Suitable Contact Materials for Axial Load Application into Glass Edges

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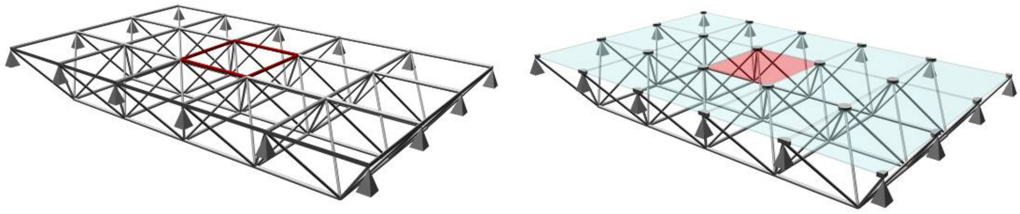
Abstract
The TU Dresden is decisively involved in the development of a glazed roof structure. The designed transparent space grid structure is based on a conventional steel space grid, in which all steel members of the compression layer are replaced by glass panes. The glazing units transfer in-plane forces, which are applied through steel knots, connecting four glass panes at their corners. Until now, no comprehensive scientific research has been carried out to investigate suitable contact materials for axial load application at glass edges. The intended detail design requires a contact material, which is softer than glass while providing a high compressive strength, low creeping and a working temperature range between -20°C and +80°C. A large number of metal alloys and polymers were tested with regard to their compressive strength. Tests on their creeping behavior started in spring 2008. The results of current investigation were applied to optimize a full-size roof mock-up, spanning over a distance of 15m.

1. Introduction

Many transparent roof structures have been built in the last decades, worldwide. Most of these transparent structures have curvilinear shapes. This form allows the activation of membrane forces, whereby the sizes of the steel profiles are minimized. In contrast to curvilinear shaped roofs plain structures usually work as bending system. Mostly they have been built as less transparent steel structure with glass panes as roof topping. Transparent space grid structures are a different concept for plain roofs. Using the principle of a steel space grid structure, 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.

2. Principle of transparent space grid structures

During the development of steel space grid structures a huge amount of different systems were designed. Mostly common are double layer grids, consisting of a compression and a tension layer. The assembling of glass panes as compression layer limits the number of economically appropriate geometries. The entire structure is defined by the grids of compression and tension layers. Especially the panes size and homogeneity of the central knot define an economic compression layer grid. One of the most efficient structures in the Mengeringhausen morphology [1] is the space structure half-octahedron plus tetrahedron that was chosen for the mock-up realization.



Figures 1a and 1b: Compression elements in the upper layer of a steel space grid structures and in one with glass panes (structure half-octahedron plus tetrahedron)

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 knots. The derivation to efficient transparent space grid structures, with regard to the material behavior of glass is detailed described in [2, 3].

3. Mock-up design

The mock-up is assembled of equal modules. Each module is a stable, statically determined structure in the shape of a half-octahedron. Each module consists of a square glass pane, four quarters of a knot at each pane corner, four tension rods in the joints, four diagonal bars and one knot 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.

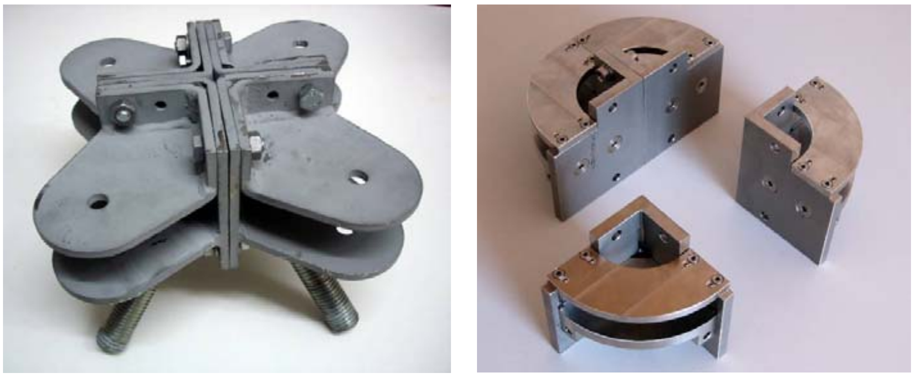
Figure 2: Prefabricated modules.

