

Frei Otto's Experimental Approach – From Physical Models to Lightweight Structures

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Abstract

Frei Otto's work with lightweight structures fundamentally relied on physical models, spanning from form-finding to build realization. From the 1970s, the Institute for Lightweight Structures (IL) in Stuttgart developed tools to translate experiments into buildable designs. As Otto's experiments evolved, from fabrics to custom apparatus such as the soap film machine, custom-built documentation and measurement tools were crucial, as commercial options were lacking. Institutes like Engineering Geodesy under Klaus Linkwitz and the Institute for Model Statics contributed, employing techniques ranging from shadow projection to stereo-photogrammetry and motor-driven systems. Structural analysis at the IL utilized gauges, optical photography, and sensors to measure model deformations. The integration of experimentation and quantitative measurement led to a unique methodology, refined through international collaborations with the Istituto Sperimentale Modelli e Strutture (ISMES) and professional exchanges (IASS). Otto's systematic approach bridged intuitive form-finding with rigorous analysis. This methodology profoundly influenced subsequent generations.

Keywords: physical models, form finding, tool development, Frei Otto, experiments, Stuttgart.

1 Introduction

Frei Otto (1925–2015) revolutionised 20th-century architecture with his pioneering work in lightweight construction. Frei Otto's approach was fundamentally shaped by his observations of natural structures. At the heart of this was the principle of self-organisation: forms are not created through calculation or planning, but through the interaction of forces, boundary conditions and material properties. Nature demonstrates the principle of form follows force: the forces work in a state of equilibrium. Beyond the classic examples such as soap bubbles and hanging chains, Otto and his interdisciplinary team of mathematicians, biologists, historians and engineers systematically studied biological lightweight structures, including radiolarians, the bird bones, diatoms, pollen, spider webs, bamboo, grasses, sea urchin shells, mussel shells, leaf veins, and insect wings at the Institute for Lightweight Structures (IL) at Stuttgart University. While his buildings are famous worldwide, the research leading to the development of specific apparatus for the creation, documentation, measurement, and implementation of complex structures is less widely known. This article provides an overview of the experimental methods used at ILEK, which have been identified on the basis of the publications issued by the institute [1], [2], [3], [4].

2 Form-Finding Models

1.1 Tension Structures

In his doctoral thesis *Das Hängende Dach*, Frei Otto examined Matthew Nowicki's (1910–1950) Dorton Arena in Raleigh (USA), built in 1950, a large-scale steel cable net roof stretched between two arches (figure 1a). He then went on to design from 1952 onwards, buildings that incorporated this principle, including the project for St. Lukas Church in Bremen Grolland (figure 1b) and a roof structure in Berlin.

In his dissertation, Frei Otto recognised that steel cable net roofs behave similarly to fabric tent roofs. He researched curved nets because he considered them to be wind-resistant; the resulting shapes resembled minimal surfaces, the significance of which was still unknown to him in 1953. The collaboration with the tent construction company L. Stromeier & Co. enabled the implementation of these principles, as in the tent pavilion at the 1955 Federal Horticultural Show in Kassel (figure 1c). The Practical experience gained in the process showed that unevenly distributed stresses lead to wrinkling and material failure, while equal stresses (minimal surface shape) allow for controlled stretching. It was only through these experiences that Otto realised that the advantageous shapes were minimal surfaces, which led him to systematic research into minimal surfaces from 1958 onwards using soap film experiments [4].



Figure 1: a) Dorton-Arena in Raleigh in the USA by Matthew Nowicki; b) St. Lukas Church in Bremen Grolland; c) tent pavilion at the Federal Horticultural Show in Kassel 1955 [J. Doub / Wikimedia Commons, CC BY-SA 4.0; p.82 in [4]; p.97 in [4]]

One major research was conducted on **soap film models**. From 1964 to 1969, the IL under Otto's direction conducted experimental research on minimal networks for the planning of transport networks [2]. For this purpose, the **minimum path device** was developed, using soap films to find the shortest total length connecting a set of points (figure 2a). The final device consisted of a horizontally adjustable glass plate and adjustable Plexiglas supports with needles. The principle relied on the formation of soap films between the needles and the glass surface [4].

