Model Behavior: The Evolving Use of Physical Prototypes in Structural Shell Design, 1959-1974

During a critical fifteen-year period of time, Heinz Isler and Frei Otto advanced the way physical models were used in the design development, analysis, and documentation of several innovative structural shell designs .

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EVOLVING USE OF PHYSICAL MODELS

Although physical models have been frequently used by designers for representational purposes throughout history, only a handful of engineers in the 20th century used physical models to estimate or confirm structural behavior of mathematically complicated structures, like shells—even fewer used physical models as design tools (Cowan, 1968). But between 1959-1974, Heinz Isler and Frei Otto both proposed designs for structural shells that used physical models for form finding *and* structural testing. To evolve their designs, they evolved their tools.

Although Isler and Otto approached their modeling processes differently, both designers used models for more than visual reference or representation. Their models were used to generate innovative and structurally efficient building forms, to discover advanced construction methods, and to help document the complex geometries of these creations. Relatively quickly the use of these models reached their limits as analytical tools for both designers but the process of building and documenting these models led to ground breaking shifts towards modern computational methods for modeling, representation and analysis.

In exploring the link between what these historic innovators designed and how they designed, this paper will demonstrate how this advanced use of physical models led to substantial improvements in the design, performance, production, and analysis of complicated spatial shell structures.

"NEW SHAPES FOR SHELLS:" ISLER AND THE DESIGN OF A PROCESS

In 1959, at the inaugural International Association for Spatial Shells (IASS) conference, the Swiss structural engineer Heinz Isler (1926-2009) gave a succinct and contentious presentation demonstrating how physical models could be used to design and analyze concrete thin shells. Using only one page of text and nine illustrations, Isler's "New Shapes for Shells" paper showed how shell forms could be cast over pressurized membranes and earthen forms or derived from inverted hanging cloth models (Isler, 1960). Instead of showing mathematical formulae like the other presentations at the Structural Morphology

Colloquium, Isler showed model prototypes he'd developed, his testing apparatus, and several shells he'd designed that had been built with these methods (Figure 1A).

This design process stemmed from years of frustration he'd spent trying to accurately generate, graphically document, and mathematically analyze geometrically complex anticlastic concrete shells using traditional means. Isler described how the continuous, naturally occurring double-curvature of his pillow helped him realize that a physical model of tensed surface under pressure "was for 3D problems what the catenary line is for arches." The physical model, he argued, was an immediate and relatively accurate visual and spatial representation of an idealized structural form. He showed a drawing of various shell forms, "39 shells, etc.," as a way of demonstrating that shell design was inherently a creative act that could be solved by physical models and not simply a mathematical or analytical problem (Figure 1B).

This approach was such a departure from the traditional models of practice and analysis that several of the world's leading concrete shell designers in attendance (including Ove Arup and the IASS conference chair and founder, Eduardo Torroja) took issue with the proposed design process. The question and answer session that followed was six times longer than Isler's presentation and, in retrospect, reflected a growing set of concerns about traditional engineering practices, analytical methods, and responsibilities for design authorship of structures. .

