THE PHYSICAL MODEL FOR THE IL PAVILION AND THE USAGE OF ITS DIGITAL TWIN

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The so-called IL pavilion in Stuttgart, constructed by Frei Otto and the Institute for Lightweight Structures (IL) served itself as an experimental building for testing the execution of a new type of cable net construction. At this 1:1 mock-up various manufacturing techniques and measuring methods were tested, additionally to model tests on physical models. These models were necessary, because at that time no adequate calculation methods were available to design the complex geometries of such wide-span cable net constructions. In this paper, the authors clarify the way the model was produced, the development of the measurement methods and the impact of model testing for the execution of the innovative construction of the German pavilion for the World's Fair in Montréal in 1967. The physical model, which is one of the few surviving measurement models from this period, was digitally rebuilt with state of the arts methods in the context of the DFG research project “last witnesses”. The data extracted from the physical model was compared with a model generated from the original cut stencils. Overall, the numbers match fairly well, nevertheless there are some outliers due to the changed numbers of elements, which have a deviation of more than 40%. The data extracted from the digital twin will further be used to evaluate changed boundary conditions, increased snow loads or wind effects for the building itself and to record the actual state of the model for future preservation measures.

Keywords: German pavilion Montréal, Cable net structure, Experimental building, Measurement model, Last witnesses, Photogrammetric method, Parametric modelling.

1 THE GERMAN PAVILION FOR MONTRÉAL 1967

1.1 Competition and Design

For the 1967 World's Fair in Montréal, the German Federal Building Directorate announced an open two-stage architectural competition in 1964. Special requirements for the design were the short planning period, as well as the prefabrication of the construction in Germany to transport it overseas. After the first competition phase, the jury, chaired by the Karlsruhe architect Egon Eiermann – who designed the pavilion for the 1958 World's Fair in Brussels – invited five architects to submit further designs. Among these architects was Rolf Gutbrod, professor for design at the Technical University of Stuttgart, who secured Frei Otto's support as an expert in lightweight construction. Their design of an expressive open space tent construction, which covered the entire exhibition area, was convincing due to its lightweight materials and thus economical transport and was therefore awarded with the first prize. The asymmetrical cable net
construction should span an area of approx. 8,000 square meters. As the design at the time was the largest uniform-meshed cable net construction ever built there were justified doubts about the implementation of the design (Weber 2011).

1.2 The Planning Team

The realization in the short planning time could only be achieved by the cooperation of various offices, institutes and companies. The architectural design for the entire building was executed by Rolf Gutbrod's office, while the construction planning for the roof was carried out at the Institute for Lightweight Structures (IL) in Stuttgart under the direction of Frei Otto. At the IL, the engineer Eberhard Haug acted as a link to the engineering partner office Leonhardt + Andrä (L+A) with project engineer Harald Egger. Responsible for the cable net design at the IL was Larry Medlin and Berthold Burkhardt assisted the membrane cutting, in close contact with the executing tent construction company Stromeyer. For the measurement technology the cooperation with the company Staeger from Berlin was important, with them the IL team developed devices for measuring the tension in the steel wires (Burkhardt 2005).

2 THE EXPERIMENTAL BUILDING IN STUTTGART-VAIHINGEN

2.1 Necessity and Use of the IL Pavilion

To contradict doubts about the feasibility of the design and at the same time to test the assembly process it was decided to erect a test structure. In 1966, a small pavilion was erected on the university campus in Stuttgart-Vaihingen, which roughly corresponds to the cable net for the German pavilion around mast A (Leonhardt et al. 1968). This pavilion was later translocated about 2 kilometers on the campus and made permanently usable (Burkhardt 2005). So, the Institute for Lightweight Structures (IL) constructed its own institute building, known as IL pavilion. The pavilion still exists, today classified as cultural heritage. It houses the renamed Institute of Lightweight Structures and Conceptual Design (ILEK) (Figure 1).

