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Swimming Pools of Glass

T. Wever [a], K. Haarhuis [a], E. ten Brincke [a] & R. Nijsse [a, b]
[a] *ABT Consulting Engineers, The Netherlands, t.wever@abt.eu*
[b] *Delft University of Technology, The Netherlands*

In projects involving swimming pools with structural glass, ABT Consulting Engineers has faced similar design requirements: maximal transparency, proper detailing, 100% water tightness and robust behavior. ABT developed a straightforward detailing to satisfy these requirements. The concept is applied in the glass swimming pool of the 900 Mahler project, where the layered and heat strengthened glass panes were designed with specific attention to the appropriate type of interlayer and functional, durable and practical support detailing. The implementation of a clear safety philosophy, backed by an executed risk analysis, led to a glass structure which functions in all circumstances. The panes were structurally analyzed on strength and stiffness with finite element software, with extra focus on the appropriate properties of the support conditions. The concept is ready to be applied in similar glass pools.

Keywords: structural glass, swimming pool, water tightness, detailing, connection, robustness, interlayer, structural analysis

1. Introduction

In recent years ABT Consulting Engineers designed several swimming pools made of glass. The Jellyfish House in Marbella has a cantilevering swimming pool with a glass bottom floor (Figure 1). In Diergaarde Blijdorp, a zoo in Rotterdam, visitors can watch polar bears in their ‘swimming pool’ from behind a 5 m high glass façade. Currently ABT is involved in the design of an open air swimming pool on the top floor of the 900 Mahler residential tower in Amsterdam, containing a bottom floor with three elongated glass panes, a glass end wall integrated in the building façade and a wind shield in the longitudinal direction of the swimming pool.

Fig. 1 Jellyfish House (www.wielaretsarchitects.com)

In all mentioned projects the same typical challenges occurred: maximal transparency, proper detailing, 100% water tightness, robust behavior. This paper addresses these items and gives an insight in the design process of the 900 Mahler project.

2. General design

In the 900 Mahler tower the two top floors form a penthouse. The upper floor has a terrace with a rectangular open air swimming pool of 15 m length, 2 m width and 1 m water depth. The bottom floor contains three glass windows. Next, one of the end walls of the pool is made of a glass pane integrated in the building façade. Both floor and end wall create a visual connection between the swimming pool and the surrounding inner rooms. At last, there is a wind shield along the long side of the pool (Figure 2 and 3).