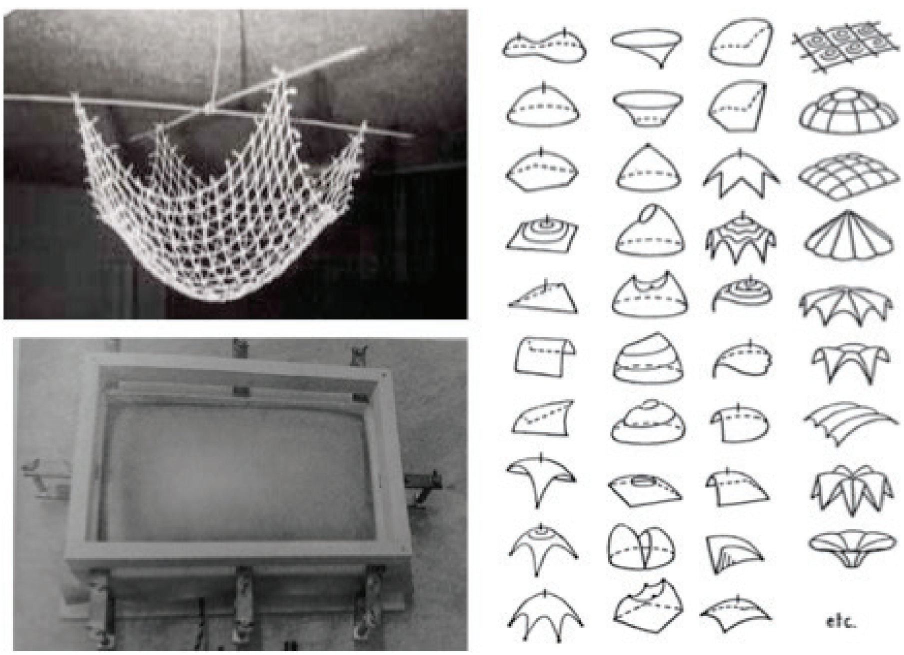

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Figure 1: Isler's hanging fabric and pneumatic forms and his "39 forms, etc." drawing. From IASS, 1960

BENEFITS AND PERCEIVED THREATS OF USING MODELS FOR DESIGN

Isler's use of physical models to test the behavior of structural shell forms was not anything new. Pier Luigi Nervi first began testing models of his concrete hangars at Orvieto in 1927 because there wasn't any accurate mathematical means of testing monolithic double-curved concrete forms for stiffness (Hossdorf, 1975). Torroja himself had also been using physical models to test the more experimental forms of his shells for twenty years (Azagra, 2012). Isler's first employer (and dissertation advisor) Professor Pierre Lardy had visited Torroja's workshop in Madrid and shared information about his visit to Torroja, and his model methods, with Isler (Chilton, 2000). So how was this different? By the time this inaugural IASS conference was convened, several high profile architects, including Eero Saarinen and

Jorn Utzon, had designed concrete shell buildings using physical models that were devoid of inherent structural logic. As a preface to one of his questions to Isler, Arup called this “a most unfortunate state of affairs” and criticized Isler for introducing a process that would allow for “an indiscriminate use of models” by inexperienced designers (IASS, 1960). At the time, Arup was in the middle of four years worth of work trying to design, model, and test Utzon’s proposal for Sydney Opera House, although he eventually found the physical model to be a good tool to disprove the validity of Utzon’s proposed roof form (Arup & Zunz, 1969).

In his defense to these questions, Isler stated that physical models were not intended to exclude any of the other types of more traditional analytical tools (he called models the “first step in design”) or to be used indiscriminately to generate non-structural forms. Conversely he argued that physical models could help simplify the process of design and mathematical analysis because they would generate a structurally viable form that would make the testing results more predictable and the building more beautiful if the form uncovered the natural flow of forces (Isler, 2008). Similar arguments were eventually made by Candela and other shell builders who felt that the act of building the shells would give real-time feedback about the geometric viability of the proposal to the designer.

