Contact Materials for Structural Glass.

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Abstract. Worldwide many wide-spanning transparent roofs have been built. Most of them have curvilinear forms. The new developed transparent space grid structures are in interesting solution for plain roofs. They base on steel space grid structures, at which the bars in the compression layer are replaced by glass panes. The glazing fulfils a double function, is serves for the load transfer and as roof covering. The application of large forces from the nodes into the glazing is realized by block elements. These materials have to fulfill certain demands. At the Technische Universität Dresden a 15 m spanning mock-up of the new transparent space structures was built and static and dynamic investigation of appropriate block elements, metal alloys and thermoplastics, carried out.

Introduction

Worldwide many transparent glass roofs have been built in the last decades. The mostly used roof geometries are curvilinear shapes. These shapes allow the activation of membrane forces and therefore need very slender steel profiles, only. A further increase of transparency is achieved by omitting the steel elements. In this case all loads in the vault are transferred by glass panes. One example is the vault roof covering the courtyard of the Maximilian Museum in Augsburg, Germany. This roof was built in the year 2000 and spans about 13.5 m wide with an arch rise of approximately 4 m. The panes are connected at their corners in a node. Within the node, the force transfer from the pane corner to the node is ensured by resin filling.

To improve the transparency of plain roofs, that usually work as bending systems transparent space grid systems are under investigation at the Technische Universität Dresden. These structures use a different concept for plain roofs than typical plain roof structures. Using the principle of steel space grid structures, the replacement of all bar members in the compression layer by glass panes increases the transparency and sustainability. This is achieved by the activation of the glass panes as primary load bearing element. The glazing of the structures has a double function; as part of the structural system it transfers in-plane and out-plane forces and it serves as roof covering, too.

Concept of Transparent Space Grid Structures and Mock-Up Realization.

Most of the steel space grid systems were invented in the 1940 till 1970. Because of their popularity a broad variety of systems were developed. Mostly common are double layer grids, consisting of a compression and a tension layer. For the research of the concept and the mock-up realization a double layer grid was chosen. The concept can be easily described by the replacement of the bars in the upper layer, the compression layer, by glass panes.

The assembling of glass panes in the compression layer limits the number of economically appropriate geometries. The entire structure is defined by the grids of the compression and the tension layers. Especially the panes size and homogeneity of the central node define an economic compression layer grid. Only homogeneous grids fulfill these demands. The space structure half-octahedron plus tetrahedron is one of the most efficient structures in the Mengeringhausen morphology [1] and was therefore chosen. At this structure the compression and the tension layer have the geometry of equal sized square grids and are dually situated to each other. The connection of both layers is achieved by diagonal bars between their nodes. The derivation to efficient transparent space grid structures, with regard to the material behavior of glass is detailed described in [2].

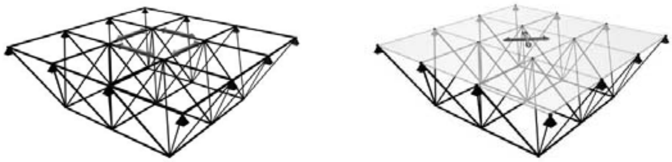


Fig. 2a and 2b: Compression elements in the upper layer of a traditional and a transperant space grid structures (half-octahedron plus tetrahedron)

To investigate the structure behavior of the overall system a mock-up was built. It is assembled of equal modules. Each module is a stable, statically determined structure in the shape of a half-octahedron. The stability of each single module results in a significant redundancy of the overall roof structure, that is particularly linear supported at the edges of the roof.

Each module consists of a glass pane, four quarters of a node at each end of the pane, four tension rods in the joints, four diagonal bars and one node in the lower layer. The dimensions of the glass panes are 1.25 m square. The panes consist of laminated glass made of two layers of 10 mm heat-strengthened glass with 0.76 mm PVB-interlayer. The dimensions of each quarter of the node are about 10 cm square. In the joints of the panes thin tension rods were integrated, mainly to keep the modules in its form.

