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

Experimental and Numerical Analysis of Glued Steel-Glass Joints

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Due to the intensive progress and research on the field of glass structures, possibilities for using glass as a load carrying elements are increasing every day. Different types of hybrid constructions, consisting of glass and another material, are analyzed or even newly developed focusing on an optimal structural interaction between both materials and in respect to architectural, static-structural and fabrication criteria. Glued joint, realized by polymer adhesive is very often the key element of whole composite structure, therefore also the key aspect of research, development and numerical modeling. This paper deals with the research pointed on the description of different adhesive behaviour under increasing load, ultimate carrying capacity of the area glued joints according to the thickness of the adhesive layer and working FE models of polymer adhesives, transferred from industry to glass construction design (epoxies, acrylics, polyurethanes, silicones).

Keywords: Steel-Glass, Glued joint, Polymer adhesive, FE modeling

1. Introduction

In glass structure engineering and design, in general, tension strength of the glass determines the load carrying capacity of whole element. Pure glass beams always fail suddenly and without extensive previous warning. In case of composite structures (hybrid beams), stiff member, assembled to the tensioned part of the beam, is able to work as a consumer of the break energy even if the first cracks in the glass pane are visible. Hybrid glass structures can this way achieve higher stiffness, load carrying capacity and also residual capacity, which is mainly depending on used kind of adhesive and type of construction glass [1], [2].

2. Long Glued Connection Between Steel and Glass

For this type of joint, definitely, glued connection is the most effective one mainly because of better (more uniform) distribution of the stress along the contact. In general, glued joint offers a bigger ability to assemble thinner materials or to connect different materials together as well as aesthetic appearance and reduction of self-weight [3]. Adhesive layer itself also provides a protection from direct contact between steel and glass, which always has to be avoided in glass structure engineering. For the purpose of hybrid structures (i.e. beams), in general, adhesively bonded joint should be rigid enough to provide an optimal interaction between both connected elements, but whole connection has to be able to compensate pertinent different temperature deformations of glass and another material (e.g. steel, aluminium, stain-less steel) especially in case of longer hybrid structures.

2.1. Suitable adhesives

Most often used adhesives can be divided according to their modulus of elasticity and shear modulus into flexible-elastic (i.e. silicones, modified silicones and polyurethanes) and rigid (i.e. epoxy or polyester resin, acrylics). Rigid adhesives have extremely high strength but very low elongation in comparison with elastic adhesives, which show elongation at break even more than 250%. Practical application of different types of polymer adhesives depends on their behaviour under loading, which comes from their material properties or even molecular structure [3].

Each adhesive shows different behaviour under increasing load regarding to the thickness of the joint. It was proved experimentally for common types of adhesives, that by increasing thickness of the joint over the ideal value, possible elongation (or slope) of the adhesive layer increases too, but the connection loses its load carrying capacity. One of the main tasks of the connection design is to find the state of the adhesive thickness, where the glued joint can fulfil the requirements on load carrying capacity and also provides a necessary elongation (or shear slope).

2.2. Hand calculation of the adhesive layer

Simple linear theories can be used for approximate calculations of average stress in the adhesive layer or to obtain average deformations of overall joint. Stress-strain relation of adhesive can be simplified by bi- or tri-linear diagram for compliant adhesives like silicon or polyurethane, sometimes by linear diagram for stiff epoxy resins. According to this theory, adhesive layer can be assumed as a volume member with three linear stiffnesses – normal stiffness and two shear stiffnesses in perpendicular directions [4]. These stiffnesses can be determined by the joint's thickness and Young's modulus or shear modulus of the adhesive, or can be experimentally investigated for specific connection.

3. Experimental Program

3.1. Choice of adhesives

With reference to previously mentioned requirements on suitable bonding material, wide range of adhesives with different mechanical and deformational properties was involved to the experimental program. Final set of adhesives was chosen by support of SIKA CZ and includes almost all common used material types of polymer adhesives - starts with a very stiff epoxy resin, goes down via acrylics and polyurethanes to very flexible silicone. Special emphasis was devoted to the UV stability and long-time behaviour of chosen adhesives. UV unstable adhesives, like most of the polyurethanes, have to be protected from UV lights by using special primer coating also on the side of the glass pane, because there is a risk of UV lights propagation also by the reflection inside the glass pane.

