Wolfsburg Science Centre - Venturing Form

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Zusammenfassung

Der Entwurf des Science Centre Wolfsburg ist in seiner Form ein sehr anspruchvolles Gebaeude und stellt damit hohe Anforderungen an alle an der Planung und Fertigstellung beteiligten Personen. Der architektische Entwurf besteht aus einer einmaligen und geometrisch sehr komplexen Form deren Tragverhalten nicht immer eindeutig einem System zugeordnet werden kann. Eine detaillierte Analyse des Tragverhaltens war deshalb nur durch den Einsatz moderner Finite-Elemente-Software und 3-dimensionaler FE-Modelle durchfuerbar. Selbstverdichtender Beton wurde bei diesem Bauwerk das erste mal in Deutschland im groesserem Umfang umgesetzt.

Summary

Because of its form of the Science Centre Wolfsburg created many challenges for planners involved in this project. The architectural design consist of an unique and geometrically complex form thus structural behaviour cannot easily assigned to simple structural principles. Therefore the intensive use of finite-element-analysis software was required using 3-dimensional models in order to understand the structure. To achieve the complex form of the building self-compacting concrete was used.

Introduction

The Science Centre Wolfsburg is a project of the phaeno Stiftung and the city of Wolfsburg. It is the first of its kind in Germany. Its programme amalgamates a museum for science, a facility to explore scientific experiments, a laboratory, a theatre for science, a lecture hall, a library of scientific phenomena. Regarding knowledge as the crucial resource for future generations it represents a laboratory open to the public – a huge knowledge based institution to investigate, to learn, to discover and to explore - a connection between science, economy, schools, universities and public. To achieve these objectives the phaneo Stiftung initiated a competition for the Science Centre.

Figure 1 - South view at the Science Centre

The site is located at a very special place in Wolfsburgs inner city. It is at the endpoint of an axis of culturally important buildings by well known architects as Aalto, Scharoun and Schweger. A residential area in the south, a rail track and train station, the Volkswagen factory and the „Autostadt" in the north are forming the sites boundaries.

The competition was won by Zaha Hadid Architects in collaboration with Adams Kara Taylor in early 2000.

Architectural concept

Starting in a first point with a massive block the surrounding landscape is continued inside the building. On the ground level the massiveness and enclosures of the block is dissolved and – on the base of visual axis – made porous. The area in front of the station grows wider inside the building. At this complex point of intersections where the building is connected with the inner city multiple directions of movement continue through. The axis of important buildings is drawn inside the Science Centre, split and finally spread in many directions towards the Autostadt.

