Shear Adhesive Connections for Glass Structures

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Abstract. Unique aesthetical properties of glass – not only transparency but also smooth, glossy and primarily reflective surface – give this material special importance in the contemporary architecture. In every structural application of glass it is necessary to solve the problem associated with connections between glass pane and other part from a different material or between two glass elements. Moreover, there are many types of hybrid structures that combine glass and different materials to achieve safe failure behaviour and high degree of transparency at the same time. Connection of brittle glass and reinforcing material is an essential part of these structures, where composite action between two parts is beneficially ensured by a glued joint. The current paper deals with the experimental analysis focused on the determination of mechanical characteristics of adhesives applied in planar connections under shear loading.

1. Introduction
Polymer materials of adhesives are no longer limited to the sealing function, they can also fulfill real load-bearing function [1], [2] [3]. Contrary to the traditional bolted connection, an adhesive joint provides many important advantages for brittle glass, such as uniform stress distribution along the larger connection area, the absence of drilling holes in the glass or possibility to join materials with different mechanical and thermal properties. The reliability of the bond is influenced by many factors, starting with selection of the appropriate adhesive for a particular joint. The shear strength of the connection may be also influenced by adhesion of glue to the substrate, cohesion of glue, joint dimensions and geometry, environmental factors (relative humidity, UV radiation, and temperature), thermal expansion coefficients of joining elements, duration of load, rate of load application, surface preparation and surface roughness, workmanship and curing [4].

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The presented article deals with the experimental analysis focused on the determination of the mechanical characteristics of adhesives applied in planar connections under the shear loading. With regard to the fact that many types of adhesives are produced, six glues with different properties (polyurethanes, acrylates and UV-curing methacrylates) were selected for the research. The research also compares two similar adhesives (the older technology and the new one) produced by the same manufacturer in case of glass-to-steel connection. Specimens of all adhesives were prepared for various substrates and their surface treatment (smooth glass, roughened glass, steel, stainless steel and aluminum). As joint dimensions and thickness play a crucial role, adhesives were tested in several thicknesses according to the type of adhesive. Firstly, small-scale test specimens were carried out and evaluated. In the following stage, the most appropriate transparent UV-curing adhesive was selected for full-scale specimens of glass beam to assess the influence of size effect. Due to these several goals, the research provides comprehensive knowledge about the behavior of the chosen adhesives in shear connection under short-term loading.

2. Experimental program
Experimental analysis of the glued connections was performed in relation to hybrid steel-glass beams research [5], therefore adhesives were chosen in accordance with the application in glass-to-metal or glass-to-glass large planar connection loaded by shear.

| Type of specimen | description | diagram |
|------------------|-------------|---------|
| 1st arrangement: glass-to-steel | 2 x float glass | 50 x 110 x 19 mm |
| | 2 x steel S235 | 50 x 75 x 25 mm |
| | Adhesives: | |
| | 1C-PU: SikaFlex-265+Booster | |
| | Acrylate: SikaFast 5211 | |
| | Acrylate: SikaFast 5211 N | |
| 2nd arrangement: glass-to-steel | 2 x float glass: 50 x 50 x 19 mm | |
| | steel S235, stainless steel | |
| | 1.4301, aluminium Al 6082 | |
| | 290 x 100 x20 mm | |
| | Adhesives: | |
| | 1C-PU: SikaFlex-265+Booster | |
| | 2C-PU: SikaForce 7550 | |
| | Acrylate: SikaFast 5211 | |
2.1. Small scale shear test arrangement

Since the important information about the glue is not only its ultimate strength but also its behaviour in the joint under loading, the research covers six types of adhesives with different mechanical properties – elastic adhesives (one-component and two-component polyurethanes), semi-rigid adhesives (two-component acrylic adhesives) and transparent rigid adhesives (UV-curing systems), which can be suitable in case of glass-to-glass bonding. Adhesives were applied in the test specimens; see Table 1, assembled from different materials to describe the influence on adhesion. The research covers glass-to-glass and glass-to-metal (steel, stainless steel and aluminum) joints with smooth or coarsened glass surfaces considering the adhesion improvement possibility.

The joint ability of flexible deformation is one of the most important conditions for the choice of adhesive for hybrid structures due to different thermal expansion coefficients of the connected materials. For the reason that flexible deformation corresponds to the adhesive layer thickness, glass-to-metal specimens were prepared in 1, 2, 3 and 4 mm thickness of the layer for polyurethanes and two-component acrylate glue.

Small-scale shear tests were performed according to three arrangements, see test setups in Table 1. The first setup was carried out according to the scheme in the first row in table 1. Specimens were prepared for three adhesives. Shear stress in the adhesive layer was reached by steel plates in tension. Tensile load was introduced to the setup by long steel rods. This arrangement is suitable for quick obtaining of glued connection stress-strain diagrams and was used only for glass-to-steel connections.