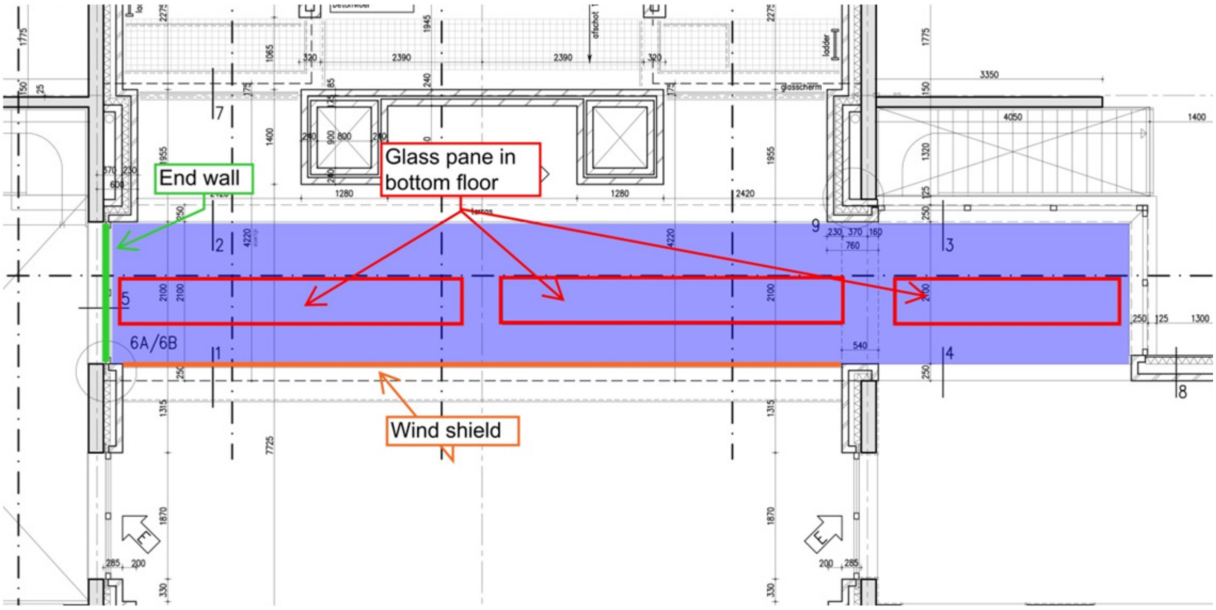

Fig. 2 900 Mahler overview.

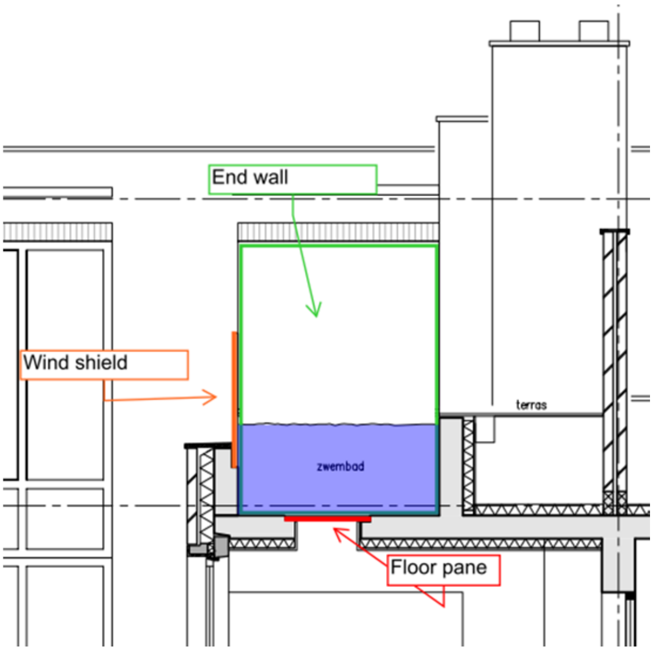

Fig. 3 Section of the swimming pool.

All panes are composed of multiple layers of heat strengthened glass with ionoplast interlayer. See Table 1 for more characteristics.

Table 1: Characteristics of the heat strengthened glass elements

Element	Position	Size (of largest element)	Composition	Interlayer
Floor pane	Horizontal	5,2 x 0,8 m^2	4x 12 mm	3x 1,52 mm ionoplast
End wall pane	Vertical	2,1 x 2,8 m^2	3x 12 mm	2x 1,52 mm ionoplast
Wind shield pane	Vertical	1,2 x 1,4 m^2	2x 12 mm	1x 1,52 mm ionoplast

The choice for laminated panes was determined by economic considerations. Sheets of 12 mm are widely available. Furthermore, it is a way to create a robust structure. As usual in glass engineering, multiple glass sheets are applied to provide safety in case of failure of one of the sheets. In this project, safety of people inside the swimming pool is important as well as safety of the building parts next to and below the pool. Failure of a glass pane can lead to significant damage throughout the building.

The expected internal forces determined the number of sheets applied: four in case of the floor pane, because of the high water pressure (10 kN/m^2); three for the end wall, which is only loaded by water on the lower 1 m of the 2,8 m high pane, by a triangular force distribution ranging from 0 till 10 kN/m^2. The wind shield has two sheets; in this case not water pressure but wind loads are dominant.