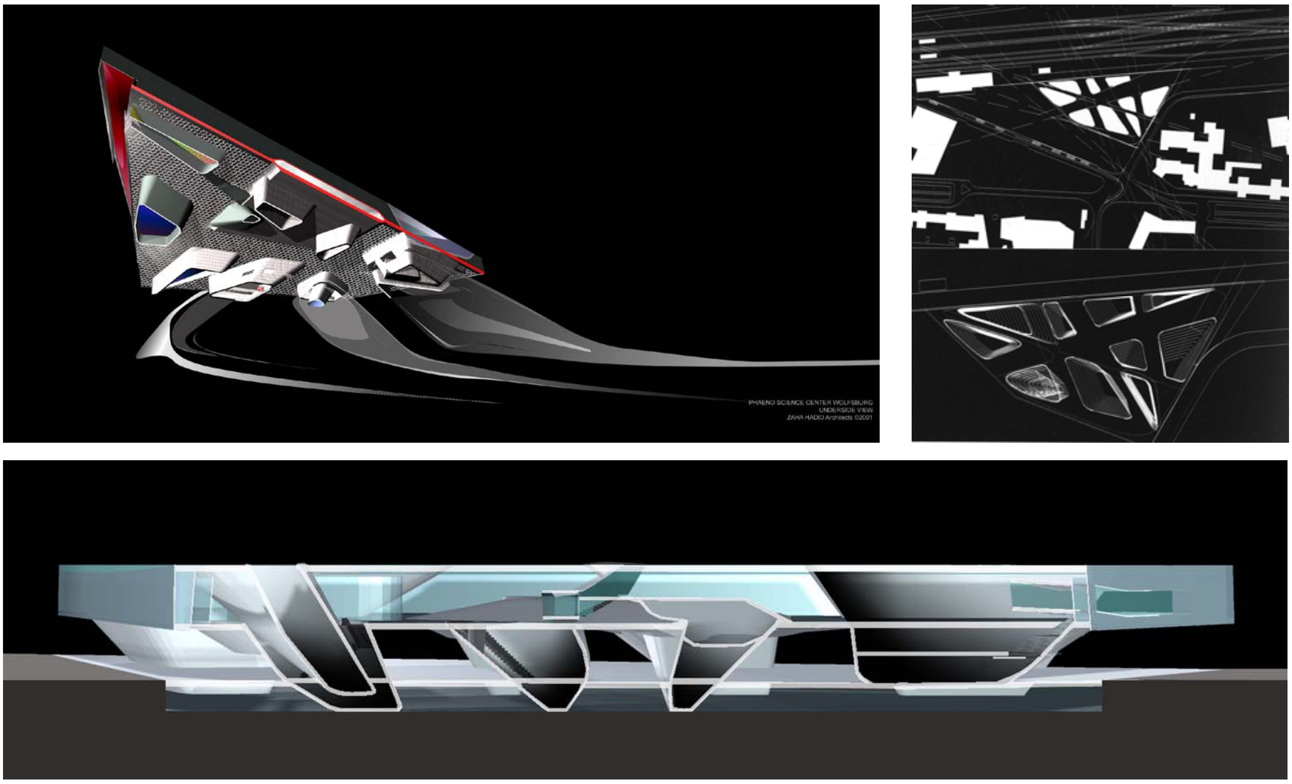


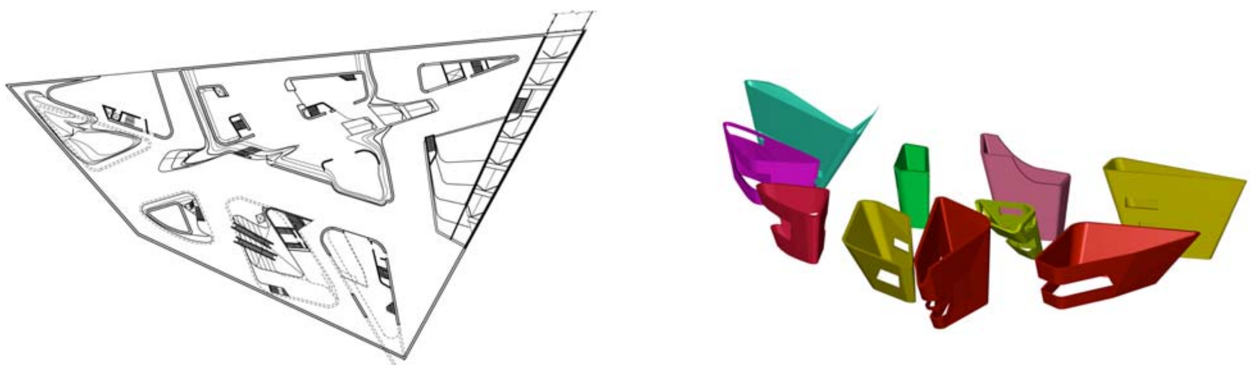
Figure 2 - architectural models

The project is based on an unusual volumetric logic. Neither floors are piled above each other nor could it be seen as a hall with large roof spanning from one side to the other. A big volume is supported and also structured by funnel-shaped cones turned inside out of the box above. Through some of these the interior of the box is accessible, others are used to lighten the space inside, some of them house necessary functions. Their figure was formed by the surrounding primary axes and directions then developed and organically shaped relative to the function inside them. One becomes the main entrance, one the lecture hall three of them fuse to become a big exhibition space underneath the main concourse level.

Structural concept

Aiming to achieve the architectural design the project created many challenges not at least because of its unusual form which is being constructed using insitu self-compacting concrete. It is a monolithic building, measuring 153 m x 80 m and provides 12000 m^2 of exhibition space. Treated as a single entity the cones, main floor slabs and parts of the façade are made from reinforced concrete without a single movement joint.

The building is comprised of a basement level, ground level, ground mezzanine levels which are within the cones, a concourse level housing the main exhibition space and a steel roof structure. The structural concept consists of ten tapered cones (Figure 3) which rise from the raft foundation to the above structure. Cones provide vertical and lateral support for the building and some of them are continued to the underside of the roof level. Although this seems to show a principle structural organisation the structure cannot be seen as a traditional hierarchical system of primary and secondary structural elements. In fact the cones, the slab and the façade act together as a single structure. Melting the structural elements together creates spectacular architectural views but causes also challenges in terms of the thermal performance of the building as temperature changes of ±30ºC have to be resisted. This can be solved but leads to increased amounts of minimum horizontal reinforced in structural concrete members.



(a) **(b)**

Figure 3 - (a) plan view an cone numbering system (b) isometric view

The building has a single storey basement that houses a car park. It has the shape of an irregular quadrilateral. The perimeter of the basement is surrounded by 400 mm thick concrete walls spanning between basement and ground floor slab. Taking support from the basement walls and the cones - which are arranged irregular as a part of the architecturally design – the ground floor slab requires large spans. Therefore the ground floor slab needs additional support using columns following a regular grid layout. Apart from that the building has no columns above ground level to support the floor structure. This create huge volumes of obstruction exhibition space. Taking the basement footprint and projecting it to the above structure determines the perimeter of the building.

