The Rise and Fall of The Thin Concrete Shell

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32 The Rise and Fall of The Thin Concrete Shell

Form Active structures and its relationship to Formwork: A cultural assessment of past application and future impact on architectural design

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Concrete was a popular material choice that stretched the imagination of building designers over past decades. This material that imbued notions of plasticity and flow, sets innovative ideals soaring with hope in the post-war landscape, seen as the material of the future. This paper seeks to perspectivise the phenomenonal rise of the material in the application of shell construction using key case studies of built examples from Nervi, Candela and Isler. It also aims to chart the subsequent demise of its application in thin shell design. By understanding the reasons to what led to its demise, designers will be able to erect concrete shells more sustainably, by modifications to the design process, construction stages and thoughtful consideration to formwork implementation to meet the demands of the 21st century and beyond.

This paper discusses the possibilities of concrete as a material of choice and by asking the question to what constituted its popularity and what led to its demise in this age of new technological advances, construction processes and environmental concerns. This paper will present a cultural perspective of the material and the important relationship between concrete with its formwork to bring about a new renaissance to the re-appearance of such structures in our built environment once again.

> *"Concrete, let us be clear, is not a material, it is a process" Forty, 2006*

1 Genesis: The birth of Concrete

Nobody really knows exactly when concrete was invented. To date, the oldest concrete , a mix of quicklime, water and stone, was discovered in southern Israel and dates from 7000 BC. Whereas mortars and concrete made from lime, sand and gravels dating from 5000 BC were found in Eastern Europe, it is known that similar mixtures were used by ancient Egyptians and Greeks some 4000 years later. (Domone, 2010)

In 2 BC, Romans started to make hydraulic cement – an amalgam that reacted chemically with water. This new type of concrete was used in many Roman structures such as in the foundations and columns of aqueducts. Extensively applied in the building of their Empire, the Romans made common the use of manmade materials such as bricks, wrought iron and importantly, concrete. This advancement in construction engineering is still visible today in the numerous remains of Imperial Rome. One of the Grand Projects, The Pantheon stands today as a testament to this material. Appearing monolithic, but sharply defined by its formwork, the interior is lit by the central oculus. The Pantheon roof is built of concrete of different grades and densities some 2000 years ago. The structure became lighter as it moved up to the top with the roof becoming thinner. To keep it lighter at the top, the builders used lighter volcanic pumice and tufa as aggregates instead of travertine and terracotta aggregates at the lower parts. It is believed that the varying mixes of concrete were laid in horizontal layers with formwork coffers deeply set to further reduce self loading. (Addis, 2007)

Figure 1: The concrete roof the Pantheon, Rome

At a time when other civilizations are still building in stone and timber, this material is starting to change the way large-span shells are made. What we are seeing is a material that broke free from the formal limitations of the predominant building materials of the day. Not only revolutionary in terms of form possibilities, concrete also offered designers and builders the ability to control compressive strength and self weight, to tailor a material to suit its uses.

The viscosity of this material to fill a mould whilst in a liquid state and to later cure and solidify into load-bearing forms changed the shapes of buildings of the future. It was possible to create fluid shapes without having to carve away a piece of marble as was done in Roman sculptures to replicate the fluidity of flowing fabric. Concrete can be poured into any shape imaginable. Morphic workability of concrete and its fluidity are its biggest attributes. Its shape and destiny depended only on its mould, process and the human imagination.

2 The Rise of Concrete Shells:

Concrete is a material of possibility.

The mouldability of the material renders concrete an ideal material for shell construction. Theorescally, the perfect shell should only have axial and shear in-plane forces. This surface transfer of forces allows shell structures to have a slenderness ratio of 1:500 or more.

Although concrete was invented and used thousands of years before, the epoch of the concrete shell really began at the beginning of the 19th century when developments, accelerated by increasing reinforced concrete use and raw concrete becoming more accepted as an architectural finish.

During the world wars, when building materials were scarce, concrete availability led to its popularity as a building material. It was also cheaper than metal and steel which were enlisted in patriotic war efforts. With labour costs cheap and plentiful, concrete shell construction gained popularity. This was especially well-documented as was the case in Italy whose battalion requirements had a major role to play in motivating Nervi's creativity and inventiveness to combine pre-cast and cast-in-place concrete to build both cheaply and quickly.