Figure 3: Completed 10 m roof mock-up.

The linked modules with completed tension layer build the mock-up in different geometries. The load application into the glass edge is explained in this paper.

4. Knot design stages

The load application from the glass pane into the knot was realized by plastic blocks. Intensive testing of different materials will have to be finished, for the mock-up POM-C was selected because of its positive experiences at glass applications. The glass panes were laid on the EPDM layers of 5 mm thickness.



Figures 4a and 4b: Different knot stages.

The FE-model in figure 5 shows the design of the knot. The gray colored block, in this case the plastic POM-C serves for the load transfer between glass and knot. The tolerances can by adjusted by the multipart design of the knot. The parts are formed as wedges in the opposite direction. They allow a tolerance adjustment up to two millimeters per block.

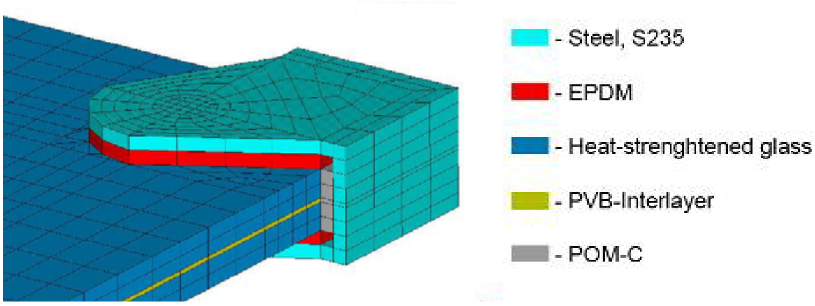


Figure 5: FE-model of the knot.

5 Local load applications
5.1 Appropriate block materials
In recent years several scientific works were published dealing with the buckling of glass. [4, 5] These investigations did not finally answer the question of an optimal load application material. Mainly glass resins, e.g. HILTI HIT-HY50 [6] have been used for the load application and offer significant advantages especially at laminated glass because the resins fit to uneven glass edges but produce a load eccentricity. The limited compressive strength of the materials and the time and cost intensive individual production are the main disadvantages of resins.

Solid block materials made of plastics or soft metal alloys allow the transfer of significant higher compressive stresses and can be cheaply produced in a large quantity. To transfer heavy loads into the glass edge solid block materials have to possess certain mechanical, in some cases contradictory properties. To them belong:

- high compressive strength, but equally

- soft material; direct glass contact must not hurt the glass edge surface
- mechanical consistency at temperatures between -20 °C and +80 °C
- small plastic deformation percentage and limited creeping behavior
- good workability
- UV-stability and stability at moisture exposure

For the mechanical investigation different materials were chosen. The choice complied with the experiences in structural glass application.

Material name	Material
Aluminum F 28	Aluminum alloy AlMgSiPb
POM-C	Polyacetate copolymer
POM-GF25	Polyacetate with 25 % glass fibre fraction
Zinc	Zinc cast Z410 ZnAl4Cu1

Table 1: Block materials for investigation

5.2 Mechanical Properties

Relevant mechanical properties of potential materials are listed in table 2. Especially the POM-CGF 25 seems to be promising, because of significantly increased stiffness, strength and creeping behavior against pure POM-C. In [7 mechanical values of the plastic materials can be compared. Generally the mechanical properties of the plastics have been derived by tension testing, only.

Property	Aluminum F28	POM-C GF25	Zinc cast Z410
Young's module E [MPa]	~70 000	~ 9300	~65 000-130 000
Yield stress [MPa]	280-370	125	220-250
Bending strength [MPa]	310-390	150	280-350
Ulitmate strain [%]	>9	3	4 - 5
Max temperature short time [°C]	-160	+140	
Temperature range long time [°C]		-30 - +110	

Table 2: Mechanical properties of block materials.

The mechanical properties of zinc cast Z410 differ, depending on the high pressure casting technology. The tested zinc possessed a low Young's module.

