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CONCRETE SHELL STRUCTURES REVISITED: INTRODUCING A NEW 'LOW-TECH' CONSTRUCTION METHOD USING VACUUMATICS FORMWORK

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1 INTRODUCTION

Concrete shell structures, often referred to as 'thin shells', have been around since the 1930's. The design of these thin shells was stimulated by the desire to cover wide spans in an economically attractive manner. Typically, the thickness of concrete shells is relatively small compared to the curvature and span. The main reason for concrete shells to be economically feasible (especially from a material point of view), is that shells are structurally efficient in carrying loads acting perpendicular to their surface by in-plane membrane stresses. Bending moments may occur locally to satisfy specific equilibrium or deformation requirements, but are considered relatively small in general. The construction process of concrete shells was considered extremely labour-intensive and time-consuming. From the 1960's the interest in concrete shell structures suddenly decreased. The reason for this was that the biggest motivation for designing concrete shells, reducing material costs, was losing ground to the rapid increase of labour costs.

In the last decade, curved (concrete) structures in general seem to have (re-)gained popularity, supposedly due to the vast developments in digital modelling technology. In contrast to a few decennia ago, nowadays literally all 'thinkable' shapes are easily drawn by Computer Aided Design (CAD) software and even calculated by advanced Finite Element Modelling (FEM) software. Nevertheless, the construction process of concrete shells seems to have lacked the same degree of development as the design and engineering processes. Although Computer Aided Manufacturing (CAM) equipment is available in some industries, the limiting factor at the moment, with respect to the realisation of concrete shell structures, turns out to be the manufacturability and adaptability of the formwork system.

This paper provides a new perspective on the construction process of concrete shell structures and introduces a new cost saving approach for constructing (single curved) concrete shells using Vacuumatics formwork.

2 DESIGN-BASED CLASSIFICATION OF (CONCRETE) SHELL STRUCTURES

The diversity of shell structures is vast. Any surface that is curved in one or more directions can be considered a shell surface. Shell surfaces may be defined by the classification of their curvature, expressed in terms of Gaussian curvature. The Gaussian curvature of a curved surface is the product of the two principle curvatures: $\kappa_g = \kappa_1 \cdot \kappa_2$. A positive Gaussian curvature characterises a clastic surface, whereas a negative Gaussian curvature characterises an anti-clastic surface. Cylindrical surfaces (as well as planes) have a Gaussian curvature of zero (Figure 1).

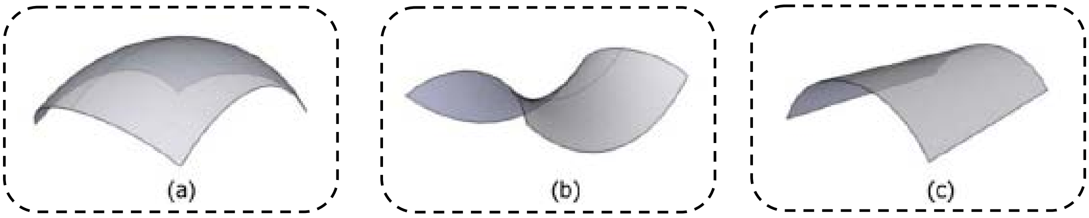

Figure 1: Gaussian curvatures: clastic (a), anti-clastic (b) and cylindrical (c)

A more comprehensive approach of describing shell surfaces, however, is by concentrating on the way the surface is generated (or designed). In 1980 Heinz Isler[1] identified three types of shells according to this philosophy, referred to as 'Geometric', 'Structural' and 'Sculptural'. In this paper we will further elaborate this classification by re-interpreting Isler's terms in an attempt to clarify the origin of each shell form.

2.1 Analytical Forms ('Geometric')

A blooming period of widespread concrete shell construction took place from the 1930's, where engineers like Felix Candela, Eduardo Torroja, Anton Tedesko and Pier Luigi Nervi managed to design, calculate and construct extremely elegant concrete shells (Figure 2).

