HOW TO JOIN STEEL AND GLASS
– Complex Adhesive Behaviour –

Anneliese Hagl

Test+Ing Material, Munich, Germany

INTRODUCTION

In the year 2000, the Herz-Jesu church in Munich was finalised featuring a glass façade with advanced bonded load carrying structures [1]. The church built almost completely with glass in a timeless shape of a parallelepiped is shown in Fig. 1. The façade was stiffened by glass beam elements of lengths up to 6.72 m joined to stainless channels by Silicone adhesives, see Fig. 2. This design – leading to a U-type bonding geometry for joining the glass beams to steel stringers of PFC (parallel flange channel) type cross sections – required comprehensive experimental and theoretical investigations as conventional guidelines such as the European guideline ETAG 002 [2] for bonded glass facades were not applicable. While the ETAG 002 covers only line type bonding geometries, the hereby applied adhesive geometry is geometrically more complex leading to significantly different mechanical characteristics.

Fig. 1. Herz-Jesu church, Munich (*Erzdiözese München und Freising, Erzbischöfliches Baureferat*)

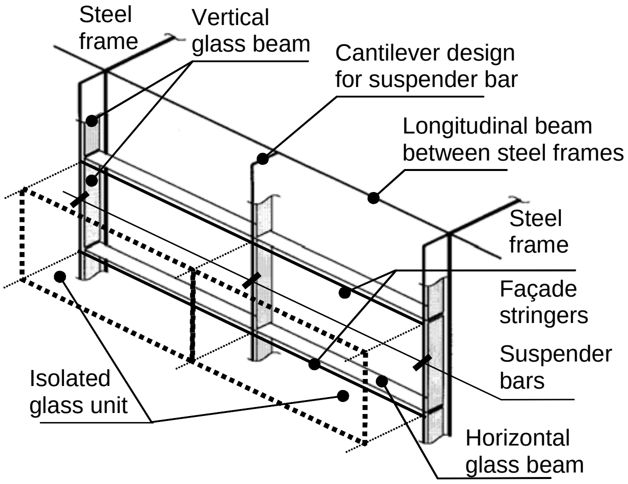

Fig. 2. Detail glass façade

1 GENERAL BEHAVIOUR OF U-TYPE BONDING GEOMETRIES

For certification of the load carrying bonding of the glass façade specimens as shown in Fig. 3 were manufactured and tested under tension and shear loading. In addition these experimental activities were complemented by theoretical and numerical strength analysis. The mechanical behaviour of the specimen is presented in Fig. 4 for a prescribed deformation velocity of 5 mm/min. At a deflection of about 2 mm, the stiffness of the sample reflected by the slope of the curve decreases significantly although the load-carrying maximum is still not reached. Between deflections of 2 mm and 8 mm, the local stiffness i.e. the tangent on the curve is almost constant. Beyond a deflection of 8 mm, total failure of the specimen occurs after almost doubling the deflection of maximum load hereby demonstrating a behaviour of good nature in case of overloading. For comprehensive understanding of this special behaviour which is e.g. totally different to the typical failure mechanism of ETAG002 tension tests, further detailed studies incorporating Finite Element Analysis of the bonding have been launched and will be presented below.

