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Construction of shells by active bending of flexible concrete

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Abstract

A novel approach for thin concrete shell construction is presented that circumvents the necessity for curved formwork. Instead, shells are erected from flat plates to which eccentric forces are applied causing them to bend into a desired curved shape. The form activating forces are induced by coupling a system of tension members to a thin—thus flexible—plate made from flexible concrete. To achieve radii of down to 1 m, the concrete cross-sections are designed so that their bending stiffness in cracked concrete is only a small fraction of that of the uncracked cross-sections. The approach was developed step by step, theoretically and experimentally and a milestone was the design and construction of a 10m long arch deformed out-of-plane with a radius of 3m. The further development of the technique led to the active bending of a flat plate into a double-curved shell. The shape development of the developable thin shell was based on a parametric design, nonlinear finite element analysis as well as a series of paper models. The design was realised by the construction of a thin concrete plate with the dimensions 7.0 x 7.0 x 0.04m, which had a triangular shape in the ground plan with another triangular recess in the middle and from whose corners relaxation cuts were arranged in a radial direction towards the supports. After central lifting with specially developed lifting beams, the tension members were stressed, whereby the flat plate was formed into a curved shell caused on the initial plate-geometry and the stiffness distribution. In this paper the authors will discuss and show the developement and bending of a shell in the metre scale.

Keywords: active bending, conceptual design, flexible concrete, form finding, experiments, concrete shells, construction method.

1. Introduction

Shell structures made of concrete are currently rarely used for the construction of everyday buildings. The highly aesthetic and filigree-looking, efficient structural form is used much more commonly applied in the construction of prestigious projects, see Sohm [1]. The limited application of shell structures is due in part to the high effort required during the construction of the structure. Both the time involved in building the formwork and the associated economic considerations currently contribute to the continued dominance of conventional construction processes with flat structural elements and the associated increased consumption of raw materials. Additionally, prevailing pragmatism and existing regulations also influence the planning and execution processes of everyday construction projects, see Kromoser et al. [2]. The aim of the method presented in this paper is to make a contribution to the development in the construction sector through the novel deformation process for shell construction. It is demonstrated that a thin, textile-reinforced concrete plate can be deformed into a shell after hardening with the use of external tendons. This innovative approach makes the use of flat formwork systems for curved structures conceivable. Consequently, formwork operations become comparable to those of well-known flat structural forms, see Kleiser [3]. Based on these principles, a large-scale experiment is intended not only to demonstrate the practical application but also to illustrate the feasibility of using flat formwork systems for curved final shapes, comparable to other thin materials in combination with active bending, see Lienhard et al. [4].

2. Shell construction through active bending of flexible concrete

For the erection of shells, a flat plate is deformed into a designed shape. It is proposed to use external tendons that apply an eccentric force into the plate. The deformation is the result of the bending moments generated by the eccentricity of the tendon and the low bending stiffness of the textile-reinforced concrete element. This results in large curvatures and small radii of deformation, respectively. The tendon absorbs the horizontal thrust of the arch and simultaneously causes the movable support to displace. It is recommended to induce an initial bending by means auxiliary supports before starting the erection process. This reduces the required displacement forces of the tendons and leads to more favorable stresses in the arch, see Berger et al. [5, 6]. Shell structures usually react to deformations with high sensitivity. For actively bent shells, a number of deformation problems may occur. One of the inner causes can be the inhomogeneity of the materials, whereas the external causes can be imperfections of the geometry, or the frictional resistance of the movable support, the support hinge, or the tendon. To prevent these causes, the deformed geometry is continuously controlled during its erection process. The following means of geometry control are considered:

1. Tied tendons: By stressing the tendons, forces are introduced into the structure by regularly arranged deviation saddles, which allow a controllable shaping.
2. By supporting at essential points, a height correction of the geometry can take place during the erection process.
3. Control of the rotation in the support hinge as a way of manipulating the inclination of the end tangent of the shell.

2.1. Strengthening measures

As the stiffness of the actively bent shell is intentionally reduced during its erection, additional measures are required to enable a proper load-bearing capacity of the final structure. The following options can be considered:

- Converting supports, for example, the movable support into a pinned support. The free tendon could be removed after erection.
- Filling the bending cracks with a construction material such as cement or grout.
- Post-tensioning of the tied tendon to generate a radial deviation force, which leads to a compressed cross section with increased resistance to bending.
- Constructive actions, such as topping with textile reinforced concrete, lattice beams, or additional external tied tendons to increase the stiffness.

