Glass Masonry - Experimental Verification of Bed Joint under Shear

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Abstract. Glass is considered as a traditional material for building industry but was mostly used for glazing of the windows. At present, glass is an integral part of contemporary architecture where glass structural elements such as beams, stairs, railing ribs or columns became popular in the last two decades. However, using glass as structural material started at the beginning of 20th century, when masonry from hollow glass blocks were used. Using solid glass brick is very rare and only a few structures with solid glass bricks walls have been built in the last years. Pillars and walls made from solid glass bricks are mainly loaded by compression and/or bending from the eccentricity of vertical load or wind load. Due to high compressive strength of glass, the limiting factor of the glass masonry is the joint between the glass bricks as the smooth surface requires another type of mortar / glue compared to traditional masonry. Shear resistance and failure modes of brick bed joint was determined during series of tests using various mortars, two types of surface treatment and different thickness of the mortar joint. Shear tests were completed by small scale tests for mortar – determination of flexural and compressive strength of hardened mortar.

1. Introduction
The use of glass for structural components, which transmit besides self-weight also death load, snow and wind load or live load, is in the contemporary architecture common. On the other hand, in building industry can be found only a few completed projects, in which were used masonry made of the solid glass bricks. But mostly it is not masonry in the true sense, because the glass bricks are bonded by a transparent adhesive.

The first realized project in the world is Atocha memorial in Madrid, [1]. Solid glass bricks with curved butt joints have been used in this project. Curved surface allows the irregular shape of the construction and prevents shift of the bricks relative to each. The bricks have been bonded in bed joints together with acrylic adhesive hardened by UV radiation in thicknesses up to 2.5 mm.

The other example of implementation using solid glass blocks is façade of Crystal house in Amsterdam, [2], [3]. As in the Atocha memorial, the transparent UV-curing acrylate adhesive has been used. Due to the low viscosity of the adhesive, bed joints have been bonded only in the horizontal direction, head joints have not been joined. The adhesive could be applied in thickness about 0.3 mm, in which it reaches its maximum strength, thanks to precision manufacturing and a control of each glass bricks. The required tolerance of used glass blocks was ±0.25 mm, so postproduction processing as grinding and polishing was necessitated.

One of the most important properties of the glass bricks masonry is the shear strength, that depends on the connection between the bricks. The presented article summarizes the experimental results of the
inceptive shear tests of specimens consisting of three glass bricks bonded together by a mortar, which were performed in the laboratories of the CTU in Prague, Faculty of Civil Engineering in cooperation with company Vitrablok, s.r.o., a specialist glass brick manufacturer. These tests were focused on the influence of the different material type used for bonding bricks together, on the influence of the surface treatment of the glass bricks and on the influence of the bed joint thickness.

As part of these tests, the flexural and compressive tests of various types of mortar, used for shear test specimens, have been made.

2. Shear strength of masonry from solid glass blocks

2.1. Test specimens

Totally six different connecting materials were tested, three types of mortar, epoxy resin and two types of tile adhesives. All tested materials are commercial products in building industry. Summary of the tested specimens and their quantity are shown in table 1.

| Material type          | Surface treatment | Number of test specimen (pcs) | Thickness of joint (mm) | Ø $F_{\text{max}}$ (kN) | Ø $\tau_{\text{max}}$ (MPa) |
|------------------------|-------------------|--------------------------------|-------------------------|--------------------------|-----------------------------|
| Mortar 1               | Smooth            | 4                              | 11                      | 0 $^b$                   | 0 $^b$                      |
|                        | Roughened         | 3                              | 12                      | 23.42                    | 0.853                       |
| Mortar 2               | Smooth            | 3                              | 11                      | 0 $^b$                   | 0 $^b$                      |
|                        | Roughened         | 4                              | 13                      | 13.38                    | 0.497                       |
| Mortar 3               | Smooth            | 3                              | 13                      | 1.49                     | 0.056                       |
|                        | Roughened         | 3                              | 12                      | 13.17                    | 0.489                       |
| Tile adhesive 1        | Smooth            | 4                              | 1                       | 42.48                    | 1.579                       |
|                        |                   | 4                              | 5                       | 7.90                     | 0.294                       |
|                        |                   | 3                              | 12                      | 0.76                     | 0.028                       |
| Tile adhesive 2        | Smooth            | 3                              | 12                      | 0.64                     | 0.024                       |
| Epoxy resin            | Smooth            | 3                              | 1                       | 54.69                    | 4.109                       |