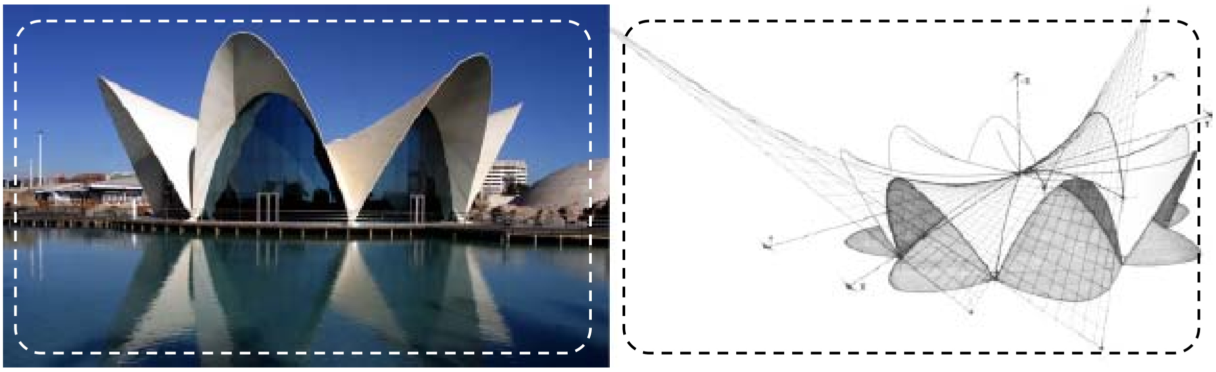

Figure 2: Les Manantiales Restaurant in Xochimilco Mexico City by Felix Candela[2]

As the designs between 1930-1950 were mainly based on mathematical defined geometries, these shell shapes can be referred to as ‘Analytical Forms’[3]. Typical traditional analytically-based surfaces are referred to as ‘revolution surfaces’, ‘translation surfaces’ and ‘ruled surfaces’ (Figure 3).

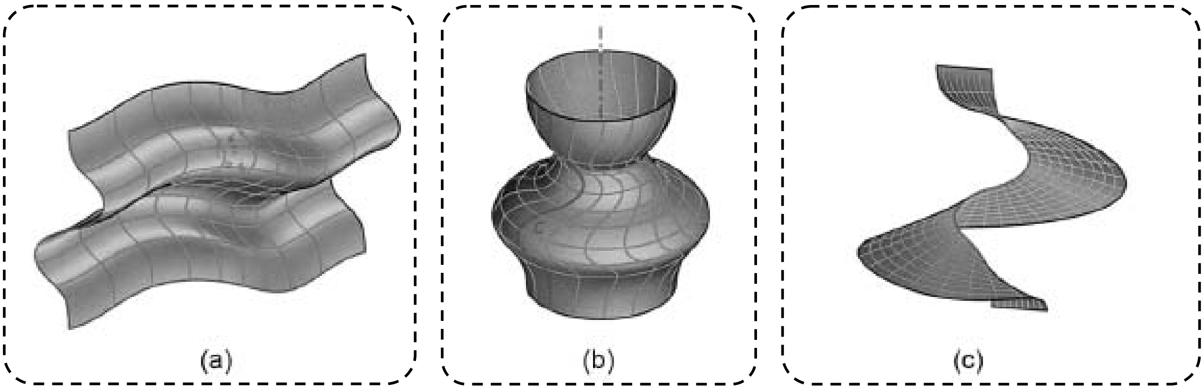

Figure 3: Analytical Forms: translation surface (a), revolution surface (b) and ruled surface (c)[4]

Since no digital design and calculating equipment was available in that time, the mathematical formulas were not only essential for drawing and calculating these structures, but also aided the actual construction process. The majority of the thin concrete shell structures were constructed by pouring wet concrete onto a rigid wooden formwork, often assembled from straight elements. This construction process required many skilled craftsmen (Figure 4).

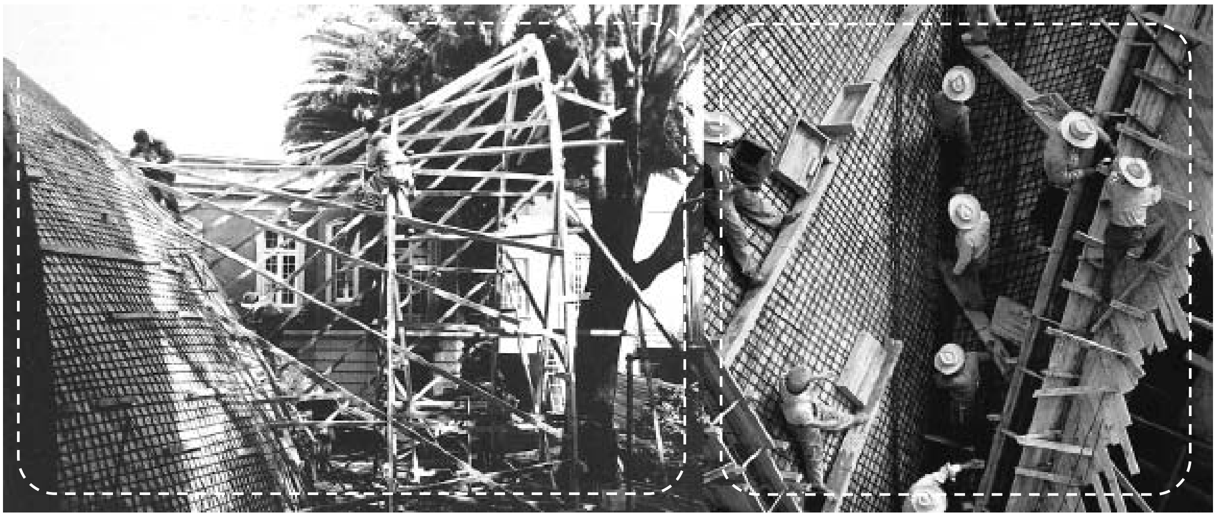

Figure 4: formwork construction by Felix Candela[2]

