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Widespanned Retractable Roofs of Thermal Baths in Wörishofen and Erding

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Abstract

The present contribution describes two main structures of the Bavarian thermal baths in Bad Wörishofen and Erding covered by retractable roofs. In both places 50m x 43m two-layer cylindrical grid shells are built which can be completely retracted in summer time. An additional structure in Erding is covered by a spherical grid shell with a span of 50m where only a 90^0 segment can be moved around a vertical axis allowing opening the interior at least partially. The contribution covers some related challenges associated with analysis, structural design and manufacturing. The stability and dynamics of these light weight structures as well as scenarios for the failure of local elements are briefly described.

Keywords: retractable roofs, light weight structures, cylindrical grid shell, steel-glass façade, spherical grid shell, stability and dynamic analyses.

1. Introduction

Due to the unpredictable weather conditions in Germany thermal baths are more and more provided with a Caribbean ambience. A first step in this direction is a design with extensive light-flooded and light weight façades. However the atmosphere staying in the open-air under palm trees is only accomplished by retractable roofs.

The two described Bavarian thermal baths in Bad Wörishofen and Erding, both contain main structures covered by retractable roofs. The design of such movable structures lives in the area of conflict between low weight and transparency on the one hand and enough stiffness of the separated movable roof structure with limited stresses and deformations on the other hand. The two structures at both places have a 50m x 43m two-layer cylindrical grid shell (Figure 1) which can be completely retracted if weather conditions allow it. A particular challenge was the remaining stand-alone front steel glass which ought to be as transparent as possible.

Figure 1: Retractable roofs in Bad Wörishofen and Erding

An additional roof structure in Erding covered by a spherical grid shell with a span of 50m (Figure 1, right) contains a tangle of several interweaved slides. Here only a 90^0 segment can be moved around a vertical axis for opening the interior.

Cylindrical shells as well as the spherical shell are pre-assembled adjacent the site and placed into position by truck-mounted cranes. The light weight constructions require geometrically non-linear analyses; they are also necessary in order to control the moving operation of the roofs. Since the structures are extremely slender stability and dynamics analyses are mandatory for the final design. The joints between roof and main structure are particularly important details, especially in view of the requirements for a tight connection. This also holds for the interaction between structure and glass panels.

2. Indoor swimming pools of Bad Wörishofen and Erding

Since both spas have an almost identical construction for the indoor swimming pools we concentrate on that in Bad Wörishofen. The conceptual design (Figure 2) of the architect Wund, Friedrichshafen, defined a hall 56m x 53m with a maximum height of 17 m; it is attached to a conventional RC building which also serves as the basis for the retracted cylindrical roof. Like the roof the *curved south façade* spans along 43m; the intersection of both surfaces defines the free boundary of the façade. Because of aesthetical reasons a heavy edge beams was rejected; in other words the façade could not be spanned in vertical direction. In order to keep a one layer construction the façade was stiffened by horizontal arch girders each manufactured by welded hollow sections (RR 280 x 80) connected to vertical rods (RR 160 x 80), see Figure 8; they were supported on both sides by truss like towers (Figure 3).The horizontal arch forces are carried by the K-type bracings of the towers. In order to minimize the thickness of the façade the insulating glass panels are continuously supported by the steel members.

The upper longitudinal girders of the structures on both sides serve as supports for the tracks of the retractable roof. Since they also transfer the wind load on both ends to the towers and the RC structure, respectively, they are designed as triangular girders with three main beams. Their supporting columns also act as main load carrying elements for the longitudinal façade of the indoor pool building.