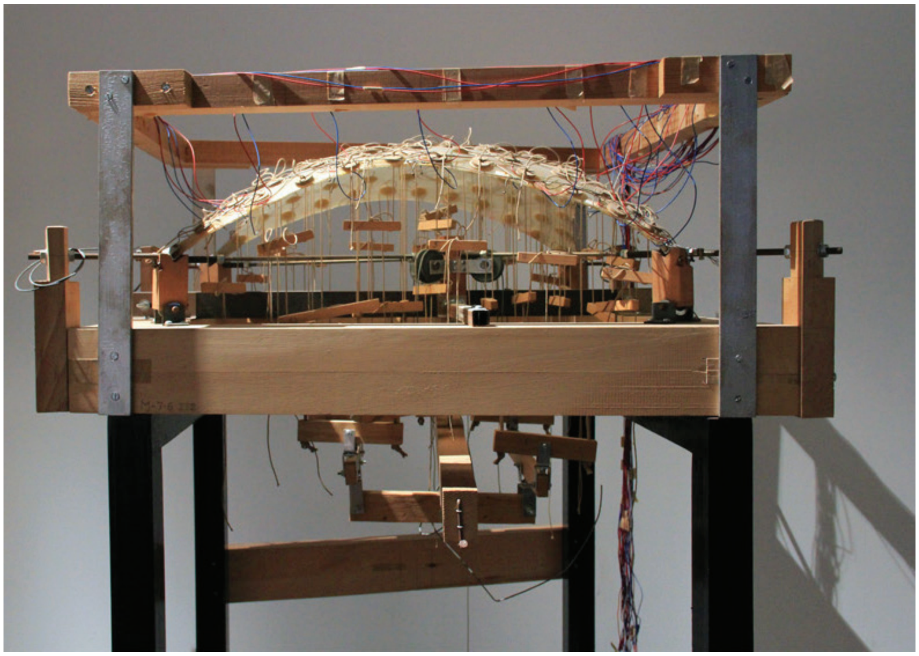
PATIENT WORK AND PRACTICAL CONSIDERATIONS

Although Isler continued to be a prolific shell designer that used his self-described “patient, accurate, and repeated” process for the next thirty years, his use of physical models in the design process was never widely used by others (Chilton, 2000). Perhaps this was a result of the fairly isolated nature of the work—Isler mostly worked alone in making and measuring the models and rarely opened the process up to others, perhaps for proprietary reasons or simply quality control.

For other concrete shell designers, adopting this complicated process involved higher risks with potentially marginal structural and economic rewards. Shell designs generated by physical models weren’t much thinner than conventional shells because, unlike the axially stressed cable and arch structures modeled by Gaudi, shells couldn’t retain the same proportions of thickness when scaled up. As a result, the thicknesses were commonly oversized during this conversation to full scale to compensate for potential inaccuracies of the model (Addis, 2014). This was commonly accepted as a good approach because a marginal increase in the thickness of the shell could be seen as a small investment compared to an uncertainty of potential structural failure. For Isler, the exactness of finding these efficiencies through modeling was the benefit of the process, but there was a practical perception that even conventionally designed shells were still quite materially efficient and that the extra risks may not be worth the effort. Even the inefficient Kresge Auditorium had a thinner shell proportionately than an egg (Saarinen, 1955).

Isler believed that making models also gave him insight into the construction process and this had allowed him to design an efficient reusable false-work in his shells that saved a significant percentage of cost (Isler, 1960). As a direct result of his physical model experiments with pneumatics, Isler correctly predicted his use of large-scale air bladders as formwork—an innovation also employed by the Binishells of the 1960s (Salvadori, 2002). But most of the significant innovations in the design and the construction of the formwork were typically already occurring through the concurrently conducted full-scale experiments of shell engineer / builders like Nervi, Eladio Dieste, and Felix Candela and not through the use of physical scale models (Isler, 2008).

For Isler, using models allowed for more complex geometric forms to be found more easily, but it complicated the process of accurately documenting and eventually building the final form. To accurately translate his three-dimensional models into two-dimensional drawings, Isler created a three-dimensional grid of reference points in and around his models and used tools (like calipers) to carefully measure the model and transfer these x, y, and z axis reference points into orthographic projections of contour plans, serial sections, and elevations. He would measure the model many times, throw out the outlying deviations, and then confirm the continuous anticlastic geometries through the drawing process—he described it as arduous work. Section drawings would be used by Isler to check for bending and stiffness using basic calculations and the final model would be subjected to testing for deflections (Figure 2). However, for others untrained in this process, or unwilling to follow to this degree of rigor, it was a risky procedure fraught with opportunities for errors. If the model couldn't be accurately measured or drawn, then it couldn't accurately analyzed.



