THE LAST WITNESSES – PHYSICAL MODELS IN ARCHITECTURE AND STRUCTURAL DESIGN, TAKING THE TECHNICHAL UNIVERSITY IN STUTTGART AS AN EXAMPLE

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Abstract

Structural model analysis marked a phase in the history of structural engineering that has run its course. For a few decades (approx. the 1930s to the 1970s), the most cost-effective method of designing and testing complex load-bearing structures was by using physical models. The models made for this purpose are important witnesses of the history of structural engineering. Taking the institutes and facilities at Stuttgart Technical University as an example, this essay documents the tradition of these objects. The models are analyzed with regard to their genesis and materiality, and their use in tests. Their present condition, their preservation in a collection, as well as the danger to and loss of them represents a further aspect.

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INTRODUCTION

As objects models have attracted greater attention over the past few years. This trend may well be related to a vague sense of loss, given the increasing virtualization in the digital design process, which would appear to be making physical models superfluous. Even if the jury is out on this hypothesis, it is nonetheless noticeable that architecture models in particular have become the focus of scholarly research (Bühler 2013, Cachola Schmal/Elser 2012, Conference "La maquette. Un outil au service du projet architectural." Paris 20-22 May 2011, Conference "Modelle und Architektur/Les Maquettes d'architecture/Models and Architecture." TU München). The various functions models served in architectural design processes have long since been the subject of research (Janke 1962). The systematic collecting and exhibiting of architects' drawing and models, which began in the 1950s in the United States, drew attention to these objects (Voss 2014). Inspired by this trend in the US, in the late 1970s the art historian Heinrich Klotz began collecting, which in 1984 culminated in the founding of the Deutsches Architekturmuseum (DAM), the German Architecture Museum in Frankfurt/Main. The following decades witnessed the emergence in Germany of a whole host of archives specializing in the collection of models and drawings. In their mandate, some of these archives also include the collection and preservation of engineers' estates. Mostly, however, a large part of the collection comprises architects' estates. As such it is not surprising that the number of models in these collections that bear witness to the creative process of engineers is very small. In collections specializing in technology as well (such as the one in the Deutsches Museum in Munich) there are only a few models from engineering firms or university institutes of engineering. University collections, on the other hand, tend to specialize in flatware and for reasons of space alone hardly collect any 3D objects at all.

The following paper is a review of physical models – taking as examples those models handed down to Stuttgart Technical University – and aims to raise awareness of the necessity of researching these relicts of structural model analysis.

STRUCTURAL MODEL ANALYSIS – AN HISTORICAL ENGINEERING PHASE

Bill Addis is one of few scholars conducting research into structural engineering that has for years now been addressing physical models. He states in his 2013 essay that "the contribution of model testing, both to the design of many extraordinary and innovative structures and, more generally, to progress in structural engineering has (…) not been duly recognised and has been addressed by very few historians of structural engineering." (Addis 2013, p. 12). In his essay he provides an extensive overview of the emergence of structural model analysis and the use of models in the construction process: Initially used for practical purposes in the 17th century, by the 19th century models were serving to determine the distribution of forces in a construction. From these early beginnings the spectacular hanging models by Antoni Gaudi (1852-1926) are particularly impressive. Significantly, as of 1982, this model, which is lost today, was reconstructed at the *Institut für Leichte Flächentragwerke* (Institute for Lightweight Structures, IL) in Stuttgart together with the *Gaudi Group Delft* (Tomlow 1989).