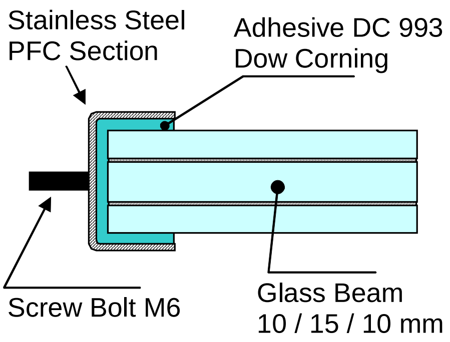

Fig. 3. Specimen, Herz-Jesu church showing the applied U-type bonding geometry

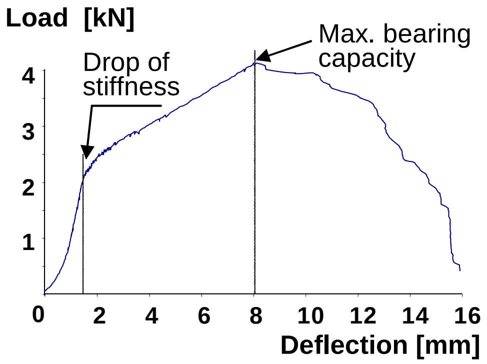

Fig. 4. Tension test results

Fig. 5 and Fig. 6 show the stress levels experienced by the Silicone material for a loading corresponding to the 2 mm deflection test point of Fig. 4. High stress levels are visible in the front region of the bonding geometry while the shear stress in the side regions is low. A detailed investigation of the numerical results leads to a share of approximately 90% for the tension stresses in the front region and approximately 10% for the shear stresses of the side region meaning that the stiffness of the adhesive in the front region is magnitudes of order higher than on the side region. This load distribution is explained by the high level of incompressibility of the Silicone adhesive and the almost perfect suppression of lateral contraction in the front region by surrounding glass and steel material [3]. Please note that for incompressible material the effect of free i.e. unconstrained lateral contraction is the halving of the cross section area when doubling the length of the material due to constant volume under any kind of loading [4]. In case the possibility of lateral contraction is suppressed, the material will react by significantly higher stiffness in tension. In case of free lateral contraction the load share would be more balanced reducing the ratio to 60% front region and 40% side region.

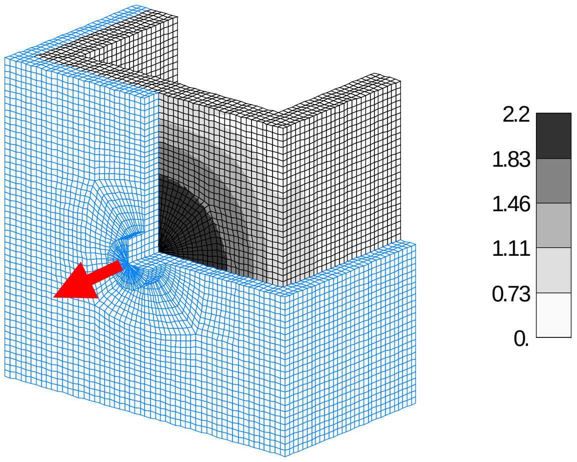

Fig. 5. Max. principal stress distribution

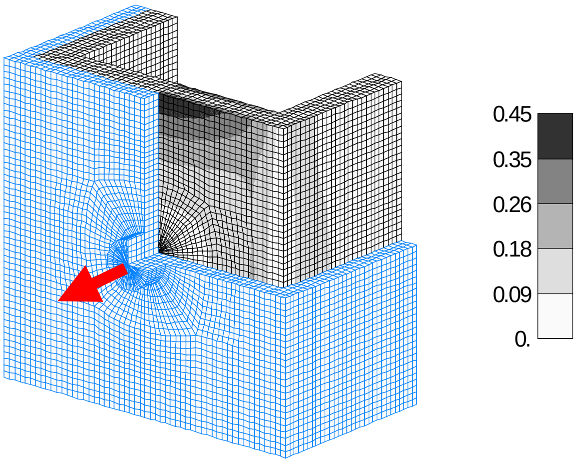

Fig. 6. Max. shear stress distribution

These issues have lead to the following hypothesis concerning the failure mechanism of the bonding [1, 5]: If the bonding is increasingly loaded by tension, mainly the front region experience significant stress levels. When first overloading of the front region occurs, this region will start to fail showing increasingly cracks in the adhesive material. As the cracks add free surface to the adhesive, the condition of significant lateral suppression is relaxed leading to increasing flexibility of the front region. Thus, the load will be redistributed towards the still intact side regions. The deflection at maximum load i.e. approximately 8 mm confirms this hypothesis of activating the side regions for large deflections as the related maximum shear strain corresponds to ETAG specimen results subjected to simple shear loads. Furthermore, inspecting the specimen visible surface during tension tests demonstrate the crack initiation in the front region confirming hereby that the high loading in the front region is critical for bonding integrity [5].

