On Shells, Structural Landscapes and Performative Geometry

Oliver Tessmann¹, Klaus Bollinger², Manfred Grohmann³
¹,²,³Bollinger + Grohmann Ingenieure, Germany
http://www.bollinger-grohmann.de
¹otessmann@bollinger-grohmann.de, ²kbollinger@bollinger-grohmann.de, ³mgrohmann@bollinger-grohmann.de

Abstract: The paper exemplifies a collaborative design approach of architects and engineers by two projects that remotely resemble shell structures. Their geometry is rather driven by a complex network of manifold requirements. Parametric modeling and scripting is used to enhance collaboration and speed up the synthesis analysis loop.

Keywords: Collaborative design; associative design; structural analysis.

The structural notion of shells

The overall performance of an architectural project results from balancing a complex network of multifaceted, interrelated requirements that originate from multiple sources. In such a collaborative design process the authors conceive of structure as an integral part of architecture. Geometry becomes an important mediator for all people and disciplines involved in the process. To enhance collaboration and speed up feedback loops of synthesis and analysis an integrative representation including architectural and structural aspects at the same time is of great interest.

The paper will discuss two projects that seemingly belong to category of shell structures. But on closer examination one can see that those forms originate from design procedures, which consider a broader set criteria then mere load bearing. The tools that enable seeing design as a dialogue in which ideas are bounced off the different members of a design team are presented here.

From an engineering perspective, homogenous, idealized shells are elegant as they transfer forces without incurring bending forces and thus can be constructed with minimal material thickness. When forces can be reduced to pure tension and compression the entire cross section of a structural element is exploited whereas bending causes stress only in the outer areas and therefore disrates the remaining material to be useless ballast. The elegant shells of architects and engineers like Heinz Isler, Felix Candela and others exemplify the slenderness, which can be achieved by finding forms free from bending forces. Surface structures like shells or domes resist forces through their double-curved form and integrity. The bearing mechanism is achieved by a membrane-like behaviour. Like a balloon that is not able to resist bending with its thin surface, shells resist external loads through tension and compression. In case of symmetrical loads the form will be kept in equilibrium by meridional forces and ring forces only. Structural shells are ideally defined by revolving catenary curves. Such geometry leads to mere membrane forces and is best supported by linear bearings. However, any incision in such an ideal shape leads to fundamental, problematic changes in the structural behavior.
A structural landscape
The Rolex Learning Center at the EPFL Lausanne by SANAA Kazuyo Sejima and Ryue Nishizawa is a single-storey building which hosts a central library, lecture halls, study facilities and services, exhibition halls, conference halls, cafeteria and a restaurant (Figure 1). The building is supposed to be the centre of campus life in the future. Instead of a planar floor slab the Japanese architects designed an architectural landscape generating a topographic separation of different zones of use. The load bearing shell consists of two perforated free-span reinforced concrete shells, spanning up to 90 metres.

SANAA's undulating landscape building includes patios, openings and various spatial qualities defined by an artificial topography. Hence structural aspects were just one set of design criteria among many in the design process. The landscape integrates a wide range of design criteria far beyond just structural aspects, which prohibited the use of conventional structural form-finding strategies for shells and barrel vaults.

The structural design rather focused on analyzing and identifying local areas of shell or arch behavior, which were subsequently further developed and modified in an ongoing dialogue with the architects.

Classic form-finding is superseded by processes of tracing performative capacities in the specific morphology. As the load-bearing characteristics vary across the landscape-like articulation, no region represents a pure structural typology. The analysis also reveals problematic areas that would necessitate a disproportionate thickness of the concrete shell. Wavy tensile force progression, high bending movements and redirected forces combined with the lack of support points in the patio areas were addressed by redirecting the force flow between the
shell perimeters through modification to geometry, size and location of the patios. Such an iterative process of tracking performance in collaboration with the architects entails ongoing design and evaluation cycles (Figure 2).

In the early design phase the architects predominately used physical models to develop their design. The obvious advantage of physical models is that they offer a common base for more than one person to work on. The workforce could be directed towards the organization of a complex program within the landscape. Details of the exact geometry were of minor interest at that stage of the process. Nevertheless the structural inquiry required a precise description of surface curvature, symmetries and singularities like patio positions. Thus the contour model of the architects was translated into a NURBS surface model. The geometry could be represented by only few surfaces with trimmed patio areas. The model's complexity increased when the structural system required a description of several arcs as primary structure and areas that span in-between. A multitude of surfaces were now necessary to represent the structural components. Furthermore their connection became important because the NURBS surfaces were translated into meshes of a finite element model. Structural coherence could only be achieved when the vertices of neighboring elements meet in the same point. With the progress of the project the workflow from architectural model to analysis model improved but at the same time became increasingly complex since all models gained detailed information (Figure 3).
A parametric shell structure

The extension of the Staedelmuseum in Frankfurt am Main designed by Schneider + Schumacher Architekten was represented as a digital model from early on. Thus communication, collaborative design procedures and data exchange could be enhanced by a parametric 3d model and scripting procedures which act as an interface between architects, engineers and fabrication.