Fig. 4: Steel-glass-module

Fig. 5: 10 m strip of the mock-up

To assemble the roof all modules were connected. The mock-up demonstrated that transparent space grid structures could well be built using steel-glass-modules. The structure served as basis for extended load-bearing tests, either on the global system or on single modules [3]. Investigations regarding to the load application into the glass edge are described in this paper.

Node Design and Appropriate Block Elements

The node is the most complex element of the module. This element ensures the load application into the glass edge. To transfer loads into a glass edge usually glass resins, e.g. HILTI HIT-HY50 [6] are used. Especially for laminated glass the load application using mortars or resins offers significant advantages, as these materials fit at uneven glass edges but produce a load eccentricity. Despite research works [4, 5] the question for an optimal load application material was not finally answered. In [4] significant compressive strength of the glass edge was testified. The application of high compression forces into the glass edge can be ensured, if the block material is on the one hand side not too hard (e.g. steel) and on the other hand not too soft and elastic to resist significant deformations. Also the visco-elastic behavior of plastics or resins should be put into considerations.

In general for the use of structural glass the pouring of mortar or resin for the load transfer is a proven technique and used for different products and projects. Disadvantages are the limited compressive strength of the materials and the time and cost intensive individual production.

The disadvantages of the mortars are the advantages of solid block materials, made of plastics or soft metal alloys. They allow the transfer of higher compressive stresses and can be cheaply produced in a large quantity. The big disadvantages of solid block materials, the compensation of tolerances and, for laminated glass, the unevenness of the edge must be handled with an intelligent node and block design.

Fig. 6a - 6b: Quarters of the node (development steps 1 and 2)

For the node design the use of solid block materials was chosen. POM-C blocks were selected to achieve sufficient test result at the global mock-up because of their good background at glass applications. Within different development steps the nodes were improved, regarding their clamping behavior, their post-breakage behavior and their assembling.

The design of the first node development is shown in the FE-model. The gray colored block, in this case the plastic POM-C serves for the load transfer between glass and node. The tolerances can by adjusted by the multipart design of the node. The parts are formed as wedges in the opposite direction. They allow a tolerance adjustment up to two millimeters per block.

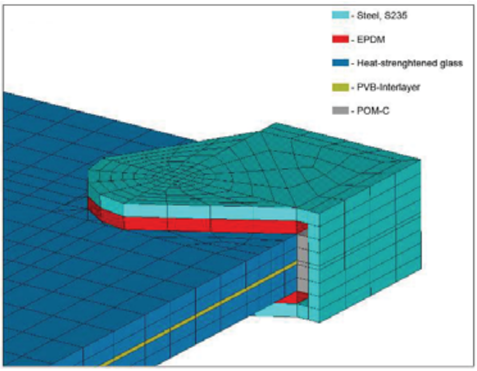


Fig. 7: FE-model of the node

Extensive research has been started because of little available information about appropriate block materials for the load application into the glass edge. To transfer heavy loads into the glass edge solid block materials have to possess certain mechanical properties:

- high compressive strength
- small Mohs-hardness; direct glass contact must not hurt the glass edge surface
- small plastic deformation percentage
- small creeping at visco-elastic plastics
- mechanical consistency at temperatures between -20 °C and +80 °C regarding the national building codes
- UV-stability
- good workability

Different materials were chosen for the mechanical investigation. Basis for the choice were experiences of load application in structural glass constructions. Point fittings, as one of the major applications, possess a ring made of soft aluminum alloys or plastics that is very often a polyacetate (e.g. POM) or polyamite (e.g. PA 6). These materials with numerous experiences in structural glass applications are the basis for the investigation.

Material name	Material	Description
Aluminum F 28	Aluminum alloy AlMgSiPb	Soft aluminum alloy
POM	Plastics	Polyacetate homopolymer
POM-C	Plastics	Polyacetate copolymer
POM-GF25	Plastics	Polyacetate with 25 % glass fibre
Zinc	Zinc alloy Z410 ZnAl4Cu1	Used for foundry purposes

Table 1: Block materials for investigation

Steel and further hard metals are no appropriate materials for block elements. Because of their hardness they scratch the glass surface and damage the material to the breakage.