Definitely, two-component adhesives or adhesives with booster system have to be used for such a kind of connection, where the width of the connection is bigger (over 30mm). Previous research proved, that one-component adhesives (mainly polyurethanes), which are cured by air humidity, can't get hard more than ca 15mm to the depth of the connection in real time. Booster component provides uniform hardening of the adhesive layer (like the 2nd component), process of curing doesn't depend on air humidity and whole curing is a question of hours, not days like for a lot of one-component adhesives. All adhesives had to be chosen also regarding to their open time (pot-time), which is very important in respect to fabrication criteria. Some of the adhesives can be applied by gap-filling, but the others (more viscous) have to be pressed between two connected parts. Both kinds of adhesive application have to be useful for production of the joint with the total length up to 6m (usual maximal construction length of one glass pane).

3.2. Material tests

Material tests of all chosen adhesives were performed in accordance with [5]. Test specimens were created by using special form and their standardized shape is drawn in the Figure 1. Their total length l_3 was 160mm, measured section l_0 was 50mm long, 10mm wide (b_1) and 4mm thick (h). All dimensions of the specimen can be found in [5].

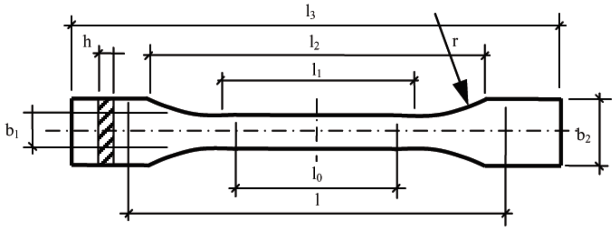

Figure 1: Specimen for material tests of chosen adhesives.

Important data like a real tension strength, stress-strain diagram, elongation at break, Young's modulus and for some of adhesives also a Poisson's ratio were obtained from these material tests. Experimentally investigated data show characteristic properties of each adhesive and serve as an input data for nonlinear FE material models of the adhesives. Comparison of different stress-strain relations of different adhesive types can be seen in Figure 2, where the epoxy resin curve is missing, because of completely different and incomparable material properties.

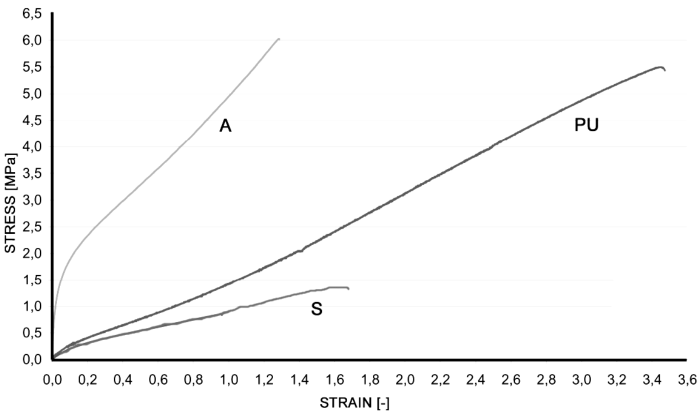

Figure 2: Comparison of the material test results for different adhesives
(S- silicone, A- acrylic, PU- Polyurethane booster system).

Stress-strain curve of tested epoxy resin was nearly linear, achieved tension strength was more than 35MPa and possible strain less than 0,5%, therefore this kind of adhesive could have been assumed (simplified) as a linear elastic material and taken into account like that.

3.3. Steel-glass connection tests

Load carrying capacity of the glued joint can't be calculated directly from experimentally assessed value of the material strength, because of another state of stress in area connection. As a next step of this research, instant tension and shear connection tests were carried out, see Figure 3, to investigate the exact behaviour of adhesively bonded joint between steel and glass, to find out its realistic tension and shear load carrying capacity and to calibrate simple finite-element models of the glued joints with adhesive layer including the non-linear material properties from previously performed material tests.

