Heinz Isler's Form-Finding Models for his "HIB" Shells: Between Experiment and Design

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Abstract. The Swiss engineer Heinz Isler (1926–2009) is among the most prominent figures in shell design. Thanks to a form-finding approach based on the use of physical models, he designed and built many shell projects in reinforced concrete. His unconventional structures still represent an important source of inspiration for today's structural engineers. The paper reconstructs Isler's experimental method by looking at the multiple physical form-finding models he developed for his tennis hall shells. Designed for the first time in 1977, they became one of Isler's most successful shell typologies, promoted as "HIB" shells in Switzerland. Despite their apparently simple shape, Isler produced the largest number of physical form-finding models for this specific shell type. Their double symmetry challenged his design method: the highest precision was needed to avoid any irregularities in finding the appropriate geometry. By studying the original materials stored at the Heinz Isler Archive (gta Archives, ETH Zurich), details about Isler's experimental approach to the conceptual design of his shell structures will be revealed for the first time.

Keywords: Form finding · Reinforced concrete shells · Heinz Isler · Physical models · Conceptual Design

1 Introduction

Shells are among the most elegant structures. They combine their form with the most appropriate flow of forces. Thanks to their double curvature, they accommodate any load configuration through pure membrane action. In this context, form-finding methods help finding their appropriate equilibrium shape under boundary conditions, in compliance with external and internal forces. The foundations of computational form-finding tools were laid in early experiences with physical models [1]. Together with the German architect Frei Otto (1925–2015), and the Italian engineer Sergio Musmeci (1926–1981), the Swiss engineer Heinz Isler (1926–2009) is considered one of the masters of physical form-finding techniques in the second half of the 20th century [2]. This paper investigates Isler's experimental form-finding approaches by looking at the models that were fabricated for the tennis hall projects. Such shells exemplified Isler's ability in mastering his form-finding technique with physical models.

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2 Hanging Membranes

As advertised in the brochure of the tennis shell projects, Isler's design goal was to reproduce natural shapes through a physical form-finding experiment [3]. Thanks to multiple models, he controlled "new shapes for shells" [4], whose geometry could not be expressed with analytical equations at that time. The most complex shapes were found through the form-finding method of the "hanging membrane". Isler was not the first one who adopted it. The technique was based on Hooke's principle of the catenary line [5]. Early examples can be traced in Christopher Wren's studies for the dome of St. Paul Cathedral [1] and Antoni Gaudí's combinations of catenary curves [6]. Isler extended the principle to continuous shells: an isotropic rubber membrane hanging from a timber frame, on which gypsum was poured. During the experiment, the membrane found its equilibrium form due to the force of gravity [7]. Even though Isler adopted other form-finding techniques such as the "pneumatic membrane" or the "freely-shaped hill", the "hanging membrane" was considered "the best method for design" [4: 2]. Most of Isler's surviving models followed this principle. For the tennis projects, the highest number of models were made.

Fig. 1. Isler's "HIB" shells during construction, Heimberg, 1978 (217-0384, gta Archives, ETH Zurich).

In the tennis halls, Isler mastered the control of the relation between form and force in a system of juxtaposed buildings (Fig. 1). Their iconic form became the reference image for any tennis hall facility in Switzerland, as had happened for Isler's industrial buildings. The series was designated "HIB" shells, from the names of the three actors involved in their promotion (Haus + Herd), design (Isler), and construction (W. Bösiger AG). Between 1977 and 1993, fourteen projects were built following the "HIB" typology, for a total of sixty shells. After the industrial structures, they became the most prolific shell typology in Isler's oeuvre. The early studies looked back at his well-known shell series, either as a roof component – like the industrial bubble shells - or as a stand-alone building – like the garden center typology [8]. However, it became clear that the requirements of a tennis field – a longitudinal dimension of approximately 40 m, an inner height of a minimum of 5 m, a maximum of 9 m, and diffuse lighting conditions – asked for a new shell typology. Following Isler's statement that "the shell is the supporting structure and the space enclosure at the same time" [9: 149], the tennis shells guaranteed an elegant structural solution to the architectural program.