With the aim to make these surfaces usable for architectural applications, the researchers extended their methods to three-dimensional soap film models: Research focused on individual minimal surfaces under different boundary conditions, such as with rigid or flexible edges, free edges, edge combinations or between two or more frames, including catenoids and screw surfaces, as well as pneus or fog droplets. In particular, the support of minimal surfaces was investigated, for example by means of high and low points (figure 2b), tyres, loops (eyes) (figure 2c) or ridges, in order to specifically influence load-bearing capacity and stability [4].

To increase the stability of the soap films for improved documentation, the IL developed a **soap film machine** in 1967/68. With the help of this device Frei Otto and his institute investigated minimal surfaces with point-like supports. The core of the device was an air-conditioned chamber with an optical bench in which models could be immersed in soap solution via a motorised model ring. A steel frame supported the transparent chamber with adjustable rails for a projector, measuring grid and camera for measurement using the shadow casting method. To capture geometric data a method of photogrammetric surveying was developed in collaboration with the geodesist Wolfgang Faig (unknown biographic data). The system was refined in iterative prototype tests combining in-house designs and industrial components (figure 2d) [4].

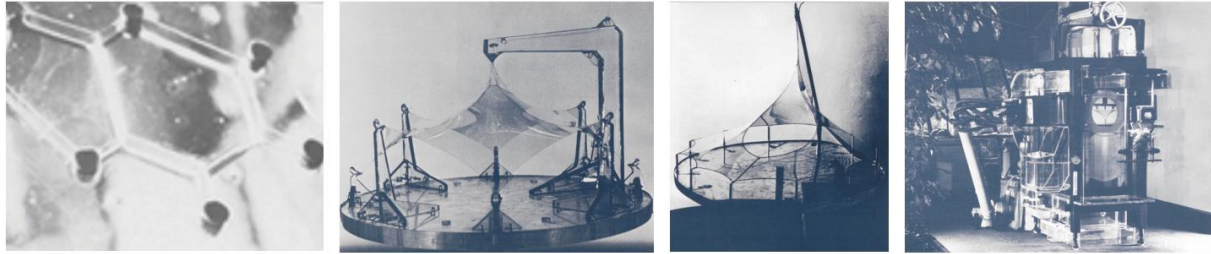


Figure 2: a) soap film in minimum path device; b) soap film study for a tent, the apex formed by lifting it; c) soap film model study of the IL building; d) soap film device [p. 11 in [4]; p. 147 in [4]; p. 163 in [4]; p.331 in [4]]

2.1.1 Wire models

To test the applicability of these designs in real-world constructions, the IL developed wireframe models, most of which were based on tulle models. To determine the orthogonal cut of the wire mesh, paper stickers on the tulle models were utilized (figure 3a); the finished tulle model was measured on the IL measuring table by means of photogrammetry and a cantilever arm for manually reading the coordinates (figure 3b).



Figure 3: a) polyester fabric net; b) surveying at the IL measuring table (plumb line in red circle); c) applying the preload [p.283 in [5]; p.283 in [5]; p.284 in [5]]

Based on the coordinates extracted from the tulle model, the measuring models were constructed from 0.2 mm spring steel wire. The wires were cut to length under a preload of 1.5 kp so that they had the correct length in the net (figure 3c). A continuous copper wire was soldered to the wire used to create the net at the desired mesh size (figure 4a). This was later separated in the middle and twisted together with the intersecting wire, then connected to form an orthogonal grid. The copper wire was used to create knots that could be rotated but not moved (figure 4b). The orthogonal net was then stretched and the edge ropes soldered on. The resulting net was stretched within a wooden frame, whose outer contour was taken from the tulle models. The high, low and anchor points were taken from the tulle model using the measuring table and measured onto a steel support grid. Finally, the net pieces were inserted and, in a lengthy and iterative process, brought to the pre-calculated pre-tension to be tested and documented (figure 4c) [5], [6].