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EXPANDING UTILITY THROUGH COLLABORATIVE EFFORTS

While Isler continued to improve upon these challenges for the hundreds shells he designed throughout his career, it was a group of German engineers working at the University of Stuttgart, including their founder and director, Frei Otto (1925-2015), that provided the next significant advancements in the use of physical models for spatial shells.

In 1964, Otto founded the Institute for Lightweight Structures (IL), where he strove to create lightweight, beautiful structural forms using a repeatable design process to create, evaluate, and construct these designs. Otto found the ultimate expression of an efficient and beautiful tensed structural surface in ephemeral soap bubble models they created. He knew structures that restricted the primary stresses to axial stresses (compression and tension) were scale-independent which meant that accurate models built of these structures could be translated into final building designs. This was the first focus of the Institute's work

In less than ten years, physical models were used by the IL to design and document three innovative spatial shell structures: the German Pavilion for the Montreal Expo (1966-67), the Munich Olympic Stadium Roof (1968-72), and the Mannheim Multihalle (1973-74). These projects all had time sensitive deadlines for design and construction so the models needed to provide more than just form-finding. The IL built accurate models of the structures that could not otherwise be defined using mathematical models, measured and surveyed these complex forms, translated these measurements into systems for mathematical analysis and produced accurate working drawings. Through their research and experimentations, they realized that

Figure 2: One of Isler's hanging glass-fiber shell models under-going testing, 1967.

physical models at various scales of complexity and resolution could be used for distinctly different purposes in structural design, documentation, and ideally, construction process.

This specialized design process wasn't just developed by Otto or the IL, it was a collaborative and reiterative process of practice and research that included architecture firms, other structural engineers, additional research groups at Stuttgart, computer engineers, and various contractors and manufacturers. Although models were still the center point of the design process, each project revealed the benefits and inherent limits of the model's usefulness. Once these limits were found, these multi-disciplinary collaborative teams evolved the process by developing more specialized uses for the model's information, eventually leading to innovative means of documenting, analyzing, and constructing these unique buildings.

IMPORTANCE OF ACCURACY

The German Pavilion in Montreal was the summation of years of research on structures made of lightweight membranes, nets and grids completed by the IL and Otto. These types of structures could cover large areas with minimal materials by taking advantage of using only axially stressed load-bearing members in tension. Pre-stressed cable net and membrane structures were incredibly new (first built in the 1950s) and relatively untested—nearly any form seemed possible to create. Like Isler, Otto had experimented with model making as an effective way of finding an efficient and expressive form for a double-curved surface for years.

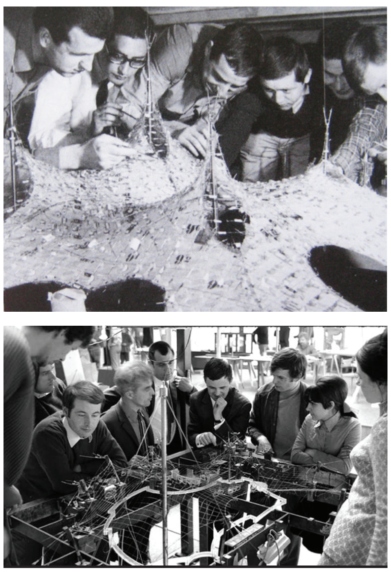

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Figure 3: Team members of the IL measuring the Tulle model for the German Pavilion (top) and discuss the development of a wire model with Otto (bottom).

The German Pavilion needed to be completed only 14 months after design began, with only a few months allocated to construction, so the building had to be structurally efficient, and easily constructed. With this compressed time frame, the design team knew that the model information would need to be accurate and translatable to construction so that the structural elements could be measured, cut, shipped to Canada for rapid on-site assembly.