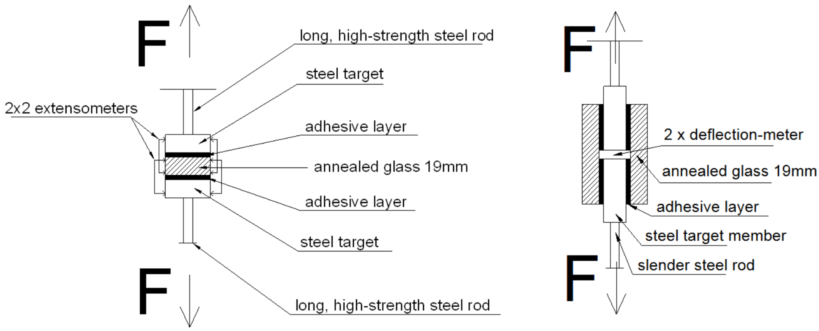

Figure 3: Set-up of the steel-glass connection tests (on the left: tension, on the right: shear).

Two different extensometer-systems were used to measure exactly the deformation of the adhesive layer under continuously increasing load. Very sensitive extensometers with small range (usually used for crack opening measurement) were used to measure the rigid connections with epoxy resin or acrylic, see Figure 4a. High-range extensometers was required in case of silicone or polyurethane, where the possible elongation of the connection was much bigger (up to 220%), see Figure 4b and c.

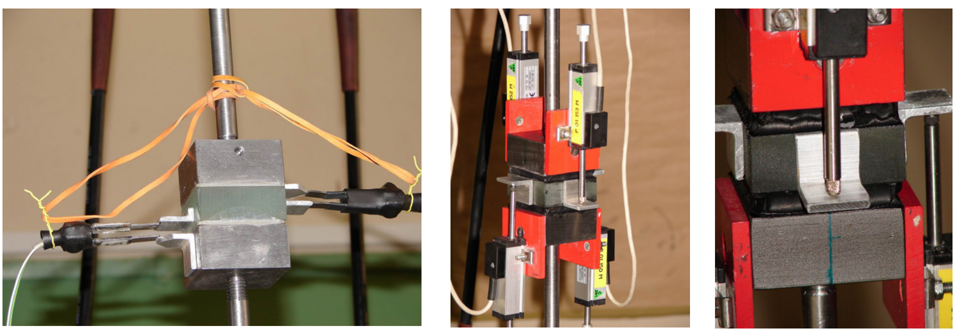

Figure 4a, b and c: Tension tests, different devices used to measure the deformation of the adhesive layer.

In the figure 5a, there is a set-up of the shear connection tests, typical shear action of compliant adhesive is in the Figure 5b and representative cohesive failure is captured in the Figure 5c.

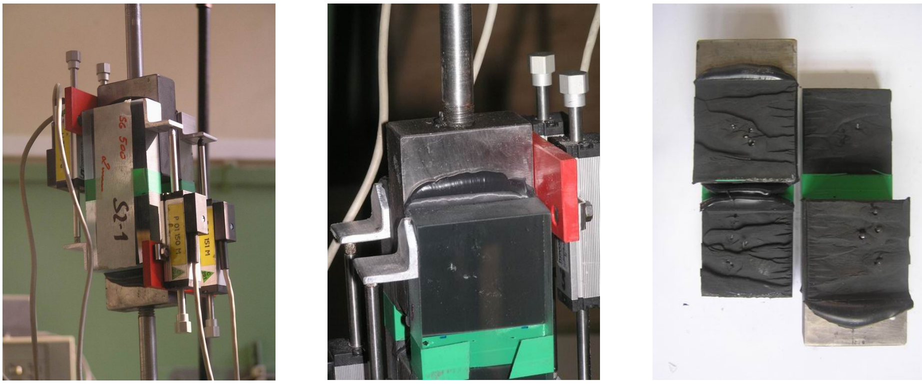

Figure 5a, b and c : Shear tests, details.

More than 50 specimens with different adhesives and thicknesses of the layer were prepared and tested. All applications of adhesives were made professionally by the bonding expert in the laboratory of SIKA CZ to ensure cohesive failure within the adhesive layer as a determinant of carrying capacity of the joint. Required adhesion was reached by using certified technologies of surface treatment and by primer coating for some of the adhesives. Generalized and summarized results of the connection tests are in the Figure 6 (tension) and in Figure 7 (shear), where the representative curves of the stress strain diagrams of the joints are drawn for each of the tested adhesives and its specific thickness.