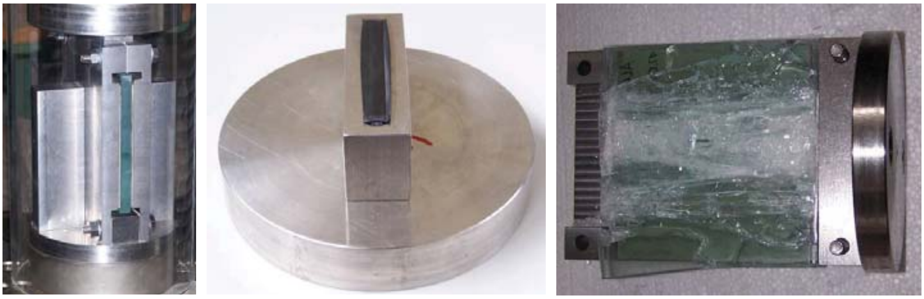
Table 2 lists the relevant available mechanical properties of the materials. The table is not complete, but gives an overview about the behavior of, for blocks, potential materials. The properties of the plastics differ slightly. Their values depend on the producer of the plastic. The differences are small and have no significant influence on the test results. In [7] mechanical values of the plastic materials can be compared. All mechanical properties of plastics base on tension. There is no data available for compressive stress. Principally the stress-strain behavior under compression should be at least equivalent to the stress-strain behavior under tension force, as there the deteriorating influence of the constriction does not exist. The mechanical properties for zinc Z410 differ extremely. This depends on the technology to use high pressure to form the zinc bodies. The in the tests used zinc alloy possesses a quite low module of elasticity.

Property	**Aluminum F28**	**POM**	**POM-C**	**POM-GF25**	**Zinc Z410**
Module of elasticity E [MPa]	~70 000	~2 800	~3 000	~ 9 300	~65 000-130 000
Yield stress [MPa]	280-370	65-70	67-72	125	220-250
Bending strength [MPa]	310-390	120	120	150	280-350
Ulitmate strain [%]	>9	25-70	25-70	3	4-5
Temperature maximum shortterm [°C]	-160	+140	+140	+140	
Temperature range Longterm [°C]		-30 - +100	-30 - +100	-30 - +110	

Table 2: Known mechanical properties of block materials

Load Tests under Permanent Pressure

To investigate the behavior of the glass-block contact at large compression forces the testing facility shown below was manufactured.



Figures 6a - 6c. Testing facility and deformed POM-C wedges in socket and failed glazing

For the testing identical test specimens of aluminum F28, POM-C and zinc were built. They had the form of a wedge with dimensions of 80 mm x 10 mm x 5-8 mm. The used glass pane was a annealed glass with 10 mm thickness and dimensions of 150 mm square. The test facility was put in a testing machine with a capacity of 250 kN. Each of the described block elements were laid on the upper and the lower edge of the glass pane. Therefore the measured deformations result from two blocks.

In the stress-strain diagram significant differences between three materials are obvious. Because of the plastic deformation of the POM-C small glass cracks occurred at 190 kN and 220 kN. At the third POM-C specimen no glass failure occurred and the test was ended at 250 kN. The POM-C was strongly deformed. At a force of about 80 kN a significant increased deformation was observed. The part of plastic deformation rapidly rose at this force.

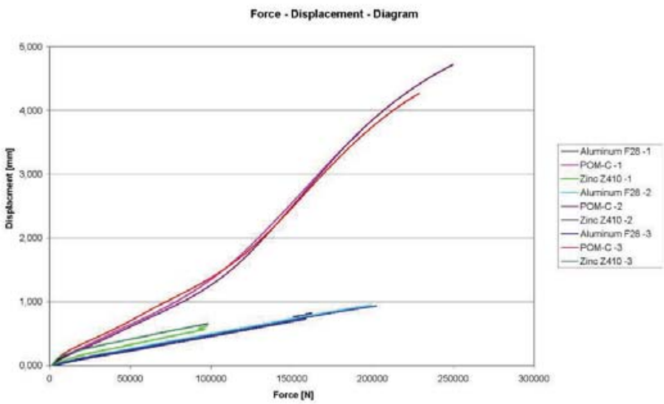


Fig. 7: Stress-strain diagram under permanent force

The two metals show a linear-elastic behavior. At the zinc the glass failure load was about 90kN, at the aluminum the load was between 160 kN and 200 kN. The crack started next to the wedges. Mostly the glass panes exploded and were completely destroyed.