3 Form-Finding Apparatus

The "HIB" structures showed the purest application of Isler's hanging membrane form-finding method: a shell with a rectangular plan sitting on four supports at equal height. However, despite the shape's apparent simplicity, they represented Isler's most challenging project. After ten years of experience with hanging membrane models, extensive refinement of the form-finding technique became necessary. At first glance, this aspect is quite surprising. Other prominent projects by Isler, like the factory Sicli SA in Geneva (1968–69), asked for highly accurate apparatuses to find the unconventional doubly-curved form [10, 11]. However, it was easier to find a completely asymmetric shape than the doubly-symmetric one of the tennis shells. While formally-complex shells allowed tolerances in the form-finding phase, the "HIB" shells demonstrated the "need of highest accuracy" [12: 222] in the physical modeling technique. The equal thickness of the gypsum layer and symmetry in both directions required many iterations until the "[geometric] solution is found" [13]. The fifteen form-finding models for the first tennis shell project in 1977 underline these difficulties (Fig. 2). Isler worked for more than two months on them. It was the biggest exploration he ever did on form-finding methods for shell design. Through the twelve surviving models, the authors traced back his experimental procedure for the first time.

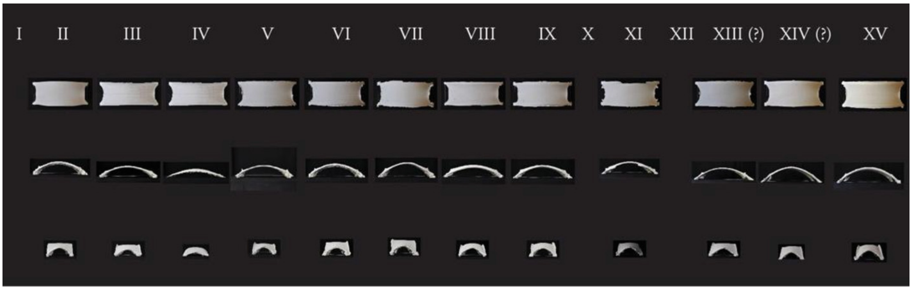

Fig. 2. Physical form-finding models for Isler's tennis shells, 1977. Surviving physical models ordered on the basis of (217-0364, S. 2/3, gta Archives, ETH Zurich).

Unlike Otto's research laboratory, where complex machines controlled his shape explorations [14], Isler's form-finding tools were constituted of economic materials borrowed from daily life [2]. However, despite the appearance, his engineering practice was the outcome of extremely accurate techniques that were refined over the course of his career [15]. The hand-crafted experimental devices allowed easy and fast repetitions of the same test. This became fundamental for the physical models of the "HIB" shells. At different stages, Isler worked on the position and prestressing of the hanging membrane, the gypsum mixture, the experimental equipment, and the overall methodology for achieving symmetrical results in a pure hanging membrane test.

3.1 Material

Even though Isler's public shows always displayed a hanging textile saturated with resin, the actual form-finding experiment he used for his projects employed a 0.3 mm-thick rubber membrane on which gypsum was poured. The isotropic material guaranteed a uniformly distributed stressed funicular shape, thanks to the even stiffness of the membrane and without the influence of the textile threads. Reference lines were drawn with black pencil and ruler, on the membrane side towards the poured material. For critical areas, a denser measurement grid was traced to provide a more precise picture of the membrane behavior. Such guidelines helped the evaluation of the most appropriate shape. Since they were automatically transferred on the model's gypsum surface during the form-finding process, they are still visible on the surviving objects. The membrane was cut according to the initial plan dimensions. Both its shape and elasticity influenced the found form: if too small and stiff, the resulting shape would be too flat; if too large and flexible, wrinkles developed. In the studies for the tennis shell projects, different cutting options were explored [16].