Figure 2: Aircraft Hangars at Orvieto Airport by Pier Luigi Nervi (1935-1938, 1939-1942)

The war created building programmes that called for large clear spanning but open-air shelters such as Nervi's geodetic aircraft hangars in Orvieto Airport (1935-1942). All these reasons made concrete popular as a cost effective and quick building system.

The wars were also responsible to the displacement of many key architects of the 20th century. Many left Europe to live and work in the New World where experimentation, hope and positivity prevailed in the architectural landscape. This epoch saw concrete represent this brave, new sense of architectural adventure and optimism about the future with many designers embracing (reinforced) concrete as their material of choice, a composite material structurally expressive, and one which offered formal liberation.

After World War II – the curved organic forms re-gained popularity. The period of between the 50's and 60's saw an air of optimism and adventurous speculation. It was a period when atomic experimentation and space travel were making headline news. Concrete fitted the mould as the material capable of producing futuristic shapes and forms. This may perhaps be perceived as a reactionary revolt against the primitive geometries of the "plain old boring" squares, rectangles, perfect circles and cylinders left behind from the modern movement – a legacy of the architectural language of Le Corbusier, The Bauhaus, Gropius and Mies van der Rohe whose pared down aesthetics of the International Style imprisoned this latent desire to be free, to be adventurous, and to be expressive.

The spirit is highly visible in the works of Felix Candela in Mexico and also in the works, although not working purely with concrete shells, Oscar Niemeyer used concrete extensively in the design of the new Brazilian capital, Brasilia. (Andreoli and Forty 2004).

Bechthold (2008) posits that the history of rigid structural surfaces in architecture is described in 2 periods – The first from 1912 to 1939 where the design and construction was derived from vault and dome construction with the beginnings attributed to the research and development of the firm of Dyckerhoff and Widman AG (Dywidag) with their first concrete shell built in 1922 for the Carl Zeiss spherical planetarium in Jena spanning 16m and only 3cm thick.

The second subsequent period of up to the 1960s saw the technical mastering of the construction and the application for new building functions such as worship, education, entertainment and sport. Post and pre-tensioning techniques were also perfected during this period. The quest for wide spanning concrete shells was believed to peak in Nicholas Esquillan's Parisian CNIT exhibition hall in 1958 measuring 218m on each side of an equilateral triangular plan. The shell was constructed with pre-cast elements which were connected on site and had a system of tension ties in the foundation that prevented it from splaying.

The majority of concrete or masonry shells were built from the period 1925-1975 when hundreds of concrete shells were constructed. The 5 golden decades saw the rise of the concrete shells grow in popularity with countless of factories, warehouses, metro stops, grandstands, theatres, cinemas, churches, restaurants, bars and houses roofed by concrete shells.

Cassinello, Schlaich and Torroja (2010) expressed that this heyday was really the result of the work and development of 9 prominent and prolific architects/ engineers, namely:

- Eduardo Torroja (1899-1961)
- Felix Candela (1910-1977)
- Robert Maillart (1872-1940)
- Pier Luigi Nervi (1891-1979)
- Heinz Isler (1926-2009)
- Franz Dischinger (1887-1953)
- Ulrich Muther (1934-2007)
- Anton Tedesko (1904-1994) and
- Eladio Dieste (1917-2000)

3 The Fall of the Concrete Shells:

The passing away of the great masters of shell design mirrored the death of concrete/ masonry shell building. During a 2005 interview with Matthys Levy of Wielinger Associates and Khaled Shawwaf of DYWIDAG Systems US, it was observed that their offices had not been involved in a thin concrete shell project since the 1970s (Meyer and Sheer 2005).

This loss of shell popularity and increasing ill-perception of concrete shells affected Felix Candela, one of the key figures of this movement, badly. The situation, in fact, destroyed his career, rendering him helpless at the latter part of his life (Cassinello, Schlaich and Torroja 2010). This was reflected in a brutally open and honest quote from Felix Candela during a lecture at The Universidad Nacional Autonoma de Mexico in 1969:

> *'As a matter of fact, I am as lost and disorientated as you are. I am around 60 years old and 20 of them I spent as contractor and designer of structures, I know the trade of the traditional architect reasonably well and I neither find market nor use for some capabilities that cost me so much to achieve. I am out of place in today's world and I do not know what to do nor if I am worth anything.'*