![Figure 1. IL pavilion (today ILEK).](image1)

![Figure 2. State of the model of the IL pavilion today.](image2)

2.2 Measurement Models for the IL Pavilion

By carrying out the experimental construction, it was possible to study the problems of scaling from the physical model to the main design. The final shape was determined by tests on these physical models with the qualitative properties of the planned building. The dimensioning of the construction by static calculations was at that time only possible at great expense, so that the use of models was more efficient and economical (Leonhardt et al. 1968).
2.2.1 Model fabrication

A series of four 1:75 scale models were made for the experimental construction to elaborate the model fabrication. The authors refer in this paper to the last and most developed model of this series (Figure 2.). In the model every fourth cable was represented to limit the production effort and to be able to use the newly developed measurement devices. The cables were made of stainless, spring-steel wires with a diameter of 0.2 millimeters. Copper wires were soldered and crimped at the nods, so that the wires could not shift, but a change of the mesh angles was possible. The cable net was produced using cutting drawings, determined from the previous textile models. The boundary cables were made of stainless, spring-steel wires, with a diameter of 0.4 millimeters. To connect the net to the boundary cables, various mechanical methods were tested on the model. The anchorage points were represented by commercial turnbuckles so that the wire lengths and pretensioning could be modified. The steel mast had a simple bolt and nut combination as mast head. The model was built on a wooden frame, which had a hole in the middle for load tests (Burkhardt et al. 1967).

2.2.2 Testing methods and measuring devices

Load tests were carried out on the model to determine stresses under load, deflection and general displacements. For this purpose, small weights corresponding to the loads to be expected, such as snow loads, were suspended from the model with threads, which, standing on different platforms, could be lowered and raised in different combinations by simple air cushions. As vertical displacements of the nodes could only be determined in a very time-consuming manner a photographic method was developed. By taking photographs using the double exposure method without and under load, the deformations on the model could be recorded quantitatively (Burkhardt et al. 1967). To determine forces in the wires, dial gauges were developed in collaboration with the company Staeger. These brackets were suspended on three-point bearings in the mesh and the scale marks could be read-out before and after loading (Haug 1967). In addition to these tests, the geometry of the cable net, the suspended membrane as well as the glazing was determined via the physical model. The cables were measured on the model with compass and ruler and drawings of the net were generated as a basis for the construction (Burkhardt et al. 1967).

2.3 The Impact of the Model Tests to the Design of the Model for the German Pavilion

The model fabrication and the testing methods for the larger 1:75 model of the German pavilion was based on the experience gained on this prototype model for the IL pavilion. The production method was mostly similar, although there were some differences: For example, none of the connections between the net and boundary cables tested were used, it was decided to solder the connections. Furthermore, the anchoring points and the mast heads were modified. There were also innovations in the execution of the tests, for example a standard scale was added to the nods in the double-exposure procedure, to allow a quantitative measurement of the deflections (Burkhardt et al. 1967). The dial gauges have also been further developed to the later so-called Montréal gauges (Haug 1967). The models for the roofing of the sports facilities for the 1972 Olympic Games in Munich could only be built so precisely and processed with sophisticated measuring methods due to the experience gained in the process of the planning for the IL pavilion and the German pavilion (Burkhardt 2005).
2.5 Provenance and Preservation of the IL Pavilion Model

As already mentioned, the last surviving model of the IL pavilion is the most developed of a series of four wire models. Due to a lack of space at the IL, the model in question came into the private possession of Berthold Burkhardt, a former employee at the institute, who donated the slightly damaged model to the model collection of the Deutsches Architekturmuseum (DAM) in Frankfurt (Bühler and Weber 2021). None of the other and much larger models used for the planning of the German pavilion in Montréal have survived, so that the small model is the last witness preserved (Bühler and Weber 2021).

3 DIGITAL TWIN

3.1 Definition

A digital twin refers to a digital copy of a physical product/process/service (Figure 1). The digital counterpart to its physical brother helps to simulate and predict the present or future behavior of a physical object, which in turn allows to optimize the object and increase business efficiency (Nedashkovskiy et al. 2020). In Industry 4.0, the digital twin is one of the main concepts that should drive the digitization of industrial production. While the term is used more and more in the aerospace and automotive industries, there are still few known applications in the architecture and construction sector (Hitesh et al. 2020).

3.2 Reverse Engineering

For the creation of the digital 3D model, a basis was created based on photogrammetry data. As has been found in previous experiments, photogrammetry is best suited to record the intersection vertices (nods) of the thin wires of the model (Wenzel et al. 2021). In a following step, the points were connected to curves and surfaces. Interestingly, photogrammetry was also used to analyze the deformation of the cable net of the original model, which was used for the static calculations (Otto 1967).