$^a$ These are mean values of tested specimens.  
$^b$ Specimens disintegrated before testing.

This first set of experiments were focused only on the final suitable connecting material, surface treatment and joint thickness choice. Low number of specimens are not sufficient for statistical evaluation. Following second set of experiments will be only aimed to the final combination of connecting material, joint thickness and surface treatment with sufficient number of specimens to obtain relevant material properties.

The first type of tested material is mortar from trass-cement intended for remediation and laying nature stone masonry, the second one is intended for connecting and grouting glass hollow block and the third one is mortar intended for solid glass block masonry. Two types of tile adhesive from the same producer were tested. The last material was epoxy resin. For each mortar, specimens from the glass bricks with two different surface treatment (smooth glass and roughened glass) were tested, for non-mortar material only specimens made from smooth glass were tested. Because it was found that
the joint thickness plays a crucial role, especially in case of special mortar for tiles with additives and plasticizers, the specimens with the different thickness of the bed joints were tested. The bed joint thickness was about 10 mm for specimens made of mortars and second tile adhesive, 1 mm, 5 mm and 10 mm for specimens made of first tile adhesive and about 1 mm for epoxy resin specimens, summary is shown in table 1.

There are three possible modes of the joint failure. The first one is interfacial crack (i.e. adhesive failure), while there is a loss of adhesion of mortar / adhesive to the surface of the bricks, the second one is failure in the mortar (i.e. cohesive failure) and the third one is the combination of two previous modes (i.e. cohesive-adhesive failure). Adhesion is the result of physical forces, intermolecular and chemical bonds, on the other hand cohesion characterizes the state of matter, in which particles are held together by the action of intermolecular and valence forces.

2.2. Test set-up

The test specimens were made from solid glass blocks, whose dimensions are indicated in the figure 1. Three bricks were bonded together with a mortar / glue, a test specimen made from bricks with smooth surface is shown in the figure 2.

![Figure 1. Dimensions of the glass brick.](image1)

![Figure 2. Test specimen.](image2)

The tests were performed according to European Standard EN 1052-3, [5]. These are the basic tests focused on the shear strength of glass brick masonry determination in the most unfavorable case, ie masonry with no head joints, with no brick bonds and with no prestressing due to the load from adjacent structures etc. In the next steps it will be supplemented by tension, compression and bending tests. As well as the influence of the head joints will be examined.

The specimen was placed in the testing machine in vertical position so, the outer bricks were simply supported and the inner one was push through down, see figure 3 and figure 4. Flexible elastic pad was embedded between the glass brick and 20 mm steel supporting plate to reduce the risk of generation local peak stresses and subsequent rupture of the glass bricks in the support area and the forcing area, see figure 5. Supporting plates were supported by steel rods with 12 mm diameter. Compression force was transmitted by ball joint placed in the middle of 20 mm steel plate with flexible pad between glass and steel.

Test specimens were loaded vertically, see figure 4, so the bed joints were loaded by a shear. Potentiometers were used for measuring of the relative displacement between bricks in several tests.
2.3. Evaluation of the experiments

Adhesive failure mode (loss of adhesion of the bonding material to the glass surface) was observed in case of all specimens. Neither cohesive nor combined adhesive-cohesive failure were found in any cases, as well as the breakage of the glass bricks. Failure was always brittle without any visible deformation of the specimen or cracking generation in the joint.