An autopsy of the demise of concrete shell suggests many questions to be answered - issues and concerns about the state of shell technology, formwork, construction methods, other competing materials (membrane and lightweight steel and glass) as well as the social and economic outlook of the time needs to be assessed. Cassinello, *et al* (2010) reasoned why concrete shells lost favour in the architecture world of today:

First and foremost, to design and use shells, designers will not just be concerned with concrete structural efficiencies, but will be considering its aesthetics as well. The fashion and changes in styles and perception of beauty (aesthetics) has affected architecture over time - most distinctly so in the periods of Baroque, Regency, Rococo, Greek and Classical revivals. Similarly, after the swinging 60's, architectural fashion saw the return of Cartesian geometry and age of the straight line. Together with factors like construction costs, and other human factors, concrete shells went "out of fashion" once again, a fad (Bradshaw, *et al* 2002) that failed to made a comeback until recently. Concrete shells were partly the beneficiary and victim of the capricious nature of architectural fashion – ultimately a reflection of architectural tastes and trends, inherently embedding the societal values, economic concerns and political outlook of the times.

Concrete shells are expensive due to specialist labour and falsework. In the 1920s, after the Great Depression and World Wars, labour was cheap, making shell construction cost effective. With industrialisation came rising labour costs. Even in industrialising countries, compared with other systems such as steel and membrane systems, concrete shells cannot be built economically any longer. As such, formwork and costs remain the driving shortcoming, causing concrete shells to fall from grace. This remained the case despite casting innovations such as pneumatic formwork, the repetitive use of straight planks or modular bays.

This is visibly the case in the complex formwork of the free-form inverted membrane shells of Heinz Isler which often consisted of individually crafted beam profiles. For example, as used in the construction of the Grotzingen Performance shell of 1977 (Chilton 2000).

The requirement of specialist skills and formwork/erection planning, coupled with a considerable lack of flexibility of the final form diminished its appeal. Architects do not have the freedom to make geometric changes as they are with other types of systems such as steel or even conventional reinforced concrete-this construction required highly skilled labour as tolerances for formwork are tight.

Unfortunately, due to morphology, shells are not practical for general applications. They create awkward junctions between walls and roof thus making space usage difficult. Although the organic shapes are replicated as structurally efficient forms found in nature, the spaces within are not practical. These impracticalities are demonstrated in the experimental work of the Ball Houses of Heinz Isler and the difficulties in furniture placements are amplified within the completed Blaz House (Chilton 2000).

Shells were difficult to analyse. Before the advancement and use of sophisticated computer softwares, shell analysis was carried out "by hand" and often required calculations of 4th order partial differential equations. This was not only mathematically tedious process, but also gave calculation results which were difficult to interpret and apply. Analytical tedium had caused the design process to become specialist and expensive, thereby losing the appeal to other comparatively straightforward structural systems.

It was also observed that thin concrete shells are by their fragile virtue, very unstable. They may buckle if there is insufficient curvature within the shell. As they are so fragile, wind vibrations and unexpected live loading may cause it to buckle and fail.

Compared to steel and glass, the optical opacity of concrete undermines the form-giving potential of concrete. Traditionally, although concrete shell surface can be punctured to allow light penetration, this leads to further complications to what is already complex structural analysis. Michael Flynn of the Pei Partnership, observed that although shells are still being designed in their office, they are not in concrete, but in steel and glass (Meyer and Sheer 2005).

Shells are not compatible with modern building physics. Many of the examples of thin concrete shells were either built as outdoor shelters (hangars and outdoor garden pavilions) or in warm climates - both situations not needing thermal insulations. They can therefore afford to be thin. To increase their application, a new way of building insulated concrete shells will need to be discovered without a loss of shell thinness. This issue is addressed in some of Isler's shells in Switzerland. Isler incorporated insulation within the shell build up but often designed a tapered and upturned edge detail to give an illusion of thinness and increase form stiffness. Without sensitive design and understanding, insulation bulk would easily negate the aesthetical attraction of a concrete shell - the quest for profile thinness. Insulated shells have since been addressed by David and Bary South in their work on the insulated pneumatic formworks in the 1970s and 80s.

As they are unusual structures with specific structural qualities, shells are not covered by building codes or building regulations. The difficulty to gauge safety easily eliminates concrete shells as a design option to the risk averse client, architect or builder.