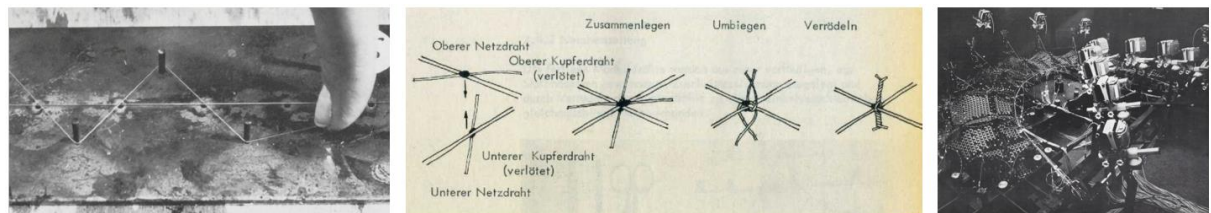


Figure 4: a) tensioning the wire; b) schematic diagram of soldering; c) multimedia test setup [p.284 in [5]; p. 41 in [6]; p.292 in [5]]

1.2 Compression structures

The IL conducted systematic research on compression structures from the 1970s onwards in particular for lattice structures: their nets must be rigid, have continuous net lines and uniform node spacing – only possible with square meshes. Initially, inexpensive fishing nets and textiles were used, later only for early form studies; until the 1970s the team applied knotted thread nets, but they were costly to manufacture [5], [7].

Because **chain nets** were manufactured mechanically from jewellery chains, links had to be cut to length, opened, connected and closed again. For the hanging model a square grid was drawn on a sheet of foil, to which a wooden frame was attached with nails. The chain was placed around the nails and stretched with rubber rings. Knots were connected and fixed with sewing silk dipped in glue. Accuracy was ensured by checking the grid (figures 5a+b). This net was precise, but difficult to modify later [7].

Equally labour-intensive to produce were **element nets**: An orthogonal grid with the desired mesh size of approximately 15 mm was drawn on a soft fibreboard or cork board. Along the first grid line, small metal rings and hooks made of spring steel wire were alternately connected to each other until a chain of the desired length was created (figures 5c+d). The advantage of the element net was that the hooks and rings could be detached again, allowing the net to be altered in size and shape or repaired. It was also the most accurate and inexpensive net [7].



Figure 5: a) member network creation; b) member network detail; c) element network creation; d) element network detail [p. 52 in [7]; p. 53 in [7]; p.33 in [8]; p. 53 in [7]]

3 Documentation methods

3.1 Photographic documentation

Photography was a key tool for documenting, demonstrating and measuring the models. For this purpose, various cameras and lenses were used to photograph the models: Zeiss Ikon Contaflex (35/50/115mm), Zeiss Ikon Hologon (18mm), Pentacon F (58mm) in 35mm format, Rolleiflex SL 66 (40/50/80/120/150/250mm), Pentacon six (80mm) in medium format, and Linhof Technika (50/53/65/360mm) in large format. All photographs were taken under standardised conditions in a darkened room with artificial lighting, with the models fixed on a tripod. While documentary photographs served to record the architectural structure or the phases of model construction, demonstration photographs were aimed less at reproducing details than at capturing the overall appearance of a hanging model, its form as an architectural structure [8].

3.2 Drawing Techniques

Sketches served as graphical models, simplifying the representation by omitting one spatial dimension. The graphic development of nets was indispensable for the manufacturing and processing of the nets and an essential prerequisite for the structural development of the lattice shells.

To create a uniform grid on a two-dimensional surface, the **template method** uses parallel displacement, similar to the construction of a sliding surface. The difference is that here, two transparent templates with curved edges serve as directrices, each of which is displaced parallel to itself. The direction of displacement is straight, similar to a generatrix. While a sliding surface creates a continuous surface,

here the two sets of curves create a discrete grid through their intersections (Figure 6a). The templates had to be transparent to allow the previously drawn lines and nodes to remain visible and align precisely [7].

This method was further developed into a device called **network box**: This tool consists of a fishing net stretched over a plate with the aid of needles. The position of the needles can be adjusted to influence the net, and templates can be used to create uniform curves similar to those found in a hanging net with a rigid edge. The plate is mounted on a light box so that the net stands out clearly against the background so that clean photographic images can be produced (figure 6b) [7].

A similar method is the **grid compass**, a semi-rigid articulated mesh with 75 mm node spacing. When one corner node is adjusted to match a point on the coarse network, all other nodes automatically adapt through the articulated connections, conforming to the curved geometry. The positions of the intermediate nodes can then be directly traced to create the interpolated mesh lines of the refined network. This mechanical interpolation method is significantly faster and more accurate than graphical construction techniques (figure 6c) [7].

