Form finding of the shell structures of the ROLEX LEARNING CENTER in Lausanne

Manfred GROHMANN, Klaus BOLLINGER, Agnes WEILANDT, Michael WAGNER

Bollinger + Grohmann Ingenieure

Westhafenplatz 1, 60327 Frankfurt, Germany

office@bollinger-grohmann.de

Abstract

Form finding of shells for building structures is normally mainly influenced by structural reasons. Therefore form finding methods as turned hanging models or pneumatic structures have been developed. The task for the structural engineers of the ROLEX LEARNING CENTER in Lausanne differed from this traditional approach. The intension of the designing architects SANAA was to create an architectural landscape which allows a natural separation of the different zones of use. Therefore a compromise between the structural and the architectural requirements had to be found during the form finding process. Form finding in the traditional sense changes so in a Pareto optimization.

Keywords: form finding, conceptual design, concrete shell, stability,

1. Introduction

One aim of the architectural competition for the ROLEX LEARNING CENTER in Lausanne was to obtain a building with sufficient space for libraries, student work places, cultural activities etc. The second goal was to create a new representing entrance to the site of the EPFL. The designing architects SANAA (Kazujo Sejima and Ryue Nishizawa, Tokio) responded to these demands by creating an architectural landscape which divides the different user zones naturally by hills and valleys instead of using walls and floors slabs.

Figure 1: ROLEX Learning Center, Lausanne, Rendering by SANAA

This landscape is by two shells with different spans and intermediate flat slab areas. Other than in usual shell construction the shells don't represent the roof of the building but the floor of the inner space. The inner space is enclosed on its top by a steel roof which is laid over the whole building with a column grid of 9 m x 9 m and which follows the geometry of the shells. On its sides the inner space is closed by a one story high glass façade.
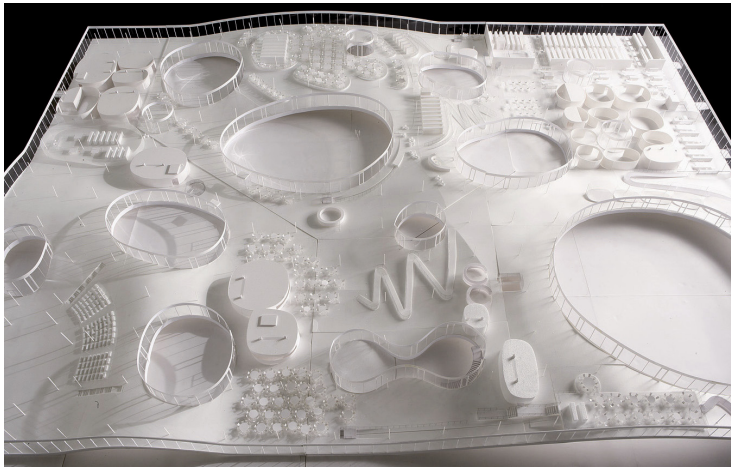

Figure 2: ROLEX Learning Center, Lausanne, architectural model of the main floor by SANAA

The so provided landscape is furthermore divided by patios which serve for the natural ventilation and illumination of the building. The entrances to the building are placed in the patios, too. Whereas some patios are only placed on the flat areas of the building or on the shells, others patios are placed so that they extend over the bearing of the shells. These patios serve for accessing the building. To access the user will immerge by the sides of the building in a public area underneath the shells above the slab above the basement. That way he can enter one of these patios, which are equipped with doors where the patios touch the slab over the basement.

The total building extend over a surface of 121,5 m x 162,5 m and has a one story high basement. Parking places, plant rooms, archives and other utility rooms are located there. Above ground one full level is located. This level is placed on the shells. So the maximum height of the building is limited to 10 m with the height of 4,5 m of the over ground level and a maximum camber of the shells of 5 m. The basement is closed on the upper side by a concrete slab. This concrete slab serves on one side as floor of the main level (in between the shells and in the south-west and north-east building corners) on the other side it fulfills an important structural function. It serves as horizontal bearing of the shells and takes up the horizontal bearing loads via post-tensioning cables.
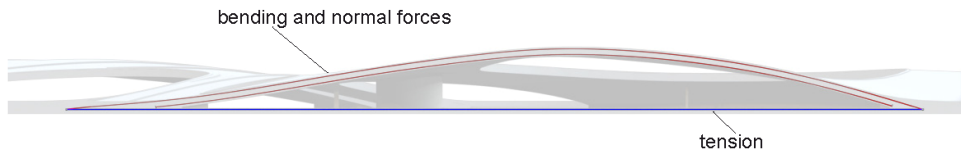
Figure 3: structural concept: post-tensioning cables as horizontal bearings of the shell