The choice for a ionoplast interlayer was, besides the excellent clarity characteristics, also based on creep behavior. The panes are more or less continuously loaded by the water in the pool. Long term loading leads to relaxation of the interlayer and thus less structural cooperation between the sheets over time. Ionoplast interlayers show less relaxation than the regular PVB interlayers and were therefore preferred.

Furthermore, the panes are applied in a relatively aggressive and humid environment. In order to prevent delamination of the sheets, the interlayer needs to be resistant against chemical impact. Since the interlayer is in direct contact with the applied sealant, most of all the interlayer should not react with the components of the sealant. This will be discussed more extensively in Chapter 3.

3. Detailing

The joints of the floor and end wall panes deserved specific attention during the design phase. Several design aspects meet here: functionality, water tightness, robustness, load carrying capacity and practicability. First of all, the amount of joints was minimized. Every joint is a possible cause of leakages and therefore the openings in the concrete floor and end wall were closed with a glass pane made of one piece.

As a consequence, the only joint left was the support on the concrete structure. All loads have to be transferred here from glass to concrete and at the same time the detail is sensitive to leakages. The principle of the designed connection is a both straightforward and effective detail. It was tried to keep it as simple as possible: just glass and adhesive. See Figure 4.

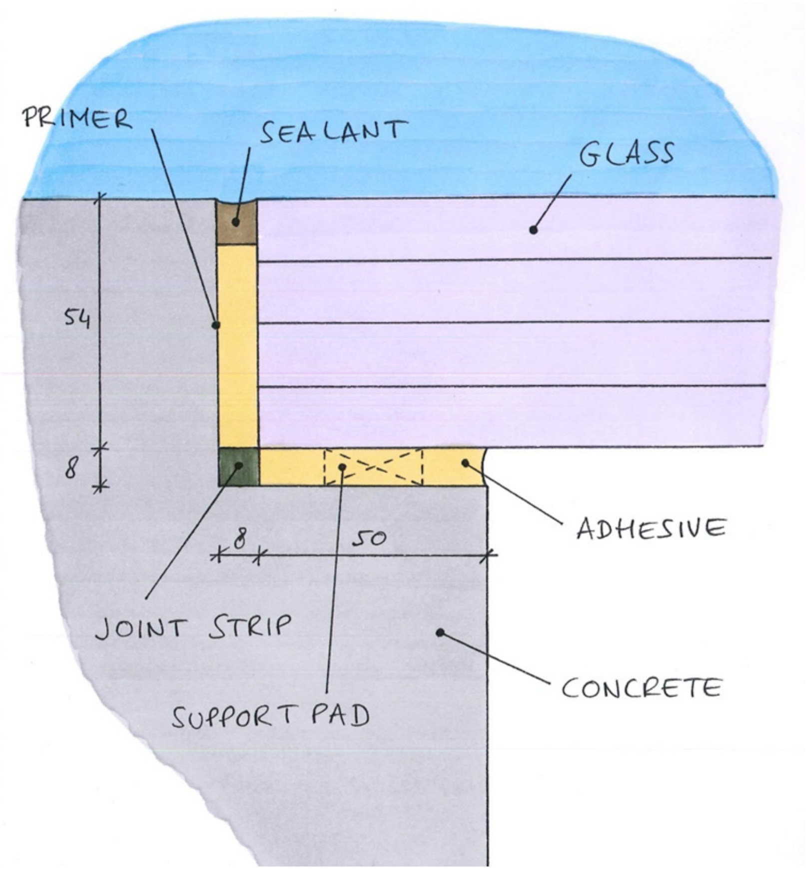

Fig. 4 Support detail (in case of floor pane)

In the 240 mm thick floor and the 250 mm thick end wall a notch of 58 width and 62 mm height is made during the casting process. This creates a sunken support for the glass pane. The weight of the water naturally compresses the connection, thus improving the water tightness of the connection.