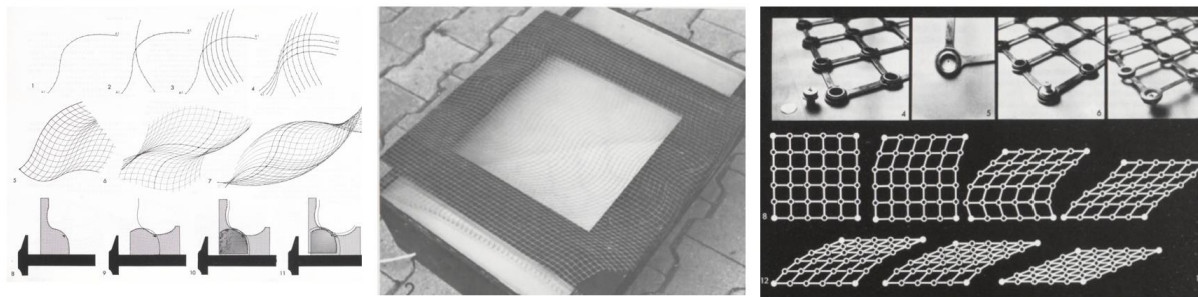


Figure 6: a) stencil method; b) mesh box; c) grid compass [p. 145 in [7]; p.160 in [7]; p.163 in [7]]

The **compass method** uses two curved lines drawn that meet at an intersection as a starting point. This intersection forms the first node in the mesh. The mesh size is selected and set on the compass. Starting from the intersection of the curves, a circle is drawn with the compass, creating a second intersection on one of the curves. Another circle is drawn from this intersection point. This process is repeated until the entire curve is divided into segments. The circles intersect and form points that run parallel to the first divided curve. These intersection points serve as centres for the next circles. In this way, the entire net is developed (figure 7) [7]. This method can be used to create a uniform mesh on any surface, which is a big advantage for the construction of 2D grids, but it is time consuming.

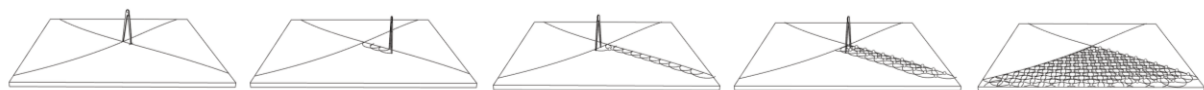


Figure 7: compass method [Baris Wenzel based on p.141 in [7]]

For the **construction of chain models** such as the Multihalle Mannheim (Figure 8a), several steps and helper models are necessary. The team at the IL started with a rubber membrane inflated with liquid plaster forming a pneumatic mould, onto which an equal-mesh net was applied using the compass method (figure 8b). With that data, a cutting stencil for the chain net is generated: A point of the mesh is selected at the center of the model. It is drawn onto a sheet of paper, and from it the four edges connecting to it are plotted. Then, proceeding from the endpoints of these edges, the next edges are plotted successively. The cut edges at the boundary are measured and plotted accordingly. Finally, the endpoints are connected to form a boundary curve (figure 8c). The form-finding is carried out iteratively, as the hanging model deviates from the plaster model, since it exhibits greater crown heights, synclastic

curvatures even at straight-lined edges, as well as stronger anticlastic curvatures in the transition zones. (figure 8d). This method is unsuitable for membrane cutting patterns – here, area-preserving methods are required, for example by taping paper strips [7].