2 EDGE EFFECTS OF U-TYPE BONDING DESIGNS

Comparing the width of the specimen with the width of the glass beam elements leads to a relation of 50 mm up to 6720 mm differing by up to two orders of magnitude. Please note that the specimen width is mainly determined by test set-up and test procedure requirements not allowing to exceed a certain width range for practical reasons. Thus it is interesting to study the impact of the bonding width on the mechanical behaviour especially in the context of high sensitivity to free surface effects due to the role of lateral contraction. Therefore, FE studies were performed analysing different bonding width for three cross sections featuring the following geometries, see Fig. 7:

- Configuration U0 (baseline): Three glass panes of 12 mm each plus twice PVB layer thickness, side region 22 mm length

- Configuration UF: Three glass panes of 12 mm each plus twice PVB layer thickness, side region 15 mm length

- Configuration USF: Two glass panes of 12 mm each plus PVB layer thickness, side region 15 mm length

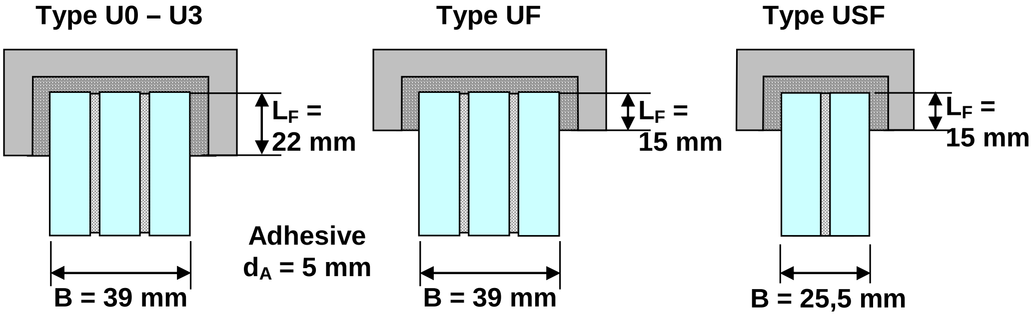

Fig. 7. Variation of U-type bonding

The loading was introduced in a line-type distributed manner by prescribed displacements at the two intersections of the interfaces steel – adhesive with the edge of the cross section. For the evaluation of the load-carrying capacity, a maximum principal stress level in the vicinity of 2 N/mm^2 was assumed to be the relevant parameter for the investigated Silicone adhesive based on the experience of experimental results according to Fig. 4. Fig. 8 presents the result in terms of averaged distributed loads for the three different geometries for varying width. Please note that symmetry conditions were applied for the calculation; thus the abscissa in the figure is related to the half length of the investigated geometries. Plotting the line loading averaged over the bonding width allows easily to assess the impact of edge effects. In case edge effects are of minor impact the slope of the curve will be small. For very large width, the averaged distributed loads will converge towards the value obtained while assuming pure plain strain state in the bonding.