The joint in between glass and concrete is filled with an adhesive. Because it is in direct contact with the ionoplast interlayer, it should meet certain chemical requirements, preventing it from causing a reaction and therefore delamination. The chosen type of adhesive is a two-part structural silicone adhesive, which has undergone a compatibility test with the ionoplast interlayer. This test showed no signs of negative influence.

The width of the support is a trade-off between support stresses, tolerances of the supporting concrete floor/end wall and practicability of the joint. In order to obtain a completely filled joint, the depth seen from the position of application of the adhesive should preferably not exceed 50 mm. In this way the joint is well accessible and the fumes formed as reaction products can easily escape, for an optimal hardening process. For this support area the support stresses were checked and approved. The joint width (8 mm) was determined by the assumed maximum deviation in the (in situ poured) concrete floor/end wall and the ideal width to correctly apply the adhesive.

Before the glass pane is placed, the concrete notch is treated with a primer, for a good bonding between concrete and adhesive. Then rubber support pads are placed at regular distances on the notch. After installation of the pane the resulting joint can be filled both from the top and from the side over around 50 mm, as can be seen in Figure 4. A joint strip in the corner serves as a backing for the adhesive. On the pool side the joint is finished off by a water and chlorine resistant silicone sealant. This results in a long-lasting, watertight connection.

4. Structural analysis

In this chapter only the (more heavily loaded) floor pane and end wall pane will be discussed. The panes were checked on strength and stiffness with finite element software. They were modeled as plate elements (Figure 5). Due to the long term loading, full relaxation of the interlayer (i.e. no cooperation between the sheets) was assumed in the calculations, which is a conservative approach. Thus the equivalent thickness used in the finite element model was determined by $t_{pl}.\sqrt{n}$, with t_{pl} as the minimal sheet thickness (11,7 mm for a nominal thickness of 12 mm) and n the number of sheets.

The panes were regarded in the model as simply supported on all four sides, both tension and compression. The stiffness of this support determines to a great extent the tensile reaction forces in the corners of the pane, due to the upward deflection there. From the modulus of elasticity of the adhesive, the width and the thickness of the joint the spring stiffness was derived. Since the actual stiffness of the support can differ from the theoretical value, the sensitivity of the parameter was checked by performing calculations with a varying support stiffness.

The dead weight of the pane and the load of 1 m water height were applied as surface loads. In case of the end wall also wind load and horizontal loadings by persons were regarded. Then the finite element calculation was performed in accordance with the Kirchhoff bending theory for thin plates. Two cases were checked: one with all sheets intact and one with one sheet regarded as broken (i.e. dysfunctional in carrying the applied loads), due to an accidental or deliberate attack. The choice for one instead of two broken sheets was based on a risk analysis with the Fine and Kinney method, described in the Dutch standard for structural glass:

$$RS = WS.BS.ES \tag{1}$$

Where WS is the probability of damage to the pane, BS the degree of exposure of people to the risk of damage, ES the severity of the consequences of a broken pane and RS the resulting risk. An RS lower than 70 comes down to one broken sheet; an RS exceeding 70 means both outer sheets should be regarded as broken. For the current project WS was rated as 3 (unusual but possible), BS as 6 (daily) and ES as 15 (one casualty), resulting in an RS of 270. But that implies a sudden failure of both outer sheets by a single attack, which is in fact impossible in this case since the opposite side of the pane is not accessible from the side of attack. The Dutch standard then allows to yet count on just one broken sheet: the one on the side of attack. This was found to be an acceptable principle for the current situation. Because the case of a broken sheet is regarded as an exceptional situation, a reduced load factor of 1,0 may be applied on the loads.

After analyzing the results, deflections appeared not to be significant. Figure 6 shows the deflection of the floor pane as an example. The maximum deformation of 1,4 mm is low and within limits, even more when taking into account that no cooperation between the sheets was assumed. From these results it was also concluded that the minor rotations of the panes at the supports would not cause significant stresses in the adhesive.

