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Model analysis as a method for planning resource-efficient reinforced concrete shells using the example of Ulrich Müther

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Abstract
The construction industry is currently facing problems such as supply bottlenecks, the retention of grey energy, and a demand for more sustainable materials. Some of these challenges have already been addressed in the past. Shell construction has proved to be a highly efficient and economical construction method but, especially in the initial phase of their development from the 1930s onwards, there was a lack of theoretical knowledge for designing these sophisticated structures. One approach to overcoming this problem was the use of model analyses. To use model analysis, it was essential to produce accurate models from materials that allowed the transfer of the measured results to the real structure. Production of the models was a highly complex process, especially in times of resource scarcity and strict political control such as during the post-war period in the German Democratic Republic (GDR). This contribution examines the example of the well-known shell builder Ulrich Müther (1934-2007) and how he succeeded in realizing cost-efficient and aesthetic shell constructions from the 1960s onwards. The project for a sports and congress hall in Rostock, for which a model shell made of glass-fiber-reinforced plastic was tested, will be analyzed as an example. During the static optimization of the design, the shell had to be modified and adapted for further tests. To gain further insights into the history of the physical model a digital twin of the model shell was created and evaluated.

Keywords: Measurement models, model analysis, reinforced concrete shells, resource-efficient planning, digital twin

1. Introduction: The shell builder Ulrich Müther

Ulrich Müther was the son of an architect and constructor. Before he began his studies at the engineering school Müther completed an apprenticeship as a carpenter in Neustrelitz in the former German Democratic Republic (GDR). At the age of 20, he completed his training in structural engineering and began working in the design office for industrial construction at the Ministry of Construction in East Berlin. At the same time, he started studying civil engineering at the Technical University of Dresden, where he was already particularly interested in concrete shell structures. In his final thesis, he planned a double-curved hypar shell construction made of shotcrete (*Spritzbeton*). While still a student, he took over the technical responsibility of his parents' company in Binz and began early on to realize ambitious and material-saving shell constructions made of reinforced concrete, which caused a sensation both in the German Democratic Republic (GDR) and internationally [1].

2. Müther's professional network

The main reason why Ulrich Müther was able to drive forward developments in the GDR with his iconic shell buildings was his good networking in the construction industry, even though his construction company was converted into a national production cooperative (*Produktionsgenossenschaft, PGH*) in 1960. He benefited from contacts with concrete construction companies and engineering offices in the Federal Republic of Germany (FRG), which he had made for example during study visits. Müther also sought contact with other shell construction specialists and took part in exhibitions and international congresses. At the 1966 building exhibition in Budapest, for example, he met Jörg Schlaich (1934-2021), Stefan Polónyi (1930-2021), and Heinz Isler (1926-2009), among others. In the same year, he also took part in the meeting of the IASS in Leningrad [1].

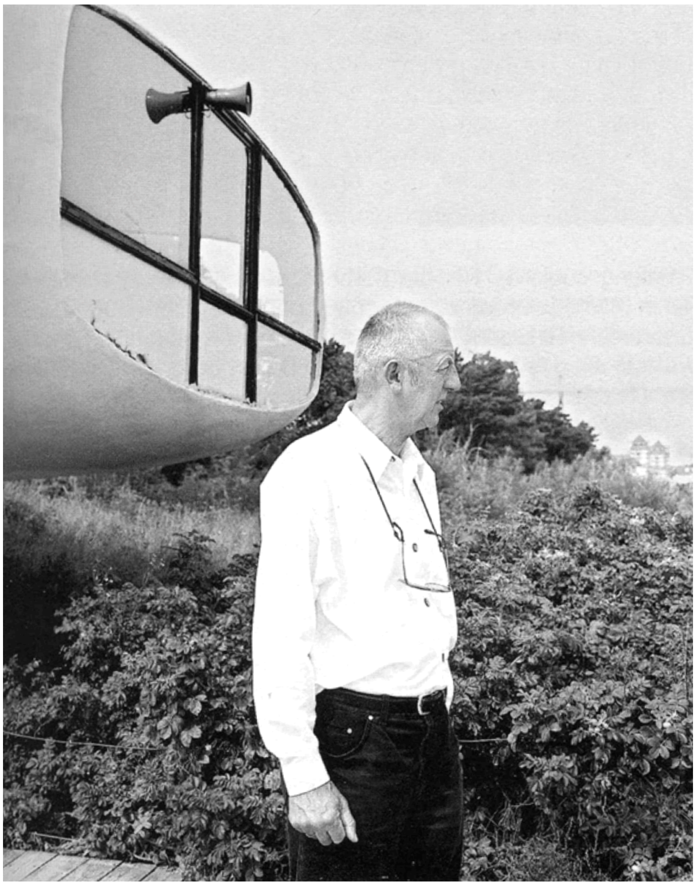

Figure 1: Ulrich Müther next to the rescue station Binz, built in 1968, photo from 1999 [© Wilfried Dechau]