2.2 Experimental Forms (‘Structural’)

In the 1950’s, engineer Heinz Isler introduced a slightly different approach for designing thin concrete shells. In the spirit of Antonio Gaudi’s hanging models, he successfully applied several 'natural' phenomena, like air pressure, gravity and material flow, to design thin concrete shells (Figure 5). Due to the experimental character of his approach, these shapes can be referred to as 'Experimental Forms'[3]. Structural calculations were made by conducting load tests on small-scale models which were interpreted for the design of the full-scale concrete structure.

Figure 5: Isler's Experimental Forms, based on air pressure, gravity and material flow[5]

From structural point of view, in particular Isler's shells based on gravity, behaved superior to the Analytical Forms from the 1930's. The explanation for this is that these shapes obey the laws of nature under their own weight (pure compression or pure tension), whereas Analytical Forms are merely approximations of these 'natural' forms.

As Isler's designs were not easily described analytically, the construction process was considered somewhat more complex than it was the case with Analytical Forms. Nevertheless, Heinz Isler managed to design his formwork is such a clever way (using amongst other things prefabricated curved wooden segments) that he was able to re-use it numerous times, even integrating thermal insulation into his formwork system[6] (Figure 6).

Figure 6: formwork system by Heinz Isler[6]

2.3 Digital Forms ('Sculptural')

After a sudden decrease in interest in curved (shell) structures from the 1960's, an increased interest arose in the 1990's as rapid developments in digital modelling technology offered new possibilities for architects and engineers. Where in the past the design and engineering of curved (shell) structures were the playing field of a few experts, nowadays a larger group of designers is able to design and even calculate almost any thinkable shape. The term ‘free-form’ has become an integral part of modern design, effectively utilising CAD, FEM and even CAM technology (Figure 7). In spirit of Isler’s afore mentioned terminology, this third type of shell geometry will be referred to as ‘Digital Forms’[3]. With these types of structures the shell shape is no longer based on structural efficiency (and thus material reduction), but rather derived from aesthetics and spatial functionality.

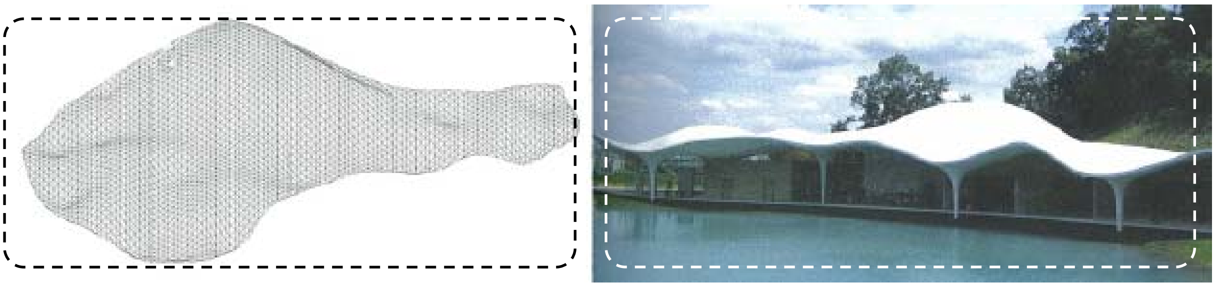

Figure 7: Kakamigahara Crematorium by Toyo Ito and Matsuro Sasaki[7]

3 (CONCRETE) SHELL STRUCTURES ANALYSED

The aforementioned shell categories might easily be considered as several consecutive steps in the evolution of shell structures. However, this would imply that each successive type is superior to the former. As can be illustrated with a timeline indicating the dominant category of each shell type, this is not the case[3] (Figure 8). All three categories are still being realised these days. Furthermore, each of the three categories has had its peaks and low points, often related to the peak of the career of an influential designer or engineer or imposed by a certain bottleneck within the building process. In many cases, his bottleneck appears to be directly related to the degree of knowledge or technology available.

In general, it can be stated that Analytical Forms originate from the need to mathematically describe a curved shell surface in order to calculate and construct them. Experimental Forms, on the other hand, are designed very intuitively and are considered structurally ‘pure’, yet more difficult to calculate and construct. Digital Forms offer an unprecedented freedom of form and can be calculated with sophisticated digital modelling technology, but are even more challenging to construct. This history of concrete shell structures teaches us that successful examples are, without exception, the result of a highly integrated design and building process. Whereas engineers of the 1930’s to 1960’s often were considered to be the architect as well as contractor embodied within one person, nowadays this synergy in (shell) building can only be achieved by making architect, structural engineer and construction specialist cooperate from the early stages of the building process[3].