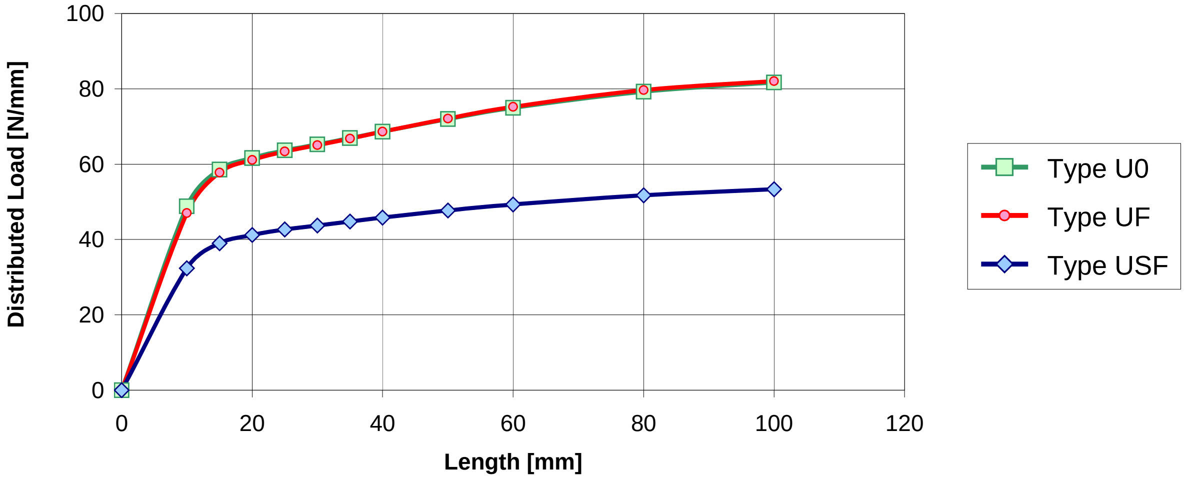

Fig. 8. Comparison of load carrying capacities for different U-type bonding geometries

Comparing the load carrying capacities of the bonding geometries, the dominance of the front region for U-type bonding geometries is visible again in the results. While changing the side region by modifying the PFC cross section flange length has almost no visible impact on the load levels, the front region geometry defined by the thickness of the glass unit is a primary parameter for the load carrying capacity. It should be noted here that the selection of the glass thickness is typically governed by other aspects like dimensioning and costs not allowing to consider the variation of glass thickness in the design space of the bonding geometry.

3 ANALYSIS OF LOAD ATTACHMENT DESIGNS

Typically, discrete attachment points will be used for introducing the loads to the glass units. In case of the glass façade of the Herz-Jesu church, eight connecting points exist for the horizontal glass beams while two connecting points are used for the vertical glass beams. In order to study the impact of local load introduction on stress levels, three different designs for load attachment were analysed for the baseline geometry, see Fig. 9. The first design – configuration U1 – is based on a plate perpendicular to the main axis while the second one – configuration U2 – refers to a plate parallel to the main axis. The idea of the third design – configuration U3 – is to use a simple bolt attached to the steel channel.

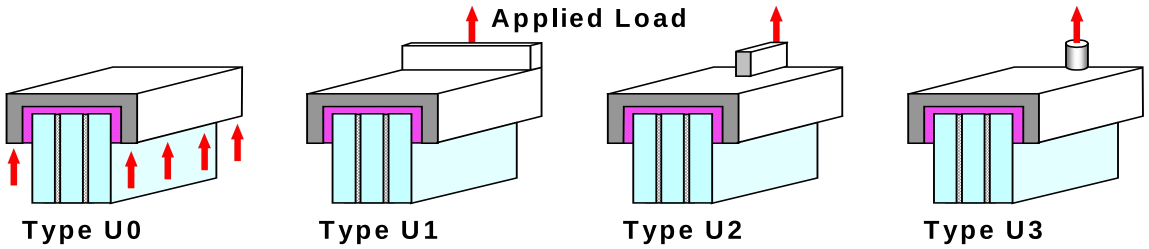

Fig. 9. Design variations for load introduction – baseline bonding geometry

Fig. 10 presents the results in a similar manner as Fig. 8. The ranking of the different load attachment points can be explained by the level of non-uniformity of stresses which they introduce. Of course best results will be obtained by introducing forces and moments as distributed loads shown by the curve for the configuration U0. Nevertheless, considering real world requirements, this is typically not a feasible design option. Configuration U1 offers best performance for the investigated discrete load transfer designs. In this case, the flanges of the cross section are activated as well by the extension of the plate to the vicinity of the flanges. The overall effect gained hereby is an increase of the effective area for load introduction reducing local stresses by smearing them over an increased area. Due to the orientation of the plate configuration U2 is not able to activate the flanges in the same intensity. Therefore, the stresses increased by load introduction are more localised. Under these aspects, configuration U3 is extreme featuring an almost pointwise load introduction. For large width, it is expected that the averaged distributed loads will converge towards zero for all configurations U1 to U3 while U0 will converge towards the plain strain state properties as already mentioned above.