The second setup arrangement was used for detailed glass-to-metal joint analysis. Glues were applied in glass-to-steel, stainless steel and aluminum specimens, which create middle part of the setup. Glass for specimens was used both with smooth and roughened surface. The second arrangement allows introducing the tensile load by the pins positioned at both ends of the test device. Shear stress in adhesive layer was reached by tensile load in test device and middle sheet of metal (specimen). The main benefit of the rearranged test setup and usage of testing device with end-pins was the elimination of additional loading.

The third arrangement of small-scale shear tests was used on glass-to-glass connections with transparent UV-curing adhesives. Shear load in adhesive layer was introduced by compressive force applied to the middle glass element. At the bottom edge, lateral restraint against outspreading was applied.
3. Small scale shear tests results

Summarized stress-strain relationships were prepared for comparisons of joint types with various adhesives and glue thickness. The summarized diagrams show representative curves, which were chosen according to their approaching to the average values of results.

3.1. Polyurethane adhesives

Both tested PU-glues demonstrated similar behavior for all tested substrates, see stress-strain diagrams in figure 1. All specimens were broken by full cohesive failure mode. Both adhesives results proved lower strength values by 10% and two-component PU adhesive had also lower strain at break by 20% in comparison with product data sheets.

3.2. Acrylate adhesives

Specimens glued by two-component acrylate adhesive (SikaFast 5211) with smooth glass surface reached shear strength values significantly between 5.5 and 7 MPa with shear strain at break 150-200%. Failure of these specimens started by adhesive mode at glue-glass interface but final failure was observed as cohesive at the places, where glue had sufficient adhesion to the glass, see figure 4. Contrary to this, specimens with roughened glass surface demonstrated satisfactory adhesion to the glass at whole joint area and they reached approx. 8 MPa shear strength, which is in conformity with the product data sheet. Summary of representative stress-strain relationships, see figure 2, provides comparison of various substrates in joints and different adhesive thicknesses as well. These results were obtained by usage of the second arrangement setup.

Stress-strain diagram illustrating the results for the first arrangement setup, see figure 3, shows comparison of adhesive SikaFast 5211 and SikaFast 5211 NT (new technology). It is noticeable that the new type of the adhesive (specimen 2) shows different behaviour than its predecessor (specimen 1). SikaFast 5211 NT reached significantly higher shear strength (7.5 MPa for 3 mm thick joint and the first type of arrangement, while originally the glue reached 4 MPa for the same joint and arrangement) and larger shear strain at break. The large initial stiffness in the joints of new adhesive did not change up to 3.5 MPa, although the older type of adhesive had the initial stiffness limited around 2 MPa. Cohesive failure with adhesion faults at glass-glue interface (similarly to its predecessor), see figure 5, or glass damage was typical for SikaFast 5211 NT specimens.

![Image 1](image1.png)

**Figure 1.** Shear stress-strain relationship – PU adhesives. 1 = steel + glass (3 mm), 2 = steel + glass (4 mm), 3 = steel + roughened glass, (3 mm), 4 = stainless steel + glass (3 mm), 5 = aluminium + glass (3 mm).
Figure 2. Shear stress-strain relationship – acrylate adhesive; 1 = steel + glass (3 mm), 2 = steel + glass (4 mm), 3 = steel + roughened glass (3 mm), 4 = stainless steel + glass (3 mm), 5 = stainless steel + glass (4 mm), 6 = aluminium + glass (3 mm).

Figure 3. Comparison of acrylate SikaFast 5211 a SikaFast 5211 NT in glass-to-steel connection, first arrangement, 1 = SikaFast 5211 (3 mm), 2 = SikaFast 5211 NT (3 mm).

Figure 4. Typical adhesive-cohesive mode of failure for the specimens glued by SikaFast 5211.

Figure 5. Cohesive mode of failure for the specimen glued by SikaFast 5211 NT.
3.3. Adhesive layer thickness comparison

As the thickness of the adhesive layer is a very important factor affecting the mechanical properties of a joint, glass-to-steel specimens were produced in a 1, 2, 3 and 4 mm thickness of glue. The comparison of the results is shown in figure 6, where 1C-PU is one-component polyurethane with the Booster system (Sikaflex-265 Booster 20W), 2C-PU is two-component polyurethane (SikaForce-7550 L15) and A is acrylate adhesive (SikaFast 5211). It is noticeable that all glues show a different reaction to the change in thickness. Experiments proved the phenomenon that the strength of joint decreases with the increasing thickness of the adhesive layer simultaneously with the increase in elastic deformation and it was observed in semi-rigid acrylate adhesive more significantly than in flexible polyurethanes. The graph includes the results from the first (1) and the second (2) type of arrangement and it also provides the comparison of the results for the same connection tested in both arrangements (e.g. acrylate adhesive in 3 mm connections). It is evident that different results were mainly caused by embedded hinges in the second arrangement and by minimizing of additional loading.