When focussing on the biggest bottleneck nowadays, with respect to the successful realisation of concrete shell structures, we can conclude that the construction process in particular requires a new impulse in order to ‘keep up’ with the vast developments of digital modelling technology (with respect to design as well as engineering). In particular the manufacturability and adaptability of the formwork system (related to construction time and labour costs) seems to be the limiting factor. Focusing on the construction methods used in the past, we can conclude that the largest number of shell structures is constructed by means of conventional timber formwork. In the last few years several ‘new’ techniques have been developed (like CNC moulds, fabric formwork, adjustable moulds using independently activated pistons), but only minor success had been reached on replacing timber moulds, mainly due to lack of adaptability or lack of repetition for prefabrication, or due to a large waste production or simply because of too large initial (start-up) costs. Therefore, the need arises for an economically attractive or perhaps ‘low-tech’ formwork system, that discards the abovementioned disadvantages altogether.

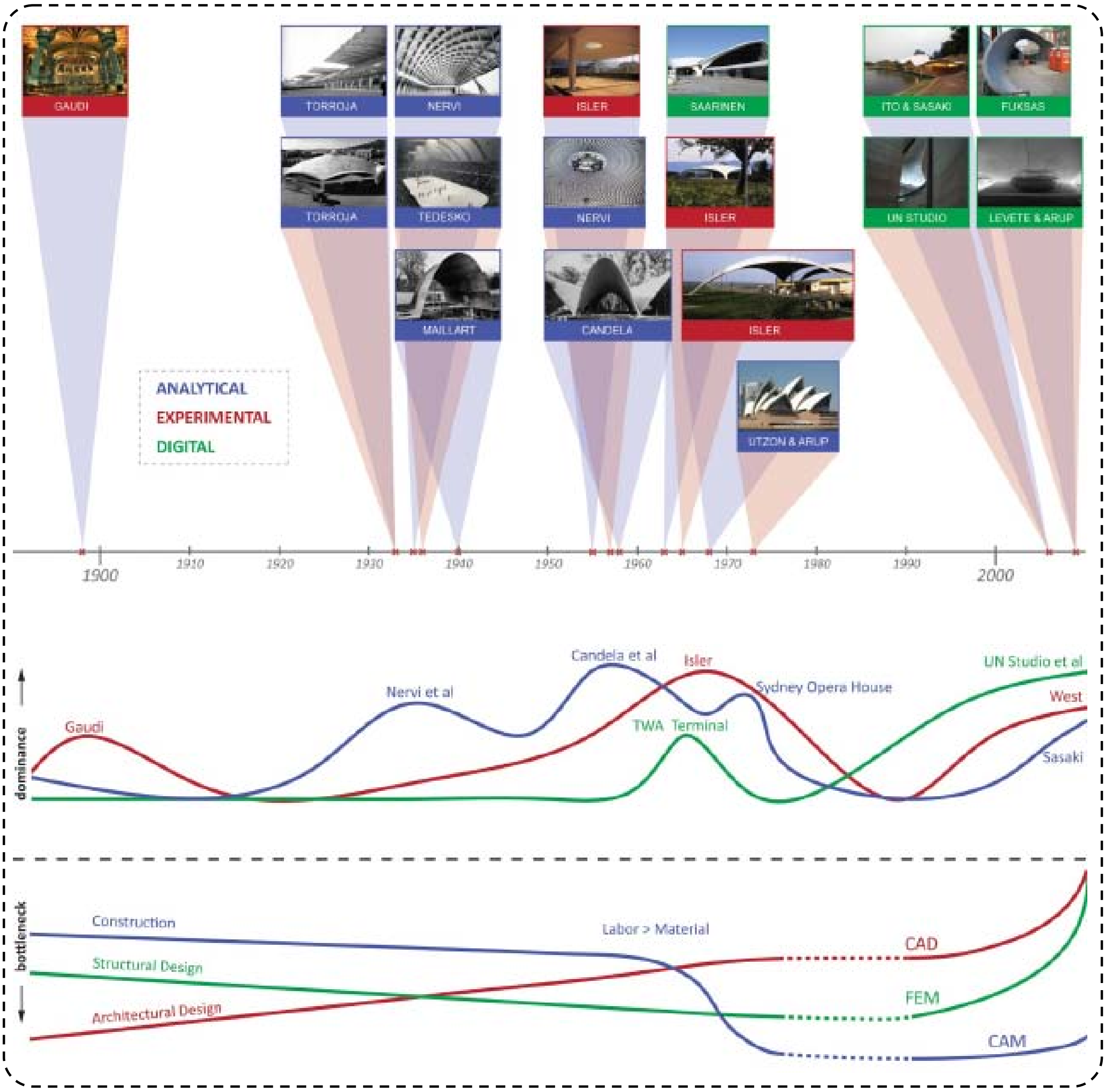

Figure 8: history of concrete shell structures[3]