The most outstanding elements of the ROLEX Learning Center, the shells, have been at the same time the biggest challenge for the structural engineers of the project. Therefore Bollinger + Grohmann Ingenieure developed in close cooperation with Walther Mory Maier a concept that reconciled the high architectural demands, the user requirements and the structural aspects. The development was effected in close collaboration with the designing architects SANAA, here the form finding of the shells played an important role.

This form finding and the conceptual design of the shells shall be discussed in this paper more in detail.

2. Form Finding

The term "Form finding" is for shell structures is mainly associated with the form finding methods as inverted hanging models, pneumatic design, etc.. Generally the form finding is in these cases is only influenced by structural reasoning, mainly gravity. Due to the unusual concept of the building, which uses the shells as a floor instead as a roof structure further requirements had to be responded in the form finding of the shells of the ROLEX Learning Center. There classic form finding methods couldn't be used during the design process.

The geometry of the shells was developed based on the vision presented by the architects SANAA in the architectural competition. A compromise between the user requirements, the architectural design and the structural limits had to be found during the design process. The user aspects have been among others the requests for sufficient usable not so much sloped areas, the respect of escape way lengths, the connections between different zones of the building, etc. Especially the requirements of handicapped people had to be considered in particular.

For architectural reasons also view axis had to be respected. This was important to cope with the exceptional panorama to the Swiss Alps given at the building site. So the view axis not only influenced the slopes of the shells but also the position of different patios. Concerning the design aspects it was important to preserve a captivating interior space and to avoid in any case the impression of being in a tunnel, when immerging underneath the shells and so entering the building. In short the image of a landscape had to be preserved during the form finding process.
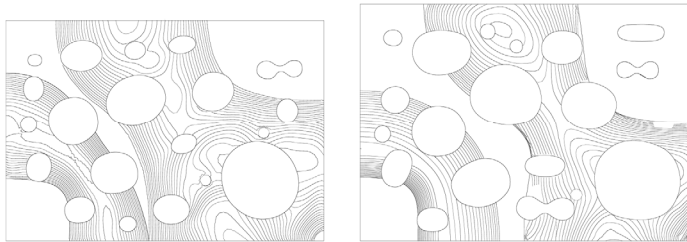
Figure 4: contour line models by SANAA; competition model (left side) – conceptual design phase (right side)

The optimization process of the geometry started therefore with analyzing of the geometries proposed by the architects. In this phase of the project the geometry was still subjected to major changes due to the user requirements, etc.. For example the flat areas between the two shells were extended to increase the surfaces that could be easier furnished for the users.
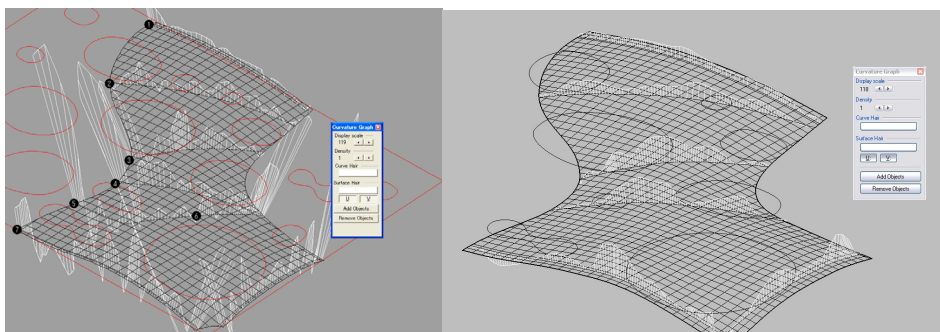