5.3 Dynamic - Mechanical - Investigation

A disqualifying criterion for the block materials is a significant mechanical inconsistency at temperatures between -20°C and +80°C [7]. The in table listed thermoplastics have temperature dependent material properties. The dynamic-mechanical analysis (DMA) was used to investigate the temperature influence on the Young's module. The DMA determines of the visco-elastic properties as well as the material properties in dependency on the temperature. [8]

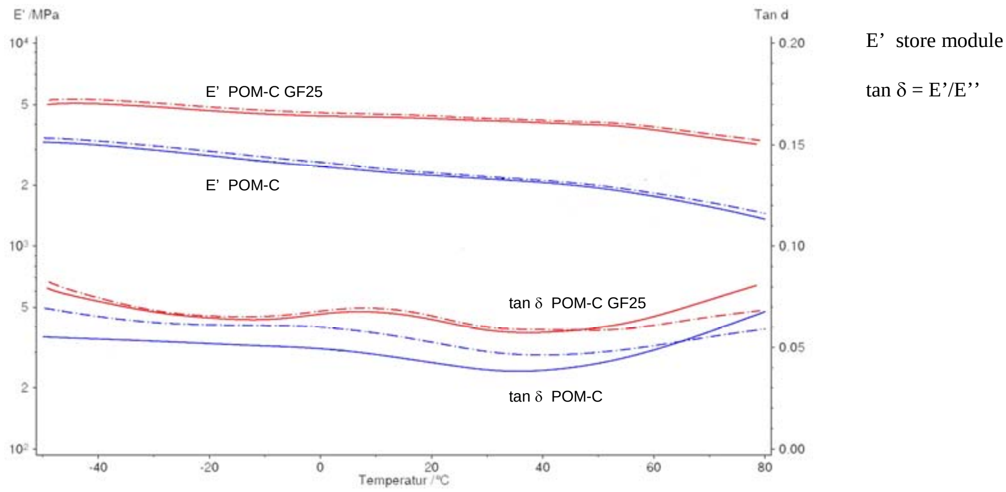
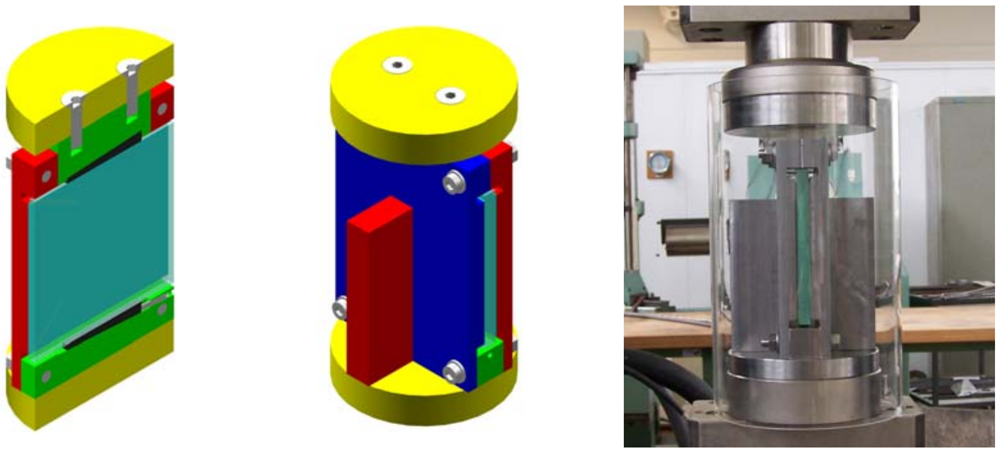


Figure 6: Store module E' and ratio tan δ of specimens.

Several POM-C and POM-C GF25 specimens were investigated and showed reasonable temperature consistency. At 80°C they lose up to 30 % of its 20°C-store-module. The small gap between continuous and dashed lines indicates no significant creeping of POM-C and POM-C GF25 specimens.

5.4 Investigation under Permanent Compression Force

The principal behavior of the glass-block contact at large compression forces was investigated in the testing facility shown below. Identical test specimens of aluminum F28, POM-C and zinc cast were built. They had the form of a wedge with dimensions of 80 mm x 10 mm x 5-8 mm. Annealed glass with 12 mm thickness and dimension of 150 mm square was used. The test facility was put in a testing machine with a 250 kN capacity that produced uniformly distributed compressive stress of 300 MPa in the block element. Each of the described block elements were laid on the upper and the lower edge of the glass pane. The measured deformations result from two blocks.