3.1 A philosophy for successfully constructing concrete shells

From a theoretical point of view, it would make sense to consider the way shell surfaces are generated as the most effective construction method. Strictly speaking, many of the successful aforementioned concrete shells confirm this philosophy. For instance, Candela's designs are constructed using straight elements to create hyperbolic-paraboloid-shaped (or hypar) shells. Although Isler (as a successful exception) still used conventional timber formwork for the full-scale construction, others however, did follow the 'generation = construction'-philosophy and used an inflatable formwork to successfully construct dome-shaped shells (e.g. Binishells[3]). With respect to Digital Forms, CAM technology seems to be the way to go.

4 VACUUMATICS FORMWORK

Inspired by the aforementioned philosophy, now Vacuumatics formwork will be discussed with respect to the construction process of (single curved) concrete shell structures. Furthermore, the analogy with the construction process of gridshells will be illustrated. First, a small introduction on Vacuumatics and gridshells in general.

4.1 Vacuumatics

Vacuumatic structures, or Vacuumatics, consist of structural aggregates (particles) that are tightly packed inside a flexible membrane envelope (skin). The structural integrity is obtained by applying a (controllable) negative pressure, or partial vacuum, inside the surrounding skin, hence prestressing and stabilising the particles in their present configuration by means of the atmospheric (air) pressure. This process is referred to as 'vacuum prestressing'. When subjected to bending forces, the particles take up the compressive (contact) forces, whereas the tensile forces are mainly taken up by the membrane envelope (Figure 9). The tensile strength (and even the flexural rigidity) can be substantially enhanced by adding a piece of reinforcement (e.g. a piece of textile) in the tensile zone of the structure (analogues to reinforced concrete).

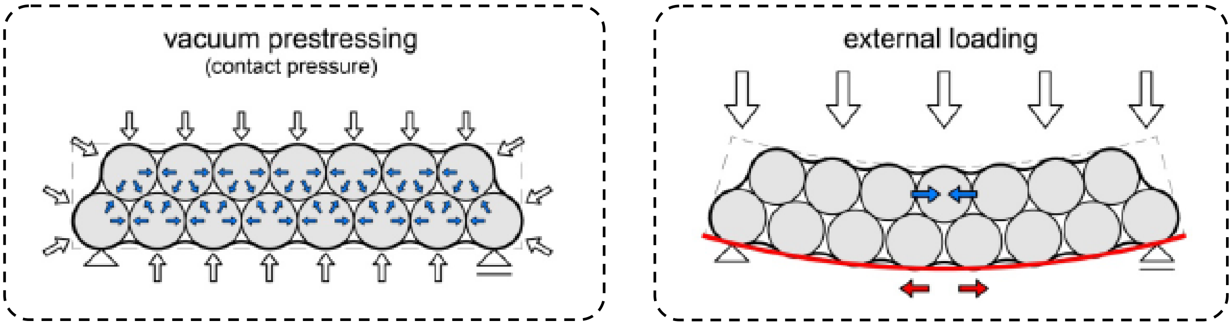

Figure 9: structural principle of Vacuumatics

The beneficial morphological characteristics of Vacuumatics are their ability to be ‘freely’ shaped and even to be re-shaped repeatedly to fulfil new geometric requirements. These characteristics provide a promising approach for the design of a temporary, adaptable load-bearing structure and thus a truly flexible and reconfigurable self-supporting formwork system[8].

As systematic research on the flexural rigidity of vacuumatic structures has illustrated[9], the structural behaviour of Vacuumatics largely depends on the individual characteristics of its filling particles and surrounding skin, as well as on the interaction of these particles with the enclosing skin and the particles mutually. Typically (when using thin plastic films like LDPE), large deflections tend to occur at relatively low bending forces (Figure 10). This specific characteristic might be used beneficially when applied as a formwork system. That is, the vacuumatic structure will be easily curved and ‘only’ needs to withstand the concrete mortar pressure until the structure is sufficiently hardened. As Vacuumatics behave substantially better when submitted to compression forces rather than bending forces, this implies that when the vacuumatic structure is shaped into its final shell form, it will be able to withstand an external load very effectively by in-plane membrane stresses. The bending stresses are, like mentioned before, considered relatively small (i.e. dependent on the shell shape).

