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

The ARoS Rainbow Panorama – Curved Glass as a Load Bearing Element

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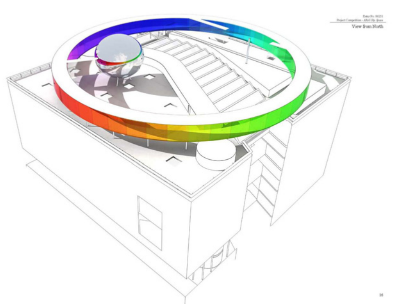
A ring-shaped, tubular steel/glass structure resting on 14 columns, diameter 52m, is one main part of the art object ”ARoS Rainbow Panorama” by Olafur Eliasson on top of the ARoS building in Aarhus, Denmark. The inner and outer walls with a total area of nearly 1,000m² are made of colored curved glass only. The glass walls have to carry dead loads, snow and especially wind loads and they have to withstand deformations of the system due to live loads and temperature. The paper at hand concentrates on the considerations of the structural design of this structure - the leading design ideas and its load bearing behaviour.

Keywords: curved glass, structural glass; structural design, load bearing Behaviour

1. Task

On top of the ARoS Art Museum in Aarhus, Denmark, at a height of about 40m, the art object “ARoS Rainbow Panonorama” by Olafur Eliasson is currently under construction (see Figs.1 and 2). At present, the building is being prepared to serve as a foundation for the extra structures. The artwork consists of a large steel sphere and a ring-shaped walkway, diameter 52m, with glass walls at the inner and outer circumference. The glass walls (made of coloured curved glass) with a height of 2.80m and a width of 3.20m are part of the primary structural system. ArtEngineering GmbH was commissioned to undertake a feasibility study and to develop the structural concept. The paper at hand deals with the basic concepts of the structural design of the walkway, detailed considerations concerning the glass design can be found in [1].



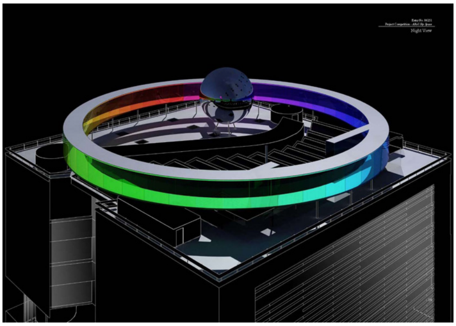


Figure 1: The ARoS Rainbow Panorama art object on top of the AroS art museum in Aarhus, daytime and nighttime views

1.1. The artist's vision of the walkway

The walkway is a tubular structure and can be seen as a steel-covered pedestrian bridge with glass walls on both sides, a roof out of steel plates and a box girder as the main bearing element (see Figs. 1 and 9). The walkway rests on columns - or almost seems to hover - 4m above the wooden floor of the roof. The glass walls are transparent and coloured in the colours of the visible spectrum like a rainbow. The ring is accessible for the museum's visitors, who can experience a panoramic view over Aarhus, which will be alienated by the colours. In the artist's vision, the walls are made solely using large curved glass panes. He stipulated that the use of any other load bearing elements or frames should be avoided (see Fig.2).

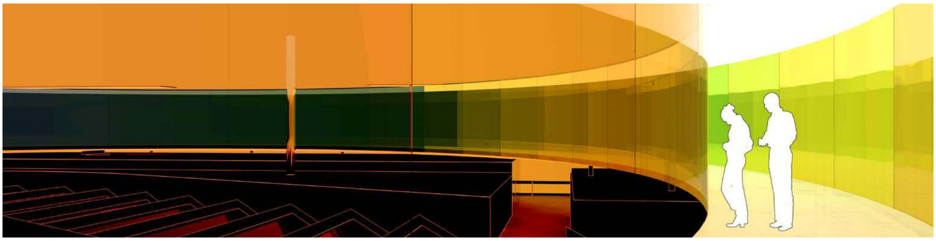


Figure 2: View of the inner appearance of the glass walls, no structural elements are in the inner and outer walls except the curved glass panes.