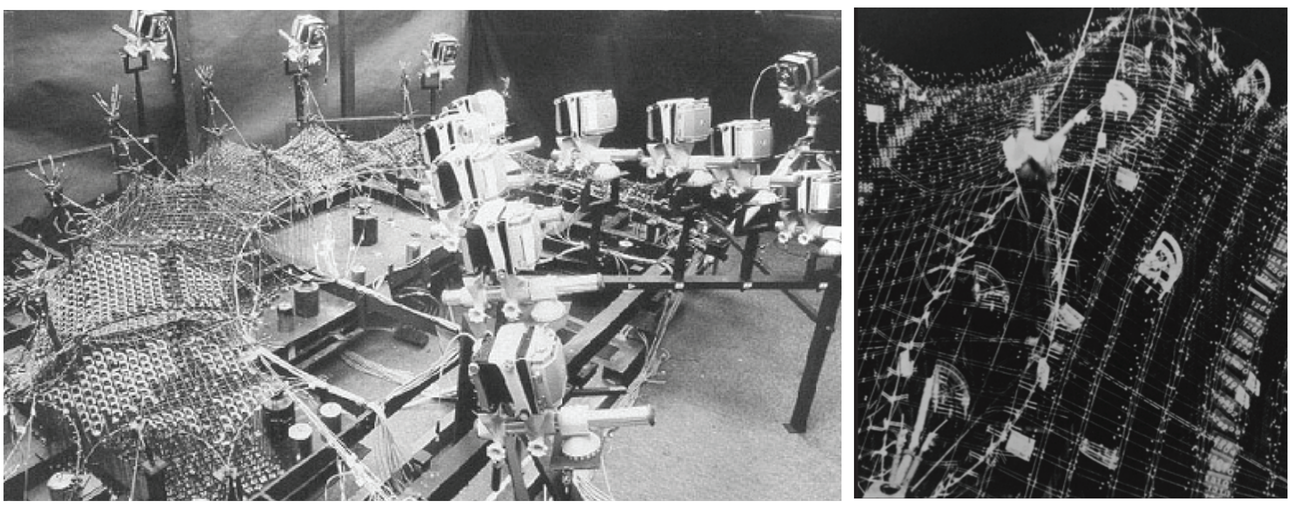
For this project, the IL developed a rigorously diagrammed design and testing process that progressed from liquid film models for form-finding, to Tulle models that accurately described the boundary conditions and tested the overall geometry, and eventually to larger pre-stressed wire models with strain gauges to test and analyze the forces acting upon structure and its anticipated deflection (Figure 3). A 1:75 model with geometrical and elastic properties similar to the roof itself was built, and the cutting pattern data for the cables and membranes was taken directly from the model, by manually measuring the length of different cables and through a rudimentary process of converting stitched photographs of the model together to produce an elevations view of the border strip profiles that could be traced and drawn by hand (Linkwitz, 1971). The geometry of the membrane patterns was found by placing tissue on the model, cutting it to fit, and then tracing the final pattern flat (like a dress) as a plan.

Similar to Isler's struggles in documenting the shell geometries, this process was inherently flawed because it relied upon the perfection of the model and accurate measurements to achieve the promised efficiencies—every error in the model no matter how well-crafted, when scaled up 75 times the size, made each problem profound. In pre-stressed cable structures, the key to achieving structural and economical efficiency is found in minimizing the size and length of the cables, and so small deviations in measurements or anticipated levels of tension stress result in over-sizing the cables diameter and length. Although the finished project was beautiful, structurally innovative, and built in only six weeks, it was still more expensive and inefficient than it needed to be. The IL recognized that this was mostly as a result of these inaccuracies of translating the model to mathematical analysis and construction.

MODELING, PHOTOGRAMMETRY AND COMPUTER INTEGRATION

Only months after the completion of the pavilion in Montreal in 1967, Behnisch + Partners and Otto's design proposal for the Olympic Stadium complex in Munich, an undulating landscape of hills and buildings covered by a massive continuous membrane roof, was selected as the winner of the design competition. However, the review committee expressed concern about the viability, technical performance, and cost of Otto's proposed continuous roof system and referenced the Montreal pavilion as the basis for this criticism (Eekhout, 1972). It took more than a year of additional proposals, refinements, and reviews before they were finally given the approval to proceed, which compressed the design and construction process to the degree that these phases would overlap. The design team knew that models again would be the main source of information, but other tools would need to be used to improve the accuracy of measurements and analysis.