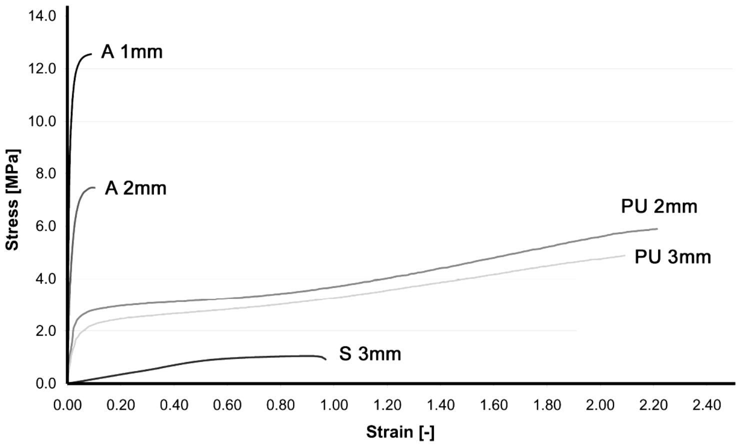

Figure 6: Stress-strain diagrams of the glued connections subjected to tension
(S- silicone, A- acrylic, PU- Polyurethane booster system).

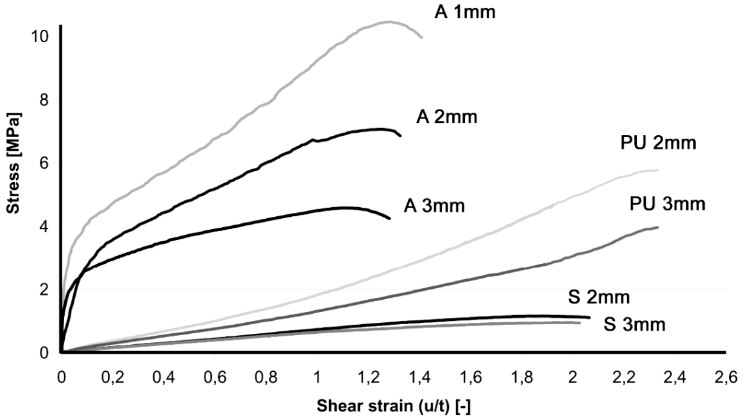

Figure 7: Stress-strain diagrams of the glued connections subjected to shear
(S- silicone, A- acrylic, PU- Polyurethane booster system).

4. Numerical Analysis

Finite-element method was chosen as a device for numerical studies. Volume models of tested glued connections were created by software package Ansys 11, see Figure 8a-c.

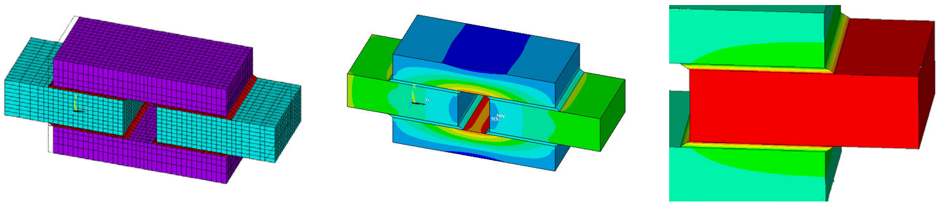

Figure 8a, b and c: Numerical model of tested shear connection.

It is always very complex task to calibrate the same numerical material model to be accurate and behave like the real one in tension and also in shear. Behaviour of the adhesive layer in shear is much more important for our problem, because the joint will principally work as a semi-rigid horizontal shear connector in composite structure. Therefore, the most important indicator of accuracy of the numerical model for each adhesive was the result of the shear connection test.

4.1. How to model different types of adhesives

Adhesives, which are tougher, for example epoxy resin or acrylics could have been modeled as multi-linear elastic, with using appropriate input material parameters. In the Figure 9, there is a comparison of FE calculation made on calibrated multi-linear model of acrylic adhesive with thickness of 3mm subjected to shear with experimental obtained results for the same adhesive and thickness.