Figure 5: Analyze of the curvature of the geometry proposed by SANAA for the big shell; before optimization (right side) –after optimization (left side)

Anyhow the major steps to the final geometry were already made during this design phase. Among others the span of the shells in regard to their camber was optimized, the surfaces were planed and the position of the patios was examined. In this stage of the project the first 3D-models were created based on the contour line models given by SANAA. These models already could be analyzed with the aid of finite element methods. By this a certain number of rules could be established in regard to the structural behavior of the shells during the further design process. For example the maximum ratio between span and camber, the curvatures, etc. were developed at that stage. At the same time the results of the first 3d-models were validated by simple 2d-models and hand calculations.

In the further design process the development of the geometry of the shells was an interactive procedure where the structural requirements were reconciled with the user

requirements and the design aspects. Hereby the following aspects were tried to be implemented in the shell geometries:

- Adaption of the localization and geometry of patio so that load bearing arches could be established between the patios
- Optimization of the geometry of the arches towards parabolic and symmetric sections
- Reduction of imperfections
- Avoiding of counter-curvatures at the shell bearings. To keep however the impression of a smooth transition between the shell and the flat areas it was therefore proposed to the architects to separate the shell geometry and the geometry of the finished floors at the shell bearing, see Figure 7.
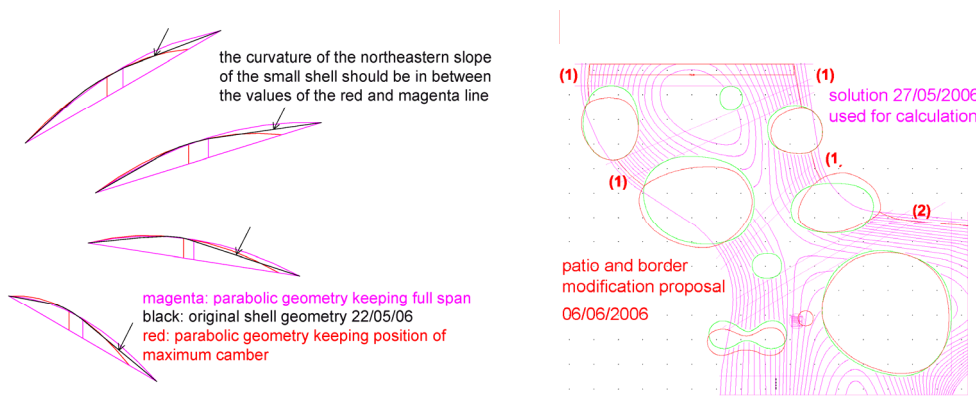

Figure 6: analyze of curvature of a geometry proposed by SANAA for the small shell with recommendations in regard to structural behavior (left side); development of patio geometry (right side)
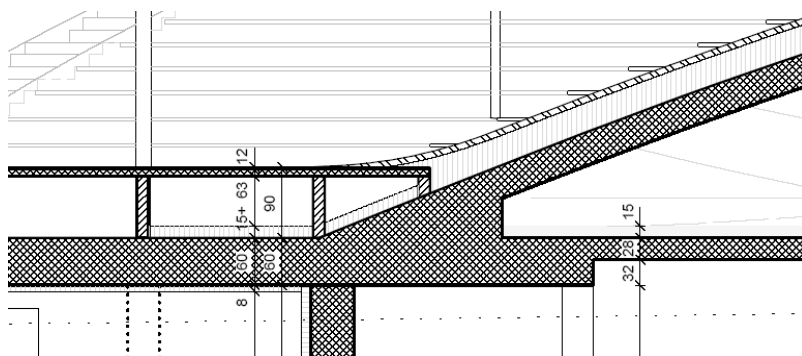

Figure 7 shell bearing detail; differentiation between finished floor geometry and shell geometry

The characteristics of the finally retained geometry can be described as following:

The small shell with a maximum span of 40 m and a camber of about 4.00 m has a relative advantageous span to camber relation with l/h=10, whereas its geometry is comparatively asymmetric. It is cut by 3 patios, so that 4 load bearing arches could be established between the bearings. The zones in between these arches, called "slab zones" are still characterized by a sufficient curvature to transfer their loads mainly by membrane forces.