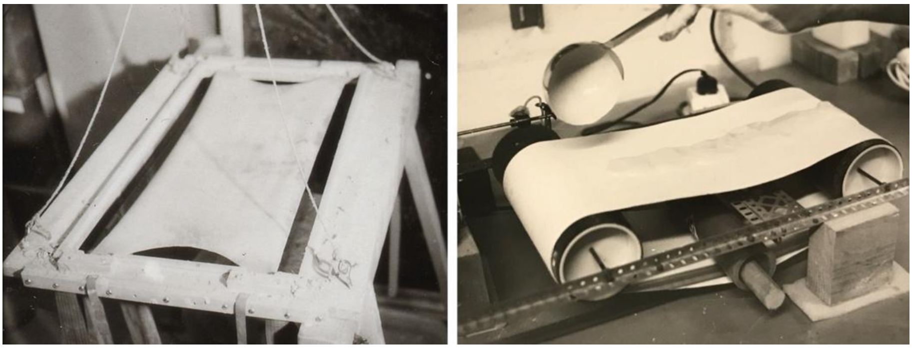

Fig. 3. Left: Rubber membrane and timber frame for the Düdingen shell project, 1977 (217-FX-2-77-18, gta Archives, ETH Zurich); Right: Setting test of the gypsum mixture, 1984 (217-FX-15-3, gta Archives, ETH Zurich).

Once the membrane was cut, it was anchored to the timber frame using nails and small timber elements (Fig. 3, left). It soon became clear that prestressing the membrane could help with controlling the form-finding process [17]. The applied prestressing force represented a design parameter since it highly influenced the final shape. Such studies are visible in the initial stages of the "HIB" form-finding explorations: the first ten physical models focused on this aspect. The more the membrane was prestressed, the more symmetric the shape was, but the lower the longitudinal curvature was. Isler explored tests with a range of membrane prestressing between 0 and 7% of the membrane's length. Experimental results showed that a prestressing of 2.8% helped achieve the most appropriate longitudinal curvature to meet the design requirements for the tennis shell projects [16].

If the choice of the rubber membrane was important for the form-finding study, the gypsum mixture was crucial for the success of the experiment. Unlike previous cases, where its quantity was expressed through the material thickness on the physical model

[18], for the "HIB" project the correct proportion between gypsum and water, together with the setting time, was investigated over the course of five different material tests in Isler's model workshop. A specific device – the "gypsum machine" – was manufactured to control the proportions of the mixture's components (Fig. 3, right) [19]. In a few tests, drops of lemon juice were even added to the mixture to slow down the setting time and avoid cracks on the surface caused by an early drying mechanism.

3.2 Equipment

Appropriate dimensions of the form-finding equipment were necessary for the experiment's success. If the device was too small, achieving the necessary precision for scaling up the results for the further design phases was difficult. If too big, the overall process could not be controlled by the two people who worked on it. In the "HIB" studies, the increase in model size from a scale of 1:100 to 1:75, with resulting longitudinal length of 47 and 63 cm, respectively, helped reduce incorrect outcomes [20].

As for the material choices, the form-finding equipment for the "HIB" experiments became more sophisticated than in Isler's early hanging studies. Each structure constituted a module that needed to be placed next to each other. For the prestressed edge beams of Isler's industrial shells to guarantee a perfect match between the modules while equilibrating the spatial structure [21], the tennis shells had to respect an accurate definition of both longitudinal and cross curvatures. The control of that connection detail on the small-scale physical form-finding model represented one of the most challenging studies. A few changes to the experimental device became necessary (Fig. 4) [22].