3.1 Other Developments:

Developments in other building systems eroded the appeal of concrete shells as advances in material technology and experimentation and research on lightweight steel, cable nets, membrane roof structures took off. Structural revolution in material engineering resulted in the new aesthetic appeal of the high-tech replacing the opaque monolith of concrete shells with an architecture of true filigree and transparency.

The shift in emphasis of building function also meant that materials with structural properties were used instead of concrete. Michael Flynn, architect at Pei Partnership New York City pointed out that the ever more popular application of retractable roof designs suggests deployable systems of articulated steel framed structures, rather than concrete shells in stadia design which required clear spans which concrete shells were previously so suited for.

The environmental movement was also responsible for the demise of the concrete shell. There was an increasing awareness of materials credentials and environmental impact and concrete was not spared. The era of the hippy movement and the proceeding environmental revolution also saw concrete suffering badly as a construction material with high embodied energy.

After the 1960s, the concrete shell lost favour in the architectural scene, resulting in the technology of concrete shells stagnating for several decades.

4 Concrete Shells and their Form Givers

To understand the concrete shell phenomenon is to understand its construction process. An amorphous material, the fundamental relationship between formwork and the resultant concrete shell needs to be raised, appreciated, understood and analyzed for a holistic understanding of concrete shells.

Generally, formwork requirements for concrete shells are relatively high, and hence costly. Traditionally, the main ways of constructing concrete shells are:

a) Concreting over timber formwork,

b) Use of pre-cast elements

c) The use of pneumatic formwork eg Bini shells and balloons

d) Fabric Formwork, Foam and Other developments

4.1 A) Timber formwork

4.1.1 Felix Candela

The use of timber shuttering is commonly used to create the shell formworks by the Spanish engineer/architect Felix Candela (1910-1997) living in exile in Mexico. His signature concrete shells largely observed ruled geometries – appearing in the forms of hyperbolic parabolas, conoids, hyperboloids, cylinders and cones. With such geometries, he was able to produce shells with doubly curving geometries using straight timber boards, thus simplifying the formwork.

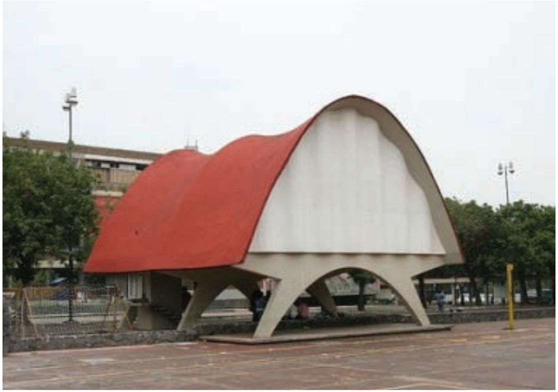

Figure 3: Cosmic Ray Pavilion, Mexico City by Felix Candela (1951)

This is demonstrated in his first work on the design and construction of the laboratory of Cosmic Rays for Mexico City University campus in 1951, believed to have brought him international renown. The shell was amazingly thin as it had to meet strict requirement of a maximum thickness of 1.5cm. (Garlock and Billington 2008)

By using ruled surfaces, Candela was able to simplify formwork as it meant doubly curved shells can effectively be created from straight boards which offered reusability. The straight board shuttering left imprints on the finished surface to give an honest expression of the concrete forming process.

4.1.2 Heinz Isler

Heinz Isler (1926-2009) was, too, a prolific proponent of concrete shells. Isler, who was born, raised and worked in Switzerland, designed and built numerous shell forms of concrete. A structural engineer by training, his work largely involved experimentation with physical models which informed the formfinding of his shells. Isler was most famously associated with the use of hanging membrane models to form-find his "inverted membrane shell series". By hanging a membrane impregnated with resin to get the perfect shell shape, he was able to find the form where with a state of equilibrium where forces are perfectly axial and shear forces acting purely on the plane of the shell. As well as this, he has also produced "compression bubble shells" based on the principles of inflating a membrane stretched onto a frame.