Note, however, that these models served form-finding purposes and for this reason had to be designated more precisely as "form-finding models" (Weber 2012). They did not serve to determine forces numerically. Only when, using a scale effect, the readings taken on a model are used to specify the dimensions of the genuine structure can there be any talk of structural model analysis in the narrow sense. This form of structural design of load-bearing structures only became established in the 20th century, the advances in the theory of similitude being an important prerequisite for this. The scientific understanding of scale effects enabled the real loads to be deduced from the data gained from the model. Measurement technology and material science, which provided the conditions needed to use physical models (Müller 1971, pp. 1-2), deserve mention as a further factor. We have George E. Beggs (1883-1939) to thank for the theoretical foundations of structural model analysis and their widespread publication. Very soon his essays were also being read in Europe. As long ago as the early 1930s test labs were set up, for the most part associated with technical universities. The *Forschungs- und Materialprüfungsanstalt* (Research and Materials Testing Institute, FMPA) in Stuttgart is one such institution. As of the 1940s one can talk of a peak stage in structural model analysis. Because at the time there were not yet any computer-based calculation methods, the design of highly redundant structures was only possible using numerical approximation methods (Müller 1978). This is very laborious, and therefore expensive. As such, using physical models saved money, as the title alone of the report that Beggs published on Stevenson Creek Dam substantiates (Addis 2013, p. 17). After World War II until the 1970s, structural model analysis was used primarily in the design of concrete shell and lightweight load-bearing structures. It was not until ever faster and more efficient computers and the first finite element programs, which were launched in Germany in 1972, made experiments on models too expensive (Addis 2013, p. 25), and since then digital models and design methods have replaced measuring procedures on physical models.

PHYSICAL MODELS OF STUTTGART TECHNICAL UNIVERSITY

The introduction of structural model analysis at Stuttgart Technical University can be traced back to the engineer Karl Schaechterle, who as of 1934 carried out structural model analysis tests for arched bridges (Leonhardt 1984, p. 78). In the years that followed, structural model analysis conducted at the Institute for Material Testing in Construction at *Forschungs- und Materialprüfungsanstalt Stuttgart* (FMPA) underwent significant development on account of Schaechterle's colleague, the structural engineer Fritz Leonhardt (Weber 2009, Weber 2011). The FMPA's estate, however, does not hold any actual physical models but only photos of them, along with planning documents and test reports (UASt/33/1).

Due to the great continuity in terms of staff, after the World War II structural innovations, which in particular with regard to the prestige construction projects under the Nazis had received generous funding, came into their own. Structural model analysis at the FMPA in Stuttgart, for example, carried on. Fritz Leonhardt continued to have load-bearing structures such as the single cable suspension bridge, which he had proposed across the River Rhine near Emmerich in 1961, tested on physical models at the FMPA in Stuttgart. Unfortunately there are only photos of these prototypes today.

A preserved physical model of the Institute for Structural Model Analysis at Stuttgart Technical University

When in 1957 Fritz Leonhardt was appointed Chair of the *Institut für Massivbau* (Institute for Solid Construction) at Stuttgart Technical University, he succeeded in establishing the *Institut für Spannungsoptik und Modellmessungen* (Institute for Photo-elasticity and Model Measurements) at the Faculty of Construction, the successor facility to the Photo-Elasticity Laboratory of the Chair of Solid Construction. In 1960 the physicist and mathematician Robert Müller was appointed its head. Renamed "*Institut für Modellstatik"* (Institute for Structural Model Analysis), the institution was the only independent university institute of its kind in Germany (Müller 1969, p. 102). When Robert Müller retired in 1993, the *Institut für Modellstatik* was disbanded and the Chair renamed *Informationsverarbeitung im konstruktiven Ingenieurbau* (Information Processing in Structural Engineering (Senatsprotokoll Universität Stuttgart 03.11.1993, p. 18).

