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

Constructive, aesthetical and psychological criteria for glass roof design

Bernhard Weller, Stefan Reich
Technische Universität Dresden, Institute of Building Construction, Germany, www.bauko.bau.tu-dresden.de
Małgorzata Górniak
Technische Universität Dresden, Institute of General Psychology, Biopsychology, Methods of Psychology

The application of glazing allows the construction of very transparent roofs. To determine a transparent structure the lightness is a measurable factor within the subjective experience of transparency. At the example of transparent space grid structures with axial load-bearing glazing the interaction between measureable transparency, percept transparency and constructive criteria is analyzed. The constructive criteria include different parameters as pre-assembling, stability, member length, knot geometry and joint sealing. The measureable transparency criteria include lightness and transparency values due to contrast investigation and the percept transparency bases on a psychological study of 325 people assessing film sequences of 3D environments.

Keywords: Glass, Transparency, Construction, Lightness, Psychological Aesthetics, Environmental Psychology

1. Introduction

In pre-schematic project design phases the influence of structural-constructive design parameters on relevant issues like cost, time or construction methods is often investigated. The appearance of the design is usually assessed by the architect and the client. This assessment bases typically on a small group of people. At the following investigation the authors tried to accomplish measureable structural parameters and measureable and percept transparency assessments of glass roofs.

The investigation is executed for a typical double layer transparent space grid structure of a defined dimension in a typical built environment with standard loads. The focus lies in a psychological study, at which more than 300 persons assessed different structures, mostly people who are not familiar with architectural and structural topics.

2. Study Basis: Four Glass Roofs as Transparent Space Grids Structures

2.1. Structural systems

The development of transparent space grid structures with axial load bearing glazing has been described in different papers as [1] or [2]. For the new development of a structure type we concentrated on the most economic grids, the plain homogeneous grids consisting of one polygon type only. In [1] eight of most efficient and economic transparent double layer grids were listed. The structures were named using Mengeringhausen's morphology. A choice of four structures is chosen for the following investigations. These four structures basically possess favourable characteristics as for instance a glass-appropriate grid of squares and equilateral triangles

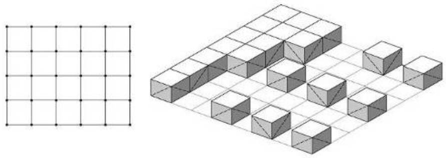


Figure 1: Structure cube (C)

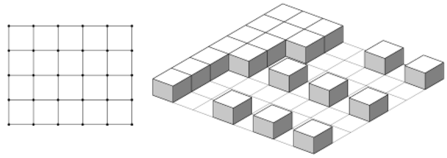


Figure 2: Structure half-Vierendeel (C-HV)

The structure cube is built of hexahedrons located between the two congruent square grids. The glass panes are situated in the compression layer, while the tension layer consists of steel bars. Vertical posts connect both layers. Diagonal braces ensure a stable structure. Another structure built of hexahedrons is the structure half-Vierendeel that is similar to the cube. Restraint bar connections in the tension layer ensure stability.

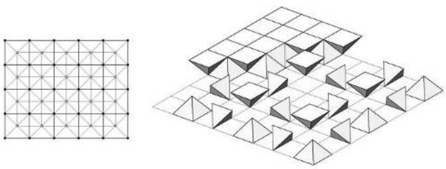


Figure 4: Structure half-octahedron + tetrahedron (½O+T)

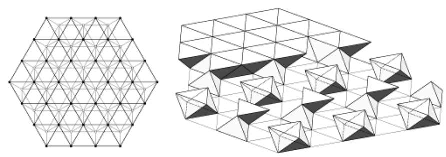


Figure 5: Structure octahedron + tetrahedron (O+T)

The structure half-octahedron plus tetrahedron consists of the two types of elementary bodies that completely fill the space between the two layers. The square grids are dually situated to one another. This structure is stable and possesses significant redundancy. At the structure octahedron plus tetrahedron the compression and tension layer grids consist of equilateral triangles. Both elementary bodies and the structure are stable.