Regarding the reaction forces, tension on the joint is normative since the tensile capacity of the adhesive is limited. In case of the end wall the tensile forces in the corners of the pane appeared to be the highest (Figure 7). The maximum reaction force of 5,29 kN/m over a joint width of 50 mm gave a stress of 0,11 N/mm^2, which is around

75% of the tensile capacity of the adhesive (0,14 N/mm^2). This rate offers a safe margin for the earlier discussed probable variation in support stiffness.

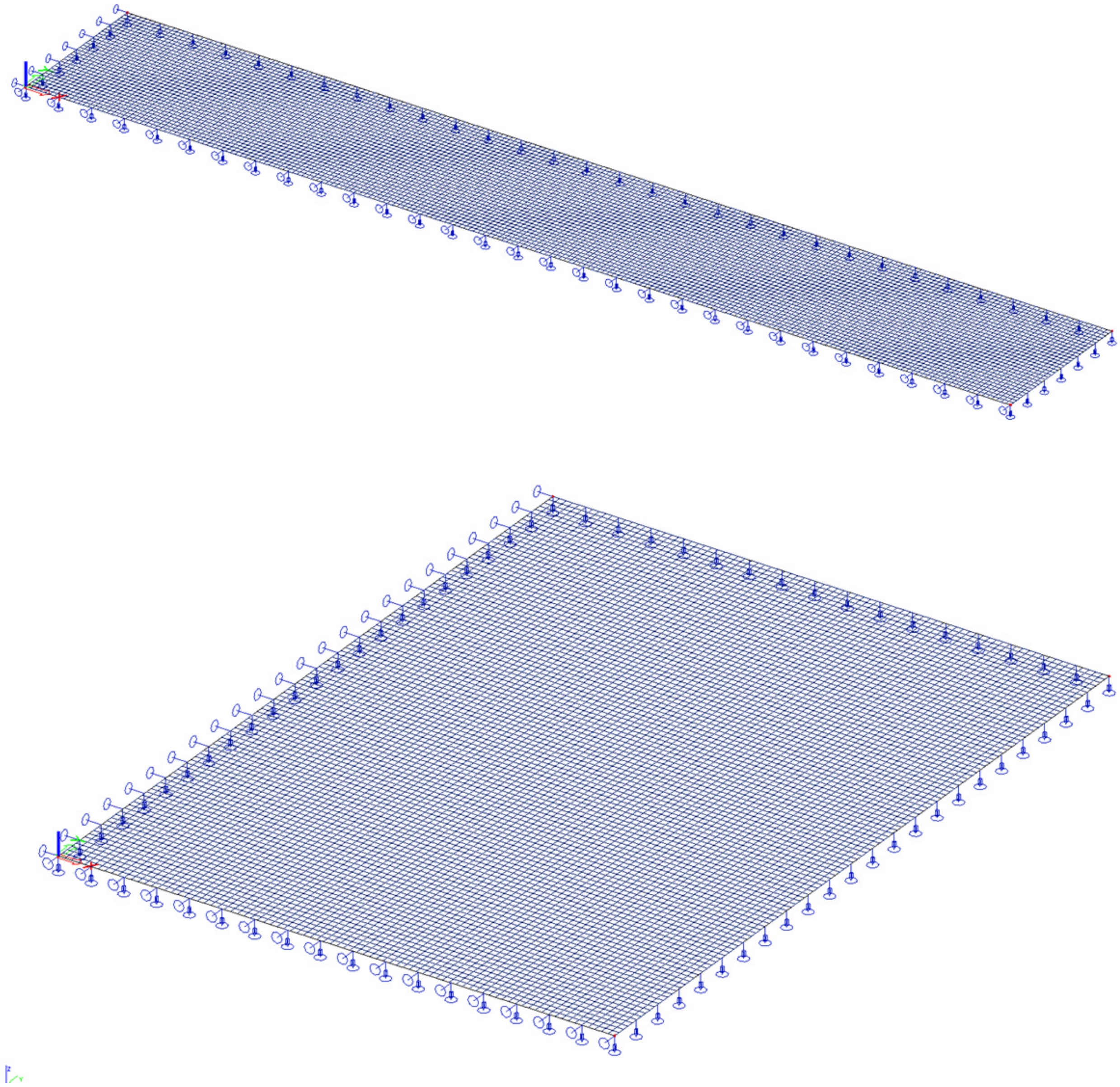

Fig. 5 Finite element model of floor pane (top) and end wall pane (below)