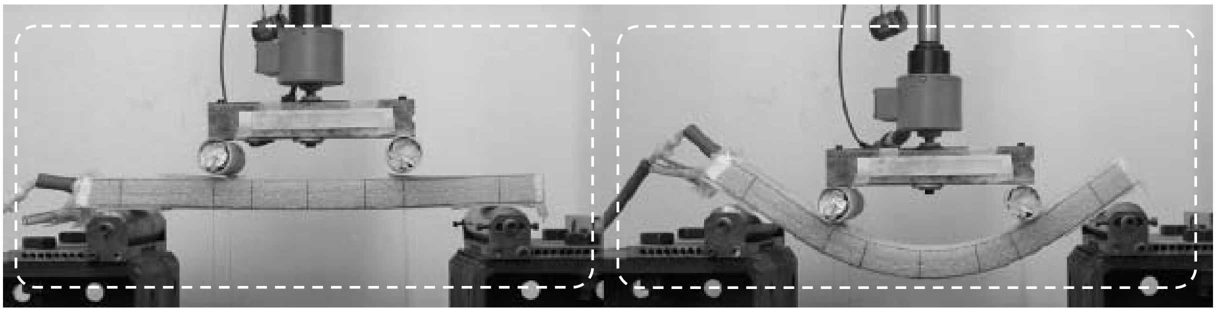

Figure 10: large bending deformations of Vacuumatics

4.2 Gridshells

An interesting approach for the design of shell structures in general was (re-)introduced by Frei Otto in the 1970’s, as he put new life into the structural principle of gridshells[10]. (Gridshells, also known as lattice shells, were originally pioneered by the Russian engineer Vladimir Shukhov in 1896). Gridshells, are basically shell structures where material has been removed to create a slender lattice grid pattern. Where in plain shells load paths are available all over the surface, in gridshells the internal forces are transferred via discrete members. Inspired by the suspension models of Antonio Gaudi, Frei Otto designed his gridshells by inverting the form of a suspended soap film or that of a flexible suspending net[10] (Figure 11).

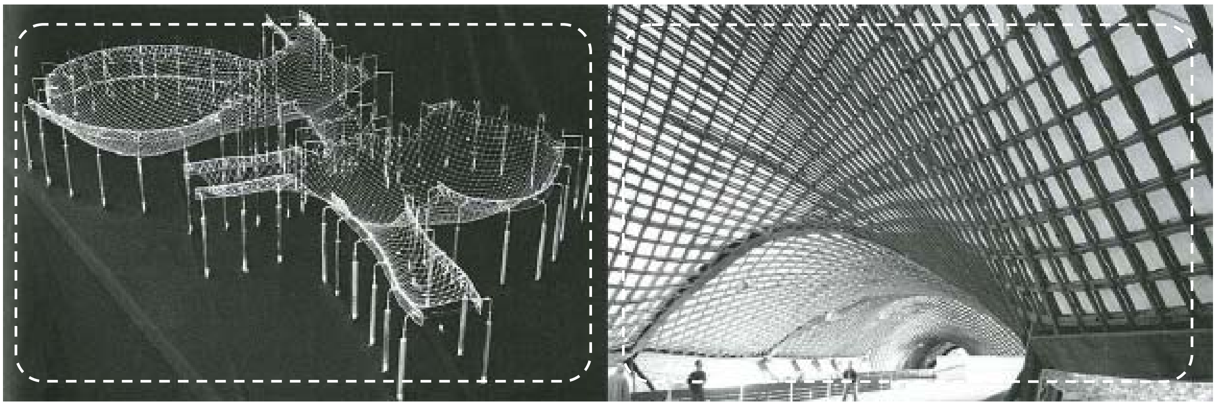

Figure 11: Mannheim gridshells design based on a hanging model[10]

From construction point of view, the powerful concept that lies behind gridshells is that the construction starts from a flat surface. The straight members are assembled on ground level as a flat mesh. The final shape of the structure is obtained by locally forcing (i.e. deforming by pushing and pulling) the members perpendicular to the surface and fixing the connections and boundaries once the shell reached it desired (equilibrium) shape (Figure 12). To allow this transformation to take place, the connections of the grid need to be initially ‘flexible’, enabling scissor motion as well as sliding motion.