1.2. Special conditions on the rooftop

The walkway rests on 14 columns, 4m above the top of the flat roof of the ARoS building, which is divided into two parts by an atrium (see Fig. 1). Above the atrium, the walkway spans 20m. The columns of the walkway do not match the columns and walls of the ARoS building at all. Therefore, a load distributing structure made of I-beams became necessary to transfer the loads from the walkway columns to points of the building's structure that are capable of conveying them to the ground (columns and walls). Since the building was not designed for such extra loads, reinforcements from top to bottom of the building became necessary. The structural height of the load distributing structure was very limited (all elements will be hidden under the final wooden floor of the roof) and its beams with maximum spans of 12m also have cantilevering parts. Therefore, one can say that the foundations of the walkway are interconnected springs, which, due to their flexibility, have a great influence on the design of the connection of the glass walls to the steel box girder and steel roof plate.

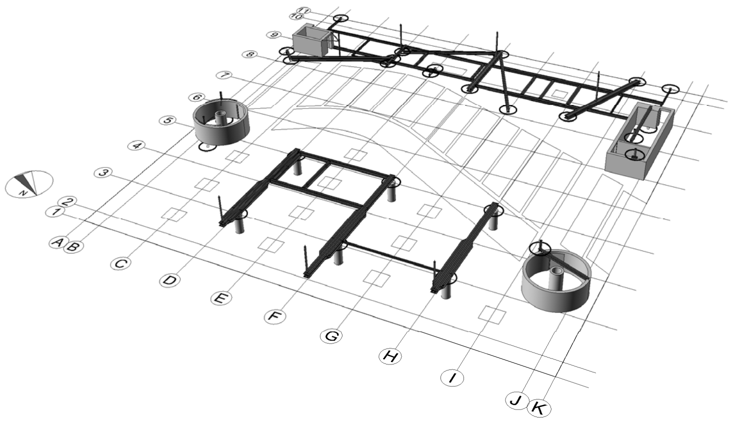


Fig. 3: The load distributing structure on top of the AroS building.

1.3. The design challenge

During the technical design of the walkway, we had to find a structure which is as light as possible due to the limited load bearing capacity of the existing building and we had to define a load distributing structure with a very limited structural height, but sufficiently stiff members.

The artist's stipulation for pure glass walls has been the most challenging aspect of the task because with this presetting, the glass walls became elements of the primary structure. They have to transfer considerable loads to the box girder and they are subjected to deformation loads from the walkway and the load distributing structure from live loads and temperature loads.

2. Solution

2.1. The glass walls as elements of the primary load bearing system

First basic design idea: Decoupling of the roof and walls from bending.

The thought to use the total height of the section as statically effective is attractive (see Fig. 4). A technical description of the walkway's section is given in 2.3 (Figs. 9 and 11), but it would not be possible to transfer the shear forces through the glass walls. They would break, even if it were possible to find a connecting method having the necessary bearing capacity. Therefore, we assign all bending and torsion to the steel box girder (see Fig. 4 right). That means, we decouple the glass walls and the roof from the box girder. The chosen box-girder section is very stiff against bending and torsion; it becomes the backbone of the structure.

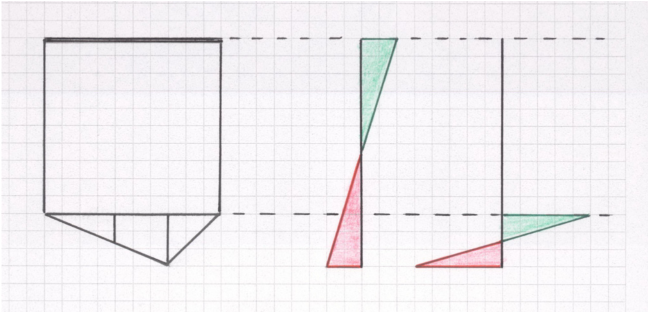


Figure 4: left: sketch of the walkway section with the triangular box girder, the glass walls and the roof plate; middle: bending stesses/strains for the complete section; right: bending stresses/strains if the box girder solely reacts to bending – this is what we wanted to achieve.

Our first idea on how to realize this decoupling was to introduce expansion and compression joints in the roof and appropriate gaps between the glass panes (see Fig. 5). We checked this solution in a numerical model and it did work well. The glass panes inclined according to the bending of the box girder and the gap between them opened and closed as we expected. But again, we were challenged by the artist to find another solution because he did not like the visible radial joints in the ceiling.