3. The success of shell construction in the GDR

As his company was based in Binz on the island of Rügen, most of Müther's buildings are located on the island or around Rostock, although he also realized projects in and beyond Europe, such as the Spacemaster planetarium in Tripoli (Libya). His shell buildings were realized from the 1960s onwards and were referred to as special buildings (*Sonderbauten*) in the GDR to distinguish them from the standardized prefabricated *Plattenbau* buildings. He mainly built restaurants, pavilions, sports halls, and church buildings, which were used as eye-catching large-scale sculptures in the serial grid of apartment blocks.

The success of Müther's shell buildings can be attributed partly to the scarcity of materials in the GDR. The design principle of material-saving shell buildings made of reinforced concrete coincided with the ideas of rationalization in the construction industry. His shell buildings were therefore also a way for the GDR to distinguish itself from the West and were actively promoted. Another reason why shell construction lasted a long time in the GDR compared to the international scene is that the ratio between labor costs and material costs was significantly different than in Western countries. Labor was cheap in the GDR at the time and concrete was available in sufficient quantities [1].

Figure 2: The *Ahornblatt* restaurant in Berlin in the middle of high-rise buildings, built between 1969-1973, demolished 2000, photo from 2000 [© Axel Mauruszat]

4. Shell buildings as material- and cost-efficient structures

For Müther's shell buildings to be realized despite the rationalization of the construction industry and the scarcity of materials in the GDR, careful planning was required. For this, Müther relied on the help of models and model tests to optimize his buildings cost-efficiently and achieve a minimum use of materials. However, the construction of models was often complicated, as suitable materials were not available in the GDR, so he had to work with the available materials. For prestigious buildings, Müther in some cases benefited from state support through engineers from the German Building Academy Berlin (*Deutsche Bauakademie Berlin*), who carried out model tests and analyses for his construction company. This demonstrates that the need for model tests was also recognized and specifically promoted at a political level in the GDR [2].

5. The project of the sports and congress hall in Rostock-Südstadt

One example in which Müther, together with the German Building Academy in East Berlin, used tests on a physical model to optimize the design and undertake static calculations is the project for an unrealized shell roof for a sports and congress hall in Rostock-Südstadt. At the end of the 1960s, planning began for a multifunctional hall in Rostock, which was to cover an area of 5,000 square meters and a span of over 100 meters with a conventional steel hall construction and a concrete shell on top. The roof shell was planned as a hyperbolic paraboloid with the geometric shape of a kite in the plan and a thickness of only 10 centimeters [3].

Because of the significant size of the proposed reinforced concrete shell and the limited experience with projects of such dimension, it was necessary to conduct model tests for comprehending and calculating the intricate load-bearing behavior. That is why in 1970 a 1:25 scale model using glass-fiber reinforced plastic was built. While previous experiences with similar models had been positive, the predominant reason for selecting glass-fiber-reinforced plastic was the unavailability of other suitable materials, like synthetic resin compounds, within the GDR at that time.

For manufacturing reasons, the shell could not be thinner than 3 millimeters, necessitating a scale of 1:25. Consequently, the model shell was crafted to dimensions of 4.00 x 3.70 meters with a thickness of 4 millimeters. The shell surface was produced by alternating layers of plastic resin and glass fiber fleeces on a negative mold. The model testing was conducted collaboratively with engineers from the German Building Academy in Berlin. Various load scenarios were tested on the shell, with deformations and stresses meticulously measured: The shell was subjected to load through small wooden plates encased in rubber and laid on its surface. Point loads, primarily applied to the edge beams, were simulated using bricks in a wooden cage suspended on steel hangers, manipulable via a hydraulic platform. Deformation measurements were taken using dial gauges, while stress measurements were facilitated by strain gauges, initially intended for automatic registration but ultimately documented manually due to equipment failure.

