Design and Modelling of Heinz Isler’s Sicli Shell

Chu-Chun CHUANG¹, John CHILTON ²

¹ 5 The Mount, Guildford, GU2 4HR, United Kingdom

Je07guy@hotmail.com

²Department of Architecture & Built Environment
University of Nottingham, UK

john.chilton@nottingham.ac.uk

Abstract
In 1969 a thin concrete shell roof designed by the master shell builder Heinz Isler was erected for the fire extinguisher manufacturer Sicli, SA, in Geneva, Switzerland. From this research carried out at the Heinz Isler Archive at ETH Zürich, it was found that more, previously unrevealed, alternative proposals and physical models were employed to accomplish this project.

This paper describes an investigation of the original physical modelling process of the Sicli shell and discusses the infinite potential of form-finding methods for shaping a good shell. Four alternative free-form design schemes proposed by Isler for the Sicli shell, in addition to the final chosen hanging cloth modelling approach, are introduced and discussed. The actual construction details of the Sicli shell will be reviewed with regard to both architectural and engineering perspectives. In conclusion, more research to be carried out on the valuable legacy of Isler’s form-finding techniques is suggested.

Keywords: Heinz Isler, concrete shells, conceptual design, form finding, optimization.

1. Introduction

Due to their economical consumption of material and large load bearing capacity, thin concrete shell structures were successfully and widely used during the 1950s and 1960s. Among all the famous engineers, including Eduardo Torroja (1899-1961), Félix Candela (1910-1997), and Anton Tedesko (1903-1994), Heinz Isler (1926-2009) was the individual who concentrated on the free-form design of shells instead of pursuing the ultimate thin surface with geometric forms. Conventional shells formed in geometric shapes were easier to calculate and fabricate but mostly were not structurally optimised. Thus, Isler has brought the design of concrete shells into a new era through his natural form finding process. At the first IASS Congress, in Madrid, in 1959, Isler introduced his most notable innovations on thin shell modelling approaches, two of them being conducted through a natural process, namely the membrane under pressure and the hanging cloth reversed method. (Isler [1])

Having constructed around 1400 shell projects all around Europe, the contribution of Heinz Isler in the field of thin shell structures has indeed inspired many engineers, architects and academics, from Princeton University and beyond. However, it is almost impossible to accurately analyse Isler’s shells since he never revealed the precise geometry of his structures and had always been reluctant to release or publish them. (Ramm [2]) Recently a research group from Delft University has been working on 3D scanning and investigation of his works of engineering art. Their research was to evaluate the structures by finite element analysis and curvature analysis aiming to investigate the shell’s behaviour, and contribute to the development of new types of shell in the future. (Borgart [3]) In-depth research providing insight into Isler’s splendid shell projects, from their artistic expression to realization are...
presented in (Chilton [4]). However, plenty of his built or unconstructed projects remain to be examined in greater detail. Thus the aim of this paper is to investigate the relatively unexplored shell design procedures for one of Isler’s shells, for Sicli, SA, in Geneva, Switzerland, to carry forward his legacy.

2. The Sicli SA Factory Shell and Isler Archive

The Sicli SA factory shell is the most complex free-form concrete shell project of Heinz Isler, completed in 1969 for a fire extinguisher manufacturer in Geneva. This reinforced concrete shell has been celebrated for its organic shape which fits perfectly with the mountainous surroundings. The building is composed of a 1,100 m² fabrication hall and a two-storey administration centre sharing an open space in between. Total span of the building is about 33 x 53.5m, with a larger shell sized of 35 x 30 metres and a smaller asymmetric surface. Rising from seven supports the shell has a maximum height of 8.75 metres above ground. This building is the result of making use of the maximum available site and an irregular plan was formed. (Isler [5]) Designed by Isler’s most notable natural modelling approach, the reversed or inverted hanging model method, the shell is derived from two adjacent hanging membranes with one mutual suspension point. However, sufficient detail of the form and the early conceptual design process of the Sicli shell have not yet been published or investigated.

The ETH archive in Zurich currently documents and organizes most of the valuable works and research of Isler, including physical models, drawings, correspondence and the equipment for conducting tests. Moved from his former office in Lyssachschachen in 2011, the archive has now been relocated in the basement of an office building near Zürich city centre. (Abel et al. [6]) Thousands of projects either completed or never constructed are documented in boxes of files and numbered chronologically in this archive. In addition, many paintings and sketches by Isler, including representations of nature can also be found there. This archive supplies a magnificent resource and plentiful source of inspiration for future generations of researchers to visit. In this research the most important material was sourced from 14 file boxes in the archive, containing papers showing the progress of the work from conceptual to detail drawings, together with additional physical models.