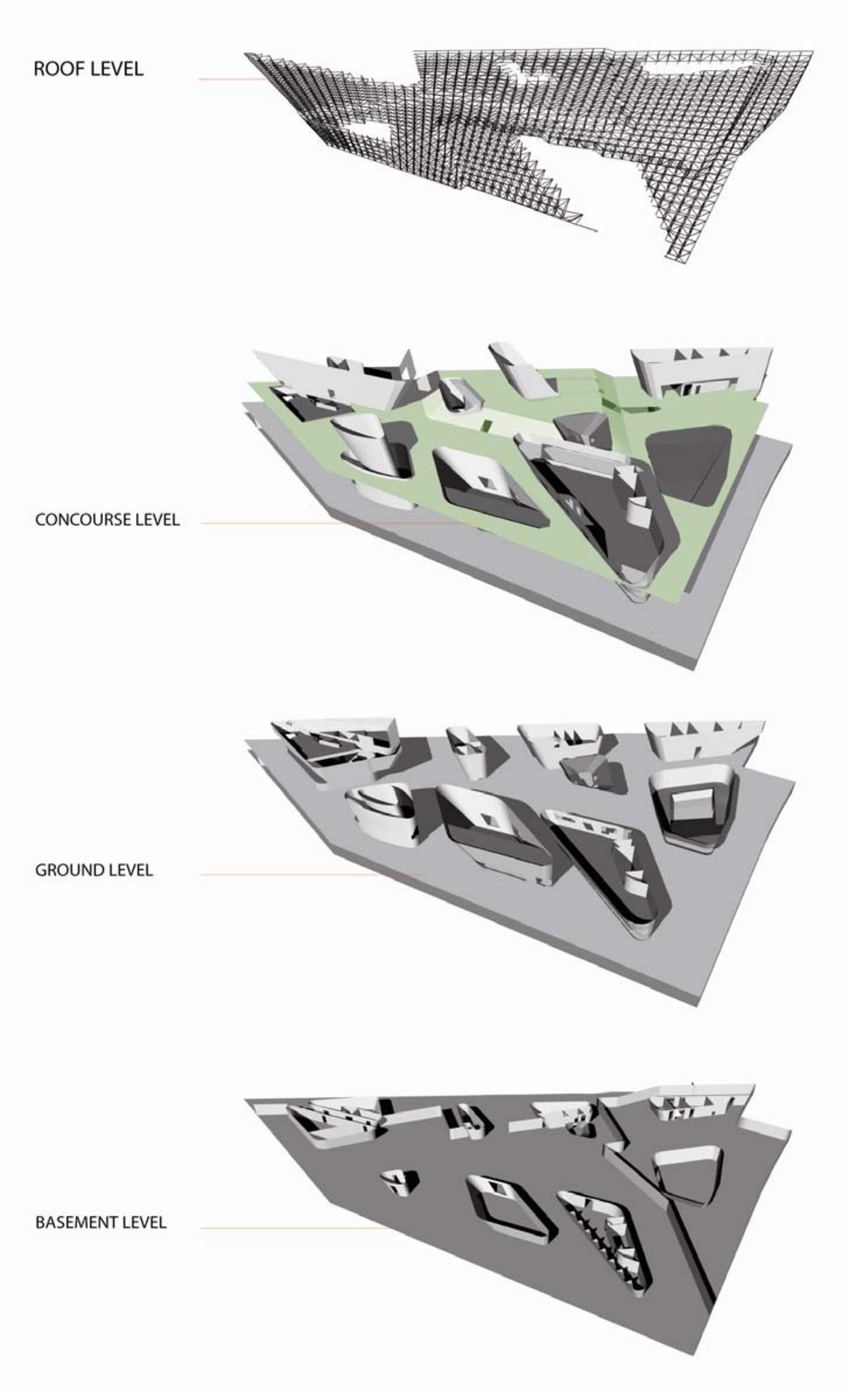


Figure 4 - Science Centre levels

Six of the cones - punch through the ground level - fold into the main exhibition level and the remaining 4 continue through to support the steel roof structure. The shape of each cone is unique but follows a similar principle. Each cone consists of three or four plane walls which are inclined by 38º to 90º angles forming a triangular or quadrilateral plan shape. Although cone walls can change the inclinations between the floor levels is continuous. Conical tapered edges connect the plane walls forming a cone. The overall height of each cone ranges between 3 to 5 storeys. Inverting the form of a mathematical cone the footprint is narrow at the basement level and widens with increasing height. The cones are also sliced with inclined cutting planes to provide architectural and functional openings. The size of the openings is balanced by functional, architectural and structural needs. Within the cones mezzanine floor are provided. Depending on the cone dimension mezzanine floors span between 8 m and 14 m. The geometrical description is complex and can only be processed using advanced 3D CAD Software.

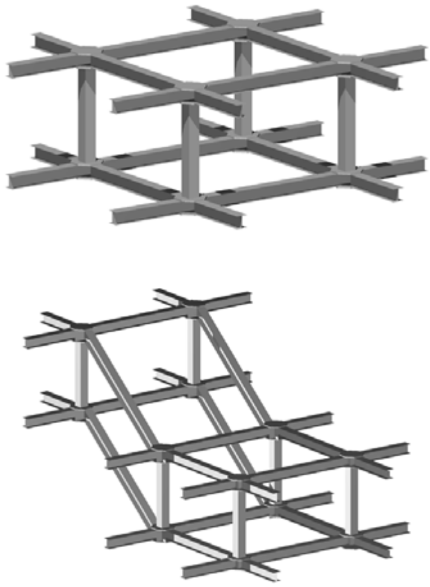
Unlike the other cones, cone 3 is a cone that consists of two cones - an inner and an outer one. The inner cone rises from the basement to main exhibition level. The outer cone rises from the ground floor level to the underside of the main exhibition level enclosing the inner cone just taking support from the ground floor.

Figure 5 - ground level view at exposed wallfe slab

The main exhibition level takes supports from the ten cones and provides level changes via its own folding form. Large spans between the cones are achieved using waffle and flat slabs. Depending on maximum span and loading the structural depth varies between 600 mm to 900 mm using waffle slabs and 250 mm to 400 mm using flat slabs. From ground level the underside of the floor slab is exposed (Figure 5) displaying the changing waffle density and the folding of the floor plate into each of the cone structures. The transition of the folding is complex and is solved by using a regular waffle grid for plane areas and flat slabs for the folding. Governed by form, dimension and spanning directions of the floor plates a diamond shape for the waffle openings is used providing an effective structure. In the area of the exhibition space imposed loads of 5.0 kN/m^2 to 7.5 kN/m^2 have to be taken by the slabs and transferred to the cones. The main exhibition level supports the steel roof structure and the façade structure along its perimeter.

Figure 6 - south façade with pre-casted concrete panels

The façade spans between main exhibition level and roof level. It consists of an ensemble of plane concrete walls, a steel structure to support the prefabricated concrete panels and glazing. Small architectural openings are implemented within the prefabricated concrete elements.