Work proceeded with the IL's design process of developing a testing a variety of models at different scales and with different materials. It was rigorous work to manually pre-stress the cables to a state of equilibrium across the model, but this was necessary to ensure the viability of the analytical information that followed. They had done this on Montreal as well, but the accuracy of measuring and recording these model dimensions improved considerably thanks to the photogrammetric surveys of Prof. Klaus Linkwitz and the Institute of Geodesy (IFG) from Stuttgart.



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Unlike the 3D measuring tables and the photographic process used in Montreal, these new image-based surveys synched several cameras together to get an accurate overall picture of the model—including the ability to generate before and after images of the model under stress testing to record deflections (Figure 4). The images were more accurate representations of the overall geometry of the structure, and provided physical documents that could be measured (and re-measured) as needed. After photographing the model they found the x, y, and z coordinates of all system points (i.e., the intersection of cable nets) and the geometry of edge cables. This information was entered into a rudimentary "automatic drafting machine," a precursor to today's computer drafting programs, which produced a contour plan of the roof and elevations of the cable grid (Linkwitz, 1971).

There was no practical precedent for designing and building a net structure at this scale so all the work needed to be innovative and verifiable. Otto wanted to build a bigger model (1:125) to improve the accuracy of these calculations using strain gauges to measure the tension in each cable, and using the model as the basis for establishing cutting patterns for cables and roof tiles. But Linkwitz and the IFG objected to this approach, arguing that "exact models and

Figure 4: Photogrammetry process of Munich roof model under loading (left). Before and after double exposures show the anticipated deflections after loading (right). Images from Zodiac 21, 1972.

measurement may be imagined but do not exist in reality.” They pointed out that to achieve their economic targets of structural efficiencies, a 50m cable could only have a maximum deviation in length of 10mm and that this degree of precision could not come from a model and called these “intolerable risks.” (Linkwitz, 1971).

Developing more accurate final refinements of the geometry for Munich’s roof was also a concern for other project collaborators, including the structural engineer responsible for construction, Jörg Schlaich, and the renowned computer scientist, John Argyris. Both men favored the use of the computer as a more accurate tool and developed a program so the roof could be analyzed based on the initial values from the photogrammetric measurements. Because the model was in theoretical equilibrium, the resulting data and dimensions allowed engineers to simplify their static calculations (although there were still 10,500 inter-related equations related to the points in space to calculate) which in turn allowed them to improve upon the exactness of their calculations of stresses in the system (Argyris, 1972).

There was a disagreement about the relative value of the model versus the computer because Schlaich, (a former student of Otto’s at Stuttgart who became a celebrated structural designer and researcher), criticized Otto’s resistance to embrace the computer in 1972, claiming that Otto, “was, and still is, against the computer applications…for him, all computer calculations are suspect,” (Linkwitz, 1972). Argyris, who is credited with developing the finite element analysis technique, which essentially analyzes the structural behavior of arbitrary cable networks (or elements) spread across a surface, needed the data on Munich to be accurate and computerized. The final computational work involved a great deal of data “very large computer installations,” but Argyris was clear that computation wasn’t automatic and that “it still required that the engineer take an active part during the calculation.” (1972).

Eventually, to complete Munich on time with the exactness required, the computer was used to make the final calculations and to establish the cutting patterns for working drawings. This process of creating a three-dimensional model with an established set of geometric and material parameters that could be drawn and calculated by a computer was certainly a precursor to the contemporary methods of parametric modeling and analysis. The data, of course, was still reliant on the basic input source of the model form.