2.2. Benefits and application

The presented novel construction method allows for the construction of simple shell structures, such as halls for events, storage, vehicles or planes, noise prevention tunnels for traffic, as well as aesthetical shell constructions, such as freeform surfaces from single curved panels with little material expenditure. There are advantages which can be expressed as follows:

- Efficient production (serial production in a precast plant, and automated production processes of concrete and steel parts).
- Reduction or complete omission of form- and falsework.

3. Design of the geometry for a large scale experiment

The design of the shell geometry is based on a development process consisting of computer-aided parametric form-finding and a series of papers model in order to fulfil the requirements for the construction of an aesthetic and highly load-bearing structure.

As a proof of concept, a demonstrator with a more complex geometry than a simple arch was chosen as a design target. This approach would not only generate a wider variety in the curvature but also present a more advanced situation in the linear actuation. From the manifold conceptual design variants, mainly generated from physical paper models, a design with three supports was chosen to fulfill all the above-described requirements. This choice was made not only for the geometric and formal constraints of the shell but also for its complexity in actuation. Working with thick paper of 200g/m² also allowed an investigation into the behavior of the shell and its reaction to slits within the material. The slits appeared to resolve the region around the point of singularity in the initially closed surface after actuation. Although the form of the cutouts could vary and be designed in many different ways, an offset triangle around the point of singularity was chosen to simplify the entire process.

In this approach, the geometric forms arise from the properties of the building material. Initially, a variant study was conducted using Revit and Rhino, along with the plug-ins Grasshopper, Kangaroo, and Karamba 3D as shown in Figure 1. Additionally, following the material-based approach, a final paper model was created.

The design was realised by the construction of a thin concrete plate with the dimensions 7.0 x 7.0 x 0.04m, which had a triangular shape in the ground plan with another triangular recess in the middle and from whose corner's relaxation cuts were arranged in a radial direction towards the supports. The oriented slits allowed for a better control of the curvature and the bending energy.

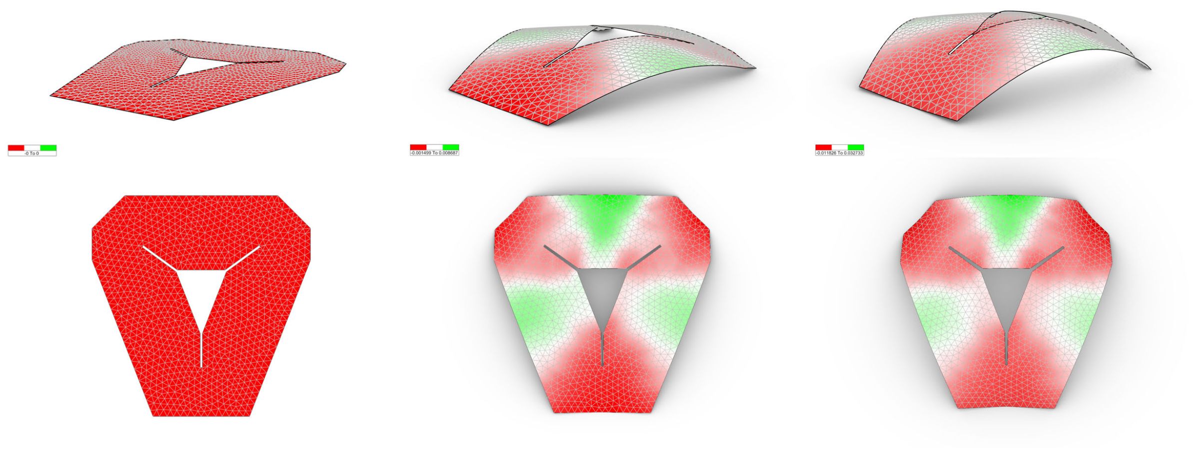
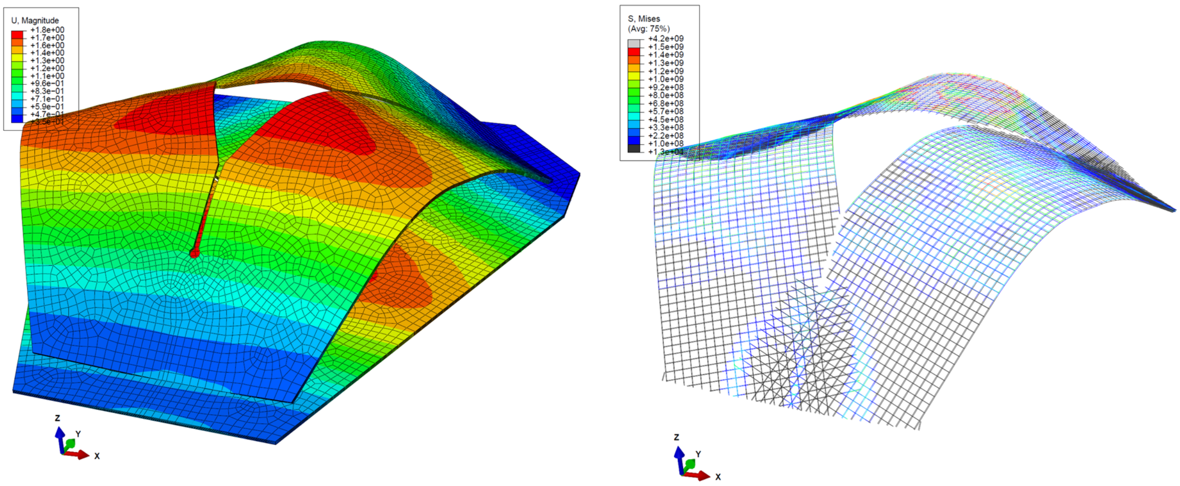