2.2. Design parameters

To create comparable situations and figures, the four named structure geometries are used for the design of a roof structure of 15 m x 15 m. This double layer grid structure covers an inner courtyard. The grid length is 1.25 m that means 12 modules x 12 modules build the roof. The structural height between the grid layers is 884 mm. The dead loads results from an identical glass thickness and the different bar dimensions. The knot sizes are identical at all four structures. The bar profiles were minimized at the design. (Table 1)

Also the visual built environment is equal at the four structures. The roofs are generated in the 3D-environment of a courtyard of 15 m x 15 m and 15 m height. The architecture of the courtyard remembers at the Gründerzeit ("founder's epoche") in Germany around 1900. These types of inner courtyards similar sizes were frequently built in those times Germany.

Table 1: Characteristics of the relevant date for the comparable roof structures

Parameter	Value
Size structures	15,0 m x 15,0 m
Assembling height	15,2 m (upper edge)
Supports	quasi-linear at every outline knot
Roof sloping	2,0 %
Size glass panes	1250 mm side length (square and triangular grid)
Structural height	884 mm
Knot dimension compression layer	ø160 mm
Knot dimension tension layer	ø 80 mm
Size vertical bars	ø 30 mm (C); 90 mm x 90 mm (C-HV)
Size diagonal bars	ø 16 mm (C); ø 32 mm (½O+T); ø 26 mm (O+T)
Size tension bars	ø 16 mm (C); ø 18 mm (½O+T); 100 mm x 50 mm (C-HV); ø 26 mm (O+T)
Width joint sealing	15 mm

3. Measureable Transparency Criteria

3.1. Lightness

The lightness of a light structure is defined as relation between structure dead load to ultimate load. [3] To determine the individual lightness all four structures are designed with minimised profiles under identical load. The difference in the dead load finally results in different bar profiles and bar length. Table 2 compares the length and weight of bars in relation to the structure cube, which is the lightest structure. The dead load of the glass is almost identical at all four structures; only the O+T structure with a triangular grid covers slightly more area because of the edge offset of the roof.

Table 3: Lightness of the four roof structures related to the cube as lightest structures

Structure	C	½O + T	O + T	C-HV
Bar length	1.016 m	1.048 m	1.174 m	539 m
Bar weight	2.367 kg	3.653 kg	2.092 kg	16.275 kg
Knot weight (compression layer)	2.535 kg	2.535 kg	3.000 kg	2.535 kg
Knot weight (tension layer)	1.183 kg	1.008 kg	1.211 kg	0 kg
Total weight steel elements	6.085 kg	7.196 kg	6.303 kg	18.810 kg
Glazing weight	19.688 kg	19.688 kg	20.424 kg	19.688 kg
Total weight structure	25.773 kg	26.884 kg	26.727 kg	39.681 kg
Related weight to cube	1	1,04	1,04	1,54

The table 2 indicates the structure cube (C) as lightest structure, followed by half-octahedron+tetrahedron (½O+T) and octahedron+tetrahedron (O+T) both on second place and the structure half-Vierendeel (C-HV) as heaviest structure.

3.2. Contrast picture investigation

Contrast pictures are another way to assess the roof transparency. From the 3D-visualisations three identical views of the four structures were chosen. The coloured rendering is transferred into an 8-bit gray picture and the histogram function of the imaging software used to analyse the ratio of white dots and total dots of the roof. All solid materials, like steel bars, knots or joint sealing is shown in black whereas the glazing is white coloured. To deal with shadows and diffuse edges 90 % bright colours (1 to 230) are defined as transparent and the 10 % dark colours (231 to 255) are defined as solid.

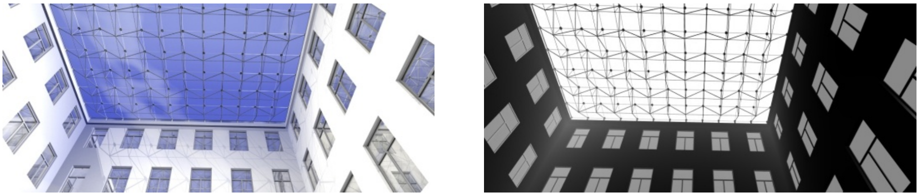


Figure 6a and b: 3D-visualisation and contrast picture at the same view (structure cube)

Table 3: Transparency at three views at the example of the structure cube

view	picture size	total dots of roof	white dots	black dots	percentage white dots	percentage black dots
position 1	1024x450	152.282	123.912	28.370	81,4%	18,6%
position 2	1024x450	153.404	130.900	22.504	85,3%	14,7%
position 3	1024x450	184.784	135.613	49.171	73,4%	16,6%

After calculating the white dot ratio the comparison of the four structures showed that the cube is most transparent at all three views. Interestingly the order of the structures is same at all three views. Table 4 gives the transparency in comparison to structure cube, whereas a figure x<1 means the structure is only x times transparent as structure cube.