3. Possible design solutions for the Sicli factory shell

“To design a good shell a few unconventional stages have to be run through. The most important is the first one: the conceptual design. Here the traditional roles are reversed. Usually the architect makes the form. In the shell design, the engineer creates the form.” (Isler [7]) Isler had ascertained the significance of structural considerations in thin shell design at the early stage, emphasising the importance of integrating structural liberation into conceptual design and that a profound knowledge of mechanical behaviour should dominate the form. However, in most cases the design process is reversed. The Sicli shell project is one of the perfect examples that support Isler’s arguments through his collaboration with the architect Hilberer.

Five possible solutions were developed for the Sicli shell in 1967, two years before its erection. Each was annotated alphabetically as a possible solution for the project and each was developed to a different level of resolution with the assistance of physical models. Solutions A to C, Figure 1(a), were found as sketches on one sheet of paper dated 5.7.67 with concise descriptions for each of their geometries, structural types and feasible building materials; these were translated as:

Solution A: a shell formed square in plan as the main factory with a flat roof for office area
Solution B: a shell shaped square in plan for the main factory and a tent as the roof for office area
Solution C: an elliptic shell roof for the main factory and a curved conical thin concrete shell over the office space.

On the other hand, solution D, Figure 1(b), dated 6.7.67, was developed subsequently, along with a physical model to demonstrate the idea. It can be described as a snail-like spiral concrete shell roof surrounding an atrium roofed with glass reinforced polyester.

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3.1. Composite Free-form shell

3.1.1 Solution A

Solution A, shown in Figures 2(a) and (b), is one of the proposals for this project that was explored in more detail and interior planning was well developed. The scheme is a combination of two different forms: a factory shell with plan dimensions of 35 m x 30 m; a free-form curved roof on a two-storey administration office to one side; and an open space in between. Resting on four corner supports, the main factory shell has a height ranging from 4 to 7 metres and forms a rectangular space in plan. This free-form shell is elevated one metre above the ground, with a basement extending 4 metres below forming its foundation. The four corner supporting structures were designed deliberately with rising slopes, as shown in Isler’s sketches in Figure 2(a), to create an elegant lenticular shape for the façade glazing. In addition, an intention to stiffen the edge by upturning cantilevers can be seen from the model. This emphasizes the significance of boundary conditions for the shell and ensures better long-term performance. For reasons of aesthetics and artistic expression, Isler usually avoided thickening along the shell edge as this conveys a bulky image. Such strategy was applied in his series of free-form shells, starting with the Wyss Garden of 1962 and terminating with the Burgi Garden Centre of 1973. (Chilton [4])

To create a harmonic language between the two different structural systems of the roof, the administration block is covered with another contoured form. High density foam was used for the 1/100 scale physical model, Figure 2(b), to study the feasibility of this scheme. Possibly the roof model for this was carefully hand crafted by Isler himself. The method is one of the approaches that was largely applied in Isler’s early work and an abundance of experience of shell design would be required. Basic circulation was already reasonably defined by the collaborating architect Hilberer to comply the specified functions for the space.

In terms of indoor light quality, a skylight at the top of the main roof was employed to solve the problem of the large covered area preventing light transmission to the interior space. Similar to most of Isler’s previous works, the skylight is assumed to be a glass-reinforced polyester dome. However, the two roofs intersect at an ambiguous detail with the two shells forming an abrupt connection where the structural behaviour may be a concern. According to the model, part of the rounded office building roof perches on the factory shell and it is likely that concentrated load would be applied on the surface over a small area. This could potentially adversely impact the behaviour of the whole shell. However,
this solution appears not to have been chosen for further development and modelling tests, as evidence was not found in the archive.

Figure 2: (a) Design sketches of solution A (left) and (b) Physical model of solution A (right) (© gta Archives / ETH Zurich (Holding Heinz Isler)) (Photos: Chu-Chun Chuang)

3.1.2. Solution B and C

Solutions B and C appear only to have been developed to a conceptual design stage, as no physical models or further detailed drawings were found in the archive. In solution B, a combination of free-form shell and tensile textile structure was suggested through sketches. However, one of the challenges may be the junction between two different types of structural system whilst keeping the two spaces linked from an architectural point of view. Possible conflicts may appear in the details as occurred with solution A. In addition, the aesthetic value was always one of Isler’s main concerns when judging his designs. In the case of Solution C, an elliptical concrete shell was suggested for the main factory and a curved conical shell over the office. This solution appears to have a similar problem of connection of the two surfaces found in Solution A. These three different solutions implied the intention of providing different heights by separating the two spaces whilst maintaining accessibility between them. All of these solutions might have been feasible, but it seems that aesthetic considerations are most likely to have been the main reason for Isler to reject them.