The big shell with spans up to 85 m and a maximum camber of 4,85 m has in contrast a disadvantageous span to camber relation with almost l/h =17.5. Due to the location of the patios, which was fixed following the rules described above only 7 load bearing arches could be established between the patios. As the "slab zones" of the big shell have less curvature than that of the small shell a higher percentage of the vertical loads had to be transferred by bending moments to the arches. In addition it was necessary to place three vertical load bearing elements under the shell in the southern part to guarantee sufficient stability and to limit the deflections. One is an elevator core which was also necessary for the user requirements, the second is built by a wall underneath the western part of the southern arch, which allowed the arch to finish in a counter-curvature, on third place a columns is stabilizing the diagonal arch with the longest span. This arch kept during the whole design process a strong asymmetry in order to preserve the view axis from the northern part of the building to the impressing panorama of the Alps in the South including the unique view to Europe`s highest mountain, the Mont Blanc.

3.   Conceptual Design

Simultaneously to the form finding process different concepts for the structure where developed and examined. A solution proposing a steel structure was excluded at an early stage of the project as the architects desired a soffit in exposed concrete.

sandwich-like cross section:

top and bottom layer: C50/60
core layer: lightweight concrete

monolithic cross section:
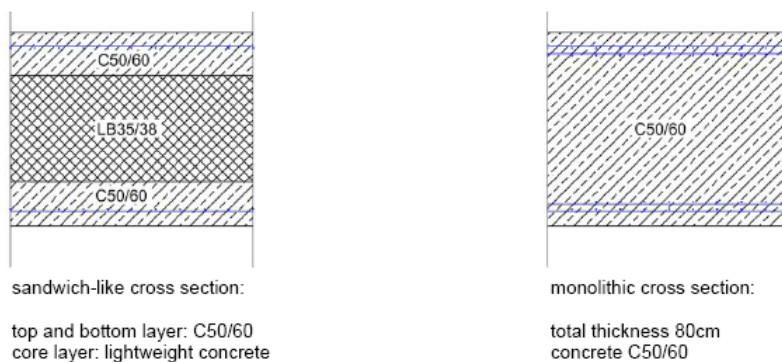
total thickness 80cm
concrete C50/60

Figure 8: different principals of the shell section

During a longer period a sandwich solution was envisaged. This sandwich was constituted of two outer layers in high performance concrete C50/60 and one inner layer of lightweight concrete. The disadvantageous geometries of the shells required to transfer a high percentage of the loads via bending moments in comparison to known shell constructions. The sandwich option allowed therefore keeping the same stiffness compared to a monolithic section by reducing at the same time the dead load of the structure. It was also envisaged in this solution to integrate the building equipment pipes in the inner layer of the sandwich to reduce the total height of the floor section. This integration with all its complexities in coordination and the higher complexity in the execution were finally the reasons to reject this sandwich solution.