Table 4: Transparency at three views at the example of the structure cube

View	C	½O + T	O + T	C-HV
position 1	1	0,97	0,94	0,92
position 2	1	0,91	0,91	0,90
position 3	1	0,92	0,91	0,77
Average	1	0,93	0,92	0,86

The calculation of the average transparency indicated the cube as most transparent structures, followed by half-octahedron + tetrahedron and octahedron + tetrahedron at similar degrees less transparent and the Half-Vierendeel as least transparent of the four. This order is identical to the results of the lightness calculation.

4. Percept Transparency Criteria

4.1. Theoretical background

Aesthetic experiences are frequent and important part in modern live for many individuals. These experiences comprehend hedonic properties and provide self-rewarding cognitive operations. One of the primary goals in the environmental psychology is to identify and understand those features of an environment that lead to pleasurable responses. Objective physical properties of an environment are not only basically for its evaluation. The formation of an aesthetical reaction also depends on the human's processing of information with three cardinal stages, namely perception, cognition and emotion. These stages are additionally moderated by such attitudes as sex, expertise, further experiences ore current emotions. Figure 7 shows the process of the aesthetical reaction [4].

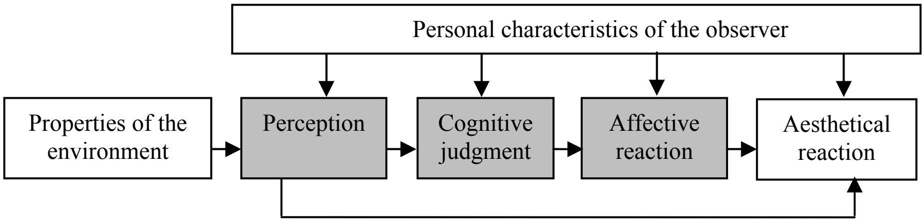


Figure 7: Model of the aesthetical reaction

There is evidence, that experts' aesthetic preference judgments differ considerably from those of lay people. The explanation for this finding is that experts try to avoid their initial, affective response in favour of an intentional and reflective mode of evaluation [5]. Whereas lay people tend to initial response, which is characterized by a preference for familiarity or typicality, experts strive for novelty. Findings in the area of product design show also that experts have more fine grained conceptual structure and require less cognitive effort to classify new information [6]. Therefore they are more likely than non-experts to search for new information. These differences between experts and lay people lead to one of the hypothesis that the aesthetical evaluation of the four different space constructions depends on the level of expertise in this study. Education and profession in the architectonical and designing area was the criterion to classify the participants into four levels of expertise. We assume that the knowledge about architecture, design, and building materials that are mediated in the architectural or civil engineering education influence the aesthetical judgment of the subjects.

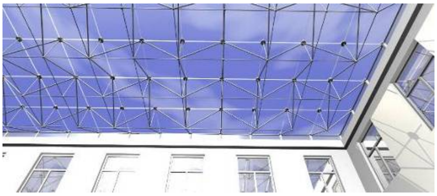
4.2. Method and study material

325 subjects from the departments of Psychology, Architecture and Civil Engineering at Technische Universität Dresden were investigated. The space structures were presented in the form of 3-dimensional 20-second film sequences. After each presentation the subjects were asked to fill in a questioner, which was developed for the capture of the aesthetical preferences. It contained 23 questions using seven-grad bipolar scales. Table 5 shows one item of this questionnaire.