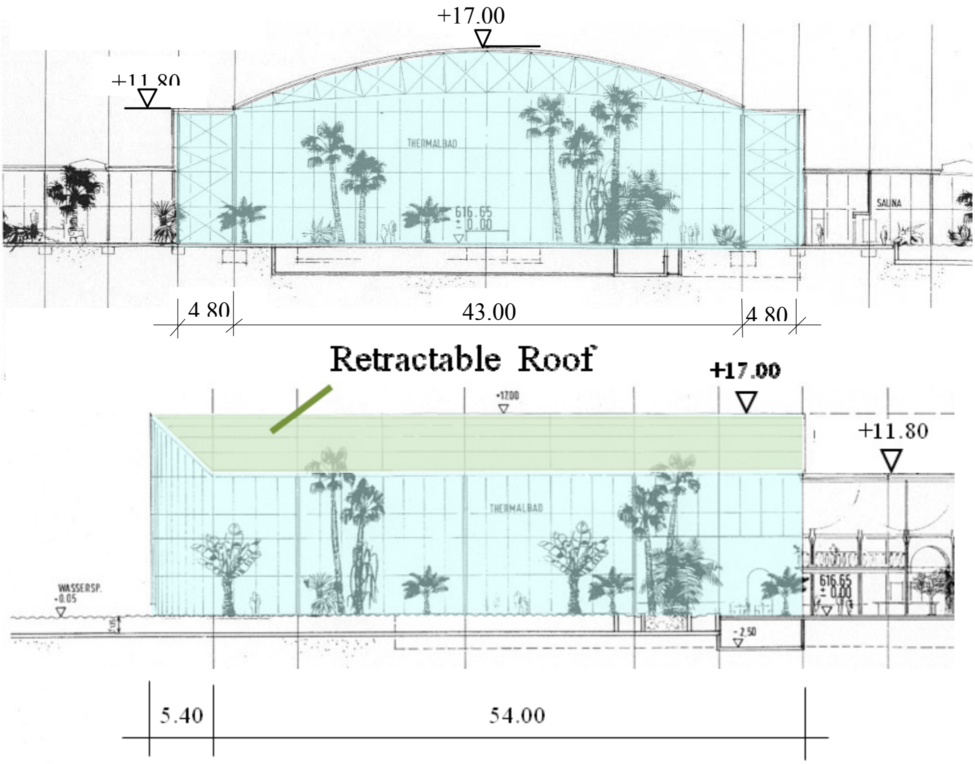

Figure 2: Architectural conceptual design of indoor pool Bad Wörishofen

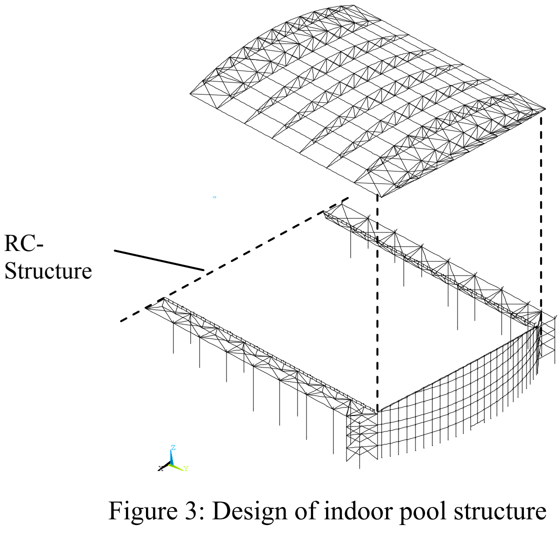

Figure 3: Design of indoor pool structure

The *roof* consists of eight curved truss girders with a spacing of 7.2 m and a maximum construction height of 3.6 m; their flanges are manufactured as tubes with a diameter of 195 mm (Figure 4).

The movable roof is stiffened in longitudinal direction by purlins and by diagonal bracings in the end bays. At the two supports continuous hollow box girders are situated which contain the wheels. On one side the wheels run on rails whereas on the opposite side they can move in horizontal direction. Standard *loading scenarios* are applied for dead load,

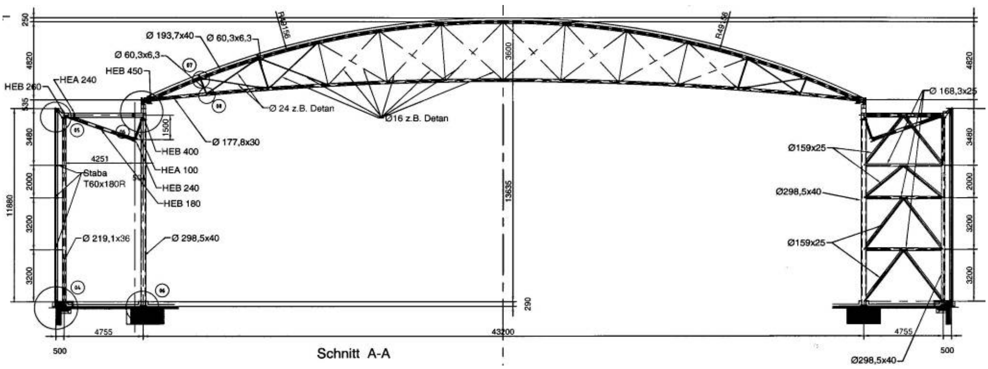

Figure 4: Cross section of indoor pool structure

snow, temperature gradients and earthquake. Wind tunnel tests for open and closed roof have been performed investigating wind attack from different directions (Figure 5).