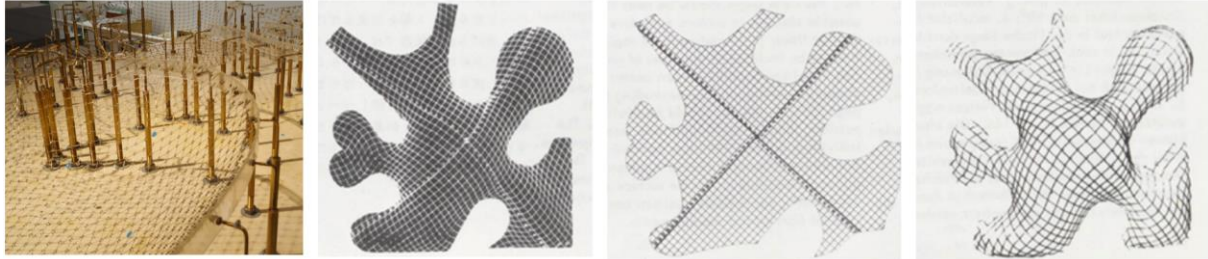


Figure 8: a) model of the Multihalle Mannheim; b) plaster model with net; c) developed flat grid; d) chain model [Baris Wenzel; p.176 in [7]; p.176 in [7]; p.176 in [7]]

4 Measurement techniques

4.1 Mechanical methods

For the use of the **measuring table** (figure 9a) the model was mounted on a frame. Above it was a polished marble slab, parallel to the frame, which served as a drawing surface on which a contour line keypad, a point-setting device, glided. A plumb line, adjustable in height, hung vertically below the drawing pen. The nodes were scanned individually; whenever the plumb line was positioned above a node, a point was marked pneumatically. The contour map was created by scanning the rope network with the plumb line set to a specific height [6].

In order to automate the process, the IL developed their own **measuring machine** (figure 9b) based on the same principle of the measuring table. An electric thread plumb line could be moved across the measuring table while the rotations of the screw spindle are converted into x, y and z coordinates. In this manner, floor plan drawings of the model can be created simultaneously during the scanning process. The measuring table was already used to measure the model of the Multihalle Mannheim and was used until the mid-1980s to compare the function of the computer programmes developed at the IL for membrane calculation with the physical model [7].

The change in length of the **springs** or threads attached to the edge of the net can be used to calculate the force exerted using a scale or micrometre screw (figure 9c). Because the measuring elements altered the shape of the net owing to their weight, measurements had to be taken on a separate model [6].

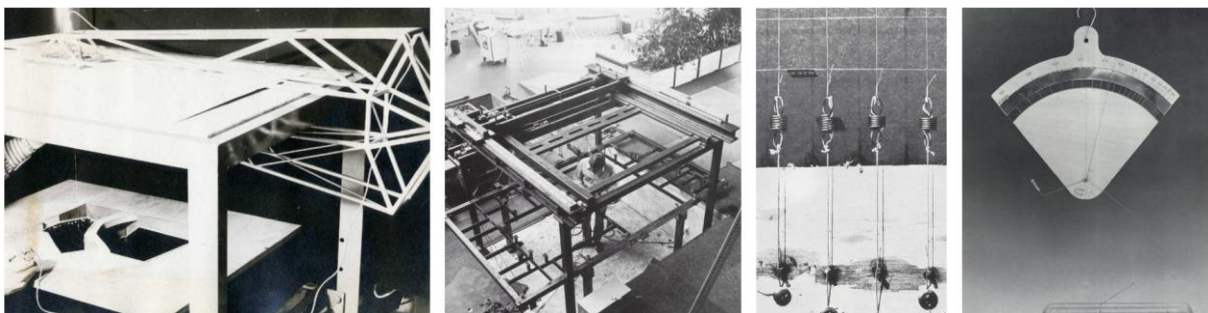


Figure 9: a) measuring table; b) measuring machine; c) springs; d) Contour line keypad [p.133 in [7]; p.80 in [6]; p.290 in [6]; p.85 in [9]]

A further development is the **dial gauge**. this device was developed by Jürgen Hennicke (unknown-2026) and manufactured by Stroppe in Bad Dürrenheim using the same measuring principle as the

measuring bracket. The deflection of the wire is precisely recorded by a dial gauge, resulting in significantly higher accuracy than with the measuring bracket (Figure 10b) [5].

Cardboard protractors were also used for wire-net models. They were hung in individual meshes to measure changes in mesh angle under load. The longitudinal wire served as a pointer, whose position on the angle scale could be read in photographs (Figure 10c) [5].

To calibrate or verify the other measuring devices the **ring dynamometer** was applied: a ring-shaped force measuring device that measures absolute forces (Figure 10d) [5].