Figure 1: Digital Models from the form finding process, with an analysis of the Gaussian curvature as colour gradient (red = negative / green positive)

4. Structural analysis

A numerical analysis was carried out to investigate the load-bearing behaviour of the structure and to quantify the support and tension forces. The results come from an analysis in which the concrete body was modelled using 3D solid elements with non-linear material behaviour and the reinforcement was modelled discretely using bars.

In Figure 2a, the deformation figure resulting from self-weight and support displacement is shown. Figure 2b illustrates the stresses in the reinforcement. Important insights for the deformation process were obtained from the calculation results, upon which optimizations such as additional reinforcement were carried out. It was demonstrated that a geometrically and physically nonlinear finite element analysis is feasible and meaningful for the given problem. Detailed information on the calculation of this shell can be found in Heck [7].



a) Deformation figure U in [m]

a) Stresses in the reinforcement in [MPa]

Figure 2: Finite element analysis results

5. Large-scale experiment

5.1. Manufacturing

For the production of the flat plate, a formwork system was used, consisting of formwork beams and panels. Within the formwork system, a lifting beam was integrated, allowing for the demolding and lifting of the plate. On the formwork table the side formwork was placed and the reinforcement was laid. Glass and Carbon fibre grids from Solidian were used as reinforcement, see Figure 3. In the apex areas, where the highest bending stress occurred, additional reinforcement was placed.

The concrete was poured using a polymer cement concrete (PCM), which was pumped in via a mixing pump. After a curing period of 30 days, the concrete plate was demolded and lifted using specially made lifting beams to imprint the initial curvature. Once the formwork was removed, the hinged roller supports for load introductions were installed and connected with tie rods, see Figure 4.

Figure 3: Formwork and reinforcement

Figure 4: Hinged roller support

5.2. Active bending process

The active bending process primarily occurred through the tensioning of the tie rods using a hydraulic hollow cylinder. Due to the interaction between the imposed deformation and the flexible structure, bending stress occurred, which significantly contributed to the deformation of the plate into a shell shape. The displacement process occurred in sections, with form corrections being intermittently carried out through local supports, see Figure 5-7.