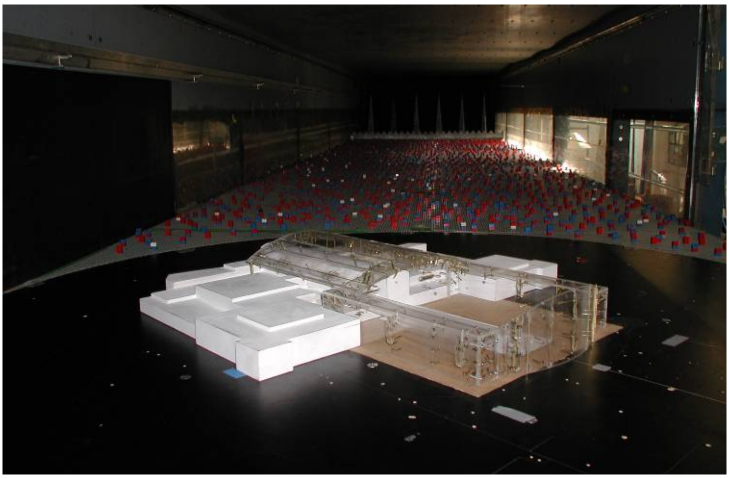

Figure 5: Small scale model in wind tunnel, open roof (courtesy Wacker Ingenieure)

However it was assumed for the final design that the roof ought to be closed for a wind force 6 (strong breeze). For the retraction operation extra loads had to be considered; in addition to the usual vertical loads brake loads and bumper stops as well as actions of slightly tilted wheels had to be taken into account. In order to capture the complex interaction between all parts of the entire structure in the analysis the complete system has been modeled as a spatial frame with three-dimensional beam elements. Slotted holes for screw joints and large drilled holes have been modeled by partially movable hinges. First linear analyses for the perfect structure have been performed checking stresses and deformations in the usual way. They have been supplemented by linear stability analyses for those parts which are buckling sensitive; for example for the arched façade critical imperfections with prescribed maximum amplitudes have been superimposed to the initial perfect geometry. Finally geometrically nonlinear analyses have been carried out.

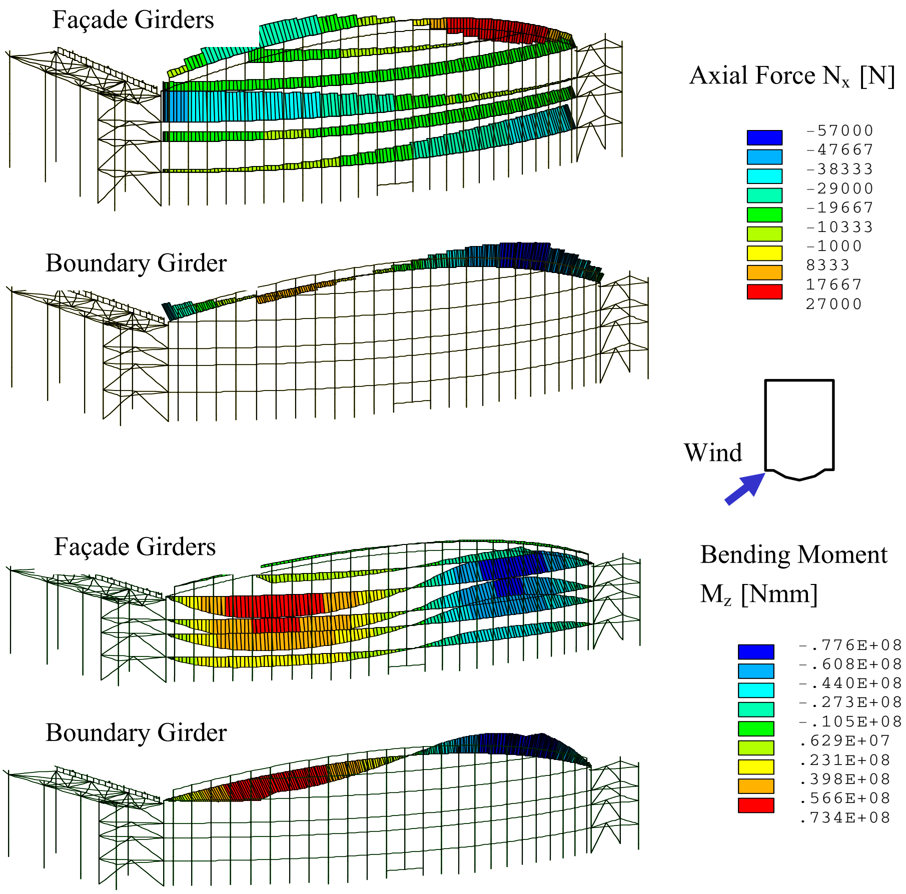

Figure 6: Stress resultants in façade girders (dead load + wind under 60°)

In the present contribution only a few selected results from *analyses* can be described. Figure 6 shows axial forces and bending moments in the façade girders for the load case dead load plus wind under 60^o. The unsymmetrical load case leads to varying axial forces resulting in considerable bending around the weak axis of the columns; furthermore substantial bending moments can be seen. The related maximum deformations are 1/137 of the span. For this rather flexible structure it was mandatory to determine the difference displacements between steel and glass panels; they define the necessary support width of the panes.