A spacious museum hall, submerged under an existing garden, is covered by a concrete shell. The double curved roof is perforated by a pattern of circular apertures, which subdivide the garden and bring light into the building. The spatial experience of the shell as a ceiling becomes a central feature of the building and its geometry is the objective of multiple requirements (Figure 4).

The architectural notion of the roof shell

The architectural approach of the museum roof shell is a continuous, quadratic surface with a central deflection. The roof dimension results from the shape of the existing courtyard. Apertures are placed according to a pattern defined in plan and subsequently projected to the shell surface. In detail the apertures form local deflections of the shell surface, self-similar to the overall form but smaller in scale. The result is a surface with a large central deflection populated with a series of similar small-scale deflections (Figure 5).

The project is supposed to be built as a concrete shell with glazed skylights. The continuous small-scale deflections will be shown in the concrete shell and then chopped and covered by planar glass panels. The aperture size differentiation is limited to five
becomes the revolve axis for the skylight profiles which than act as fall-off curves for the deflection of the reference surface by repositioning the affected control vertices. A dense uv-sample rate in the reference surface provides the necessary precision for defining those local small-scale deflections. The result is an undulating reference surface that integrates one large and many small-scale deflections. However in the built project concrete shell and apertures alternate constantly. Thus the continuous surface has to be split. Furthermore the apertures should not be projected anymore but become exact circular skylights in the ceiling. This requirement causes the challenge to intersect a free-form surface with a plane in a certain position and retrieve a circle from this operation. The procedures can only provide an approximation of a circle, which is acceptable as long as a certain tolerance is retained. Closer approximation of the circle could be achieved by a higher uv-sample rate of the reference surface, which, at the same time, leads to discontinuity of the reference surface. To successfully achieve the circular apertures a script was developed which manipulates the control vertices in accordance to the local properties of the shell surface. The relation between vertex manipulation and circle approximation had to be investigated empirically through trial and error and was subsequently described by a formula that drives this operation (Figure 7).

**Parametric representation of the shell**

The above described requirements are represented and negotiated in a single parametric surface model, which serves as an interface between the different parties of the design team.

Due to the mathematical properties of NURBS surfaces and the architectural aim for continuous curvature the cross section of the shell is curved in two directions to provide a smooth blend from the horizontal areas of the surface into the shell-like deflection. This cross section is not beneficial for the structural behavior of a shell because is obviously deviates from the catenary curve. Thus a second cross section curve, which better approximates a structural shell section, is superimposed on the architectural section curve (Figure 6). The 3d model conducts a kind of collision detection to ensure that the structural section curve never exceeds a certain boundary defined by the architectural section.

The roof is represented by a single NURBS surface that serves as a reference for all subsequent steps. The skylight locations are defined by a two-dimensional pattern, which is projected on this reference surface.

The different sized skylights are distributed along the surface according to a predefined set of rules. The surface normal at the skylight’s center becomes the revolve axis for the skylight profiles which than act as fall-off curves for the deflection of the reference surface by repositioning the affected control vertices. A dense uv-sample rate in the reference surface provides the necessary precision for defining those local small-scale deflections. The result is an undulating reference surface that integrates one large and many small-scale deflections. However in the built project concrete shell and apertures alternate constantly. Thus the continuous surface has to be split. Furthermore the apertures should not be projected anymore but become exact circular skylights in the ceiling. This requirement causes the challenge to intersect a free-form surface with a plane in a certain position and retrieve a circle from this operation. The procedures can only provide an approximation of a circle, which is acceptable as long as a certain tolerance is retained. Closer approximation of the circle could be achieved by a higher uv-sample rate of the reference surface, which, at the same time, leads to discontinuity of the reference surface. To successfully achieve the circular apertures a script was developed which manipulates the control vertices in accordance to the local properties of the shell surface. The relation between vertex manipulation and circle approximation had to be investigated empirically through trial and error and was subsequently described by a formula that drives this operation (Figure 7).

Thus the algorithmic approach of geometry
generation was accompanied by a kind of automated modeling. The underlying mathematical rules of NURBS surfaces proved to be too complex to be revealed and instrumentalized. Nevertheless the procedure provided the necessary data and served helpful in case of changing geometry of the overall form during the design process.

**Conclusion**

A parametric description of the complex dependency-network as an associative geometric model and a script supported the different stages of the design process. It served as a tool to quickly generate different versions of the roof shell geometry, which could be visually evaluated through renderings.

Deviations from the fabrication requirements could be quantified and put into relation with predefined specifications. The complex and time demanding process of geometry-generation could be automatized, which proved helpful in the iterative process of refining the structural calculations. A super elevation of the shell, which takes into account the deflection after removing the scaffolding can be reflected in the parametric model and taken into account when producing the formwork.

The procedure exhausts the possibilities of representing various design constraints in one single NURBS surfaces. Nevertheless such a singular surface enabled global optimization of continuity, and structural performance and proved suitable for the different parties involved in the design process.