With the form finding process the final solution with the so-called arches and slab areas emerged. First only the grade of reinforcement differed between the arch section and the slab area sections. Later an alternative with variable section heights was favored.
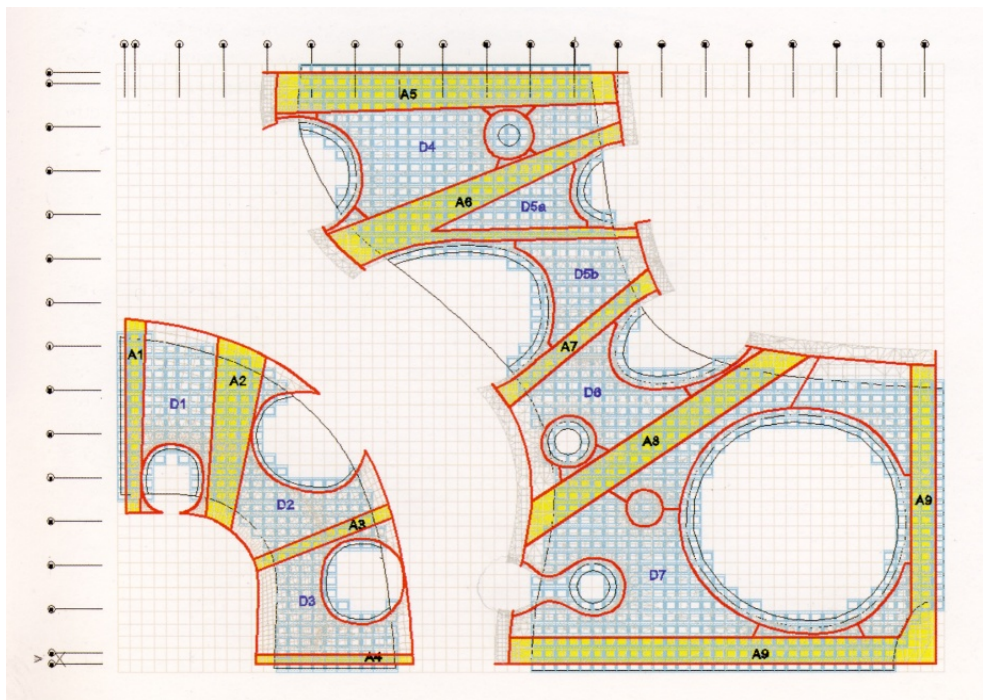

Figure 9: arches and slab areas of the shells

In this alternative the required height for the arches and the zones around the vertical load bearing elements and the patios of the big shell was 80 cm, whereas the height of the slab areas could be reduced to 60 cm. The smaller span of the small shell and its more advantageous span to camber relation enabled a section height of 40 cm, respectively 50 cm for the western arch, for the small shell. The height difference between the 80 and the 60

cm zones were sufficient to place the technical equipment pipes, so that the total construction height could be limited also in this solution.

The high amount of reinforcement in the arches gave rise to discuss further structural alternatives for the arches. Instead of using reinforcement bars it was examined to develop a composite construction placing steel pipes in the arch sections.
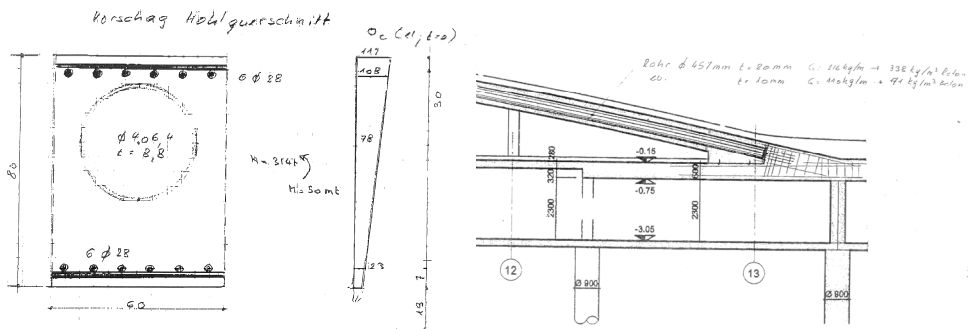

Figure 10: proposal for composite section of the arches, sketch by René Walther (Walther Mory Maier)

This alternative was not further pursued due to the higher costs of sectional steel compared to reinforcement steel. The execution seemed to be also more complicated in regard to the positioning of the steel pipes and their welding on site. Furthermore in this solution a higher amount of steel was necessary to guarantee the same inertia of the section, which was necessary for the stability of the whole structure.

In the finally retained solution the high amount of reinforcement is covered by reinforcement bars with a diameter of 50 mm, which guarantee sufficient space between the reinforcement bars for concreting. Further details for the execution of are given in Weilandt *et al.* [1].

4. Design

The verification of the shells was done respecting to the Swiss construction standard, SIA. As the "normal" construction standards don't respond to all question evocated during the design of that unusual construction other European standards or literature were consulted.