Table 5: Item beautiful-ugly of the questionnaire for capture the aesthetical preferences

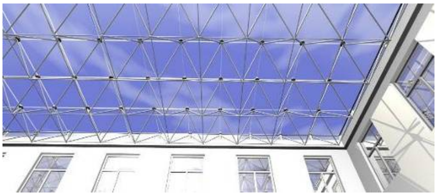
	very	quite	rather	Neither nor/ as well as	rather	quite	very	
Beautiful	O	O	O	O	O	O	O	Ugly

The factor analysis was used for reducing the data from the questionnaire. It confirmed four qualitative factors of the aesthetical evaluation, which were named (f1) originality, (f2) attractiveness, (f3) openness and (f4) structure. These factors were used as the dependent variables in the next statistical data analysis.



Figures 8: Picture of the film sequence with structure cube

Figures 9: Picture of the film sequence with structure half-Vierendeel



Figures 10: Picture of the film sequence with structure half-octahedron + tetrahedron

Figures 11: Picture of the film sequence with structure octahedron + tetrahedron

325 individuals participated in the study. 300 questionnaires were completely filled in and used for the data evaluation. The sample consisted of 151 women and 139 men at the age between 19 and 62. To examine one of the hypotheses, that the expertise as a changeable personal variable affects the aesthetical judgment, we selected the subjects on the basis of their education. Finally the participants were divided into four groups. The first group consisted of 139 psychology students, which were categorized as laypeople (1st expertise level). Second group consisted of 100 students of architecture or civil engineering (2nd expertise level) and the third group consisted of 34 students of architecture or civil engineering, who were at least in the fifth semester (3rd expertise level). The last group consisted of 20 Institute of Building Construction employees and was categorized as the highest level of expertise in this study (4th expertise level).

4.3. Results

Four one-factor analysis of variance (ANOVA) were used to evaluate the differences in the aesthetical judgement of the space constructions for the factors originality, attractiveness, openness and structure. It shows significant main effects for the factors attractiveness (($F(3.276)=3.055$, $p=0.029$, $\eta_2=0.032$) and openness ($F(3.276)=2.653$, $p=0.049$, $\eta_2=0.028$). For the factors originality ($F(3,276)=1.467$, $p=0.222$, $\eta_2=0.005$) and structure ($F(3.276)=2.391$, $p=0.069$, $\eta_2=0.025$) no statistically significant main effects could be identified. In summary it shows positive evaluation of each of the space structures. The average answers of this evaluation were mostly arranged in the positive half of the scale from -3 to +3 (figure 12). The influence of the degree of expertise on the aesthetical judgment could be recognize for the factors attractiveness ($F(1.278)=2.789$, $p=0.041$, $\eta_2=0.029$) and openness ($F(3.278)=2.955$, $p=0.033$, $\eta_2=0.031$).

This results support the hypothesis, that laypeople and experts evaluate their environment in a different way. Knowledge about architecture, design, and building materials, which are mediated in the architectonical or civil engineering education influence probably the aesthetical judgment of the subjects. It also leads to better differentiate skills and better recognizing of details.

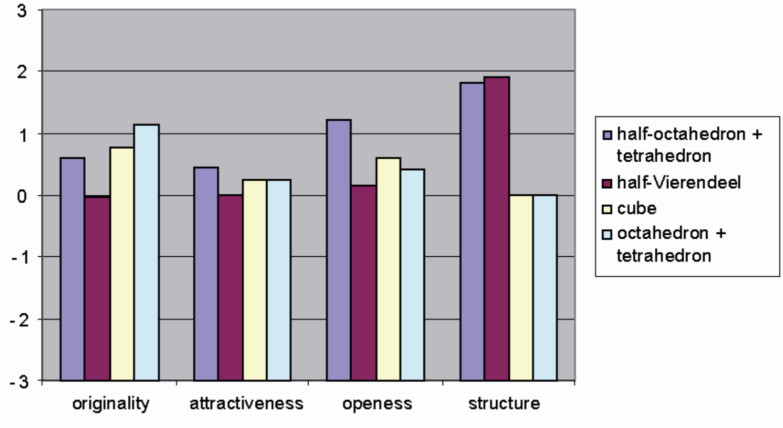


Figure 12: The average evaluation of the factors originality, attractiveness, openness and structure for the space structures half-octahedron + tetrahedron, half-Vierendeel, cube and octahedron + tetrahedron.