In the more than 30 years it existed, the institute has played an important role in the use of physical models for measuring load-bearing structures. One particular model from this era is especially remarkable, and has been preserved to this day: the shell roof over the "Alster-Schwimmhalle" swimming baths in Hamburg. The project was based on a 1956 design by the Hamburg architects Niessen & Störmer and is striking on account of its expressively projecting pre-stressed concrete shell, which was only completed in 1973. The engineering firm Leonhardt + Andrä was responsible for the structural design of the outward curving construction comprising two hyperbolic paraboloids, while Jörg Schlaich was the engineer responsible within the company. Because calculation of the distribution of stresses in the overhanging pre-stressed concrete shells using the 1960s methods of calculation, the engineers determined the distribution of stresses required for design purposes in an experiment using a model. Initial plans envisaged the physical model in micro concrete. With this particular material, the surfaces of the shells would have needed to be at least 1 cm thick on account of the pre-stressing reinforcement, which meant that the micro concrete model would have been too big (Kayser/Müller 1970, p. 245). Not least of all due to the complexity of the formwork and the far higher costs involved, micro concrete was therefore rejected. Instead, the engineers at the *Institut für Modellstatik* built an elastic model made of plastic. It comprised easy-to-make individual parts, which were then stuck together using suitable adhesives to form a single piece. All the parts had to be geometrically similar and on the same scale. In his publications Müller propagates this type of plastic model, whose elasticity quotient must correspond to the genuine structure (Müller 1982, p. 265-266). For manufacturing reasons the thickness of the shell for the model could not be less than three millimeters. Shells eight centimeters thick were envisaged for the structure itself. This produced a scale of 1:26.67. As such the maximum dimension of the model was four meters. So as to achieve sufficient height for the weights and load equipment, the model was placed on three concrete pedestals.

Figure 1-3: *Institut für Modellstatik* Stuttgart, "Alster-Schwimmhalle" swimming baths Hamburg 1956-1972, physical model, under load, the preserved model 2014 (saai Karlsruhe/photo Johanna Moosmann 2014)

The physical model was used to test the load by means of dead loads, snow and loads resulting from the compliance of the ground, as well as individual forces caused by wind load at the highest points. Strain, bending moments, and deflection of the boundary supports and the shells were all calculated using the model. In the model test the dead load and snow load were applied by means of several small individual loads. To this end, holes two millimeters in diameter for hanging the weights were drilled in the shell and boundary supports. The individual weights were secured by means of rubber rings, such that application and easing of the load was not sudden but continual. A pneumatic lifting platform was used to lift and lower the lead weights. In order to simulate load scenarios caused by the supports shifting, and by deformation, the supports were mounted on balls and moved by weights. The strains were measured using strain gauges and an automatic measuring system. A total of 317 rosettes and 26 foil strain gauges were attached. Only the automatic measuring system, which evaluated the punched tape readings made by an electronic calculator, enabled an economical study of models with several measuring points.

As far as we know, this particular model is the last plastic model to have come from the former Institute for Structural Model Analysis in Stuttgart. It was assembled, without the measuring device and the horizontal cross bracing, in the foyer of the *Fakultät für Bauingenieurwesen und Umweltwissenschaften* (Faculty of Structural Engineering and Environmental Sciences) at Stuttgart University. In 2009 its intentional demolition could be prevented. Since then the defects have increased: The splices have become brittle, and the plastic shells broken through mechanical impact. To date its size has prevented it from becoming part of a collection.

The preserved physical models from the Institute for Lightweight Structures in Stuttgart

Generally speaking, architects are more concerned than engineers about safeguarding their personal life's work. As such, in some cases collection objects tracing developments in engineering find their way into archives via architects' estates, in particular when the protagonists tread a fine line between architecture and engineering. Having trained as an architect, Frei Otto was a major influence in the second half of the 20th century on the development of load-bearing structures, especially in the filed of lightweight construction, and served as a prominent example. In 1964 he was appointed head of the *Institut für Leichte Flächentragwerke* (Institute for Lightweight Structures, IL), which had been set up especially for him at Stuttgart Technical University (Bubner 2005). The following decades of his appointment in Stuttgart saw a wealth of models being built, most of which the *Südwestdeutsches Archiv für Architektur und Ingenieurbau/saai Karlsruhe* (Southwest German Architecture and Engineering Archive) acquired in 2011. Though it embraces in excess of 400 models there are, despite an impressive number of form-finding models, no physical models.

Publications by IL, however, attest to the Institute's extensive commitment to structural model analysis and to collaboration in the Technical University itself with the *Institut für Modellstatik* (Institute for Structural Model Analysis) and the former *Institut für Anwendungen der Geodäsie im Bauwesen* (Institute of Applications of Geodesy to Engineering, IAGB) under the supervision of Klaus Linkwitz. During the research into Frei Otto's models, the few physical models handed down were recorded (Weber 2011, Weber 2012).