Figures 7a - 7c: Testing facility for block materials.

The stress-strain diagram shows significant differences between the three materials. The plastic deformation of the thermoplastics prevented a complete glass failure; glass cracks occurred between 190 kN and 220 kN at few specimens, only. At 80 kN compression force, (100 MPa uniformly distributed stress) significant deformation increase occurred. The metals aluminum and zinc cast show a linear-elastic behavior. At them the glass suddenly failed. At the zinc cast the failure load was about 90 kN (112 MPa), at the aluminum block between 160 kN and 200 kN (200 MPa to 250 MPa). The cracks started next to the wedges.

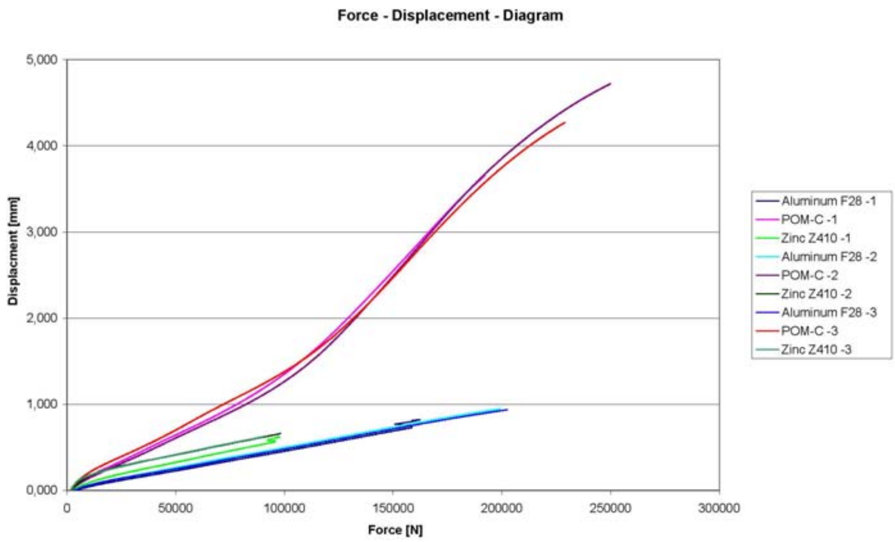
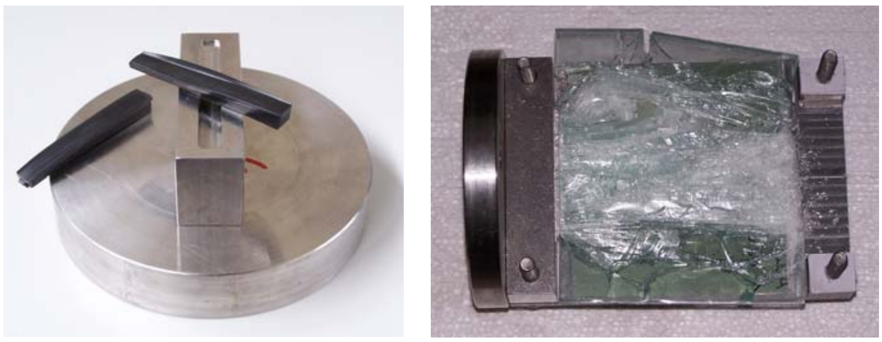


Figure 8: Stress-strain diagram under permanent force.



Figures 9a and 9b: Deformed POM-C specimens on the test facility socket and failed glazing with aluminum wedges.

Further tests to verify the influence of glass fiber strengthening at polyacetate blocks POM-C GF25 were executed at blocks of 80 mm x 16 mm.