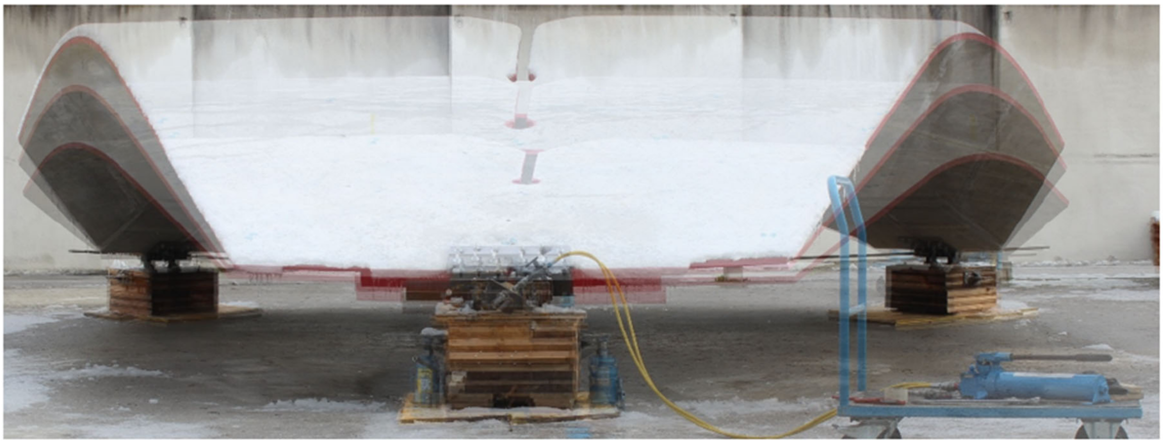


Figure 5: Incremental active bending developement

Figure 6: Actively bent concrete shell – side view

Figure 7: Actively bent concrete shell – bottom view

The cracks required for the deformation process occurred as expected, primarily on the top side in the area of the apex, see Figure 8, and on the bottom side in the area of the load application. The deformation figure was always somewhat asymmetrical, which could be corrected by unilateral tensioning and localised supports. The test was carried out until fracture, which resulted in a large crack that developed into a yield joint, followed by collapse. Regarding the geometric analysis, it can be stated that the maximum height reached was 2.10 m, the shell had an inclination to the horizontal in the load application area of 32° and the smallest radius of curvature measured was 2 m. The maximum displacement applied to the supports was 0.33 m.

Figure 8: Crack pattern on the surface

6. Conclusion

The approach of actively bending concrete plate into shells has been successfully implemented in practice. It has been demonstrated that the deformability of flexible concrete enables the construction of complex, curved shapes previously unknown.

The form-finding process for this new construction method with this new material required new design approaches, leading to numerous design phases. Based on this, a structural analysis for active bending using geometrically and physically nonlinear finite element calculations was possible, providing numerous insights and enabling improvements.

The construction implementation could be carried out quickly and cost-effectively using standard building materials, supplies, and equipment. The result was a shell curved multiple times from a flat plane, with dimensions of 7x7 m in plan and a height of 2.1 m, with a shell thickness of only 0.04 m. The smallest curvature radius achieved in the experiment was 2 m.

7. Outlook

The presented strategy, as mentioned above, could have a fundamental impact on the construction of thin concrete shells if the application can be brought to the AEC industry. This strategy will be particularly advantageous for sites with tight spatial circumstances for the fabrication of curved molds, caused by close neighboring buildings, heritage reasons, or other constraints. Difficult non-standard plan geometries, which cannot be covered with classical prefabricated concrete shell elements, could also be addressed with this method. As shown in Figure 9, such a non-standard plan can be covered with a shed-like structure using this method, based on a planar mold table. This will reduce material as well as manpower, and therefore cost.

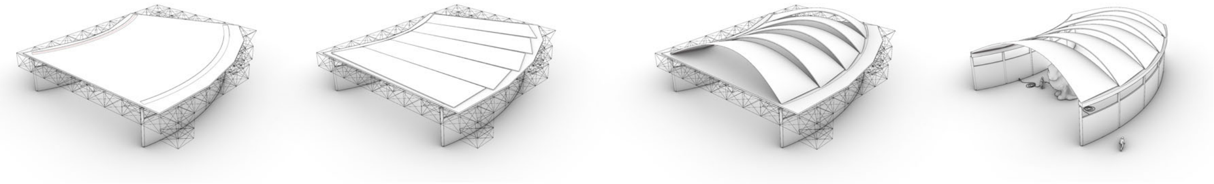


Figure 9: The entire process applied for a roof with a non-standard floor plan.

Until these ideas can be applied, many open questions must be answered. The potential geometric constraints for the design process must be clarified, and design tools further developed. Especially the tuning of the reinforcement fibers could allow for a design freedom that can potentially be used to approximate a wide variety of freeform surfaces. Controlled pre-cracking or a process that allows for a more detailed prediction of the cracks might lead to a more sophisticated erecting strategy that will also respect the targeted structural behavior. The question of the finishing or further processing in the bent state is also key to successful implementation in the AEC industry. From preparation in a flat state and finishing in the final bent state to a process where the entire roof structure, including insulation or watertight layers of sheet material, is prefabricated in a flat state and bent into its final finished form, a wide range of perspectives and ideas are the topic of ongoing investigation.

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