3.4. UV-curing adhesives

Specimens bonded by UV-curing adhesives (RiteLok UV50, Conloc 685) showed similar behavior for both smooth and roughened glass surface. Shear strength reached was approx. 15 MPa with shear strain at break 100%; see figure 7, which is in accordance with the product data sheets. Failure was observed as a combination of cohesive break of glue together with rupture of glass.
Figure 7. Shear stress-strain relationship – UV-curing adhesives; a = RiteLok UV50 (1 mm) smooth glass, b = RiteLok UV50 (1 mm) sand-blasted glass, c = Conloc 685 (1 mm) smooth glass, d = Conloc 685 (1 mm) sand-blasted glass.

4. Glued glass beam with I cross-section
The knowledge of the glued glass joint behaviour was verified in a real structural element – a fully transparent glass beam with I cross-section. The glued glass beam consists of a glass pane (web) that is double sided strengthened by rectangular glass profiles at its upper and lower edges. The connection between the rectangular glass strengthening profile and the web is adhesive bonded by Conloc 685. The span of the beam was 4.0 m. The beam was produced from heat-strengthened glass because of the high shear strength of the adhesive. Rectangular sheets of heat-strengthened glass may be manufactured in a width-to-length ratio of up to 1:10. For this reason, glass profiles at the edges had to be divided into segments. The whole beam geometry was developed so that no seam between two segments was in the same place of the flange from both sides.

For full-scale tests of a glued connection, two beams were prepared. The specimens were subjected to a 4-point bending test. In the test setup, each point load was at the distance 937 mm from supports to avoid seams in the flanges. Lateral restrictions were provided at supports and the mid-span. The beams were loaded at a rate of 50 N/s and loading was continued until the total collapse.

Full-scale tests proved the expected behaviour of the adhesive connection according to the previously performed small-scale tests. The measurements of strain gauges showed that the adhesive connection transferred stresses between cross-sectional parts very well, see table 2 representing stress transferring below the load introduction point at the bottom edge of the beam.
Contrary to expectations, the collapse of both specimens occurred at relatively low loading and the failure started near the support by a shear crack, not in the middle of the span. The early failure was caused by several factors. Firstly, considering hand-made manufacture of the beams, there is a risk of stress concentrations near the bottom flange edge due to geometrical imperfections. Secondly, the asymmetrical seam arrangement of rectangular sections creating flanges caused additional transverse loading of the beam. As a result, at the seam locations, the upper compressed part of the cross-section
with a seam was additionally bent to the web with the continuous rectangular section and the bottom tensile part of the cross-section was inflected to the interrupted rectangular flange section, thus both flanges were additionally bent in the same direction and the glued connection was loaded by peeling-off.

5. Conclusion
Sand-blasted glass surface can improve the shear strength, if the pure cohesive failure mode is not reached in the joint with a smooth glass surface and if the glue has a low viscosity. No decreasing strength values caused by sandblasting of the glass surface were observed because the cohesive strength of the adhesive was crucial in the glued joints. The influence of different metal materials in glued connections was not decisive.

The effect of thickness was noticeable for the semi-rigid 2-component acrylate adhesive (SikaFast 5211) – the strength of a glued connection was decreased while increasing the thickness of the adhesive layer, especially in the glass-steel type of connection. In flexible PU-adhesives, the influence of thickness was not noticeable.

Important difference was proved for behaviour of 2-component acrylate adhesives. The new type of acrylate glue (SikaFast 5211 NT) showed completely different behaviour under shear loading with significant, almost linear part of stress-strain diagram with high stiffness up to stress level of 3.5 MPa. For higher levels of loading, behaviour was changed and noticeable increase of strain was observed.

Behaviour of adhesive connections in glued glass beams as full-scale specimens corresponds to the knowledge of adhesive joints in small-scale test specimens. The joint between the glass web and the strengthening profiles (flanges) transferred stress very well.

Except for the above mentioned, it is important to say that long-term loading, cycling loading and ageing can significantly change the mechanical properties of glued joints and further research is necessary.

6. References
[1] Belis J, Van Hulle A, Callewaert D and Dispersyn J 2012 Proc. of Challenging Glass 3 – Conf. on Architectural and Structural Applications of Glass (Delft University in Technology) ed F Bos et al (Amsterdam: IOS Press) pp 177–186
[2] Weller B, Härth K, Tasche S and Unnewehr S 2009 Detail Practise – Glass in Building, Principles, Applications, Examples (Basel: Birkhauser) pp 68–71
[3] Abeln B, Richter C and Feldmann M 2014 Proc. of Challenging Glass 4 – COST Action TU 0905 Final Conf. ed Ch Louter et al. (Luiden: CRC Press/Balkema) pp 321–329
[4] Haldimann M, Luible A and Overend M 2008 Structural Engineering Documents 10 - Structural Use of (Zürich: IABSE-AIPC-IVBH) pp 152–163
[5] Netusil M, Eliasova M 2012 Proc. of Challenging Glass 3 – Conf. on Architectural and Structural Applications of Glass (Delft University in Technology) ed Bos F et al (Amsterdam: IOS Press) pp 715–724

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