3.2.1 Modelling the cable net

In a first step 19 target points were attached to the 45 x 45 centimeters cable net model. After the photographs have been taken with a digital single lens reflection camera (Pentax K1 with 31 millimeters lens), they are manually located with the photogrammetry software “Photomodeler” using the 19 target points and an overlap is calculated. To determine the cable net pattern all 175 intersection and 12 anchor points were extracted to connect them in a next step in Rhinoceros3d to the cable net. The tension rod at the anchors, since they are repeated elements, were modelled...
as a block and placed at the intended places using a plane to plane transformation. All relevant information was written in real time into a Sqlite database file in order to be able to use the data obtained in the best possible way.

3.3 Comparison with the Cut Pattern

3.3.1 Modelling the cable net from the original cutting pattern

Because there is data about the clipping mask and the grid of the wire mesh for the original model (Figure 4), the grid could be morphed and relaxed to the anchor points extracted from the photogrammetry using a particle-based live physic engine (Figure 5). As in the physical model, attention was paid to the different pretensioning for the boundary cables as well as for the inner cables, which is customary for cable net constructions. This allows to compare the manual method with which the model was built in 1967 with the digital formfinding.

Figure 4. Original grid and clipping mask. Figure 5. Original grid (red/blue) and morphed grid (green).

3.3.2 Differences between recorded and digital formfinding model

The most noticeable difference is that the boundary cables in the morphed version are much shorter. This is due to the fact that in the original model they were already cut in the length they reach in the state of pretension. In the digital formfinding the pretension usually is applied after morphing the grid which shortens the cables so that the overlap between original and digital model differs here significantly. Once the cables are morphed, you can see that some cables are very short in the boundary areas and if you look at this point on the original model, you notice that these were not installed here, even if they are in the drawing and the photo of the grid before it was mounted and tensioned on the model base.

Table 1. Comparison properties – Cutout cable net and morphed cable net.

<table>
<thead>
<tr>
<th></th>
<th>Original net</th>
<th>Morphed net</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number edge ropes</td>
<td>9</td>
<td>9</td>
<td>0 %</td>
</tr>
<tr>
<td>Edge ropes (length)</td>
<td>1481 mm</td>
<td>1478 mm</td>
<td>- 0.2 %</td>
</tr>
<tr>
<td>Number warp ropes</td>
<td>14</td>
<td>17</td>
<td>+21.43 %</td>
</tr>
<tr>
<td>Warp ropes (length)</td>
<td>2042 mm</td>
<td>2093 mm</td>
<td>+2.49 %</td>
</tr>
<tr>
<td>Number weft ropes</td>
<td>7</td>
<td>10</td>
<td>+42.86 %</td>
</tr>
<tr>
<td>Number weft (length)</td>
<td>1860 mm</td>
<td>1974 mm</td>
<td>+6.13 %</td>
</tr>
<tr>
<td>Intersection vertices</td>
<td>68</td>
<td>75</td>
<td>+10.29 %</td>
</tr>
</tbody>
</table>
4 CONCLUSION AND FUTURE USAGE OF THE DIGITAL TWIN

The outliers in the deviation analysis, which are the weft ropes (42.86%) and the warp ropes (21.43 %) are due to the changed number of elements. The missing ropes are all very short edges close to the boundary ropes, which could be the reason they were considered as not necessary and were removed once the mesh was hung in place. After getting rid of the items which have a different element count, the deviation is between 0.2% and 6.13% which seems to be fairly low.

Since the model could be successfully replicated and the original cutting patterns could be mapped onto the existing structure, various scenarios for the future are now conceivable. One could unroll the relaxed and morphed geometry and compare it with the original clipping mask. This is certainly very interesting, especially at the points on the mast where there is no anticlastic surface curvature. Making the data accessible to an interested public in a digital model and a digital database, the gain in knowledge can be maximized. In particular, the model will be helpful for the restoration professionals: They can now use the model for an exact mapping of the damages and thus provide a basis for the restoration and preservation of this important last witness.

So, the possibilities for future usage are wide-ranging: besides structural calculations for mutable factors like caused by climate change for the existing building of the IL pavilion, it can be used as teaching material or be explored in exhibitions with virtual reality devices.

References