His concrete shells were constructed by laying concrete onto a matrix of prepared timber falsework. The bubble shell series often had a regular geometry and were often repeated. As such, the formwork could be easily reused for any project. As for his inverted free-form shells, the formwork are specialized and bespoke. The bespoke formwork included numerous trusses defined by a complex geometry. Tailored to create one-off concrete shells, many of these formwork can only be used once, making them less economical than conventional construction. However, over many years, Isler built up good working relationships with specialist contractors and as a cost measure, were able to retain and use them again.

The warm climate of Mexico enabled shells to be singly shelled and impressively thin. Insulation is required in the case of Heinz Isler's shells in temperate Switzerland. Often, insulation panels acted as permanent shuttering in many of Islers' shells. In the 1962 Wyss Garden Centre, thin timber boards were placed at regular intervals across the beams or trusses. On top of this, the insulation were positioned and acted as permanent shuttering.

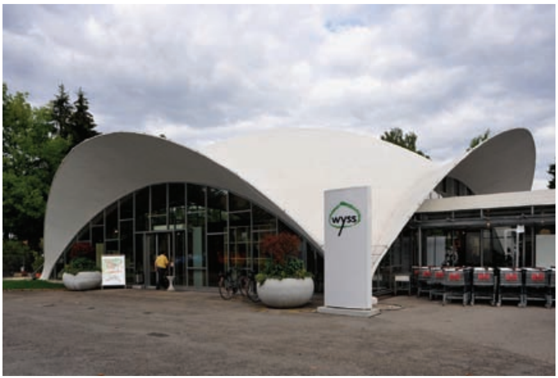

Figure 4: Wyss Garden Centre, Switzerland by Heinz Isler (1961)

Through this discussion and by analysing the process of design, it can be seen that the inflexibility of the formwork, and its rigidity is a big factor that needs to be overcome. This is possible with the help of modern timber engineering (moulded plywood), or synthetic fibres, but such solutions remain difficult to justify economically (Deplazes 2005).

4.2 B) Pre-cast elements

4.2.1 Pier Lug Nervi

Pier Lug Nervi (1891-1979), an Italian structural engineer first designed large spanning concrete geodetic aircraft hangars for Italian Air Force. The use of concrete pre-fabricated panels and open girders, was driven by economy in material at a time when timber resource was scarce. These were assembled and reinforced by the use of in-situ solid beams at points of greatest stress. For the first time in the development of shells, the structures combined the use of pre-cast and cast-in place concrete which became the precursor to his future work.

The creation of *ferro-cemento* is a big step in concrete thinking and had a big impact on how concrete shells are made. Credited to Nervi, layers of fine steel wire mesh (0.02-0.06 inches diameter, set 0.4 inches apart) were incorporated into concrete allowing shell structures of impressively thin profiles to be achieved. For heavier construction, reinforcement bars are inserted into the sandwich of mesh and concrete sandwich. Sometimes, concrete was sprayed (shotcreted) directly onto this mesh which is prepared and already in position, thus making obsolete the use of scaffolding that normally supported the freshly poured concrete shell. Using this method, Nervi was also able to create pre-cast panels which would become instrumental in the development of pre-cast panels in forming concrete shells.

Figure 5: Torino Exposition Hall, Italy by PL Nervi (1947-1948)

For the competition to design a fast and cost-efficiently built exhibition hall in Turin to replace one destroyed during the war, Nervi proposed a revolutionary way of working with concrete that changed the way architects and engineers built. The winning design took the form of a roof covered with corrugations of 8 foot span, divided into 13 foot long units. These precast units were made from ferro-cemento (to a thickness of 1.5 inches) to be as light as possible. They were then joined together by poured-in-place concrete at the peak and troughs of the corrugations. Nervi said, "*In this way, these units would act as junction units between the insitu ribs which in turn would take over the main structural work*." (Huxtable 1960)

To further reduce cost and increase speed of erection, these precast elements were erected on a rolling scaffolding with a lifting device which wheeled down the entire length of the exhibition hall. The idea of pre-fabrication and construction efficiency is strongly reflected in not only the building design, but also the designs in the stages of shell erection.

Figure 6: Palazzetto dello Sport, Rome, Italy by PL Nervi (1956-1957)

This method also set precedence for his forthcoming 1960 Olympic sports buildings in Rome. Built in the Flamimio district, the Palazzetto dello Sport roof, precast concrete panels were laid atop scaffolding and "stitched" together by poured-in place concrete which formed an intricate pattern liken to radial Fibonacci grids on a sunflower. The forces were collected and transferred to the ground by Y-shaped columns which allowed windows to let light into the small stadium.