5. Constructive Criteria

5.1. Constructive parameters

The qualitative assessment of constructive parameters bases on the quantitative or qualitative measurement of different items. The choice of items is orientated to the specifics of transparent space grid structures but can be adjusted to different construction types too. For transparent space grid structures the following items are of interest: stability, knot connection value, load application, modularity, sealing length, member length, knot number, number of different knot geometries. The criteria stability expresses the stability groups by Mengeringhausen [7] and determines the stability of parts of the structure and the amount and distribution of supports.

The knot connection value assesses the complexity and therefore cost of the knot, which connects panes and bars and must allow tolerance adjustments. As the cut or cast steel knots are the most complex elements they cause a significant part of the overall cost. The optimisation of the knot, including performance and fabrication may decide an economic success. The modularity is an indicator for an economic prefabrication and time saving assembling. Only modularized systems allow free-cantilevering assembling or uncomplicated assembling of parts of the structure. The pre-fabrication with high quality and short assembling periods are a countable economic advantage. The remaining criteria member and sealing length, knot number and knot geometry number are measureable values and possess direct connection to production time and cost.

5.2. Example and overall value

Exemplary table 6 shows the number and length of bars and panes. The result of this investigation is summarised in table 7. In this table all structural-constructive criteria are summarised in a qualitative matrix. All criteria possess the same weight. Their value is expressed in a 3-value-scale with positive (+), neutral (±) or negative (-) grades. The structural-constructive evaluation showed significant advantages of transparent space grid structures with square grids in the compression layer against triangular grids. The differences between the three square grid based structures are small. Single items may be used to decide about the application of a certain structure geometry.

Table 6: Length and number of bars and panes of the structures

Structure	C	C (HV)	½O + T	O + T
Number of bars in tension layer	312	312	264	466
Number of vertical bars	169	169	0	0
Number of diagonal bars	312	0	576	519
Total number of bars	793	481	840	985
Length of bars in tension layer	390 m	390 m	330 m	583 m
Length of vertical bars	149 m	149 m	0 m	0 m
Length of diagonal bars	477 m	0 m	718 m	591 m
Total length of bars	1016 m	539 m	1048 m	1174 m
Number of panes	144	144	144	345

Table 7: Overall matrix of structural-constructive criteria

Structure	C	C (HV)	½O + T	O + T
Stability	+	+	+	+
Knot connection value	+	+	+	-
Load application into glass edge	+	+	+	±
Modularity	±	±	+	-
Joint sealing	+	+	+	±
Total member length	+	+	+	±
Total knot number	+	+	+	±
Number of knot geometries	±	+	+	+
Overall value	6+	7+	8+	±

6. Summary

At the example of transparent space grid structures a structural-constructive and aesthetical assessment was executed. Whereas the structural-constructive assessment depends on measureable and therefore comparable criteria, the aesthetics and transparency was assessed with three different procedures, which finally showed similar results. The introduced methods can be transferred to further glass roof constructions.

7. References

[1] Weller, B.; Reich, S.; Ebert, J., *Testing on Space Grid Structures with Glass as Compression Layer,* Proceedings of the Challenging Glass Conference; Delft, The Netherlands, 2008.

[2] Weller, B., Reich, S.; Ebert, J., *Selbsttragende Glasdächer mit lastabtragender Verglasung,* Stahlbau Spezial - Konstruktiver Glasbau, 2009. pp. 7-12.

[3] Schlaich, J., *Leichtbau,* Stahlbau 69, 2000, pp. 581-584.

[4] Nasar, J. L., *Urban design aesthetics. The evaluative qualities of building exteriors,* Environment and Behavior, 26 (3), 1994, pp. 377-401.

[5] Cupchik, G. C. & Winston, A. S., *Reflection and reaction: A dual process analysis of emotional responses of art*. In: L Ya. Dorfman, D. A. Leontjew, V. M. Petrov & V. A. Sozinov (Eds.), Art and emotiones (Vol. 2, pp. 65-72). Perm, CIS: The Perm State Institute of Culture, 1992.

[6] Alba, J.W.; Hutchinson, J. W., *Dimensions of consumer expertise*, Journal of Consumer Research, 13, 1987, pp. 411-454.

[7] Mengeringhausen, M., *Komposition im Raum - Raumfachwerke aus Stäben und Knoten*, Güterloh: Bertelsmann, 1975.