2.3.1. Influence of the surface treatment. Treatment of the bricks surface by fine sandblasting has a significant impact to the shear strength. While the major part of the specimens made of smooth glass could not be tested, because they have been disintegrated during handling (mortar 1 and mortar 2), the specimens from roughened glass had more than ten times higher load capacity in comparison to tested smooth glass specimens. Due to bad aesthetic effect of roughened surface, it was decided that for the other specimens we are using only the bricks with smooth surface.
For non-mortar materials, only smooth surface of the glass bricks was tested due to better optical quality. Sandblasted surface increased shear strength, but worse optical properties means disadvantage in appearance / visual aspect of the whole structure.

2.3.2. Influence of the material. Connecting material used in tests can be divided to three parts – mortars, tile adhesives and epoxy resin. Mortars and tile adhesives are both based on cement, and their main difference is in thickness for which they are intended. Mortars are usually used in thicknesses of joints about 10 mm, while the tile adhesives are intended for small thicknesses (about 5 mm). Likewise, for the mortars and the tile adhesives the results of the specimens with the same surface treatment and with a similar thickness were very similar.

On the other hand, the results of specimens made from epoxy resin were significantly higher. The strength was the order of a hundred times higher than in case of conventional connecting material. This evaluating is not unexpected - all adhesives based on epoxy resin are designed for bonding inter alia non-absorbent materials. The use of epoxy resin is in case of glass bricks masonry appropriate, but it leads to the high cost. Also the optional thickness of adhesive layer is very small and the requirement for an appearance similar to a conventional masonry is not fulfil. Additionally, the preparation of epoxy resin in situ would be difficult and challenging skill workers and would require far higher accuracy of the manufacturing of the glass bricks due to lower thickness of joints.

Conventional mortar designed for glass or similar material connecting seems to be the best solution with sufficient strength and adequate price rather than epoxy resin. In addition, for large thicknesses can be better compensated the variations by changing the thickness of the joint.

2.3.3. Influence of the bed joint thickness. Used mortars showed insufficient adhesion in case of smooth surface, because the specimens made of mortars with about 10 mm thicknesses disintegrated during handling. The mortars are unsuitable for connecting of two glass surfaces. They are mainly appointed for porous material e.g. classic ceramic bricks. For tile adhesive were made specimens with different thicknesses. Tested tile adhesive showed characteristics typical for adhesives. With decreasing thickness distinctly increases the strength, even at half the thickness was about tenfold increase in strength. For ten times lower thickness was the strength about fifty times higher. This phenomenon is similar to that which was described in case of the acrylic UV-cured adhesive in the wall made of glass bricks of the Crystal House in Amsterdam, [2], [3]. This phenomenon was also observed in the experimental research of adhesive joints in glass structures in which PU adhesives, acrylate and UV-curing acrylates were tested, [4]. The big advantage of mortar or tile adhesive respectively is on the one hand the possibility of creating larger joints so that the walls look like classic ceramic walls, secondly its easy workability in situ and, ultimately, lower cost compared with polymer adhesives.

3. Flexural and compressive strength of hardened mortar

As a part of the experiments there were carried out also tests in accordance with EN 1015-11, [6] in order to determine flexural and compressive strength of mortars and tile adhesives used in shear tests. These tests are very important for mortar material properties determination that will be used in a numerical model in the following research of masonry from solid glass blocks.

3.1. Flexural strength test

The limiting factor for the construction members made of mortar is tensile strength. To determine the tensile strength serves flexural strength test.

Specimens used for this test shall be prism with dimensions 160 x 40 x 40 mm. The specimens were made by mortar filling into a special mold, which coincides with standard test specimens procedure. Three specimens for each mortar and tile adhesive have been made. The tests were performed after sufficient hardening of the mortar of at least twenty-eight days after manufacture. Test set-up is three-point bend test where the loading force acts in the middle of the specimen and the
support is 30 mm from the edges as is shown in figure 6. The prescribed support and force distances were assured by the special device into which the test specimen was mounted, as shown in figure 7. The specimen was placed in this device so that its upper surface was during the test on the side of the specimen. This measure aims to the influence of unevenness surface elimination. Test specimens were loaded continuously with load rate 100 N/s to failure.