(a) **(b)**

Figure 7 - (a) roof steel structure (b) truss module

The roof structure covers the full area of the concourse slab below. It is supported by the four main cones which extend to the underside of the roof level. Because of the irregular position of the cones the roof structure results in large spans. It consists of a fanning truss arrangement (Figure 7) which also incorporates level changes. The truss uses a double “H” arrangement which when connected to adjacent modules form a vierendeel. The dimensions of the modules are 3 m x 3 m with a structural depth of up to 2 m. The modules are connected orthogonally there possible to simplify the manufacturing. In general modules are fanned to follow the perimeter edges. The largest spans within the roof are between 30 m and 40 m.

Thermal expansion and contraction of the roof required a careful consideration as restraining structure over its 147 m length induces high stresses and can cause buckling within the roof at extreme temperatures. Support is taken from just four cones and perimeter steelwork thus providing an exhibition space clear of obstructions. The roof is fixed laterally and vertically in position at the internal corners of the four cones and uses the remainder of the core walls for vertical support only allowing the roof to expand horizontally. The calculated movements at the roof perimeter due to temperature changes of 40 ºC vary between ±5 mm and ±35 mm.

Self compacting concrete

The concrete structure achieves its shape using specialist timber forms. The advanced technology of self-compaction concrete is used to achieve the finish and aid compaction within the complex geometries. Given that the cones are constructed in insitu concrete with the external face exposed it was important architecturally to cast the concrete in one continuous pour between external floor plates to avoid pour lines on the visible surface. This involves pours between 3.0 m and 7.5 m height with walls inclined by 38º to 90º.

Using normal concrete would have led to poor quality of the surface finish. Ensuring concrete compaction in areas of inclined cone walls and the extent of penetrations would have involved guiding vibrators at the inside of the shutters through a series of tubes and would have made the pouring process very difficult.

(a) **(b)** **(c)**

Figure 8 - (a) and (c) formwork reinforcing of cones (b) slump test

The use of self-compacting concrete was chosen to overcome these problems. It provides a high workability when placing hence avoiding the need to vibrate due to its consistency that is similar to honey. Furthermore it enhances the properties of concrete maintaining a cohesive mix, which avoids segregation and limits gout loss and minimizes voids.

Analysis of Geometry

Understanding the geometry and structural behaviour of this project is a complex task and almost impossible to do without using advanced 3D CAD and FEA modelling software packages. Solving this task was not only a challenge for the design engineers defining the buildings geometry but it also pushed the available 3D modelling software to its boundaries as this is a real 3-dimensional structure. Using 3-dimensional drawings has several advantages - As the design of a building is a highly iterative process - which involves a continuous exchange of information between architects and engineers - working with 3-dimensional models makes changes of the geometry easier to implement. - Based on these models 2-dimensional plan, elevation and section drawings can be easily created or updated. - Having all information in 3-dimensional model reduces the amount of errors in related drawings as references can be used to cross check the drawings. - Furthermore 3-dimensional drawings are easier to read than 2-dimensional drawings - despite being more complex to create.

In a first step the geometry of the building was defined in 3-dimensional CAD models by the architect. In discussion between the architect and the engineers it was agreed to reduce the geometrical parameters of the cones using a minimum amount of fixing tangent points and radii (Figure 9 and) to describe the curved corners in space. By fixing the tangent points in space plane walls could be created between two levels. Having defined the fixing point of the adjacent walls a radius at the bottom and a radius at the top of the wall was derived and circle segments were drawn meeting the walls, which could be also used to interpolate the curved corners. Once the details of the cones geometry was defined architectural openings were implemented. The size and location of the openings is described by setting out two points on plan and defining an angle of the cutting plane. Applying this principle make it possible to create a 3-dimensional CAD model.

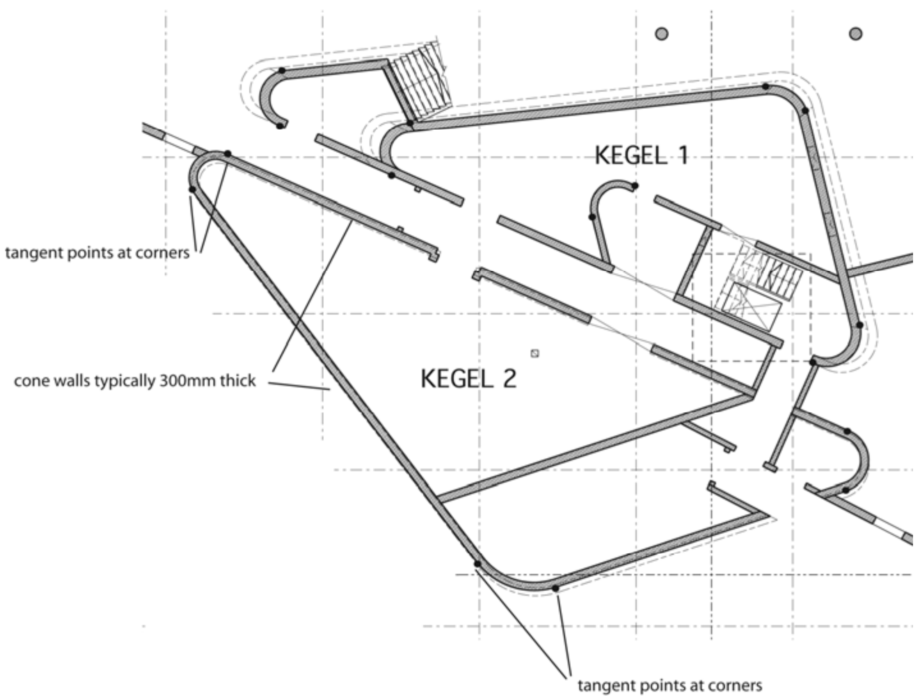


Figure 9 - setting out tangent points of cone 1 and 2 in plan view at basement level