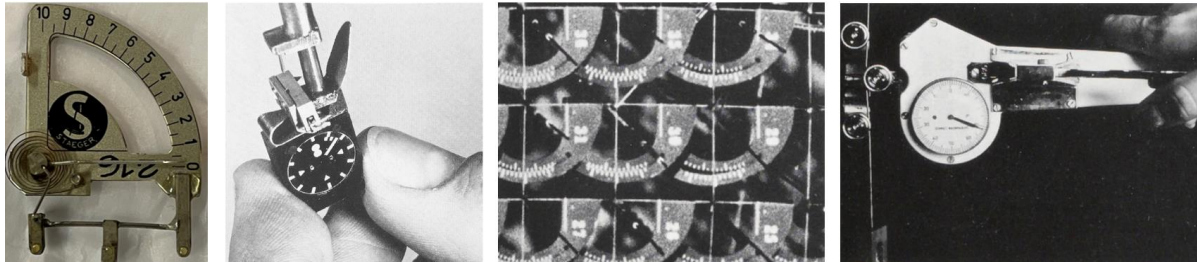


Figure 10: a) Montreal measuring calliper; b) dial gauge; c) protractor; d) ring force gauge [ILEK; p.24 in [10]; p.295 in [5]; p.289 in [5]]

4.2 Optical methods

Because the models were extremely fragile, the IL developed contactless methods for capturing their shapes. Moreover, due to the large number of nodes, manual reading would have been very time-consuming. Therefore, the principle of double-exposure photography was employed, with a height gauge attached to the wires to record the vertical displacements of the nodes. For this recording method the same photographic plate was exposed twice with an aperture of 22 – once in an unloaded state (2 seconds) and once in a loaded state (4 seconds). A standard scale attached to the node made it possible to evaluate the recordings quantitatively (figure 11a). Spring steel wire measuring hooks with scale marks attached to the mesh nodes carried steel weights to simulate loads, sometimes raised or lowered using car tire tubes placed underneath. To simulate wind suction, load tests were carried out in the high point area and evaluated using this method (figure 11b) [5], [7].

The **stereophotogrammetric images method** is similar and was developed in cooperation with the geodesic engineers at the Institute for Applied Geodesy in Construction (IAGB) at the University of Stuttgart: images were captured using special stereo cameras, not on film, but on plane-parallel glass plates. They were evaluated using an analogue stereo comparator. A special version of the Rolleiflex SL 66 with 40/80 mm lenses, converted and calibrated by Rollei-plant Braunschweig and Zeiss- plant Oberkochen, was used, as well as a design developed in-house by the IAGB for plane-parallel glass plate material measuring 130×180 mm (figure 11c) [7].

With **stereophotography** Wolfgang Faig developed a more cost-effective device for stereo photography at the IAGB under Prof. Klaus Linkwitz (1927–2017) as part of his dissertation submitted in 1969. A standard Sinar Norma camera was modified with an adapted back and mounted on a slide consisting of two parallel tubes, which could be moved and locked in place continuously. For stereo images, a second camera was modified in the same way and aligned parallel to the first (figure 11d). The accuracy achieved of 1/10 mm was sufficient to digitally archive hanging models by storing the geometric data and later evaluate them without a physical model [2], [4], [7].

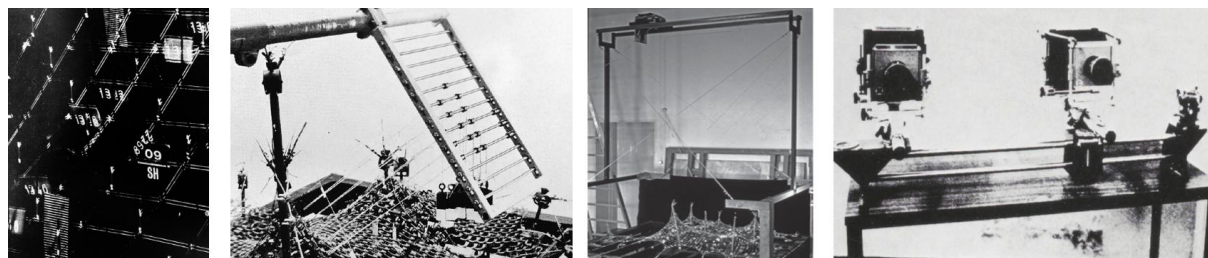


Figure 11: a) double exposure deformation measurement; b) double exposure wind suction measurement; c) stereophotogrammetry Montreal; d) stereophotography [p. 294 in [5]; p. 289 in [5]; p.81 in [6]; p.78 in [2]]