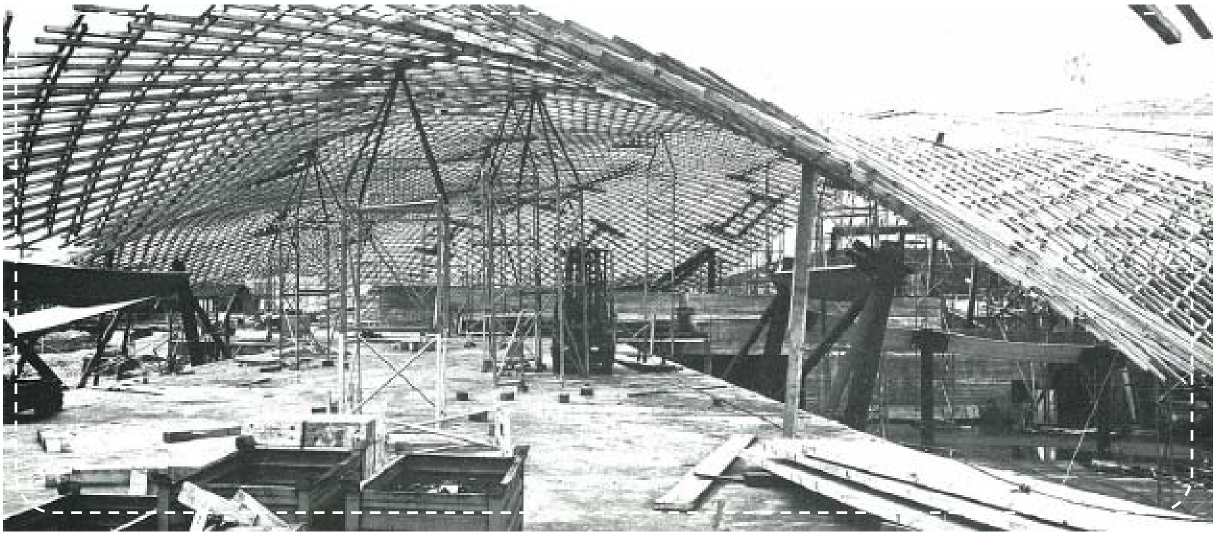

Figure 12: Mannheim gridshell construction[10]

5 VACUUMATICS FORMWORK IN THEORY

Analogues to gridshells, the simplistic (or rather low-tech) assembly of Vacuumatics enables an intuitive design approach for constructing shell structures by manipulating a flat surface. From design point of view, it can be stated that in some cases a close relationship might be seen with the second category of concrete shells (Experimental Forms), as these forms are also often derived from manipulating a flat surface into its desired (equilibrium) shape (e.g. by inflation or suspension). A big difference, however, is that with Vacuumatics (as is the case with gridshells) some degree of initial flexural rigidity exists that influences the internal equilibrium and therefore the shaping process.

A beneficial characteristic of vacuumatic structures is that the flexural rigidity can be (partially) regulated by simply adjusting the level of vacuum pressure. A higher degree of 'deflation' will lead to a higher amount of structural prestressing and therefore to a larger resulting bending stiffness. Only a marginal amount of vacuum pressure is required in order to keep the particles from shifting inside the membrane envelope due to the gravitational forces as the structure is being deformed. When the intended shape is reached, the level of vacuum pressure can be increased to its maximum (approximately 1 bar), which stabilises the shell shape. After hardening of the concrete (which will most likely be applied like shotcrete), the Vacuumatics formwork can be re-inflated (or 're-flated') and peeled off from the cured concrete surface and even be re-used to create an entirely different curved shell shape. Using this so-called 'flexibility control' (Figure 13), the shaping process of Vacuumatics formwork can be effectively directed[8].

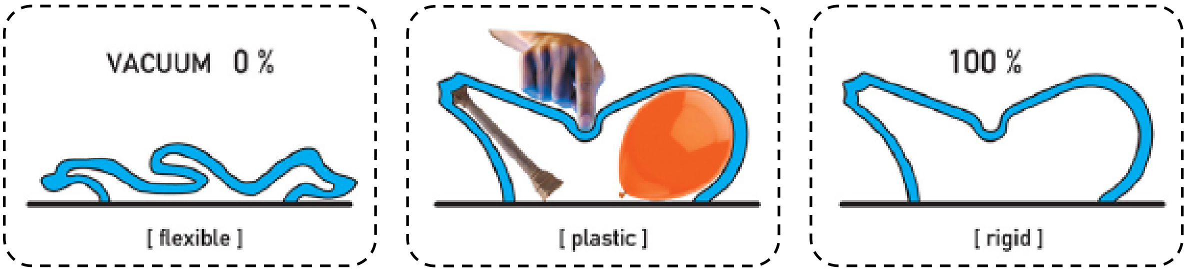

Figure 13: flexibility control of Vacuumatics formwork

5.1 Shaping of Vacuumatics formwork: suspension method

One of the most imaginative methods of shaping Vacuumatics is the so-called 'suspensions method' (analogues to Isler's suspended cloth and Frei Otto's cable nets). In initial, flexible (or 'deflated') state Vacuumatics behave like a tensile structure (i.e. under pure tension), where the particles act as the (enhanced) dead-weight of the structure. Preliminary small-scale tests of the suspension method (total length = approximately two meters) show promising results (Figure 14).