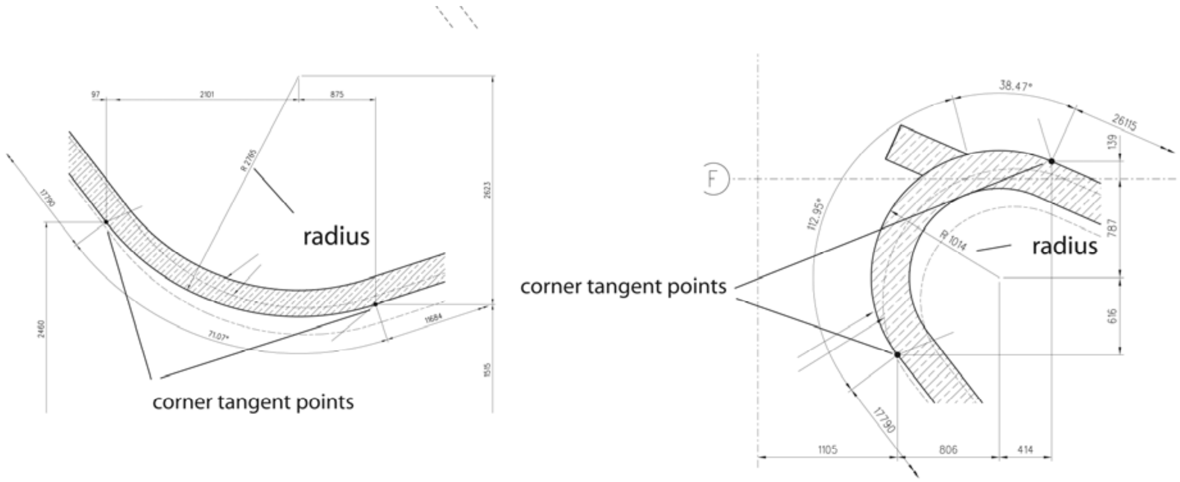


Figure 10 – corner detail of setting out tangent points cone 2

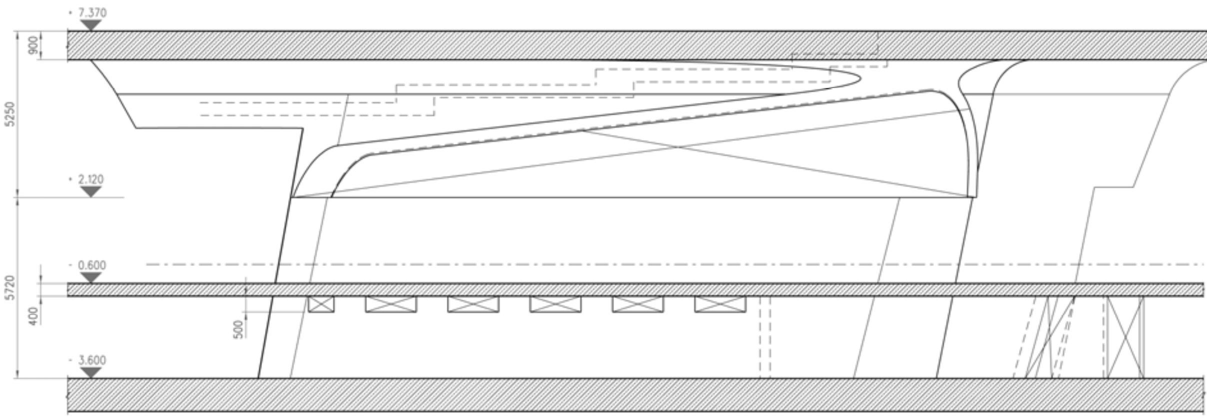
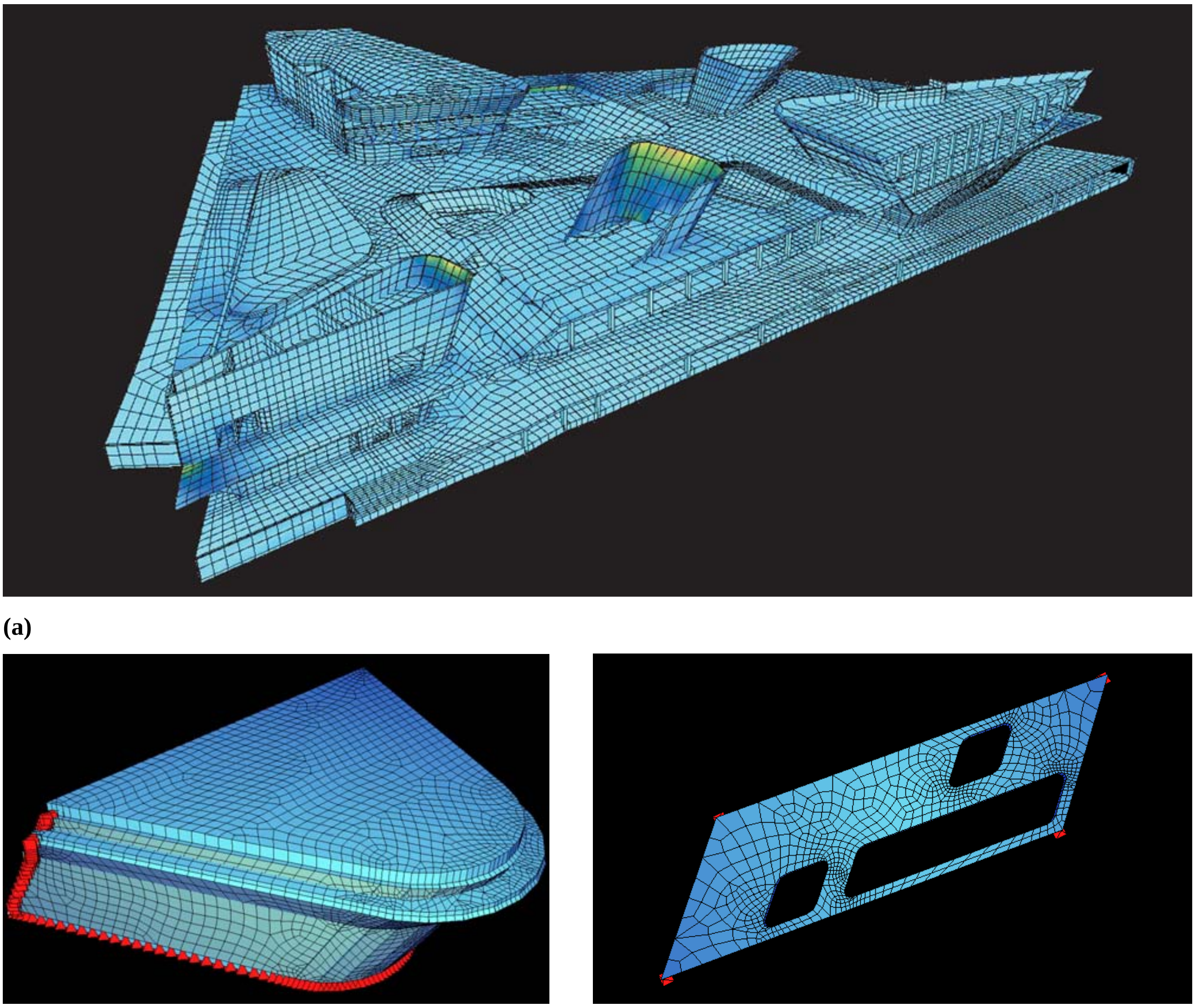