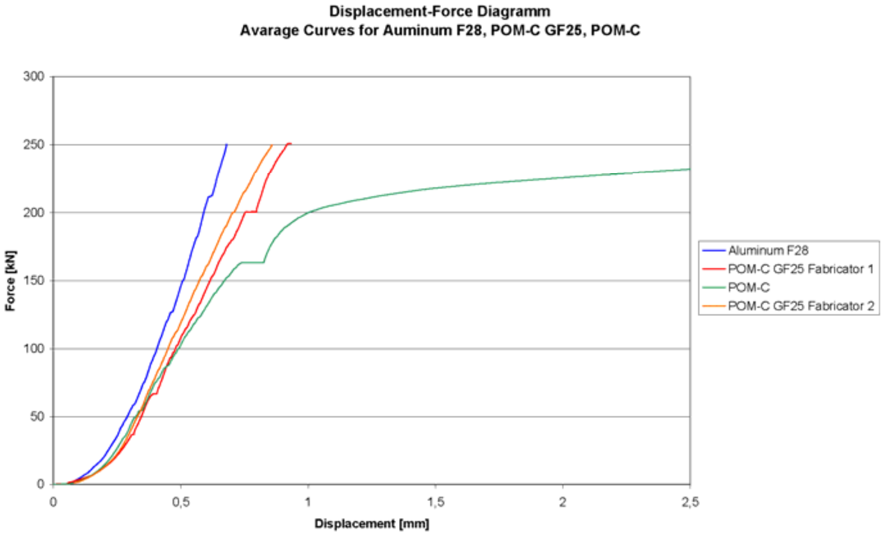


Figure 10: Average force displacement curves of different block materials under short term pressure.

Figure 11: POM-C GF25 specimens (80 mm x 16 mm) of different fabricators.

The average materials curves were produced by test series of up to 15 specimens. POM-C GF25 specimens of two fabricators were used for the tests. No uniformly distributed glass fibers can be guaranteed due to the production process, the extrusion. The color of the specimens indicates the fraction value and distribution of the glass fibers. A gray specimen indicates a high fraction grade.

5.5 Long Term Behavior

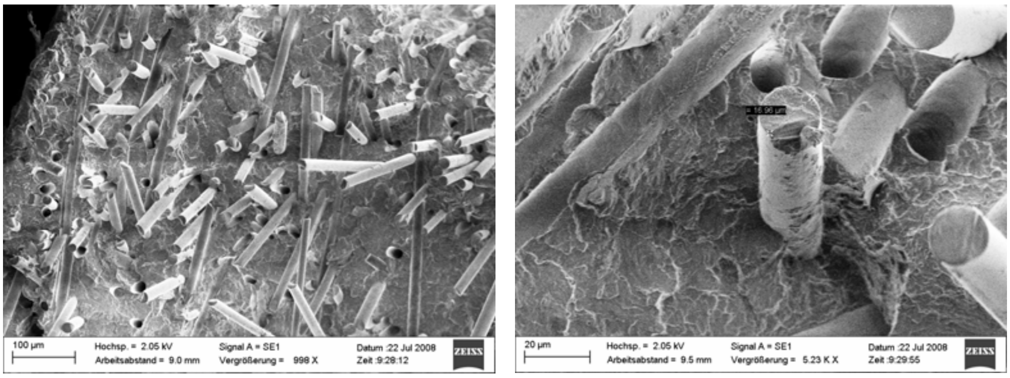
The estimation of the creeping behavior over the next 50 years, the standard lifetime of buildings, is necessary for a safe application of plastic block elements in glass structures. The investigated plastics have existed since the 1920s. For tension load there is substantial data available and demonstrates the relation between module of elasticity, tensile stress, tensile strain, temperature and time [7]. Using the time-temperature-shifting principle [8] the influence factors time and temperature can be described by two independent functions. This allows the formulation of a good materials law [9]:

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

with and

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

The materials law (Eq. 1) allows the calculation of remaining Young's module at given times, temperatures and stresses. In the testing especially the glass fiber strengthened POM-C GF25 shows very encouraging results. Comprehensive creeping investigations were done to check the influence of distribution and order of the glass fibers. The glass fibers tend to be organized in extrusion direction. The pictures made by the scanning electron microscope proof a kind of order.



Figures 12a and 12b: Scanning electron microscope pictures of POM-C GF25.

For creeping small specimens in ring geometry with an outer diameter of 11.1 mm and 5.1 mm inner diameter and 6 mm height were built. At room temperature a compressive stress of 25 MPa was applied to the specimens.

Figures 13a and 13b: Specimens and testing facility for creeping tests.

The comparison of POM-C and POM-C GF25 indicates an improved creeping behavior of glass fiber strengthened POM-C. At the creeping specimens the load is applied longitudinal to the extrusion direction and therefore to the principle order of glass fibers.