3.2. Free-form shell design

Solution D, Figure 3(a), was subsequently developed. It is very distinct from the previous proposals in that through the idea of merging the two main spaces together - administrative office and factory - a more unified form could be perceived. Since Isler had always been fascinated by nature and inspired by its creations, it is inevitable to associate the form with some natural object – a shell perhaps - that Isler had been observing. The unprecedented spiral form unifies the two spaces with one surface and the relatively slim shell thickness avoids a bulky appearance. This solution also meets the desired building area of one and a half floors above the ground. A slightly concave roof made of polyester at the centre connects to the surrounding concrete shell by clerestory windows to introduce light into the interior. An interesting level change ascends with the rising height of the spiral. The shell roof is self-supporting connecting to the ground at fourteen points to form a scalloped edge and creating a semi-outdoor space around the building. However, before this solution was developed to a higher level of detail, Isler proposed another fascinating solution to create an alternative all-encompassing surface. This striking scheme is perhaps his most notable shell design using the reversed hanging membrane modelling approach and resulted in the Sicli factory as it stands today.
3.3 The Reversed Hanging Membrane Modelling Solution

The final approach, which resulted in the present Sicli shell, was applied to find a form that naturally splits the mass into two separate functional spaces whilst unified by one single surface and also allows light to penetrate into the interior. It was formed by Isler’s most notable approach, the reversed hanging modelling technique. The idea was to hang an elastic surface between supports and allow gravity to shape the form of a catenary surface in tension. If inverted this creates a form in pure compression under its self-weight and provides the stiffness to resist local instability. Isler’s first project demonstrating the same method was the laboratory and research facility for Gips Union, SA, Bex, completed in 1968, which was closely followed by the iconic Deitingen Süd Motorway Service Station, with its remarkable double triangular shell roofs. (Chilton [4]) This form finding approach was deemed by Isler to be the best way to achieve the structurally optimal state. Hence, during the design procedure Isler carefully conducted every modelling step on his own to assure the ideal outcome.

Figure 3: (a) Physical model of solution D and (b) models of both solution A and D for Sicli project © gta Archives / ETH Zurich (Heinz Isler Archive) (Photos: John Chilton)

Figure 4: Experimental model on rectangular grid fabric © gta Archives / ETH Zurich (Heinz Isler Archive) (Photo: Chu-Chun Chuang)

3.3.1. Experiments for Reversed Hanging Membrane Modelling Shell

About 15 physical models for the Sicli shell, produced by the hanging membrane technique, were found in the Isler archive, and each of them was an experiment based on various materials, such as isotropic rubber or orthotropic textiles, in order to determine the optimal shell form. Different high quality rubber membranes were tailored to fit seven suspension points fixed on a timber board. A uniformly thick layer of plaster was subsequently applied to the rubber membrane and distributed evenly on the surface. The weight of the plaster induced pure tension stresses in the membrane surface to shape the equilibrium state. At this stage, the building height can be influenced by the initial size and tension of the membrane and thickness of plaster used. To ensure that the model acquired the
desired equilibrium state, Isler applied a selected high-quality latex rubber membrane which has consistent isometric properties to allow stresses to be evenly distributed on the shell surface. (Chilton [8]) According to Isler this technique is worthwhile for shells of medium span (up to 30m) but it is indispensable for shells of large span to conduct a high precision form-finding investigation. (Isler [5]) In the case of the Sicli shell an in-depth structural investigation through physical modelling was subsequently carried out on the preferred form.

3.3.2. Load Testing for Sicli Shell

Although computers were already in use for solving structural problems in the 1960s, and could possibly have been used for simulating the behaviour of his shells, Isler still insisted on making physical models to predict their behaviour by experiment. However, much patience and accuracy are required to guarantee adequate structural performance through physical testing and many tests need to be conducted for innovative shapes. After the final shell surface was defined, a jig that allowed Isler to set up a grid of x- and y-coordinates in plane was constructed to measure the form and transform it into tangible numerical data. This jig allowed Isler to measure the z-coordinate of each set node with a pointed probe according to the variable surface. The density of the grid could be amended to adapt to different demands in terms of different size of the shell and curvature of the surface. (Chilton [9]) In the Sicli shell, a 1/50 scale model was assigned and a grid of 57 x 35 was used to obtain accurate measurement data. The contour lines were first projected on paper to overlap with grid lines and distribute the measurement points on the shell’s surface. The z coordinates which represent the height were then transcribed into a table of all the point data to present the form accurately. Over 1500 coordinates were measured in the Sicli shell project to an accuracy of 0.01m.