The results revealed that the planned shell geometry, particularly in areas with flat surfaces, detrimentally impacted the overall stability of the structure. Consequently, modifications were made to the design, favoring larger curvatures in these areas. No new model was built for this optimized design, but the existing model underwent adjustments, followed by a second testing phase, which yielded successful results, indicating the feasibility of constructing such a shell at the planned thickness [4]. Despite the promising outcomes, the implementation of the shell roof did not materialize. The reasons remain undisclosed, although speculations point towards factors such as cost constraints, political considerations, or apprehensions regarding the span of the shell.

6. Digital twins of the two shell models

The project was not significantly larger than other shells planned by Müther, but the unsupported span of the concrete shell was to be about five times larger than in other projects, which is why intensive tests were planned. Three load cases were to be simulated on the test model to obtain data on its load-bearing behavior:

- Dead load + traffic load + wind/snow load (full load)
- Dead load + partial load from traffic loads + wind/snow load
- Horizontal wind load

After the first tests with the full load case, it became apparent that the deformation of the shell was too large, so the other tests were not even carried out. It was concluded that the shell had insufficient surface curvature in the upper area, which was then changed in the model.

In order to understand the changes, the design underwent during the testing, the original shape and the changed shell design are to be analyzed and compared. To do so, the first shell geometry was modeled using documents from the Müther archive. As the original shape was a mathematical ruled surface, this was possible using a ground plan and a section. There are two final reports available for the project, whereby the second report describes the adaptation of the geometry, which was used to create a digital model of the changed design. For this purpose, the upper third (marked in red in Figure 3) of the physical model was cut off along the edge beams and removed. The new transverse edge was increased by 1.5 meters in stitch height in the structure, corresponding to 6 centimeters in the model. Therefore, the shape of the shell could no longer be described as a hyperbolic paraboloid [4].

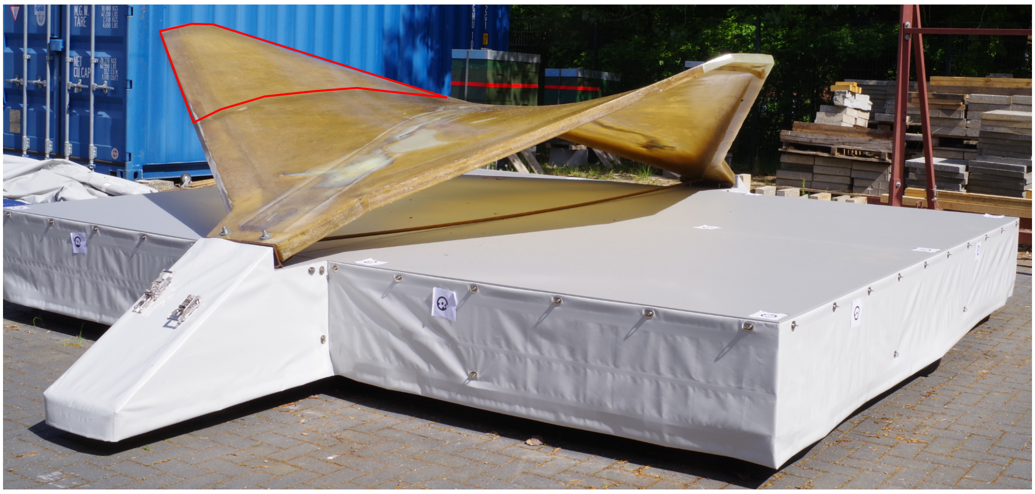

Figure 3: Test shell marked with the modified tip, photo from 2023 [© Baris Wenzel]

7. Comparison of the two shells

As described in Müther's second report, the curvature of the shell design had to be increased in the upper third to be able to absorb more bending moment [4]. If the shell was a membrane structure, a purely mathematical surface would be more efficient since they have a curvature of +1 in one direction and a curvature of -1 in the other direction, which means that the forces neutralize each other. However, the membrane theory cannot be applied to concrete shells with a certain thickness, and very flat areas of a hyperbolic paraboloid become very susceptible to bending moments. Additionally, the edge beam plays a major role in the areas of the bearings [7]. As there is not enough information available about the edge beam of the original shell, it was not possible to carry out a detailed comparison of the two shells in terms of load-bearing behavior. At this point, reference should be made to the tolerances that are common in manual model construction, which makes it difficult to give an exact statement in retrospect. The focus of the comparison lies therefore on the geometric shape of the shell designs.