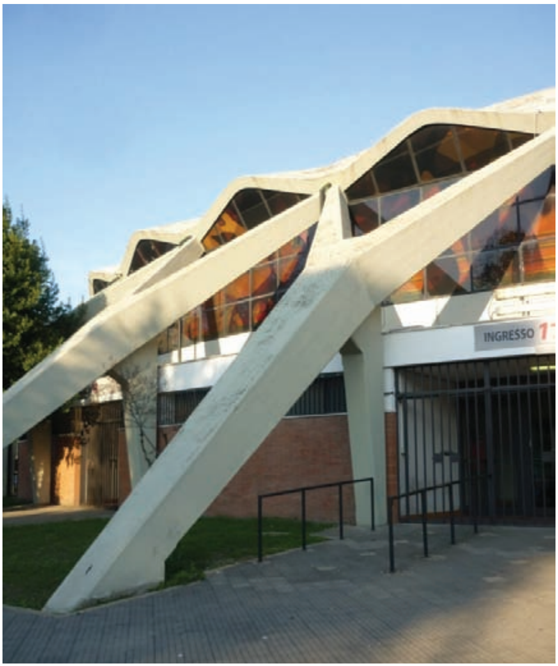

Figure 7: Y-shaped columns on the outside of Palazzetto dello Sport, Rome, Italy by PL Nervi (1956-1957)

The invention of using thin precast *ferro-cemento* panels and cast-in-place concrete cleverly eliminates the use of timber formwork and metal, both materials which were in short supply during war-time Italy. This method was set to change how concrete shells of the future are built.

Nervi has introduced a revolutionary idea which embraced speed and economy in construction, addressing issues pertinent even in the construction industry today. This method, although still used today in projects such as the Duxford Aircraft Museum by Foster and Partners in 1997, is most suited to shell-forms with repeated components however.

4.3 C) Pneumatic (Inflatable) Formwork

The principles of this is based on a formwork supported by air. With the membrane tightly fastened to the ground, air is pumped to inflate the formwork. Variations and development on this principles has evolved over the years with varying success. Once inflated, reinforcement bars are placed over the formwork and secured with chairs. Chairs can become problematic as they can depress or even puncture the inflated formwork. Concrete is then applied and sometimes sprayed on (shotcrete). As one might imagine, it is difficult to affix reinforcement bars onto a smooth pneumatic membrane. Attributed to Dante Bini, the Bini system breathed new life into shell construction.

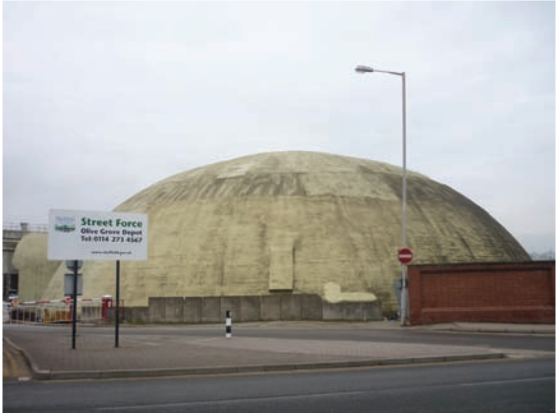

Figure 8: A grit salt storage made using pneumatic formwork, Sheffield UK

In the late 1970s and early 1980s, David and Bary South developed a system in which polyurethane foam was spray applied to the inside of an inflated fabric formwork. The foam provided stiffness and support on the inside. Shotcrete is then applied on the interior of the form and eventually the formwork is either removed, reused or left in place. This system is frequently used in the US. The inventor said that spans in the range of 30-60m are common and spans up to 300m are feasible. The Texas based firm reportedly shipped 150 pneumatic forms in 2001 and has participated in the construction of shells in 48 states and in over 30 countries.

Another method of using pneumatic formwork is to lay on the concrete while the formwork membrane is deflated. Before the concrete cures, it can be inflated with special reinforcement patterns used to control the displacement and sliding of the bars while the formwork is inflated (Bechthold, 2009).