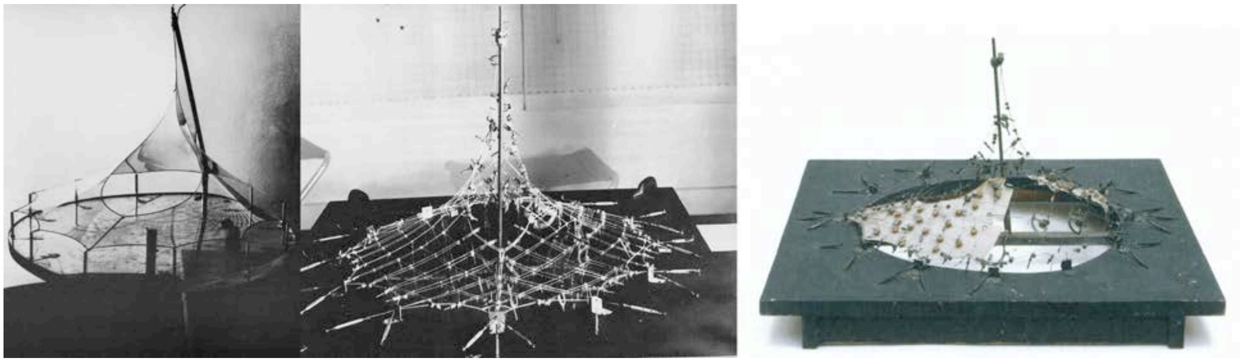

Figure 4-6: *Institut für Leichte Flächentragwerke* Stuttgart, IL-Pavillon 1966-1967, form-finding soap-film model, physical model 1965 double-exposure shot, the preserved model 2012 (IL 18, p. 477/saai Karlsruhe/DAM Frankfurt)

The small physical model of the IL pavilion bears witness to the first experiments with tensile structures and their design. Today this pavilion, which was erected in Stuttgart as a life-size prototype of the German Pavilion at Expo 67 in Montréal, still houses the successor institute to the IL (Weber 2011). In the course of the design process the IL employees had built the geometrically similar model on a scale of 1:75 using stainless spring wire. By means of double-exposure shots the model was used to calculate the deformation of the tensile structure under strain. The Montréal dial gauges developed especially for the project, which came with the model, served to measure the tension in the cables and thus to determine the level of pre-stress. Because the large physical model, which likewise modeled the entire Montréal pavilion on a scale of 1:75, no longer exists, this small physical model is the only witness of the unique experiments using models in the context of the design of the German Pavilion in Montréal. DAM Frankfurt succeeded in acquiring the model, which formed part of Bertold Burkhardt's collection at Brunswick Technical University, for its 2012 exhibition "Architectural Model. Tool, Fetish, Small Utopia" and it now complements the Museum's collection of architecture and form-finding models by Frei Otto (Weber 2012, p. 45).

The choice of Frei Otto's tent roofs, which were based on a design by Günter Benisch, for the 1972 Olympic Games, saw experiments into tensile structures using structural model analysis at Stuttgart Technical University being stepped up. Based on the geometric specifications of the numerous form-finding models, physical models were built on a scale of 1:125 (IL 8 1975, p. 287). The scale resulted from the size of the measuring table at IL, the foundations of which are still visible today on the inside of the IL pavilion. Measuring 1.9 x 4 meters, the model of the stadium was the largest. Using the more advanced dial gauges it was possible to measure the tension in the wires. By means of photogrammetry the IAGB determined the pattern of the roof skin and the coordinates needed for the subsequent digital calculation (IL 8 1975, p. 289). Addis talks in this case of "hybrid analysis" (Addis 2012, p. 23). So as not to strain the highly sensitive models too often, multi-media tests were conducted, in which the Institute for Structural Model Analysis was also involved, which by means of strain gauges calculated the force changes in the cable edges. Unfortunately the fragility of the models (alongside the large model of the stadium there was one of the swimming baths and several detailed models) caused them to be lost to us. Though they were handed over to Deutsches Museum, we must nowadays consider them lost. Though there are richly illustrated research reports (IL 8 1975, p. 274-301) and the former IL's slide collection ought to be a source of further images, the objects themselves, and as such a great deal of information about the production and use of the models, are now lost.