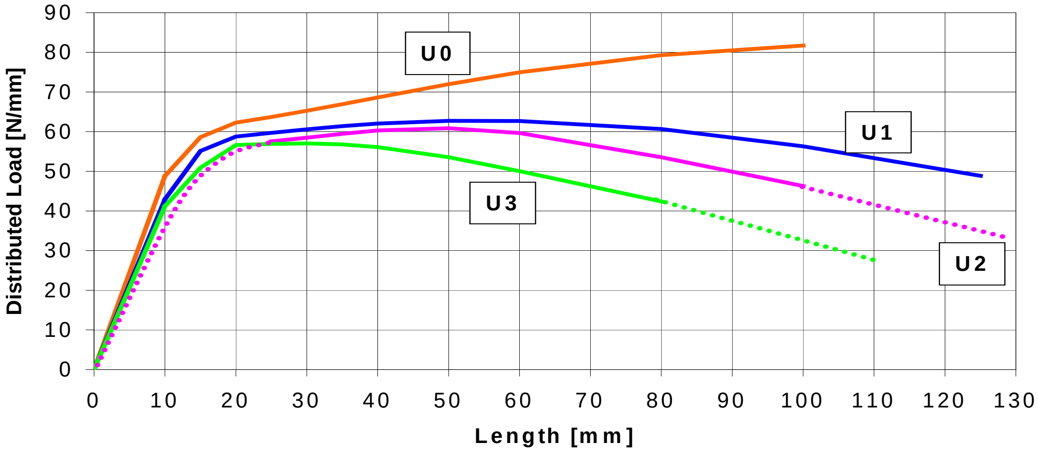

Fig. 10. Comparison of load carrying capacities for different load attachments – baseline geometry

More detailed information concerning the local stress levels is given in Fig. 11 for the case of configuration U1 and for two different widths. The impact of the free edge is clearly visible by the differences of the maximum principal stress distributions in this region comparing the numerical results.

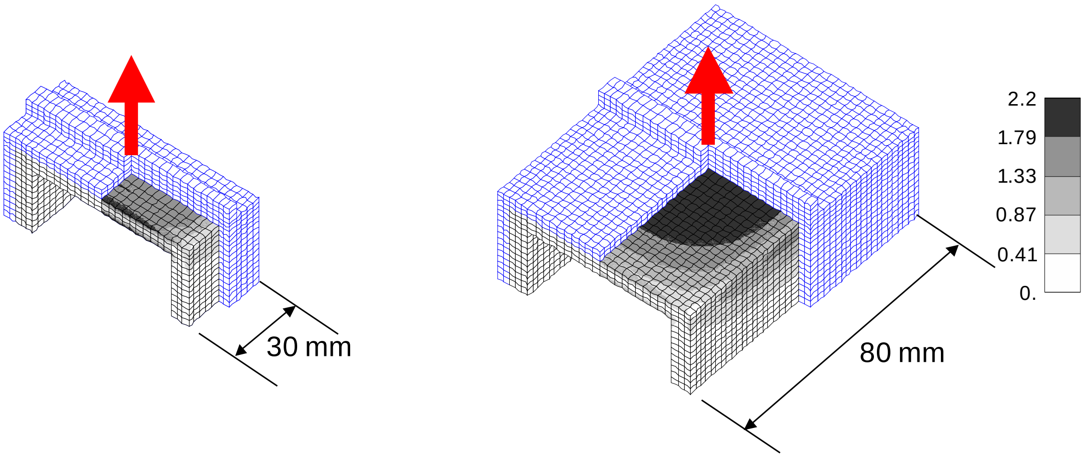

Fig. 11. Max. principal stress distribution for the configuration with perpendicular plate (U1)

