context of two possible bonding designs, a conventional one-sided bonding and a three-sided bonding finally selected for the glass façade of the Herz Jesu Church. The three-sided bonding shows advantages in the fields of encapsulating of high stresses, low loading of interfacial regions exposed to the surface and establishment of a redundant load path in case of primary failure. Furthermore, the design of the bonding using a channel type steel section as adherend leads to beneficial effects with respect to diffusion of aggressive moisture (e.g., cleaning agents). Experimental results are presented with respect to the load carrying capability of the three-sided bonding design without and with pre-loading.

The innovative design of the bonding of the glass façade of the Herz Jesu Church has focussed the interest of glass manufacturers, adhesive manufacturers and civil engineers on structural adhesive joint potential which is not totally evaluated and exploited at the moment. Therefore, the author of this article has founded within the non-profit organization ‘Fachverband Konstruktiver Glasbau’ a working group ‘Bonding’ (‘Arbeitsgruppe Verkleben’), which is dedicated to fundamental research in structural adhesive joints with respect to the load carrying bonding of glass elements to structures.

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