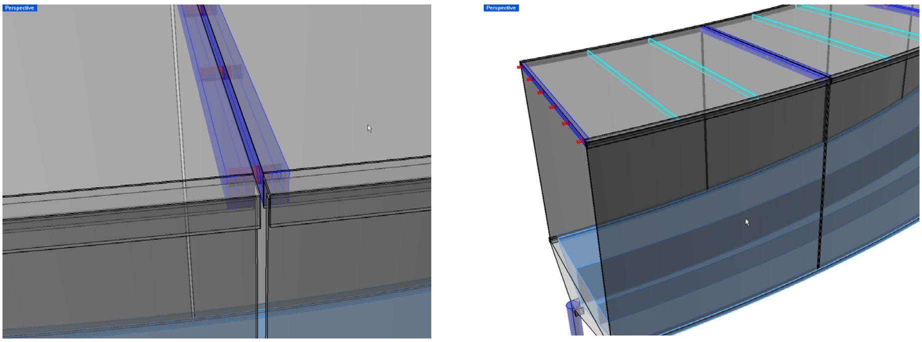


Figure 5: First concept of decoupling: extension/compression joints in the roof could be one method to exclude the roof and glass walls from forces out of bending.

Therefore we tried to decouple the glass walls with soft connections of the panes to the roof plate and box girder (see Figs. 6 and 10). This soft connection - soft against relative movements between the glass panes and the steel parts - also can decouple the roof and walls from the bending of the box girder as we proved with FE-models. Now the roof can be made as one simple ring-shaped plate element with a seamless ceiling. The clamp connection is soft for vertical movements of the glass, but it is fairly stiff against bending due to wind forces on the glass pane. This clamped support reduces the bending and bending stresses in the middle of the panes considerably.

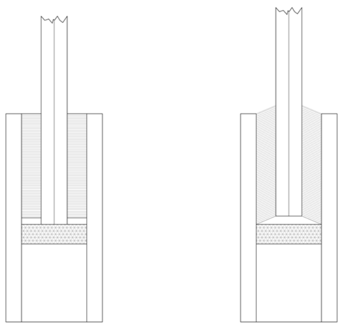


Figure 6: Left: Sketch of the connection detail for the glass panes at the lower and upper edge. The glass panes are glued into a steel clamp - which is fixed to the edges of the roof and the box girder – with structural glazing material. Right: The glass can execute relative movements to the steel parts, at the same time it is partly clamped.

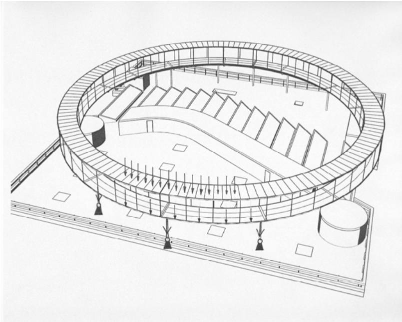
Basic design idea II: In-plane action of the roof can activate an effective three-dimensional load transfer.

The roof is designed as a steel plate structure. Dead loads and snow loads are transferred to the glass walls by bending, but forces from wind action (on the upper half of the glass panes) shall be transferred from their origin by in-plane action through the ring to stiffer parts on the sides of the structure (see Fig. 8). Thus, we use capacities of the structure as a whole three-dimensional object. The section with the glass walls and the roof (see Fig. 9) does not (!) work as a framework - this would generate bending moments in the glass panes that are too high.

2.2. How the load transfer works

Keeping the two basic design ideas in mind, it becomes clear, how the system works. Dead loads (roof and walls), snow loads and wind loads on the roof are transferred directly through the glass walls to the box girder (see Fig. 7, left). Live loads ($3kN/m^2$) on the box girder are transferred directly to the columns (see Fig. 7, right). Due to the decoupling of the bending deformations from the glass walls with the special steel/glass connection (see Figs. 6 and 10), the glass panes are not affected by bending deformations of the box girder due to live loads! From the box girder, all forces flow into the columns and then into the bearings of the load distributing structure (see Fig. 3).

Wind actions are of major impact on the glass walls and add up to high horizontal reaction forces. The lower half of the wind forces is transferred directly into the box girder, the upper half is transferred into the roof plate. There, the forces flow via in-plane action to the stiff sides of the structure and from there through the glass panes into the box girder (see Fig. 8). This applies for the inner and the outer glass walls. Bearings in 4 stiff concrete parts of the AroS building are designed to take the horizontal forces from wind (see Figs. 3 and 8).