The results presented in Fig. 10 can also be used for design purposes of the investigated Silicone adhesive. Fig. 12 demonstrates the procedure how to extract strength information of this kind of figure for a selected bonding width. The distributed load value has to be multiplied with the total width of the bonding in order to get the maximum estimated load carrying capacity. An alternative way would be to plot the total loads instead of the distributed loads versus the width parameter for direct extraction of limit loads. Using this scheme, the total load curves for configurations U1, U2 and U3 will converge to constant levels for large width hereby demonstrating the fact that regions far from the discrete load introduction are inefficient due to flexibilities of the steel part.

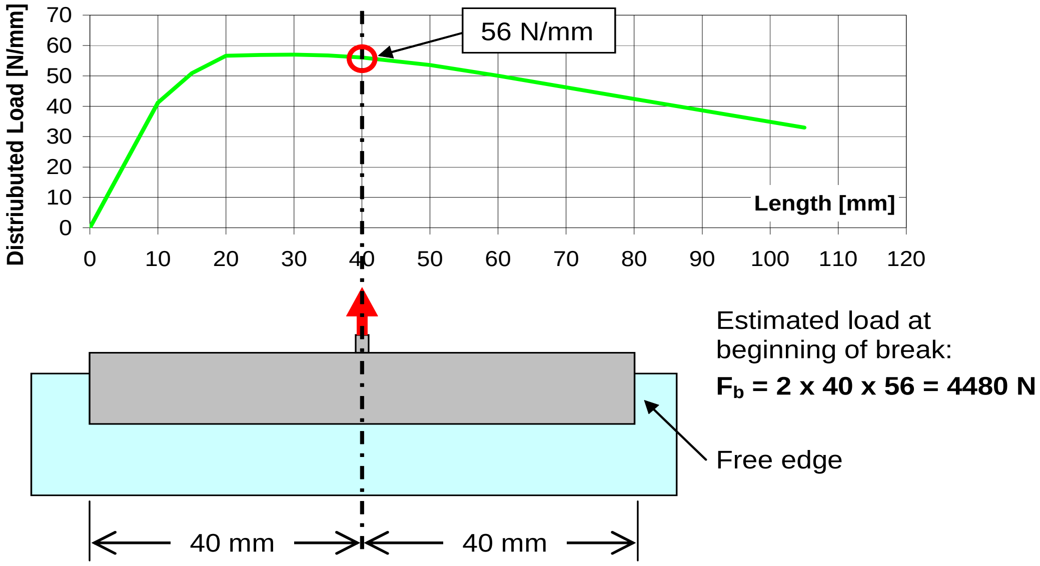

Fig. 12. Sizing procedure for U-type bonding geometry with discrete load attachment

5 SUMMARY AND ACKNOWLEDGMENT

U-type bonding geometries offer a lot of advantages in terms of:

- Load carrying capacity: Redundant load paths of front and side regions and thus favourable fracture behaviour
- Elasto-mechanic behaviour: High joint stiffness in tension while low joint shear stiffness – favourable in terms of thermal loading
- Aging/Durability: Protection of highly loaded front side and small free surfaces exposed to environment

Starting from the large full-scale application of U-type bonding geometries at the Herz-Jesu church in Munich, several aspects such as cross sections and load introduction have been analysed in this paper. These activities have lead to fundamental understanding of the physics using Silicone adhesives for this kind of application.

The author would like to thank the *Erzdiözese München und Freising* for unconditional support of the advanced design of the Herz-Jesu church, Munich. Furthermore, the author would like to thank the DowCorning company for their outstanding technical support provided during the design of the façade as well as in the related research phase.

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