A summary of all specimens and their results, is in table 2.

![Scheme of flexural test, [6].](image1)

![Specimen in testing machine.](image2)

**Figure 6.** Scheme of flexural test, [6].

**Figure 7.** Specimen in testing machine.

**Table 2.** A summary of flexural strength tests.

| Material type     | Number of test specimen (pcs) | $\bar{\sigma}_{\text{max}}$ (MPa) | $\bar{F}_{\text{max}}$ (kN) |
|-------------------|-------------------------------|-----------------------------------|---------------------------|
| Mortar 1          | 3                             | 6.15                              | 2.67                      |
| Mortar 2          | 3                             | 8.95                              | 3.97                      |
| Mortar 3          | 3                             | 5.69                              | 2.43                      |
| Tile adhesive 1   | 3                             | 7.09                              | 3.13                      |
| Tile adhesive 2   | 3                             | 7.45                              | 3.27                      |

* These are mean values of tested specimens.

3.2. Compressive strength test

For the compressive test there were used half prisms from the flexure tests. Totally, six specimens for each mortar / tile adhesive have been tested, specimen in the special device placed in testing machine is shown in figure 8.

A summary of all specimens and their results with mean values of maximal force at collapse and maximal stress, is in table 3. Test specimens were loaded by compression with load rate 100 N/s to the collapse.
Figure 8. Specimen in testing machine.

Table 3. A summary of compressive strength tests.

| Material type    | Number of test specimen (pcs) | $\bar{F}_{\text{max}}^a$ (kN) | $\bar{\sigma}_{\text{max}}^a$ (MPa) |
|------------------|-------------------------------|-------------------------------|-----------------------------------|
| Mortar 1         | 6                             | 30.05                         | 18.78                             |
| Mortar 2         | 6                             | 59.87                         | 37.42                             |
| Mortar 3         | 6                             | 28.48                         | 17.80                             |
| Tile adhesive 1  | 6                             | 37.18                         | 23.24                             |
| Tile adhesive 2  | 6                             | 43.50                         | 27.19                             |

$^a$ These are mean values of tested specimens.

4. Conclusion
This experimental research focused on the shear strength of glass block masonry. Experimental results can be defined in following points:

- Shear resistance of roughened glass surface was in comparison to the smooth one ten times higher.
- Resistance of epoxy resin was in accordance with the assumption of the order of a hundred times higher than in case of conventional mortars.
- When comparing specimens made with the same joint thickness and the same surface treatment, but made of different material, is evident that the values of shear strength, except epoxy resin, are approximately the same.
- The joint thickness has a significant impact on the shear strength of glass bricks masonry. With decreasing thickness, the strength increases in case of special mortars or tile adhesives with chemical adhesives changing the behaviour. This can be explained by the composition of the used mortars. This phenomenon is typical for the adhesive joints, where the strength
strongly dependent on the thickness for rigid adhesive. For joining glass bricks with a smooth surface cannot be used the classical mortar as common bricks masonry, but it is necessary to use a special fine-grained mortars in connection with adhesive or a special ingredient that ensures sufficient adhesion. The structural behaviour of special mortars with additives and plasticizers under loading is closer to the behaviour of glued connection.

- Although the various types of mortars / tile adhesives have had the different flexural and the compressive strength, the influence of material on adhesion to glass bricks was negligible.

Finally, for glass bricks masonry the mortars based on cement blended with a special ingredient increasing the adhesion to glass should be used and the thickness of the joints should be chosen with regard to the significant drop on the shear strength with increasing thickness as small as possible e.g. from 1 to 5 mm. Sandblasted surface should not be used for its worse visual aspect compared to smooth surface, although it has a distinctly higher strength. Likewise, polymer adhesives are suitable for use in glass bricks masonry, but it is necessary to keep in mind that they have high demands on precision manufacturing and assembly, and not least in economic terms.

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