To compare the two surfaces, their curvature was examined. The aim here was not to assess the Gaussian curvature, as one might intuitively assume. The Gaussian curvature is calculated by multiplying the two principal curvatures at a certain point on the surface:

$$k = k_1 \cdot k_2 \tag{1}$$

i.e. if the curvature in one of the two main curvature directions is zero, the product of the equation is zero. If the Gaussian curvature were compared, one would even notice a deterioration of the second surface compared to the first. However, for the load-bearing behavior of the shell, this is not important, rather the curvature must exist in one direction. The individual elements of the equation therefore had to be compared. No native component is provided for this in the Grasshopper3D program environment, but the calculation method is publicly available in the Rhinoceros3D API [8]. Here, the *Kappa (Int32 direction)* method can be called in the *SurfaceCurvature* class. The method requires *uv-points* as input parameters. To compare the two surfaces, 1631 measurement points were evaluated. In the original shell design, the $\sum_{Kappa1Old}$= 0.013603 and $\sum_{Kappa2Old}$= -0.006985 were measured, which is why it is assigned to a hyperbolic surface according to Table 1.

Table 1: Surface shape classes

	K_1<0	K_1=0	K_1>0
K_2<0	Concave Ellipsoid	Concave Cylinder	Hyperboloid Surface
K_2=0	Concave Cylinder	Plane	Convex Cylinder
K_2>0	Hyperboloid Surface	Convex Cylinder	Convex Ellipsoid

The new area could be created with the values $\sum_{Kappa1New}$= -0.036501 and $\sum_{Kappa2New}$= 0. 000505 and can also be assigned to the hyperbolic surfaces. The sign is random and depends on the assignment of the uv-directions. These are influenced by the creation of the surface, for example by the direction of the curves from which they were created. They can be inverted with a command in the Rhinoceros3D program environment. What is visible, is that the increase in curvature in the $Kappa_1$ direction is approx. 2.65 times higher, while in the $Kappa_2$ direction, it is reduced by approx. 13.81 times. Depending on the tolerance, the area in Table 1 can also be attributed to the convex cylinders. The resistance to the bending moment should have been significantly increased by the new curvature.

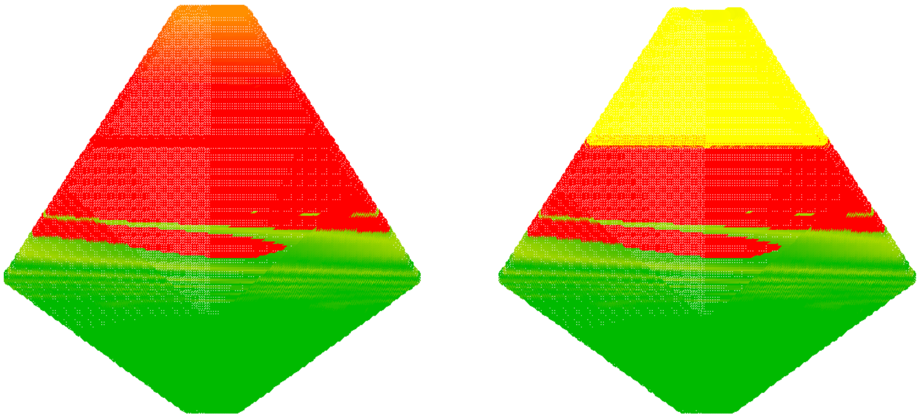

Figure 4: Quantitative comparison of the two shells (left = shell 1, right = shell 2 with new tip) created with the computer from red=flat, to green=curved [© Baris Wenzel]

8. Conclusions

The paper highlights Ulrich Müther's work and gives a brief insight into the use of physical measurement models. Without the use of measurement models, it was not possible to assess the structural behavior of such complex building projects.

Due to the digital modeling and comparison of the first shell and adjusting the geometry, it was finally possible to confirm the load-bearing capacity of the structure. Because of a lack of documentation, a detailed mathematical comparison could not be carried out, but a geometrical comparison of the digital models confirmed the behavior documented in the final reports.

Acknowledgments

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