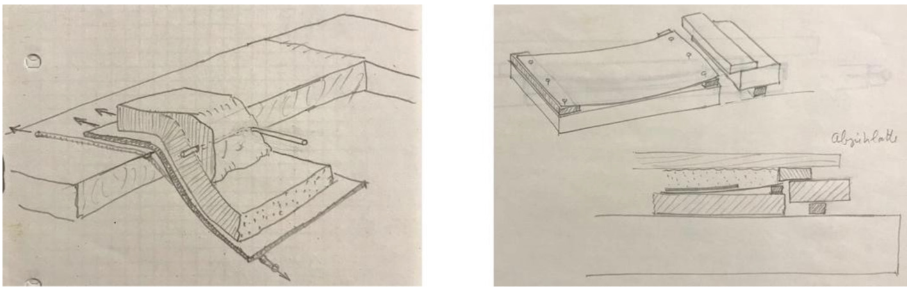

Fig. 4. Changes to the form-finding equipment for Isler's tennis shell projects, 1977. Left: Additional rubber bands along the longitudinal edges; Right: Curved bottom plate for the gypsum pouring process (217-0364, S. 2/3, gta Archives, ETH Zurich).

The longitudinal curvature was monitored through equal membrane prestressing thanks to a pre-tensioning mechanism in the timber frame. Along and close to the border of the longitudinal edges, two prestressed rubber bands were placed to control the symmetry of the cross curvature (Fig. 4, left). Additionally, a curved bottom plate was located right below the membrane and within the timber frame (Fig. 4, right). During the pouring process, the material distribution was not uniform due to the plate's transversal section: more gypsum in the central area increased the cross curvature of the hanging membrane.

4 Form-Finding Procedure

The form-finding experiment was based on a trial-and-error approach. If nowadays a computer program adopts a digital iterative procedure to find the most appropriate shape for a specific design problem, Isler's approach led to multiple physical models that were refined based on the experiment's observations. Each model was generated in approximately 20 min (preparation, pouring, and drying process). Therefore, it could be easily replicated multiple times. For the "HIB" shells, thirteen tests were conducted before the correct procedure for the form-finding study was defined [23]. The edges and the supporting points represented the most critical areas. They were carefully controlled. Additionally, the prestressing of the membrane and of the longitudinal bands was checked through visual observation and simple tensional tests [24]. After these preliminary steps, the experiment could start. Two timber trestle legs and a stool supported the hand-crafted apparatus (Fig. 5). The form-finding device consisted of the timber frame and the rubber membrane was placed on a timber board with curved bottom plate. The gypsum mixture was poured onto it. The material was distributed over the surface. After a few minutes, the membrane was hung from its supports and adapted its shape to the gypsum's load during the hardening phase. The timing was carefully controlled. If the operator had waited just a minute longer, cracks would have appeared on the surface. The experiment ended as soon as the material was fully hardened.

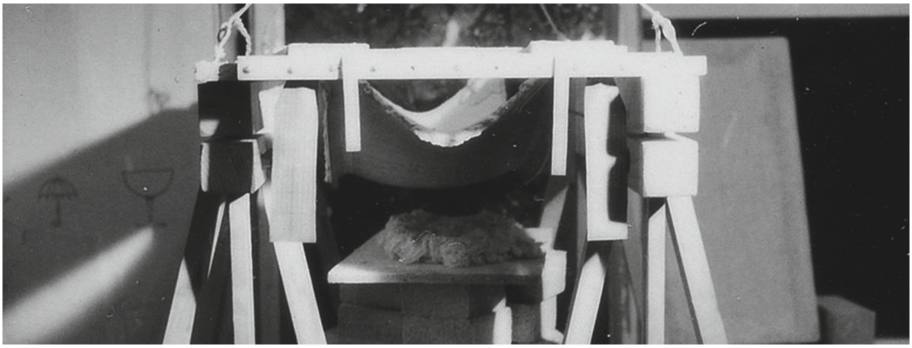

Fig. 5. Form-finding studies for the Düdingen tennis shell, 1977 (217-FX-2-77-18, gta Archives, ETH Zurich).