Figure 11 – 2-dimensional section drawing cone 2

Based on these models a preliminary FEA model was developed to study the feasibility and structural behaviour of the building. Sofistik was used to create models and to analyze the cone and slab structure whilst the roof structure is analyzed with the frame analysis package MultiFrame.

In order to analyze the structural members in an appropriate way it was decided to create several FEA models. A global model (Figure 12a) was built to analyze the behaviour of the ten cones in interaction with the floor slabs. One of the main purposes was to calculate the response of the structure under applied loads, especially due to shrinkage and temperature loads as there are no movement joints within the slabs. Having floor lengths of up to 134 m leads to high stresses that need to be identified and designed. Local models (Figure 12b-c) are used to design the waffle slabs, the roof structure, façade structure and façade panels.

Shell elements – which are described in /Bathe – Finite-Element-Methods/ - are used to model the plate and membrane action of the cone walls and the slabs, beam elements are used to model the columns of the basement and the façade structure.



(a)

(b) (c)

Figure 12 - (a) global analysis model (b) local model typical cone corner (c) local model façade panel

A global 3-dimensional model is used to analyse the concrete structure with Sofistik. The model contains basement, ground floor level, main exhibition level including the 10 cones and mezzanine floors and contains over 17000 finite elements. The steel roof is analysed in a different model, however equivalent loads are applied instead. Considering the complex geometry and the amount of resulting elements the model needs to be organized carefully. Therefore different types of members were identified following a simple system of structural behaviour and their position within the structure. The identified members, for example raft foundation, slabs or cones, are assigned to separate groups during the modelling process. Meshing of the structural elements was completely done manually using AutoCAD surface meshes and converting them into finite elements. This insured a high quality of the finite element mesh. After discussion it was decided to consider the waffle floor slabs are as flat slab within the global model by choosing a flat slab with an equivalent thickness. This simplification was made to reduce the complexity and the number of elements.

Having the structural members modelled in different groups makes applying loads to the structure very convenient and simply done by selecting groups and applying loads in SOFILOAD or ASE. Following load cases were defined

- self weight for the concrete and roof structure,
- imposed load,
- snow,
- wind pressure and suction at north, south and east façade,
- shrinkage of concrete,
- and thermal loads.

The following extract shows the typical load case definition done in ASE

```
+PROG ASE  m20 urs:1
…
$ Self weight concrete
LC 1 FACT 1 DLZ 1.0 TITL 'Eigengewicht'
…
$ Self weight roof structure (façade self weight similar)
LC 2 FACT 1 TITL 'Dachlasten'
LILO XA -51.7843 YA -5.71093 ZA 7.71 DX 0.50034 DY 0.638815 DZ 0 TYPE PZS PA -389 PE -389 SEL ALL
NL NO 1061 TYPE P P1 30.5 P2 -45.8 P3 0.0
…
$ Imposed loads applied to the slabs
LC 4 FACT 1 TITL 'Verkehrslasten'
ELLO FROM 20000 TO 29999 TYPE PZZ P -5.0 ETYP QUAD
…
$ Thermal loads
LC 5 FACT 1 TITL 'Temperaturslasten'
NL 8478 TYPE P P1 139.5 P2 17.5 P3 0.0
ELLO FROM 10000 to 19999 TYPE TEMP P 15.0 ETYP QUAD, BEAM
…
$ Shrinkage loads main and mezzanine level (ground and raft level similar)
LC 6 FACT 1 TITL 'Schwinden Hauptebende und Zwischenebene'
ELLO FROM 10000 to 19999 TYPE TEMP P -10.0 ETYP QUAD
…
$ Wind loads north façade (other directions similar)
LC 9 FACT 1 TITL 'Windlasten'
ELLO FROM 60000 TO 69999 TYPE PZ P -0.64 ETYP QUAD
…

CRTL SOLV 2 $ use iterative solver
END
```

Self weight of the concrete structure is calculated within Sofistik. Additional dead loads caused by floor finishes and ceiling are derived by taking 25% of the imposed load and applying it as dead load case. Since the roof and façade are not contained in the global model the reaction the local models are applied as nodal and line loads at the position of their support and along the perimeter of the main exhibition level. Imposed load is dependent on the function of the structure hence it varies between 5 kN/m^2 for the roof exhibition space and 7.5 kN/m^2 at the concourse slab. Thermal loads and shrinkage are considered as temperature changes in slabs of the ground floor, mezzanine, concourse level and the façade. Reactions resulting by the expansion and shortening of the steel roof structure due to temperature changes are applied at lateral fixing points of the inner cones. Since there is no snow on the concrete structure at the final construction stage it is implied within the roof loads.