Interestingly and of note, Heinz Isler worked with this method of shell construction in his “Ball Houses” series in the 1970s for earthquake resistant houses in Iran. They were made with sprayed gypsum/loam mixture or gypsum/cement mortar. He has also worked with the architect Michael Balz on the Balz House at Stetten auf den Fildern, near Stuttgart in 1980. The shell was constructed in 3 layers with internal concrete, foam insulation, then external grade concrete. It was noticeably difficult to place traditionally shaped furniture in the house and many had to be commissioned especially. (Chilton, 1999)

4.4 D) Fabric Formwork and other developments

Recent technologies in CAD/ CAM manufacturing has meant that computer generated forms can be manufactured by cutting foam into suitable shapes using a CNC mill. When assembled together, the mould can act as concrete formwork with the possibility of combining formwork and . Some of these ideas are presented and researched by Prof Dombernowsky and Asbjørn Sondergaad of Aarhus School of Architecture. The use of expanded foam is a solution of interest to many researchers and industry including Prof Arno Pronk at The University of Technology in Eindhoven, Holland.

The use of geo-textile fabrics as formwork has been explored and investigated in depth by Prof Mark West and his associates in Canada. When filled with concrete, these fabric formwork produces gravitationally expressive forms, and sometimes eerily beautiful organic forms. All these innovations are impacting on how we view concrete as a material and also the way that concrete can be shaped.

5 Shell Resurrection: A Concrete Renaissance

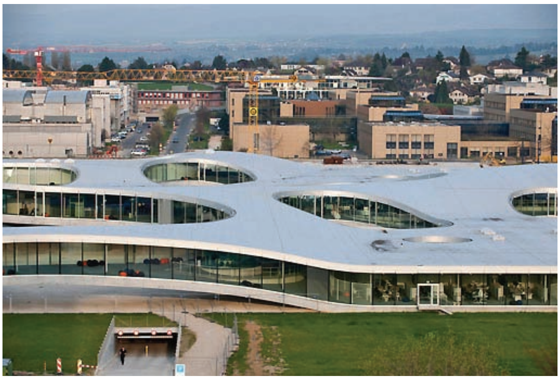

Figure 9: The Rolex Learning Centre walking surface concrete shell by SANAA for EPFL Lausanne Switzerland 2011

Concrete shells and their derivatives are making a return to the architectural landscape as seen in contemporary examples being built. They include the Saijo Crematorium in Kakamigahara, Japan by Toyo Ito in 2008; The Rolex Learning Centre walking surface concrete shell by SANAA for EPFL Lausanne Switzerland 2011, and the 2005 “Grin Grin” Park roof also by Toyo Ito.

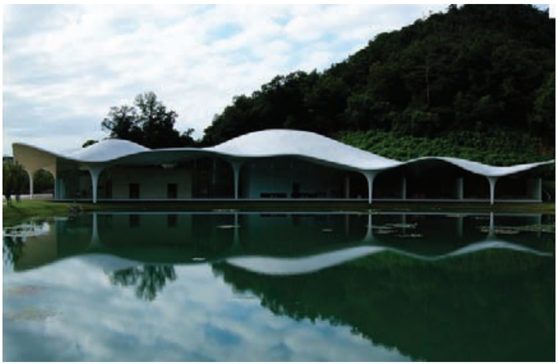

Figure 10: Saijo Crematorium in Kakamigahara, Japan by Toyo Ito 2008

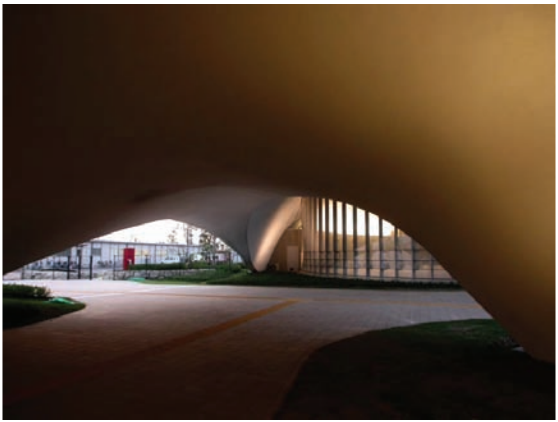

Figure 11: Fukuoka central “Grin Grin Park” roof by Toyo Ito 2005

In their 2002 paper, Bradshaw *et al*, expressed their opinion that although shells are attracting “interests amongst the new generation of architects and engineers, they will never be en vogue as they once were, but will regain some of their former popularity when used appropriately.” This is an inevitable fate given the current state of material and technology advancement.