Soap skin models could only be captured visually; a dedicated measuring method was developed for these in collaboration with the geodesists. An **optical bench** was used to measure soap films and chain models with parallel light: a parallel light beam with a diameter of around 30 cm was generated using a point light source, four condenser lenses ($\varnothing$ 300 mm), intermediate apertures ($\varnothing$ 0.5 mm) and a plastic matt screen as a projection surface instead of photographic paper. The shadow projection was recorded from the rear with a Linhof Kardan Color camera (6.5×9 cm, Schneider Xenotar 1:2.8/80 mm) on Ilford HP4 roll film (27-29 DIN) in Linhof Ideal format cassettes (56×72 mm). An Aristo millimetre glass with etched grid, as reference coordinates, was placed in front of the screen (figure 12a) [1], [2].

To document the surfaces, contour lines were projected using a second experimental setup, known as the **shadow method**. The shadow of a horizontal grid of threads illuminated from below produced contour lines on the model. The contour projection was made onto photographic paper or traced onto foil (figure 12b) [2], [7].

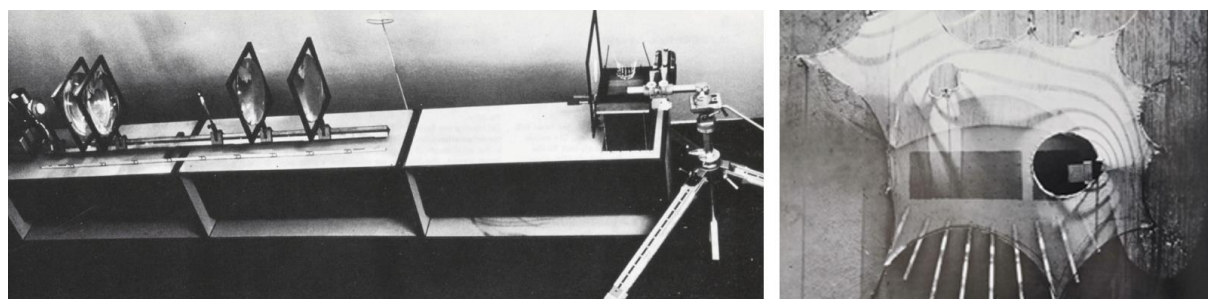


Figure 12: a) setup of the optical bench; b) model with contour lines through projection [p.11 in [11]; p.2 in [7]]

5 From model to construction

5.1 Cutting procedures

In order to realize the designs developed using form-finding models, further methods had to be developed to determine the dimensions (the cutting) of the individual components. For the **rope net cutting plan** a 35 mm Contaflex camera with a 0.2 m lens was used. A metal frame ensured a consistent distance to the net (figure 13a) resulting in three to four contact points (figure 13b). Four scales in the measuring plane enabled verification of image dimensional accuracy (figure 13b). Slides were projected and traced on a scale of 1:10. Due to cost and time constraints, usually only every third or fourth wire was built into the model and later the missing data was interpolated. The drawings were superimposed, perspective foreshortening was averaged and compared with control dimensions. Gaps with a fish-belly shape, occurring on anticlastic surfaces, were also averaged, whereby the sum of rope angles at the edge nodes had to be 360 [6].