The building is supported by a raft foundation which provides vertical restrain via bedding pressure whilst horizontal restrain is provided by fixing the ground floor slab in position at its perimeter.

Once the pre-processing was completed single load cases were analyzed and superposition and load combinations were calculated using MAXIMA.

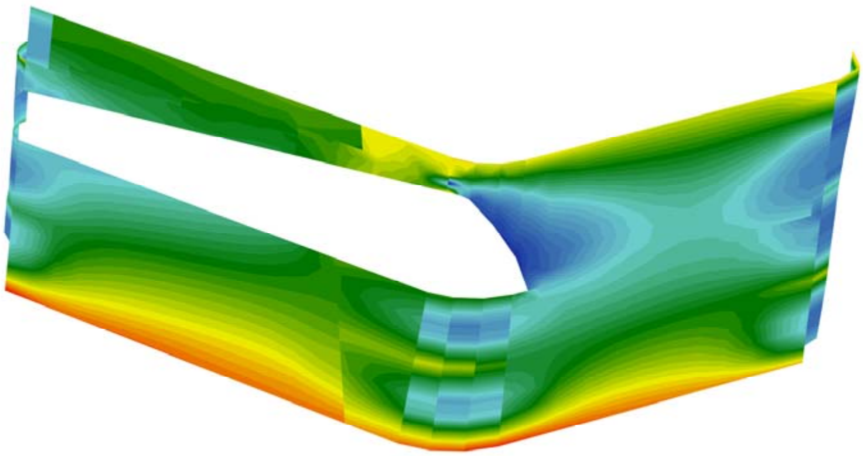


Figure 13 cone 2 membrane stresses in local x - direction due to temperature expansion

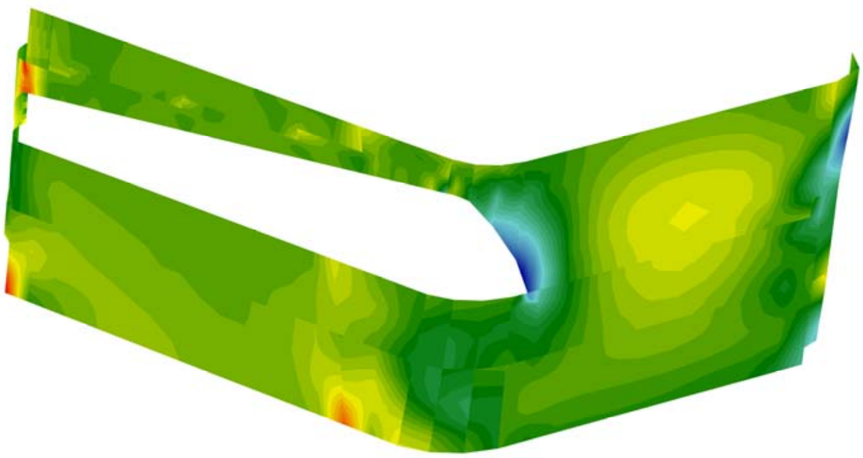


Figure 14 cone 2 membrane stresses in local y - direction due to temperature expansion

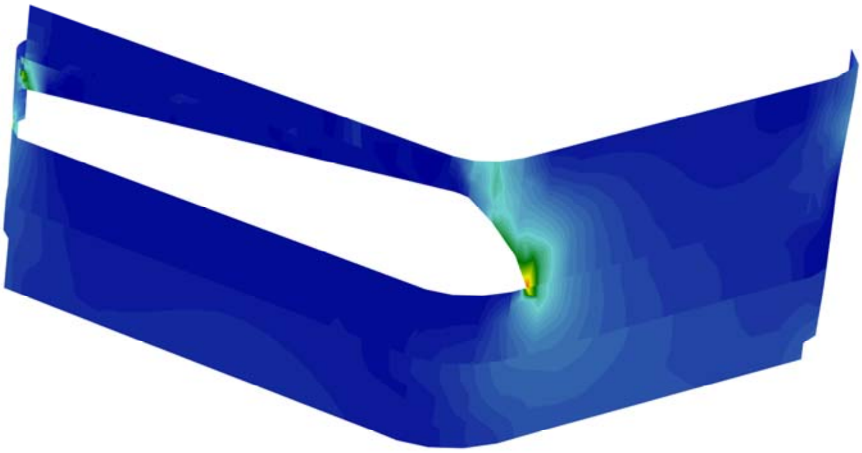


Figure 15 cone 2 membrane stresses in local y - direction due to temperature expansion

Figure 13 and Figure 14 show results of the analysis for cone 2. Cone 2 rises from the basement level to underside of the concourse slab having a huge opening defined by virtual cutting planes. Since cone 2 is located close to the boundary of the raft foundation high horizontal stresses are shown at the bottom which results due to thermal expansion and contraction of the floor slab. Figure 15 represents the stress plot due to superposition of dead, imposed, temperature and shrinkage loads. In the area of plane walls the stress is distributed evenly whilst in the area of the curved corner and the opening a high concentration of stresses occur. Local stress concentrations close to openings is a typical situation for all cones with openings which is mostly caused by geometrical discontinuities and need to be considered carefully in the design process as finite element analysis is highly sensitive in terms of discontinuities and boundary conditions.