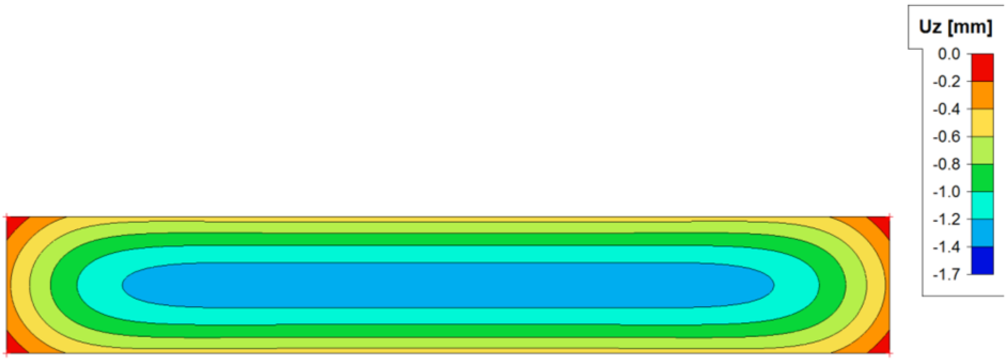

Fig. 6 Deflection of floor pane (intact case)

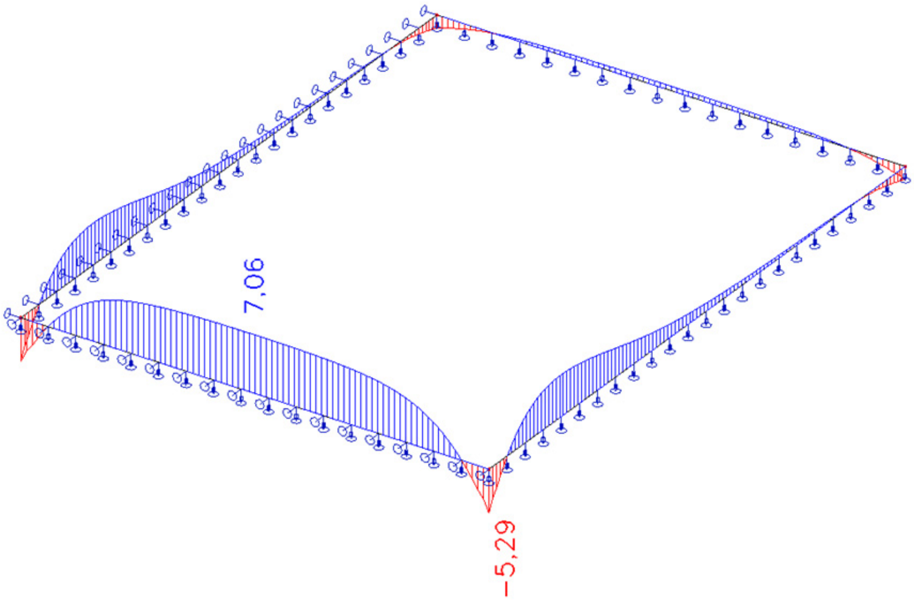

Fig. 7 Reaction forces of end wall in kN/m (case of broken sheet)

The strength results are presented in Table 2. The occurring tensile stresses under bending (see Figure 8 for an example) were compared with the tensile capacity of the applied heat strengthened glass. The normative zone in the pane appeared to differ between the floor and end wall. Whereas the floor pane showed the highest unity check in the middle of the pane, the stresses in the end wall were relatively higher in the corners, where the glass strength is lower due to the general effect of reduced prestress in the sheet corners.