As mentioned linear buckling analyses give a first indication for possible instabilities; these analyses are in particular necessary to determine the geometry of the imperfect structure. However in view of the glazing the structure has to be designed in such a way that it stays in the linear regime under service conditions. Through geometrically non-linear analyses for the imperfect structure it could be verified that the relatively large stiffnesses of façade and roof render essentially a linear response.

The degree of prefabrication in the plant was very high in order to satisfy the aesthetic requirements for the design, a necessary protection against corrosion and an efficient construction progress; for example bolted joints were not accepted in visible areas. The girders of the roof have been manufactured in the plant and transported to the site by special trucks. Due to the special out-of-plane flexibility extra analyses for the erection process have been performed. The roof was manufactured and covered by macrolone panes on site; each of two halves, weighing 120 t, is put into place by crane mounted trucks (Figure 7). At that time the steel structure of the façade was already erected so that the glass panes could be added.

Figure 7: Half preassembled roof placed into position by two truck mounted cranes

Figure 8: Upper detail of façade

Further details of design and realization are given in [2]. The indoor pools in Bad Wörishofen and Erding are very well accepted by the public (Figure 9).

Figure 9 Indoor pool Bad Wörishofen; closed,open, at night

2. Water slide paradise in Erding

The steel dome at the thermal bath in Erding houses Europe's largest water slide paradise (Figure 13, right). The spherical *structure* with a diameter of 50 m and a height of15 m is made up of a 270^o fixed segment and a 90^o retractable segment which can be turned around onto the fixed area. The grid shell is supported by a conventional RC structure.

The steel structure is made of standard I-sections (Figure 10). In the fixed area the joints between the purlins in hoop direction and the meridional girders can be modeled as hinges. In this part the roof is covered by trapezoidal sheets. The girders have a fixed hinged support; however due to the deformations of the support beam in certain parts an elastic foundation is assumed in the structural model. For the movable 90^o-segment the number of beams in hoop direction has been doubled. In order to get a sufficient stiffness these purlins have been screwed to the girders leading to rigid connections. A wheel is placed under each girder moving on a circular welded beam; the horizontal displacement in radial direction is not constraint. The retractable segment is covered by the semi-transparent macrolone and is guided by a pin at the apex.

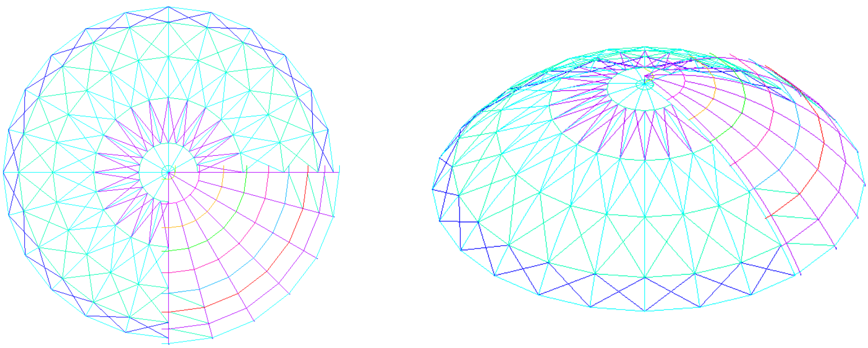

Figure 10: Structure for water slide paradise in Erding

The entire structure has been modeled as a spatial frame with beam elements and was analyzed applying the program ANSYS. Besides the usual load cases for dead load, snow and temperature gradients the wind loads have been determined again by the consultants Wacker Ingenieure. In total 46 load cases have been investigated.