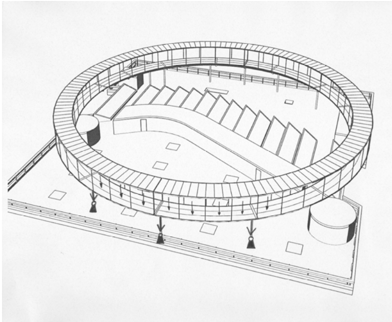


Figure 7: Transfer of vertical loads on the roof and dead loads from the glass walls; left: dead loads, snow loads and wind loads on the roof; right: live loads on the floor surface of the box girder .

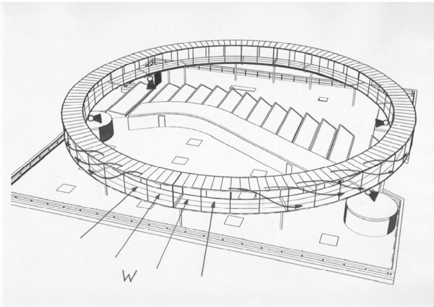


Fig.8: Transfer of wind loads; the wind loads act against the glass walls.

Fig. 9 shows a section through the walkway and column. The inner accessible space is 3m high and 3m wide. In Fig. 10, the upper and lower detail of the special glass/steel connection is depicted in its conceptual design state. At present, the clamp is being tested.

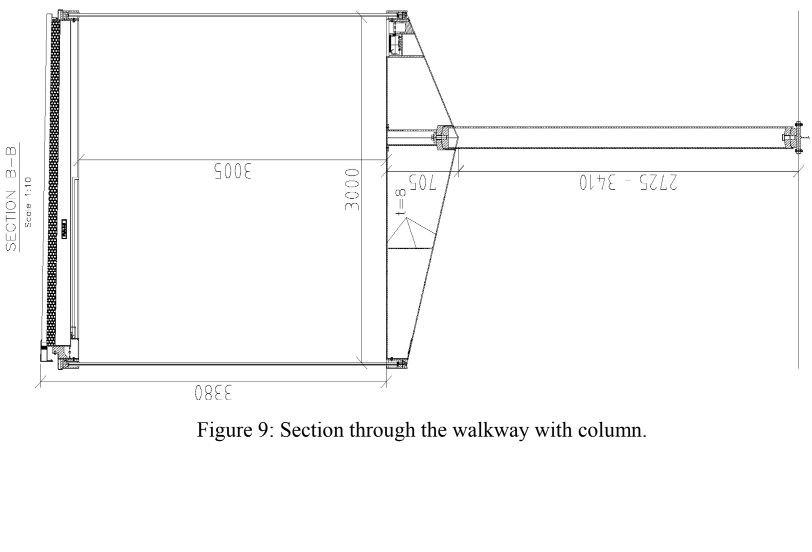


Figure 9: Section through the walkway with column.

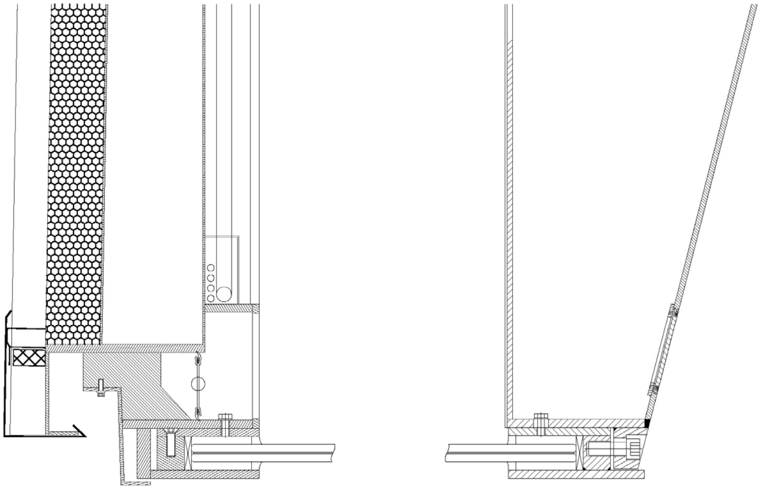


Figure 10: Clamping details at top and bottom.