Only a model of a section, of the low point of the swimming baths on a scale of 1:25, is still exhibited in the former IL pavilion. It is positioned on the original marble slab, which serves as a deformation-free girder. Despite having a cover, the model is slightly damaged and should be urgently restored and, if possible, put in a collection.

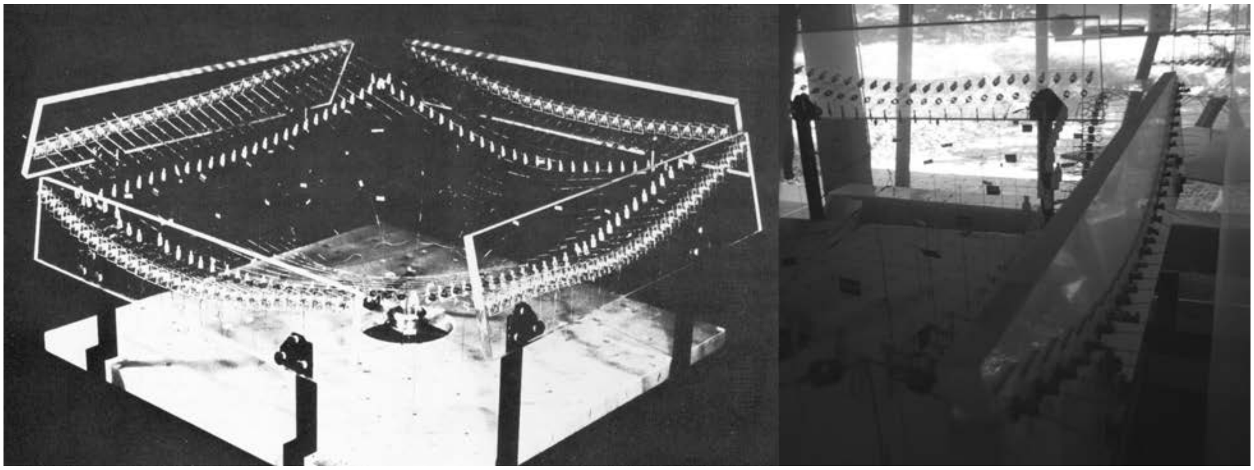

Figure 7-8: *Institut für Leichte Flächentragwerke* Stuttgart, detail physical model of the low-point of the swimming arena for the Olympic Games 1972 Munich, the published model and the preserved model 2014 (IL 8, p. 297/photo Daniel Klausner 2014)

FURTHER RESEARCH

As mentioned, today only a few physical models bear witness to the extensive innovative experiments using structural analysis that were conducted at Stuttgart Technical University. No doubt a similar picture can be painted at other technical universities. There have been even more losses at companies' own test laboratories: As long ago as the 1920s under Franz Dischinger (1887-1953) the firm *Dyckerhoff & Widmann*, together with Hubert Rüsch (1904-1979), used to-scale models to test wide-span shell roofs such as that over the wholesale fruit and vegetable market in Leipzig dating from 1927. According to current research, none of the to-scale models used in these experiments still exist. In Spain Eduardo Torroja (1899-1961), who collaborated with the Instituto de la Construcción (ICON), is worthy of mention. Whether 3D witnesses of these experiments still exist is open to question. Only photos have survived of the spectacular models Pier Luigi Nervi (1891-1979) made together with the I.S.M.E.S. in Bergamo to test his constructions (Chiorino 2010, Neri 2010). Hopefully with the estate of Heinz Isler, objects used for structural model analysis will have made it to the archive of the *Institut für Geschichte und Theorie der Architektur* (Institute for the History and Theory of Architecture) at ETH in Zurich. It can also be assumed that there are further models and remains of measuring systems to be found in the collections of the individual institutes. This essay aims to be seen as a call to document and preserve these objects. Collections and museums should focus increasingly on engineers' estates. The task for the history of building could well be to offer support to the employees of these archives with regard to their specialist knowledge and thus play a role in the preservation of the witnesses of the history of structural engineering.

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