The concept of *analyses* follows that of the above described indoor swimming pool: linear analyses, linear buckling analyses, geometrically nonlinear analyses for the imperfect

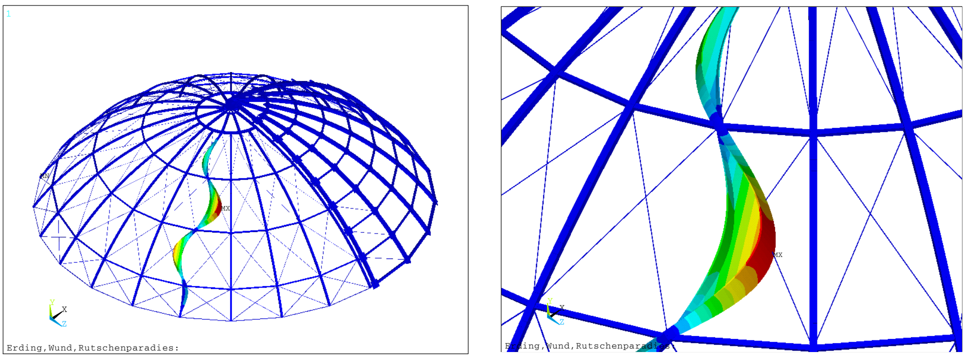

Figure 11: Linear buckling analysis with detailed shell model for girder

structure. For example an individual girder extracted from the entire spatial model has been modeled by shell elements allowing capturing the lateral torsional buckling (Figure 11).

The partioning of the entire structure into two separate systems destroys the ideal load carrying behavior of a closed dome. The load carrying procedure in the circumferential direction is disrupted in each of the two parts. The fixed 270°-segment can handle this situation very well and transfers the loads primarily by axial forces with a minimum of bending; on the other hand the movable 90°-segment reacts with substantial bending moments. This can be seen in Figure 12 for dead load and snow: axial forces are dominant for the 270°-segment, whereas the movable 90°-part shows a considerable amount of bending.

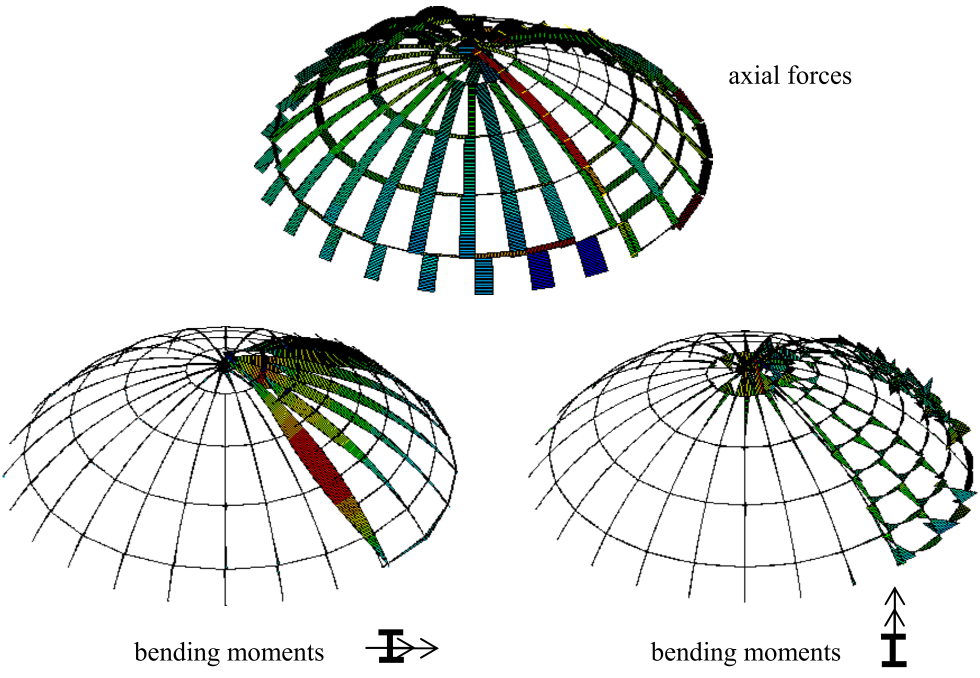

Figure 12: Stress resultants for load case dead load plus snow

Also the two structures are preassembled on site and put into place by crane mounted trucks (Figure 13, left). In this stage the structures are very flexible so that they have to be additionally stabilized for this operation. Several temporary load cases have been investigated. Figure 14 shows a bird eye view of the entire thermal bath of Erding.

Figure 13: Roof of water slide paradise in Erding

Figure 14: Thermal bath in Erding-
left: open indoor swimming pool, right: water slide paradise

2. Final remark

Steel-glass structures became very popular in the last years; this applies in particular for innovative façades, see for example Burmeister *et al.* [1], [2] and Ramm *et al.* [3]. The specific challenge for the design of the present structure was coping with the retractable roofs. They necessarily required light weight structures which in turn mean that the loads have to be carried primarily by membrane action. In addition for the moving operation the size of the deformations had to be limited. Transport and erection phases in which the roof elements are very flexible needed special attention.

References

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