2.3. Conceptual Design

The load distributing structure (see Fig. 3) is technically not ideal at all. Due to the very limited space we had to choose a combination of extremely low profiles to arrive at high masses. Esthetical considerations concerning the overall appearance of the art work lead to this solution.

The box girder is made of steel plates with a thickness of 8mm. It has an asymmetric triangular shape (see Fig. 11). At the inner edge of the floor there are openings for the ventilation which also contain special lighting. The closed section with its inner stiffener plates has a high bending and torsion stiffness.

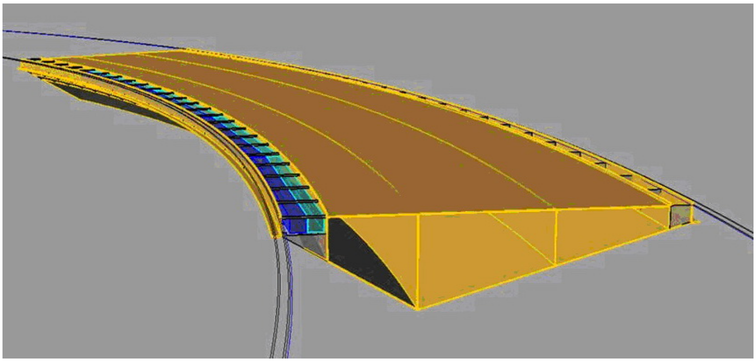


Figure 11: The steel box girder as the backbone of the structure.

3. Calculations

3.1. Shell Element Model

To verify the design ideas of chapter 2, FE models have been elaborated. Using beam models of the total structure including all elements of the load distributing system, we calculated general forces, dimensions and deflections. For the quantitative verification of the decoupling method and the stresses in the glass panes, we created a large shell element model (>900,000 degrees of freedom, nonlinear analysis) of half of the walkway, together with relevant parts of the load distributing structure, because the low stiffness of the latter does influence the relative movements of the steel/glass connection considerably (see Figs. 12 to 15).

Calculations of the single glass pane showed that stresses under wind loads and all loads from the roof are in a moderate range, even when we neglected the compound effect of the lamination (this makes sense, because the coloured glass could warm up under sun radiation and the PVB foil could become too soft to guarantee the compound effect). The shell element model proved that the inevitable deformation loads from the box girder affect the load bearing capacity of the glass panes only to a very small extent.

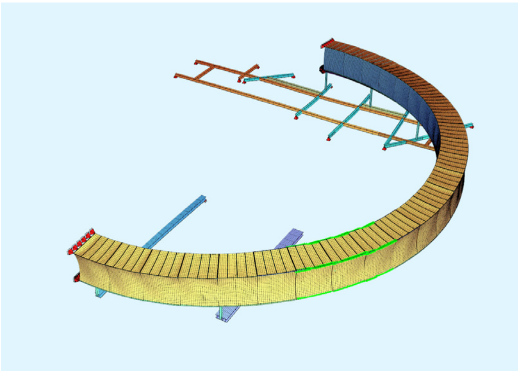


Figure 12: Shell element model of one half of the walkway under live loads, wind loads and snow loads (scaled up deflections).

3.2. Relative Displacements in the Steel/Glass Connection

For the clamp design one needs maximum values of the relative movements between steel and glass in the bonded connection. These can be derived from the shell element model, where the clamping detail has been represented by a system of auxiliary small beam and spring elements with a vertical orientation. The beam elements, which connect the steel and glass parts, have been modelled as free of normal forces, such that both parts can slide relatively in a vertical direction. Spring elements simulate the shear stiffness of the structural glazing material in the connection. Fig.13 shows the deformations of the system under maximum loads. The vertical gap between two adjacent glass panels, which shall be closed with two very small overlapping profiles which allow the necessary vertical movements (see Fig. 15), has been modelled as an open slot.

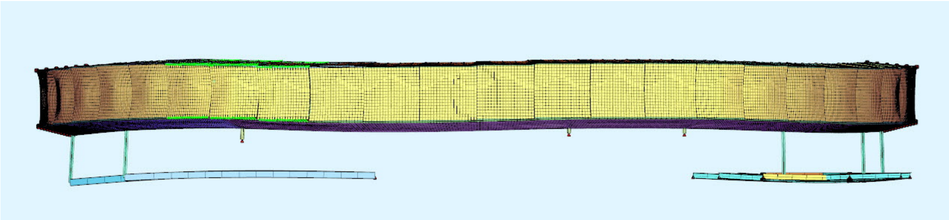


Fig. 13: Shell element model of one half of the walkway under maximum loads, displacements are scaled up.