Table 2: Strength analysis

Element	Intact/broken sheet	Normative zone in the pane	Maximum stress in FE model	Tensile capacity after 50 years	Unity check
Floor pane	Intact	Center	15,4 N/mm^2	28,4 N/mm^2	0,54
Floor pane	Broken	Center	13,7 N/mm^2	28,4 N/mm^2	0,48
End wall pane	Intact	Corner	6,0 N/mm^2	7,6 N/mm^2	0,78
End wall pane	Broken	Corner	6,0 N/mm^2	7,6 N/mm^2	0,78

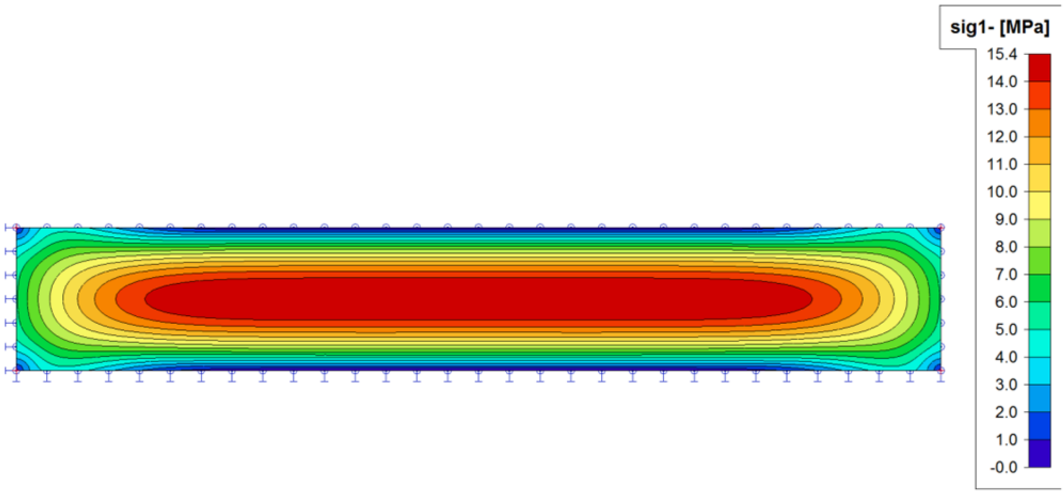

Fig. 8 Principal bending tensile stresses on bottom side of floor pane in N/mm^2 (intact case)

The intact case and the situation with one broken sheet show similar unity checks, which makes sense because the reduction in applied load factor is proportional to the reduction in the squared thickness (strength) of the pane.

From this structural analysis it was concluded that both the floor and end wall pane suffice regarding deflections, support reactions and stresses.

5. Conclusion and discussion

The challenges pointed out in the introduction have found their way in the design of the 900 Mahler swimming pool. Livelong maximal transparency is achieved by the choice for a ionoplast interlayer, non-susceptible of delamination due to chemical reactions with the environment. Much effort was put in designing a support detail that is first of all guaranteed water tight, but also sustainable, robust and practical in terms of execution. A safety philosophy counting on a potential failure of one of the sheets created a robust structure, capable of sustaining the applied loadings in every possible situation.

Because building costs and material limitation were not prime design aspects in this project, in contrary to risk limitation and safety, the glass elements will not be fully utilized in terms of strength. For example, full relaxation of the interlayer was a conservative assumption; the cooperation between the sheets will in fact be higher. Besides, the unity checks are relatively low. So in terms of material efficiency optimization is possible.

With this project, as well as previous projects involving watertight structural glass, ABT has acquired experience in designing proper and effective detailing. The next step is to push the limits: at the moment we are working on a water filled channel between two residential buildings, as part of a swimming pool, fully made of glass.

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