Load Tests under Cyclic Compression Forces

Load tests under cyclic compression force were run to determine the ratio elastic and plastic deformation. As the metals aluminum and zinc possesses a linear-elastic material behavior this investigation was only performed with POM-C specimens. The curves of six POM-C specimens show a continuously increasing deformation during the test.

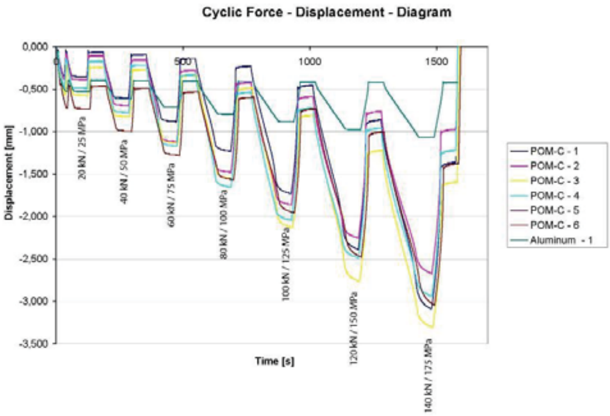


Fig. 8: Stress-strain diagram under cyclic force

The measured deformation is the sum of two specimens, one at the top and the second at the bottom of the glass pane. Especially at higher compressive stresses, more than 50 MPa, a significant rheologic behavior is obvious in the figure above. There is a quick creeping at loading and a slower creeping back at unloading. The creeping speed at high stress is tremendously quick. The compressive stress, as parameter for the creeping speed, must be limited. [8] For structures, like the glass roof, especially the compressive stress from dead load as well as the sum of dead load and snow load are the relevant values for creeping investigation.

Creeping Behavior

The estimation of the creeping behavior over the next 50 years, the standard lifetime of buildings, is a necessary knowledge for a safe application of plastic block elements in glass structures. The investigated plastics have been known since the 1920s. For tension load there is substantial data available. Single curves demonstrate the relation between module of elasticity, tensile stress, tensile strain, temperature and time. [7] Using the time-temperature-shifting principle [9] the influence factors time and temperature can be described by two independent functions. This allows the formulation of a good materials law [10].

$$E_C(t,\vartheta) \approx E(t_0,\vartheta_0)\cdot a_0^{\left(\frac{\vartheta}{\vartheta_0}-1\right)}\cdot\left[1-\frac{1}{3}\cdot(1-c_c)\cdot\log_{10}\left(\frac{t}{t_0}\right)\right] \qquad (1)$$

with

$$a_0 = \left[\frac{E_C(t,\vartheta_2)}{E_C(t,\vartheta_1)}\right]^{\frac{\vartheta_0}{\vartheta_2-\vartheta_1}} = \left[\frac{\varepsilon_C(t,\vartheta_2)}{\varepsilon_C(t,\vartheta_1)}\right]^{\frac{\vartheta_0}{\vartheta_2-\vartheta_1}} \quad \text{and} \quad c_c = \frac{E_{c0}}{E_{c3}} = \frac{E_c(t=10^0\,h)}{E_c(t=10^3\,h)} \qquad (2, 3)$$

The materials law (1) allows the calculation of remaining modules of elasticity at given times, temperatures and stresses. Objective of the recently started creeping investigation is the data collection of creeping behavior under pressure. The determined data will be compared to the materials law (1) for tension. Creeping tests at small specimens and at the full-scale mock-up were started to collect data of the creeping behavior. The small specimens are hollow cylinder with an outer diameter of 11.1 mm and an inner diameter of 5.1 mm. Their height is 6 mm. The applied load causes a compression stress of 25 MPa. This value is equal to the compression stress under dead load of a 15 m to 20 m transparent space grid structure. Currently only POM-C and POM-GF25 material is investigated at room temperature. Far more extensive creeping tests are under preparation. At them different stress values, different temperatures and further materials will be investigated.