Subsequently, both small- and large-scale load testing models were made of epoxy resin referenced from the dimensions measured on the plaster cast. Given the considerable time and effort that needs to be invested in accurately reproducing the measured surface it is suggested that the former, shown in Figures 4(a) and (b), was used for a preliminary rapid study to establish feasibility and that the latter, Figure 5, was used for a more accurate investigation of potentially critical areas where buckling of the surface might occur. The large-scale experiments aimed to test the buckling resistance of the surface using a rig which allowed Isler to modify the internal forces in the shell by varying the load distribution on the surface and to explore the effect of differential movement of support points. (Chilton [8]). Dimensional analysis was used to simplify the scale problems of the physical models for solving geometric problems.

Figure 5: (a) Small-scale epoxy resin model (left) believed to have been used to prove feasibility and (b) (right) detail of the load application system (Photos: John Chilton)
4. Construction Details of Sicli factory shell

Due to the complexity of shell surface, the on-site construction had to be carried out very carefully in all important details. Three main factors in the construction process brought Isler’s shells to a successful outcome, namely: the high precision and economic on-site construction methods; the materials for the formwork were selected so that they could be easily moulded in all directions; and the high quality of the concrete. (Bösiger [10]) Despite the quality of building material and on-site techniques, certain temporary works were required including scaffolding which was usually used to support the load of up to 300kg/m² of the total system. (Chilton [4]) Glulam timber beams were applied in a parallel array to support transverse timber laths. Insulation was then used as left-in-place formwork before applying concrete on the surface. All the details were prudently designed in advance to guarantee its high quality.

The necessity for extensive formwork and false-work was one of the main concerns for the expense of constructing shells in the 1960s and also influenced shell sizes in general. Fortunately, the Sicli factory was erected before the recession in 1975, after which industry and commerce invested much less in new buildings. Thus a more customized form could be adopted. Nevertheless, due to the constantly changing curves of the Sicli shell surface, the construction became more challenging and expensive compared to more conventional construction where repetitive formwork could be used. However, having the extra support from his collaboration with Bösiger the construction company, Isler had already accomplished many shells with benefits including keeping the price competitive in the market. According to Bösiger, Isler initiated novel construction methods. Thus they had an agreement that the know-how would not be passed to third parties. In particular, Bösiger would use special glued binders in timber which were produced specifically for Isler’s shells and most of them were rather costly. (Bösiger [10])

The general thickness of the concrete in the Sicli shell is a mere 90 mm, which is only about 1/500 of the maximum span. However, in order to prevent buckling at the supports, where roof loads are concentrated, the thickness of concrete is increased up to 300 mm near to the foundation, incorporating additional pre-stressing. The seven supports were laterally fixed on the concrete foundation. The shell surface was formed without edge beams along the boundary but with a fluted, curved edge naturally shaped by its modelling process. This helps to increase the shell’s stiffness and create a visually pleasing shape. In addition, four pre-tensioning cables were incorporated in the foundation to resist lateral forces from the shell under all possible external loading conditions. They are used to hold the shell’s supports from diagonal directions thus to maintain its stiffness.
5. Architectural Aspects of Sicli Shell

One of the challenges for shell design is the fact that they are both primary structure and building envelope, where architectural functions such as providing human comfort and aesthetic value should also be integrated. (Isler [7]) Thus Isler paid much attention to details to control the interior qualities including thermal performance, daylight and relative humidity levels. The general thickness of the shell was determined by the requirement for two layers of steel mesh composed of two directions of 6mm bars with 35mm diameter plastic tubes in between as spacers to maintain the appropriate distance. Covered with just 15mm of high-quality concrete on each face to protect reinforcing steel from corrosion, the total thickness reaches about 90mm, see Figure 6(a). Wood wool slabs 50mm thick, for thermal and acoustic insulation, were applied as permanent formwork under the concrete layer to achieve cost savings in the shell construction. Combined with the light pre-stress applied to the shell surface, this system practically eliminates concrete cracking, making it more waterproof and improving long-term durability. According to Isler, the double-layer reinforcement accommodates any local bending moments and/or unforeseen tension stresses.