Figure 16 shows a reinforcement detail of cone 2 designed according to DIN 1045-1988. It also shows that these drawings need to be unfolded in order to present the reinforcement details on plan and make the concrete contractor able to produce setting out details for formwork.

To control cracks within the structure was one of the main challenges to overcome. Cracks are mainly caused by thermal loads and shrinkage, especially near the outer cones. Using a global analysis model made it possible to predict the response of the structure under these loads. The analysis results were used to develop a concept to minimize crack widths introducing horizontal reinforcement bars at 7.5 cm to 10.0 cm centres.

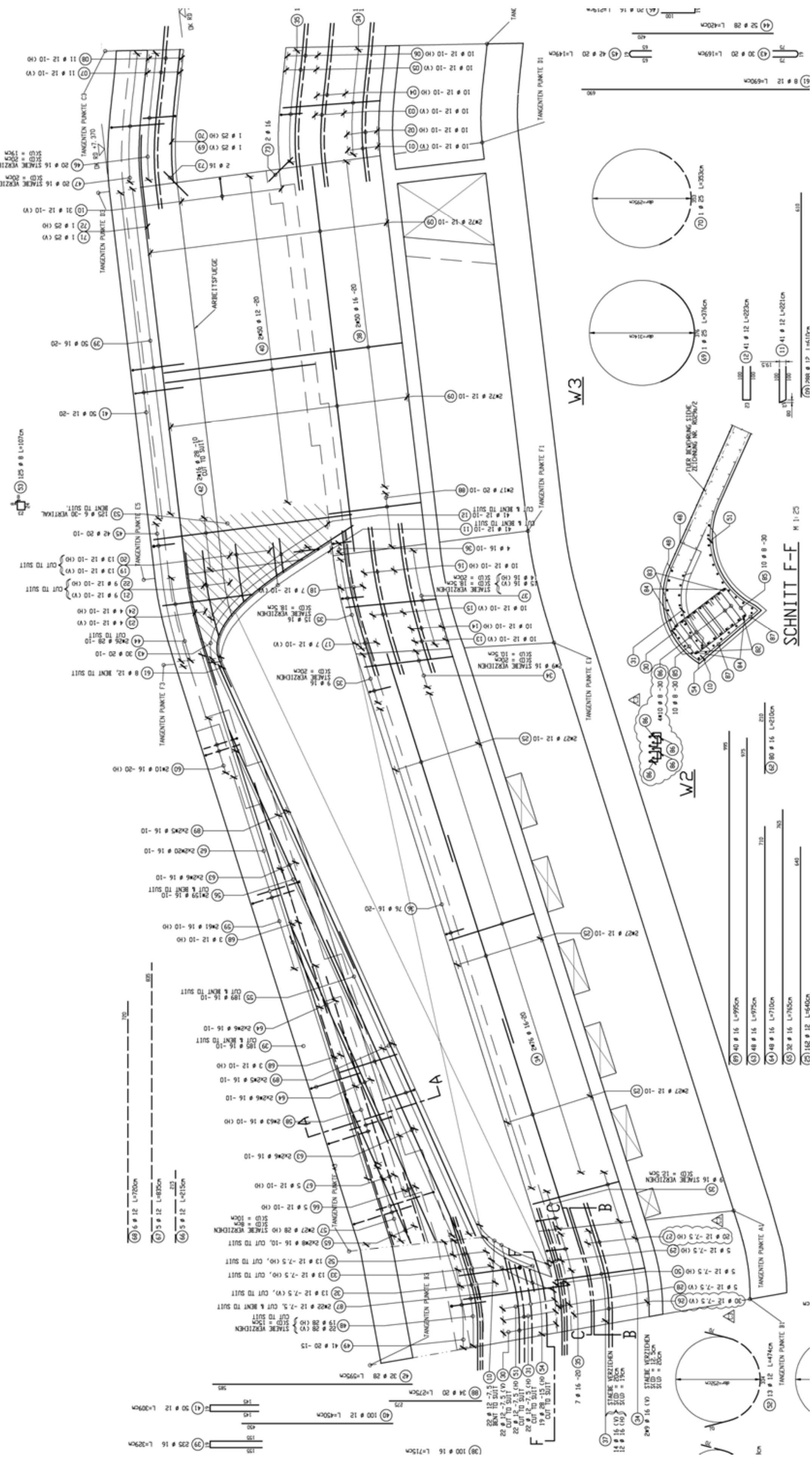


Figure 16 cone 2 reinforcement drawing

Conclusion

Form and design is complex and required an intense use of finite-element-analysis software, challenged DIN requirements and fully exploited the use of drawing packages as it is truly a 3-dimensional engineering and drawing process. The use of self-compacting concrete was necessary to achieve high quality finishes of the exposed concrete structure.
This linked together with working across languages, codes and disciplines is made possible only by teamwork and the latest IT technology.

Programme

Client	Stadt Wolfsburg
Architects	Zaha Hadid Mayer Baehrle
Structural Engineers	Adams Kara Taylor Torkarz Frerichs Leipold
Project cost	72 Million Euro
Areas	
Science Centre	$12000m^2$
Underground car park	$15000m^2$
Dimensions	
Main exhibition floor plate	153m long by 80, across at its widest point
Height	16m above ground level
Quantities	
Concrete	30000m3 or 75000 tonnes
Steel reinforcement	4700 tonnes
Formwork	$67000m^2$
Roof steelwork	750 tonnes