The design of the curved plates was mainly influenced by the following three conditions: The verification of the sections under design loads and characteristic loads, the deflections and finally the buckling stability. All these items were analyzed considering the effects of cracking, creep and shrinkage. Therefore the shells had to be analyzed with a finite element program which allows considering all these non linear phenomena's. Therefore the program SOFiSTiK was chosen.
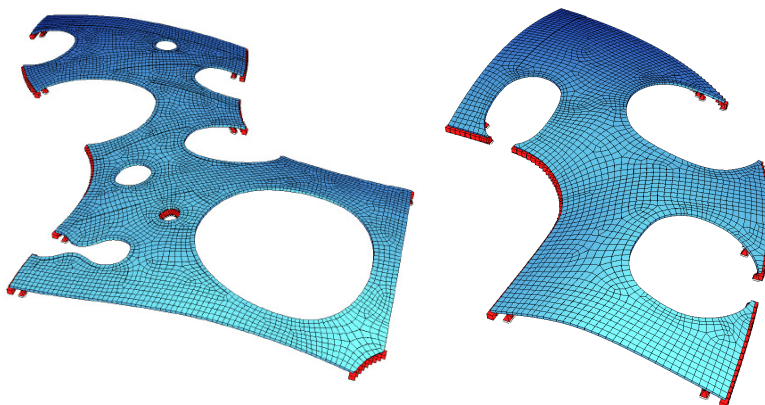
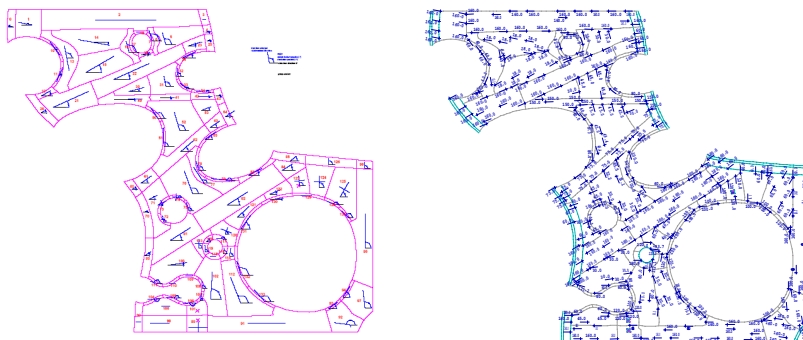Figure 11: meshes of the finite element models of the big and the small shell

Figure 12: orientation and amount of reinforcement considered in the finite element model of the big shell

4.1. Verification of sections and deflections

The verification under design and characteristic loads was calculated respecting the limits given in the Swiss building standard. At the characteristic load level the stresses were limited to values given in regard to the crack width w < 0,2mm. At the design load level the given limits of stresses and strains were respected. Therefore on one side the values calculated by the program SOFiSTiK were analyzed and on the other side moment-normal-force diagrams (M-N-diagrams) were established to control the given results by SOFiSTiK. Furthermore the M-N-diagrams allowed to analyze the different particular zones more in detail by taking into account the real orientation of the reinforcement bars. This was for example necessary for the patio edge areas, where the tangential and radial orientation of the reinforcement couldn't be represented exactly in the finite element model.

Figure 13: Stresses (upper reinforcement layer) at design load level after creep and shrinkage and M-N-interaction diagram

Aside the verification of the reinforcement stresses in regard to the crack width the deflection analyze was a major item at the characteristic load level. As the building standards don't define a deflection limit of shell structures with spans up to 80 m, the limits had to be specified in regard to the steel roof structure and the façade installed on the shells. The resulting long term values of vertical deflection were calculated up to 220 mm which seems to be quite high. But in comparison with the span of about 80 m they represent values < l/300, which is a quite normal value for concrete floor slabs.