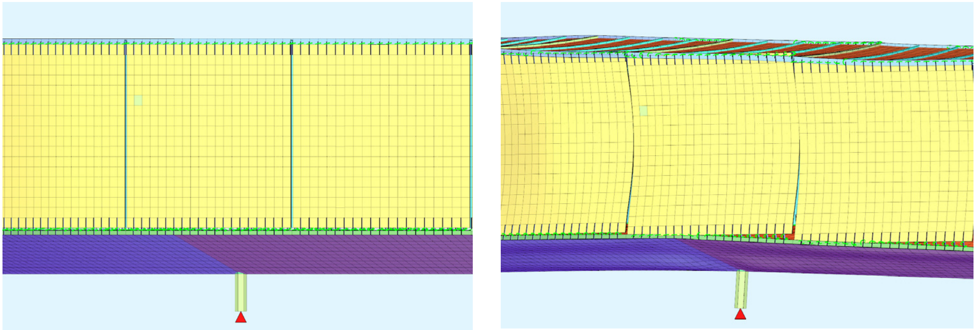


Figure 14: The soft connection between steel and glass under action, displacements are scaled up.

Close to the short column on the left side and at the beginning of the big span, we have the biggest inclination of the deflection curve and thus the highest relative movements between steel and glass. This part is shown in detail in Fig. 14, being unloaded on the left picture and loaded on the right one. One can clearly see how the system reacts: The box girder deforms independently from the glass panes, which remain in a vertical position. The shear force due to bending is not transferred to the glass walls as we did aspire. Absolute values of the relative movement are shown in Fig. 15. They deviate between -3mm and +3mm. That means that the steel/glass connection should allow at least 6mm of shear movement.

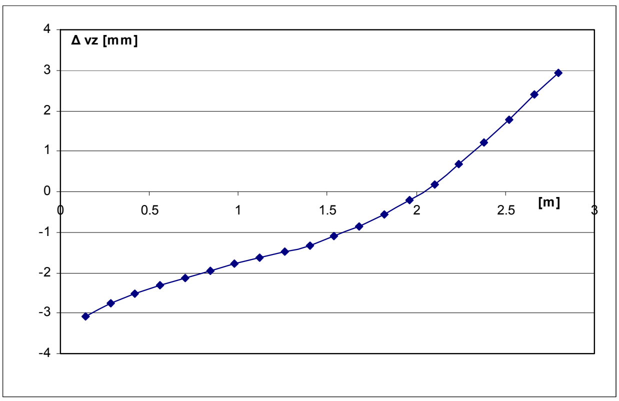


Figure 15: Relative movements Δvz in the steel/glass connection; abscissa: horizontal extension of the pane; ordinate: relative vertical monements Δvz in [mm].

3.3. Summary of Technical Data

Glass:

Total area of glass wall	982m²
Type and thickness of glass:	2x12mm, toughened
Number of glass panes:	2x58 pieces
Size of single outer pane	3.20x2.80m²
Lamination:	2 clear PVB foils, 0.38mm, 4 coloured PVB foils, 0.38mm (Vanceva colour system)

Structural sealant material in clamp: Dow Corning DC993

Glass tests: impact tests with soft and hard body of the clamping detail

Steel:

Load distributing structure:	varying I-beam sections and combinations, 95t
Walkway box girder:	52m outer diameter, 85t
" columns:	steel tubes 244.5mm diameter, 3t
" roof:	20t

4. Conclusion

The use of glass as a load bearing material depends very much on the structural design. Only successful team play between all members of a structure can guarantee success. The paper shows that it is possible to build the described walkway structure with pure glass walls even though the structure is heavily loaded and has big spans and is supported by a soft load bearing structure, which deflects considerably under live loads. This is achieved by decoupling the glass walls from deformations of the walkway due to live loads and the activation of a three-dimensional flow of forces under wind loads. The decoupling is provided by a special steel/ glass connection. And the wind forces are transferred to the stiff sides of the ring via the activation of an in-plane action in the roof plate.

5. References

[1] Henriksen, Thomas; Greiner, Switbert, AroS, *Your Rainbow Panorama by Olafur Eliasson*, (GPD 2009).