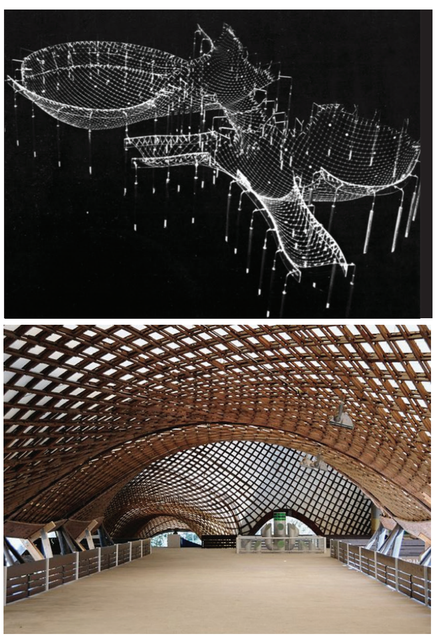

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Figure 5: Computer model of the Multihalle shell geometry translated from Arup’s hanging chain model, 1973 (top). Interior view of the finished Multihalle timber grid shell, 1974 (bottom).

COOPERATIVE TOOLS FOR INNOVATION

The following year, Frei Otto worked with architect Carlfried Mutschler and Ove Arup & Partners on a competition winning entry for a large timber grid shell for the Bundesgartenschau Multihalle in Mannheim. Like Montreal and Munich, the project was unprecedented in size and complexity and there was no clear analytical system in place to understand the structural behavior. Arup, who had been critical of Isler’s approach to form-finding through models fifteen years previous, knew now that building and testing physical models would need to be a central part of this design process. In correspondence with manual structural analysis and computer analysis, Arup’s office built wire mesh models as 1:300 to establish the basic form of the structure and then a 1:98.9 scale hanging chain model to find the geometry of the boundary supports and the final roof form (Addis, 2014).

These timber grid shells overlapped in a lamella pattern, resembling a net. Arup’s engineers manually hung and adjusted the chains until a continuously curved tensed surface appeared—somewhat expectantly this resembled the hanging fabric models presented by Isler. Because of the continued development of the IFG’s photogrammetric process, this model was surveyed and converted into a computer program that produced an accurate 3D model of the hanging structure. This model was used for manual and computer analysis for the shell, but it also was able to present three-dimensional information about the building on the screen (Figure 5A).

While these advancement in computer modeling are significant, one of the project's most significant innovations—a construction scheme that allowed the project to be built flat and lifted it into its final double-curved shell form in place—was found by building the scaled model and prototyping the double lath pinned connection of the grid shell (Figure 5B).

"IS THE PHYSICAL MODEL DEAD?"

Nearly 40 years after his initial presentation at the IASS conference, at a Structural Morphology Colloquium, Isler presented a paper titled, "Is the Physical Model Dead?" While ceding that computers excelled in calculating and defining complex geometries of shells, he argued that the physical act of making the models provided insights that couldn't easily be replaced. First, he noted that because the computer's output is dependent upon the quality of information put into it, the logic of finding and shaping a form in three dimensions is still enhanced by the visual and haptic senses used in making models. But he ended with a more philosophical argument that shell designs should be exploratory—whether that exploration is about physical form, structural behavior, or construction process, and that physical models were uniquely insightful in this exploratory process. In a conversation with his biographer, Isler was more explicit about the computers and models, "Today with computers you can simulate it but it is not real…you can't touch it, you cannot see the stresses. But here you see it," (Chilton, 2008).

In an interview in 2004, when asked about the usefulness of computers in the search for optimized forms, Otto also made a larger philosophical argument about the role of models in the design process, stating, "The computer can only calculate what is already conceptually inside of it; you can only find what you look for in computers. Nevertheless, you can find what you haven't searched for with free experimentation," (Songel, 2010). In 2015, weeks before his death, Otto was named the 2015 Pritzker Prize Laureate, architecture's highest prize.

Ultimately for both designers, model making was simply an effective, albeit central tool used to help them create new structures and to explore the limits of traditional practice tools and processes. Although the specifics of their processes developed differently, both designers saw models as simply one tool out of many required to understand and document the building designs. Ultimately, to build their highly creative and experimental structures, they relied upon corresponding evolutions in the models they used and the information it provided—a critical lesson for designers in any era.

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