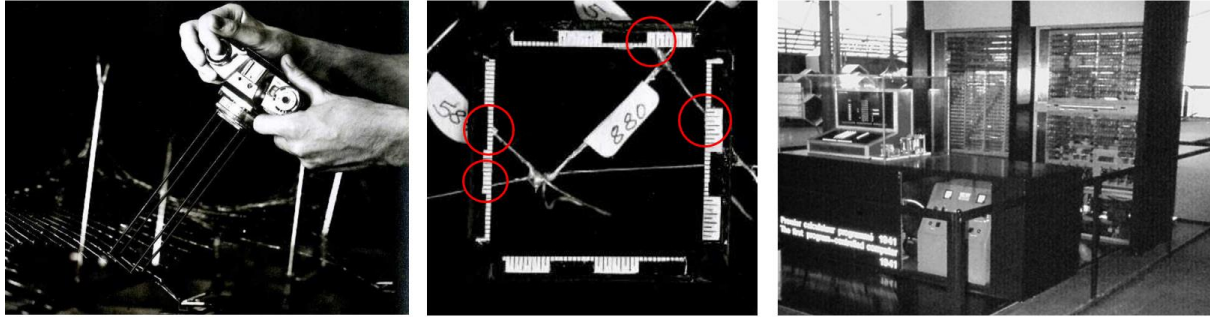


Figure 13: a) camera with spacer; b) contact points and scales in focal plane; c) Zuse Z3 computer on display at Expo 67 Montreal [p.98 in [6]; p.100 in [6]; Horst Zuse]

With this method, the shape of suspended insulation ceilings was determined, measuring the models of the roof on the IL measuring table. A wood and plaster model was used for the Olympic Stadium and a wire model for the Montreal Pavilion. Paper strips with a square grid pattern that could be bent on one side were glued to the model in order to divide the curved surface into developable strips. The cut edges could be transferred directly to the working drawings [5], [6].

5.2 Computational Integration

Though Otto was initially sceptical of computers, his projects eventually transitioned from physical to digital models. For the German Pavilion at Expo 67 in Montreal, a wire mesh model of Klaus Linkwitz's (1927 – 2017) geodetic institute at the University of Stuttgart was measured using stereophotogrammetry, the three-dimensional coordinates were extracted mathematically, and sections of the building were automatically drawn using Konrad Zuse's (1910 – 1995) Z3, the first programmable electronic computer, and a Graphomat plotter (13c). These were exhibited in the same pavilion, directly under the roof whose shape they described [12]. At the same time, Eberhard Haug developed a computer program at the IL, which from 1969 onwards was able to calculate completely numerical soap film shapes, thus complementing the physical soap film experiments with a computational counterpart [4]. For the Olympic Stadium in Munich, the precision of physical models was no longer sufficient. Linkwitz developed the force density method for determining cuts, John H. Argyris contributed finite element analyses, and the construction drawings were plotted by machine for the first time. The same methods were used again for the Multihalle Mannheim, supplemented by non-linear FEM calculations at Arup offices [13]. What had been a poetic fringe experiment in Montreal, 4 years later had become a technical necessity in Munich, heralding the transition from analogue to digital.

6 Contemporary relevance and conclusion

This study reveals how Otto's integration of physical experimentation and systematic measurement created a methodology that bridged intuition and rigor. The experimental methods developed at the Institute for Lightweight Membrane Structures are not merely precursors to digital computation, but constitute early forms of material computation. The apparatus and techniques developed at the IL between 1960-1985 not only enabled ground-breaking projects but established principles still relevant today. Soap films, suspended models and wire mesh structures functioned as analogue systems that solved complex equilibrium problems through physical processes. Modern numerical methods, such as dynamic relaxation, force density methods or non-linear finite element analyses, formalise these same principles algorithmically. Thus, what has changed is not the logic, but the medium of calculation. Current developments indicate a renewed convergence: high-resolution 3D scanning, digital image correlation and sensor-integrated models now enable the direct translation of physical experiments into digital datasets. As digital tools become increasingly powerful, Otto's insistence on physical validation remains crucial. In hybrid workflows, physical and numerical models are no longer sequential but are coupled, forming iterative feedback systems. Against this backdrop, Otto's methodology is gaining new

relevance, as it anticipates contemporary approaches that combine simulation, experimentation and validation into an integrated design process. After Frei Otto's retirement in 1995, Werner Sobek took over the IL and merged it with the Institute for Construction and Design in 2001 to form the ILEK (Institute for Lightweight Structures and Conceptual Design). This merger led to the reunification of architecture and civil engineering in one institute. Interdisciplinary research was expanded through collaborations with mechanical engineering, aerospace and textile technology in order to consistently conduct lightweight construction research across materials and methods. Since 2020 Lucio Blandini is the head of the ILEK, and drives the integration of digital tools to continue to play a central role and now encompasses the entire life cycle from design, form finding, planning and execution to operation and dismantling [14].

7 Acknowledgement

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