The free edges represented the most critical areas from the perspective of both symmetry and structural behavior. In early form-finding studies such as the one for the Grob shell (1968), a membrane reinforcement along the perimeter was adopted. This translated to a hidden edge beam in the real construction [17], which was discovered during the shell's demolition in 2021 [25]. Oppositely, the "HIB" studies showed that a more elegant alternative was possible. If the membrane was cut a bit bigger than the actual hole, the excess of flexible material folded over locally forming a negatively doubly-curved shape, which automatically resulted in a stiffened edge. Moreover, these upturned longitudinal edges, a reminiscence of Isler's garden center series, prevented the thin shell from buckling.

Once the gypsum hardened, the rubber membrane was removed. The multiple form-finding models were collected on a table. Their shapes were examined and compared. The one that accomplished the requirements of geometry, symmetry, structural behavior, and architectural appearance was chosen. The correlation between the model's form and the drawings for manufacturing the timber binders of the falsework made it possible to translate its geometry in full scale on the construction site.

5 Conclusion

Over his career, Isler consolidated an extremely accurate engineering practice that linked a form with its internal stress state. The fifteen physical models for the "HIB" shells embodied Isler's approach to the conceptual design of shell structures. Such physical modeling techniques highly inspired computational form-finding methods [26]. In the early 1990s, the geometry of the tennis hall shells was explored with digital tools at the University of Stuttgart [27]. Interestingly, Isler's physical models and these computational ones showed comparable results (Fig. 6, right). Even with different media, both were based on optimization processes linked to iterative procedures. The physical form-finding method of the hanging membrane considered gravity as the governing design load. On the contrary, computational tools combined different load cases to define the most appropriate shape. Only one-quarter of the shell was considered to run the optimization process digitally: the double symmetry helped reduce the calculation time and the complexity of the procedure. Isler adopted the same approach for the geometric studies and the consequent preparation of the timber falsework for the construction site. In this way, the risks of inaccurate results were reduced. However, the physical hanging model needed the full shape to produce the gypsum model during the experimental phase. While digital form-finding methods confirmed Isler's experimental results, recent FEM studies on the tennis hall shells highlighted that they helped find shapes with an appropriate structural behavior also from the point of view of stiffness and concrete allowable stresses [28]. Additionally, the shell's formal clarity reflected the shape's efficiency linked to the appropriate use of concrete as building material [29].

Isler's career took place during the generation shift from physical to digital approaches to designing structures. Isler understood the potential of digital methods

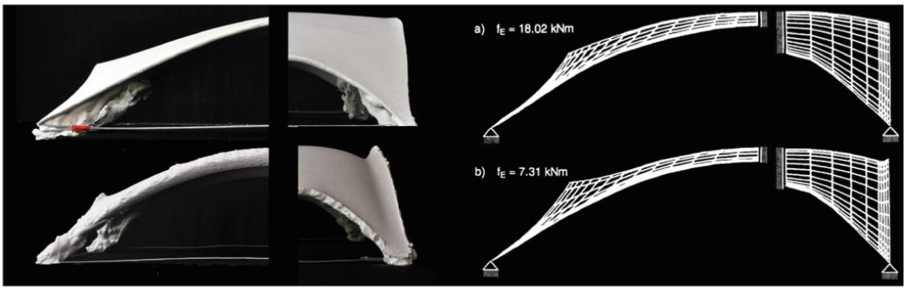

Fig. 6. Left, top: Physical model n. 2 (217-M-7-2:103, gta Archives, ETH Zürich); Left, bottom: Physical model n. 15 "Urform" (217-M-7-2:105, gta Archives, ETH Zürich); Right: [27]: 35.

to explore different design options in only a few seconds of calculation time. However, in his opinion, "the computer only answers the question we have asked it. It is not in a position to point out questions that we have not yet asked, if we have not yet recognized or experienced the problems. The comprehensive [physical] model, on the other hand, can do that." [30: 61, translation by the author]. Therefore, despite the recent discovery of Isler's use of early computational tools [15], his physical form-finding models remained the most important aspect of his unconventional engineering practice.

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