Figure 14: Deflections of the big shell after creep and shrinkage at characteristic load level

4.2. Buckling Stability

Finally the design of the shells was completed by detailed analysis of their stability. In a first approach the first eigenfrequencies and their critical load increasing factor were analyzed with linear finite element models. Later the analyses were completed by calculating load-deflection diagrams considering the non linear effects in regard to geometry (second order theory) and material (cracking, creep and shrinkage). These load-deflection diagrams allowed calculating the critical load increasing factor in regard to the stability of the shells. For the big shell a load increasing factor of 2.8 compared to permanent and variable loads was achieved. This factor corresponds to an increase of the total load by 50 kN/m² compared with the characteristic load level. Due to the high percentage of permanent loads (22.5 kN/m²) compared to the variable loads (5 kN/m²) this critical load progression factor was considered satisfying.
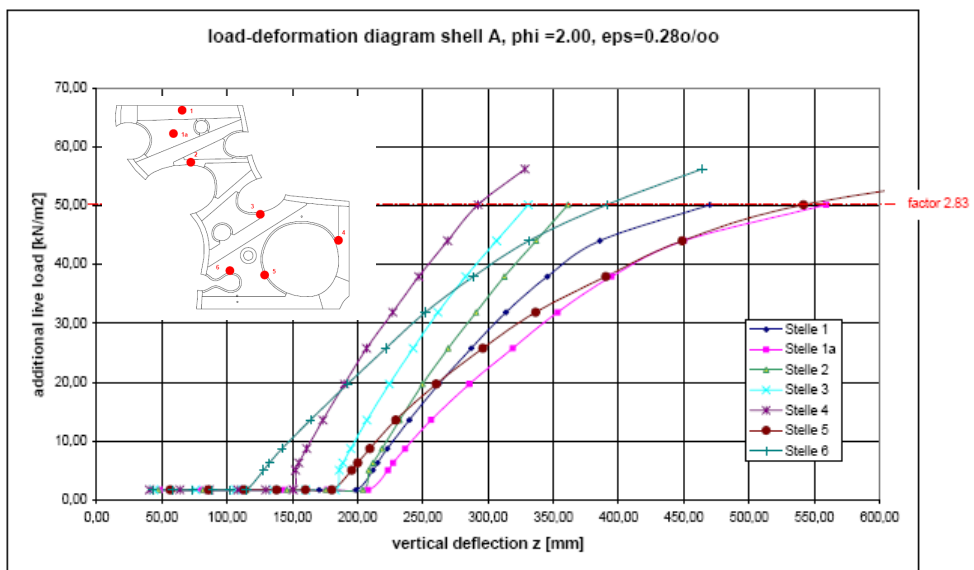

Figure 15: Load-deflection curves of the big shell

Furthermore this development of load-deflection curves allowed analyzing the behavior of the shells while increasing the critical load factor. In case of pure membrane state structures the development of these curves is linear until rupture. Non-linear curves show a sign of bending failure. As the decisive curves of the big shell (see point 1a and 5 in Figure 15) show a highly non-linear behavior already for small load increasing factors it could be concluded that a failure of the shells is more due to bending than to buckling.

This low sensitivity of the shells to buckling can also be explained by the imperfections in the geometry of the shells. As the user and the architectural design requirements played a major role in the form finding process of the shells the given geometries are in structural points of view pretty imperfect. Therefore certain amount of loads is already under uniform

loads transferred by bending moments. So the shells are not very sensitive to imperfections or asymmetric loads. The analyses of different imperfect geometries or asymmetric load cases have shown an increasing of the stresses lower than 10 % compared to the base geometry under uniform loads. This influence of imperfections and asymmetric loads was considered in the verification of the structure by reducing the given stress limits to 90 % of the allowed building standard values.

The three described design items - verification of sections, deflections and stability – defined the required amount of reinforcement in the shells, whereas for the curved parts of the slabs the stability and for the more flat areas the deflections where mainly decisive.

5. Conclusion

The form finding and the design of the curved slabs of the ROLEX Learning Center in Lausanne had been a big challenge for all participants of the project. The impressive pictures of the concrete structure which were taken in spring and summer 2008 justify the unusual form and the immense complexity of the structure.

Figure 16: Big shell in September 2008

Finally the retained geometry of the shell represents a compromise between architecture and structure. Form finding in its classic signification is so transformed to a Pareto-Optimization.

References

[1] Weilandt, A., Grohmann, M., Bollinger, K., Wagner M., ROLEX LEARNING CENTER in Lausanne: From conceptual design to execution in *IASS 2009 Evolution and Trends in Design , Analysis and Construction of Shell and Spatial Structure,* Domingo and Lazaro (eds.), 2009