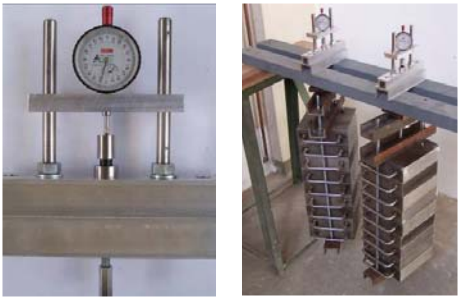


Fig. 9a - 9b: Testing facility for creeping

Beside these elementary tests also the 15 m glass strip is under dead load for almost 2 years and under an additional load of 1.20 kN/m² since February 2008. This load causes a compression force in the block elements of 36 kN. At the mock-up the dimensions of the block elements are about 50 mm x 23 mm. The contact surface between plastic and glass edge is about 50 mm x 16 mm. The uniformly distributed stress is 45 MPa in this case.

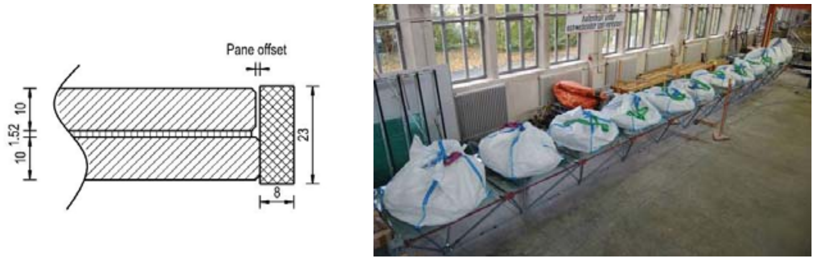


Fig 10a - 10b: Pane offset and creeping testing of 15 m roof strip with 1.20 kN/m²

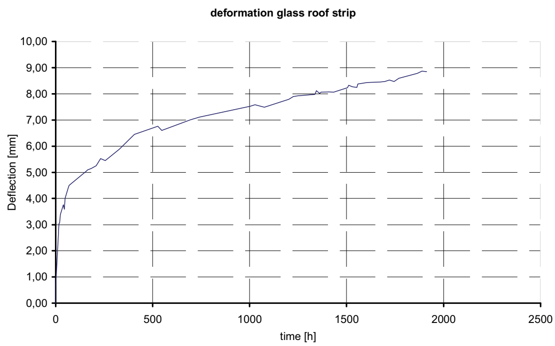


Fig. 11: Deflection-time diagram of 15 m roof strip

In the middle of the roof strip the deflection is measured by a dial gauge. The increasing deflection should give information about the deformation behavior. Besides the creeping of the plastics, especially local plastic deformation at uneven steel node surfaces and the uneven glass edges are relevant for the measured deflection. In the case a huge offset of the panes causes a load transfer over one pane only, the compression stress is 90 MPa, at which stress significant creeping was observed at cyclic compression tests.

Conclusions

Roofs, working as bending systems, are usually less transparent structures. Transparent space grid structures assembled of steel-glass-modules are also bending systems with an increased transparency and lightness. They base on the structural principle of traditional steel space grid structures, at which the bar members in the compression layer are replaced by glass panes. Within the compression layer heavy forces must be transferred between glass edge and node. For this transfer economic block elements are investigated at the Technische Universität Dresden. Possible materials, mainly thermoplastics or soft metal alloys need to fulfill a broad range of demands. Testing to identify appropriate materials for roofs as transparent space grid structures are described. The creeping investigations will proceed, as at them the suitability of plastics can be judged.

Acknowledgments

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