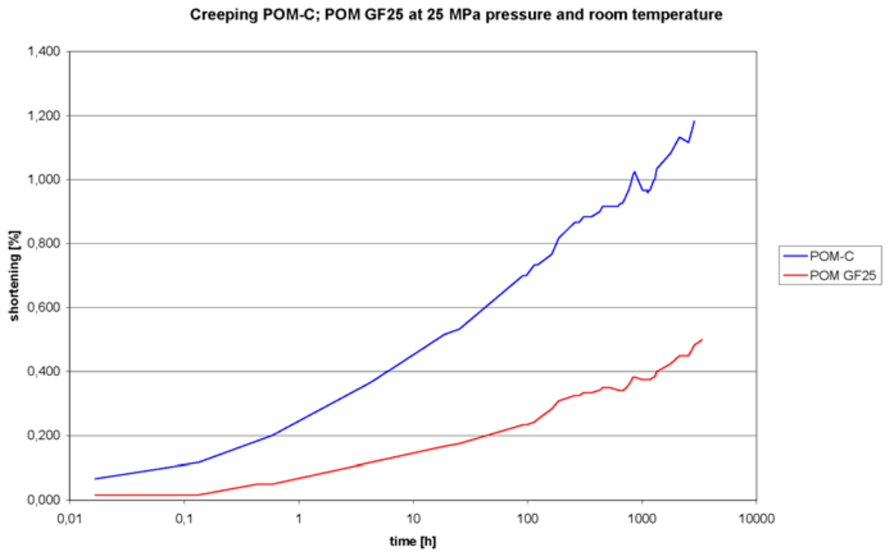


Figure 14: Creeping of POM-C and POM-C GF25 at 25 MPa compressive stresses.

Additional tests were executed to clarify the influence of the direction of the glass fibers to the creeping behavior. The load application occurred longitudinal and perpendicular to extrusion direction.

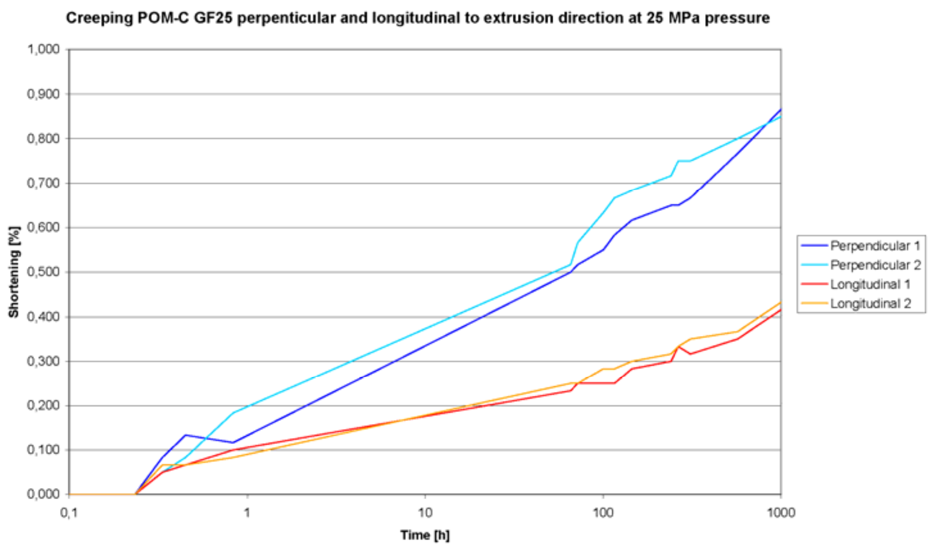


Figure 15: Creeping of POM-C GF 25 at 25 MPa compressive stresses at room temperature with longitudinal and perpendicular load application.

6 Conclusions

Roofs, working as bending systems, are usually less transparent structures. Transparent space grid structures assembled of prefabricated 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 knot. 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 including compression and creeping tests are described.

7 Acknowledgements

This research project is funded by the Federal Ministry of Economics in Germany and the following companies: MBM Metallbau Dresden GmbH, Thiele Glas AG, Saint-Gobain Flachglaswerk Radeburg GmbH, Pauli + Sohn GmbH. Without the support of all of them, the various mock-ups would not have been built.

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