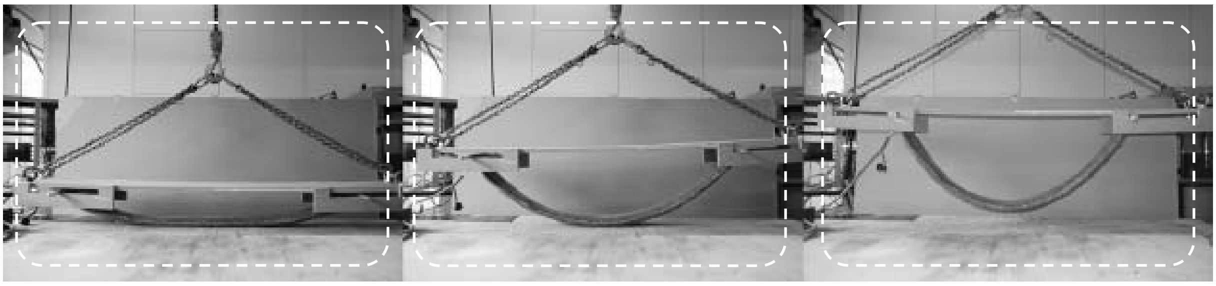

Figure 14: preliminary tests of the suspension method using Vacuumatics

When inverted, the Vacuumatics formwork (and with this the intended concrete structure) behaves like a shell structure under pure compression. Self-evidently, the inverting process might be considered a rather delicate operation, in particular in case of relatively large shell structures.

In addition, the deformation of the Vacuumatics structure due to its dead-weight can even be restricted (or rather regulated) if desired by increasing the level of vacuum pressure (and thus the flexural rigidity). In other words, an equilibrium state will be reached at a relatively smaller deflection. Even the opposite is possible, as the derived suspended deformation can be enlarged by locally manipulating the structure (i.e. pulling parts the structure downwards or moving the edges of the structure inwards).

5.2 Shaping of Vacuumatics formwork: lifting method

Another (and perhaps more practical) method, derived from real-time gridshell construction, is to locally lift the structure into its final shape. The deformation can be controlled by jacking up 'internal' supports or even using inflatable devices (Figure 15).

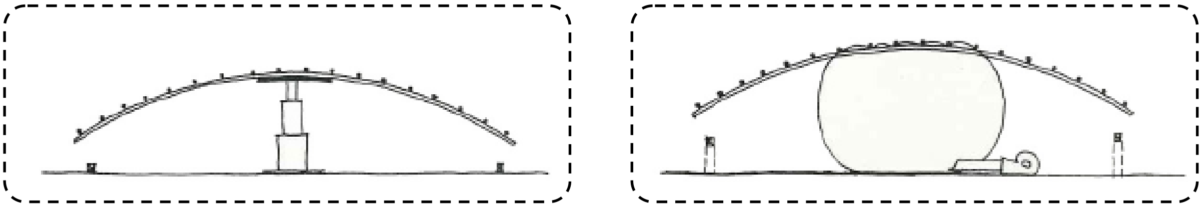

Figure 15: lifting method of gridshell construction[10]

It needs to be taken into account, that in this case the gravitational forces in fact initiate the deformation process, which requires the structure to have a certain minimal degree of (initial) flexural rigidity. A big advantage, is that with this method no inversion of the formwork in its the final shell shape is required. A simple example of lifting a piece of paper by its symmetry axis, perfectly illustrates the potential of this method (Figure 16). Once the structure reaches its intended shape, the edge supports need to be fixed in order to stabilise the shell, before the concrete (e.g. shotcrete) can be applied.

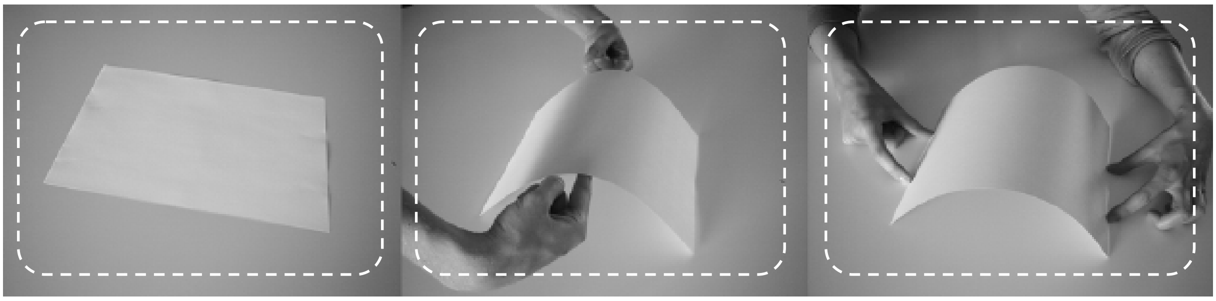

Figure 16: potential of lifting method illustrated with a sheet of paper

6 CONCLUSION

The construction process of concrete shell structures appears to be the limiting factor with respect to realisation of concrete shell structures in a economically attractive manner. There for, a new impulse is required to keep up with digital modelling technology used in design and engineering. From a theoretical point of view, it would make sense to consider the way shell surfaces are generated (analytically, experimentally or digitally) as the most effective construction method. Inspired by this philosophy, Vacuumatics formwork provide a relatively intuitive and 'low-tech' approach for constructing efficiently shaped concrete shells, by using principles derived from 'nature' as well as real-time gridshell construction, hence saving time, labour as well as material.

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