5.1. Transparent Dome as Skylight

A skylight 1.2 metres high on top at the centre of the roof in the area of relatively low stresses was used to provide natural daylight permeating through the interior of the factory shell. In the Sicli project, a double layer translucent dome was used. With 5mm air gap between, the two layers of glass reinforced polyester are stiffened with ribs on the inside face. Considering the weatherproof performance, the reinforced polyester shell dome had to cover a 3.25m radius opening in the concrete. From the detail drawing, a customized skylight would have to be made in order to adapt to the unique shape and size of the shell roof.

Figure 7: (a) Detail of shell section and (b) deformations of the observed points (© gta Archives / ETH Zurich (Heinz Isler Archive) (Photos: Chu-Chun Chuang)

6. Deformation and Structural Behaviour

The deformation is the proof of good or bad form. (Isler [11]) Isler always insisted on assuring the quality of long-term behaviour of his shells and believed that an innovative shape should be examined after its erection. Only after years of careful observation and monitoring could he guarantee the quality of a form. The good form of the Sicli factory can be confirmed by its long term deformation
characteristics revealed by Isler’s observations. For nearly two decades after the factory was completed, Isler carefully measured and observed the deformation of the structure since the shell was erected (from 1969 to 1988).

Different from elastic deformation which disappears when the load is removed and can be predicted by calculations, the long term inelastic behaviour is what concerned Isler more. This requires much more patience to measure, due to the results being somewhat influenced by the external conditions such as temperature and humidity. Thus the deformation needed to be compared under similar conditions. Six measurement points, including four near the edges and two on top were observed for 19 years after the shell was erected with the benchmark of each point on the shell itself. From the diagram illustrated in Figure 6(b), it can be observed that the deformations of shell are relatively influenced by the environment and increase when temperature rises. The maximum deformation observed was about 100mm at a point near the edge of the office building, which is only about 1/460 of the diagonal span of the shell. The Sicli shell apparently was not one of the most statically efficient projects if compared to many of the others formed by Isler using the reversed hanging membrane technique. Some of his shells deform by just 1:50,000 of the span. (Isler [5]) Isler always considered the importance of observing the inelastic deformation, which determines the long term durability of a shell and implies the greater sustainability it can achieve. Not only predictions by computer simulations, but real time observation of physical models or full-scale structures are needed. (Isler [11])

7. Conclusion

Based on the extensive free-form modelling experiments and over ten years’ experience of building thin shell structures, the Sicli factory shell is indeed a good form which has been evident by its long term deformation behaviour and aesthetic pleasing form, Figure 7. The design procedure for Sicli factory shell can be summarized as:

1. Develop alternative conceptual designs for possible solutions with implications of form and building material
2. Experiment on physical models with different materials to determine the desire form
3. Conduct load tests on the selected form of the shell with high accuracy
4. Measure the deformations after the shell’s erection for future study to assure the shell’s quality

From the design process of Sicli shell, it can be concluded that the conceptual design is the most important stage for determining the shell’s form. However, the approaches should not be limited when exploring a variety of possibilities at the early design stage. In the proposals for five possible solutions for the Sicli shell Isler implied that all the physical modelling approaches have potential for developing innovative forms. Creative engineers are capable of giving full scope to their imaginations and artistic instincts at this stage.

The Sicli factory shell can be seen as a major development in Isler’s experiments using the reversed hanging membrane modelling technique and it was probably the most appropriate method to achieve static equilibrium on the asymmetric plan.

Beside the profound engineering background, the patience of trial and error is essential in Isler’s process of form finding. It is only through numerous iterations of optimization procedures that he was to develop a more structurally efficient design without the aid of computer simulations. Furthermore, the necessity of observation and physical testing are essential for building a well-formed shell. Other than form-finding approaches, appropriate construction details are vital when the shell becomes a building envelope. Here is where the ventilation, lighting condition and waterproofing as a building roof need to be considered and solved by customized detail design. 

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From the perspective of sustainability, the research of thin shells is promisingly valuable for the future, as only small quantities of material are required to span large distances. However, more innovative modelling approaches with integration of new materials are expected for the future shell design.

Figure 8: Sketch of Sicli factory shell by Heinz Isler (© gta Archives / ETH Zurich (Heinz Isler Archive))
(Photo: Chu-Chun Chuang)

References