In support of the concrete shell revival, Jorg Schlaich professed numerous reasons why there would be a future for the concrete shell. In the 2010 paper in memorian to Felix Candela, he wrote:

- Concrete shells are the most honest structures as shape and structure are identical.
- Concrete shells are natural and beautiful if they are made to work without or almost without bending.
- The material concrete is genuinely used as shells work mainly in compression and use the sculptural formality of concrete to the maximum.

Technology, especially in form analysis and digital manufacturing, has eroded many of the limitations of shell design experienced by designers in the last century, and so no longer apply. Owing to computational advancement, structural analysis has become increasingly straightforward. On building science terms, concrete outweighs any other lightweight structures in terms of noise and thermal capacity. Also, with new CNC-guided machineries, formwork can be made more cost effectively.

The findings of an interview with architects and designers carried out and presented by Meyer and Sheer 2005 showed architects and engineers as being generally aware of the benefits of thin shelled concrete - efficient use of materials, relatively low cost and general availability of materials (concrete and reinforcing steel); their fire, blast and impact resistance also provides safety and may reduce insurance costs with the clean uncluttered interior and exterior surface appearance offering the potential of some visually interesting geometries. However, all these still do not justify the high cost of construction.

It must be emphasised therefore, that a key factor for its demise is the high costs associated with the intricate and sometimes bespoke formwork. Innovators like Bini and South have clearly realised the best way to reduce costs is to develop alternate construction techniques, but perhaps more innovative methods could work to reverse this demise.

Edward De Paola of Severud Associates said that “Flexible and easily adjustable forms would make complicated shapes easier and much less expensive to build” (Meyer and Sheer 2005)

To perpetuate this rising momentum of concrete shell interests, new technology (construction methods) and new materials must be embraced to compete with other innovations offered by competing construction systems. Concrete reinforced with steel and glass fibres are prime avenues of further investigation and research. In 1978, Jorg Schlaich set a precedent in the design of a shell for garden exposition in Stuttgart, Germany. The shell structure had a thickness of 10mm and covered 640 sqm, it weighed 21.5kg/sqm (Meyer 1978). That was an impressive advancement in concrete mixes comparable to a tensile roof structure. Another improvement is better shotcreting technology that reduced rebound and, stiffer fabric forms and almost constant monitoring of the curing process, and better types of fibre-reinforced concrete composites.

To improve techniques and reduce costs, the close working relationship between the architect, the engineer and the builder needs to be fostered and maintained for concrete shells to flourish. Prof John Abel of Cornell University said, “ the designer can work with the builder to devise construction processes that are efficient, for example, by together designing reusable form modules appropriate for the shell” (Meyer and Sheer 2005).

Evidently, concrete shells as an architectural application must be judged within the context of other technologies and materials available. This structural purity and the thermal capacity are obviously aspects which can work to the advantage of this material.

Research is being carried out by numerous institutions at both Sheffield Hallam University and The University of Edinburgh where the author is affiliated with. The author proposes a hybridised method of concrete shell making using a deployable grid-shell and fabric membrane as formwork. In this work, a compressed gridmat forms a frame upon which shotcrete is applied. Elaborated in the paper entitled “*Deployable Gridshells and their application as temporary, reusable and flexible Concrete Formwork*” at the International Conference of Flexible Formwork 2012, the author speculates the reusability of the gridmat, where flexible fabric membranes are being laid and stretched upon to act as concrete formwork. This method allows the concrete to readjust by flowing into the indentations within this grid in reaction to gravitational forces bringing about a new sense of aesthetics which might bring rise to a new generation of concrete gridshells, and with a wider application of fabric formwork.

6 Conclusion

Very importantly, concrete shells are not the only way to build, but their construction, structural efficiency, tectonics and thermal qualities should taken into account in the process of design decisions and specifications. The understanding that the shape, structural action and behaviour of this shapeless *liquid stone* is completely dependent on the formwork. This can act as a starting point to innovate news ways of using this material exemplified by the pre-cast construction method as pioneered by Nervi.

Creation and *creative re-creation* is definitely a way of sustaining and securing the existence and continued longevity of concrete shells in the architectural landscape of today and in the future.

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