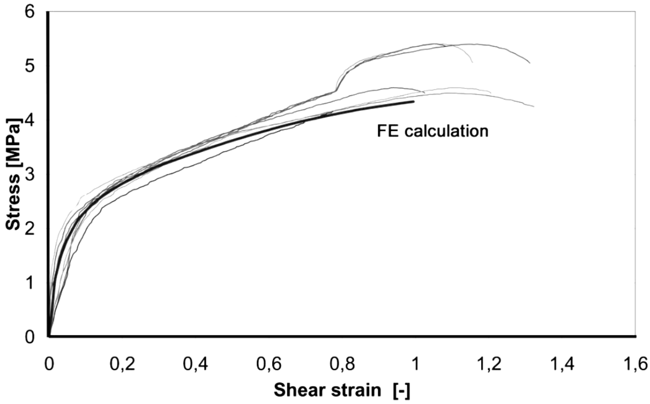

Figure 9: Comparison of FE calculation with experimental results for acrylic adhesive.

Due to the negligible (almost immeasurable) deformation of the connection with very stiff epoxy resin, it was possible to assume tested material as a linear-elastic with appropriate linear input parameters determined from material test. In the Figure 10, there is a comparison of FE calculation made on calibrated linear elastic model of 3mm thick epoxy resin subjected to shear with experimental results for the same adhesive and thickness.

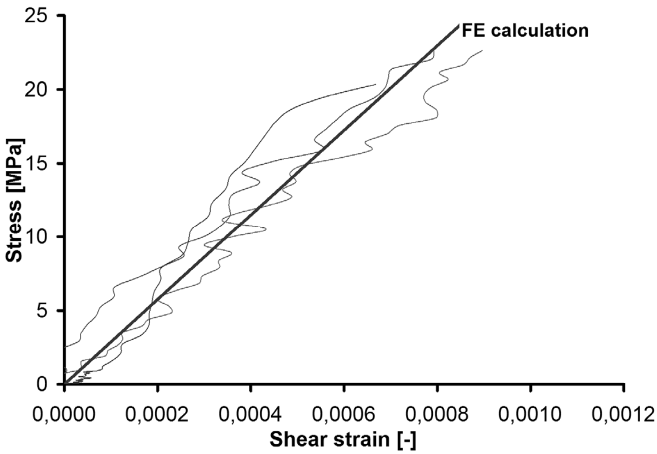

Figure 10: Comparison of FE calculation with experimental results for epoxy resin.

There is a possibility to use phenomenological material models, which are included in most of the common used finite element software. Hyper-elastic models, i.e. Mooney-Rivlin, Arruda-Boyce or Ogden, can very accurate predict the behaviour of compliant adhesives like silicones or tested polyurethanes. Their calibration isn't easy because a lot of input parameters are needed and longer calculation time is required. Whole process of calibration of the material model is more complex, but these models can withstand extensive deformations. Therefore they can be very useful for materials, which show high-elastic elongation. In the Figure 11, there is a comparison of FE calculation made on 2mm thick Mooney-Rivlin hyper-elastic model of polyurethane with experimental results for the same adhesive and thickness.

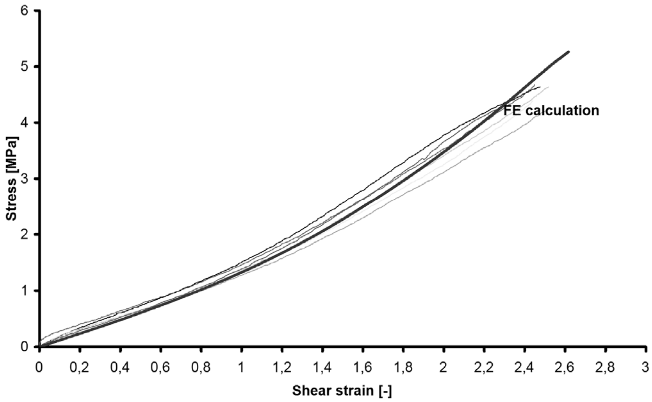

Figure 11: Comparison of FE calculation with experimental results for polyurethane.

5. Conclusion

Clear idea about the behaviour of adhesively bonded joint under increasing load, knowledge of its exact load carrying capacity and verified numerical model are the first steps, needed to be done on the way to successful FE modeling of complex hybrid structure, including semi-rigid shear connection realized by polymer adhesive.

6. Acknowledgements

This research has been carried out with a support of the project VZ01 CEZ MSM 6840770001.

7. References

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