An overview of historical and contemporary concrete shells, their construction and factors in their general disappearance

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by

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An Overview of Historical and Contemporary Concrete Shells, their Construction and Factors in their General Disappearance

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ABSTRACT: Only through understanding why concrete shells' loss in popularity over the course of modern history can designers be equipped with the skills to create and apply this type of construction. Through modifications to design processes, construction stages, material understanding and relevant formwork improvements will architects and designers be able to meet the demands of the 21st century and beyond.

To understand why concrete shells are no longer commonly built 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. Through understanding this, issues and factors affecting concrete shells can be tackled and designed out in reviving this type of structures because they can be efficient in structural performance, economical in cost and provide high aesthetic value.

This paper discusses concrete shells as an architectural solution by asking the question to what constituted their popularity and factors that led to their demise in the modern age of technological advancement, construction process and environmental concerns. This paper presents a cultural perspective and an overview of seminal, historical and contemporary concrete shells so as to bring about a renaissance of such structures in our built environment once again because of all the benefits it can offer.

Key Words: Concrete, shells, formwork design, construction process, history

“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).

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In 2nd century BC, Romans started making hydraulic cement – an amalgam that reacted chemically with water. This new type of concrete was used in many Roman structures such as aqueducts foundations and columns. Extensively applied in the building of their Empire, the Romans made common 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, remains standing today as a testament to Roman ingenuity.

Appearing monolithic, but sharply defined by its formwork, the interior of the Pantheon is lit by the central oculus opening to the heavens. The roof was formed of concrete of varying grades and densities some 2000 years ago. The structure became lighter as it rose with the roof becoming thinner at the top. To keep it lighter at the top, the Roman builders used lighter volcanic pumice and tufa as aggregates at the top instead of travertine and terracotta aggregates which were heavier at the lower sections. It is believed that varying mixes of concrete were laid in horizontal layers with formwork coffers deeply set to further reduce self-loading (Addis, 2007). The Roman understanding of construction and their manipulation of such a material bear testament to the versatility of concrete, making it a material highly adjustable in physical characteristics for concrete shell construction.

At a time when other civilizations were still building in stone and timber, concrete was starting to change the way large-span shells were 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 and hence the ability to tailor and create a material to suit its uses.

The ability of this material to fill any mould whilst in a liquid state that then cures and solidifies into load-bearing forms changed the shapes of future built environment. It was possible to create fluid shapes without having to carve away a piece of marble as was done in Greek and Roman sculptures to replicate the fluidity of flowing fabric. Concrete was poured into any shape imaginable. The workability of an amorphous material and the fluidity of concrete are its most exciting attributes. Its shape and destiny depended on its mould, process and the human imagination.

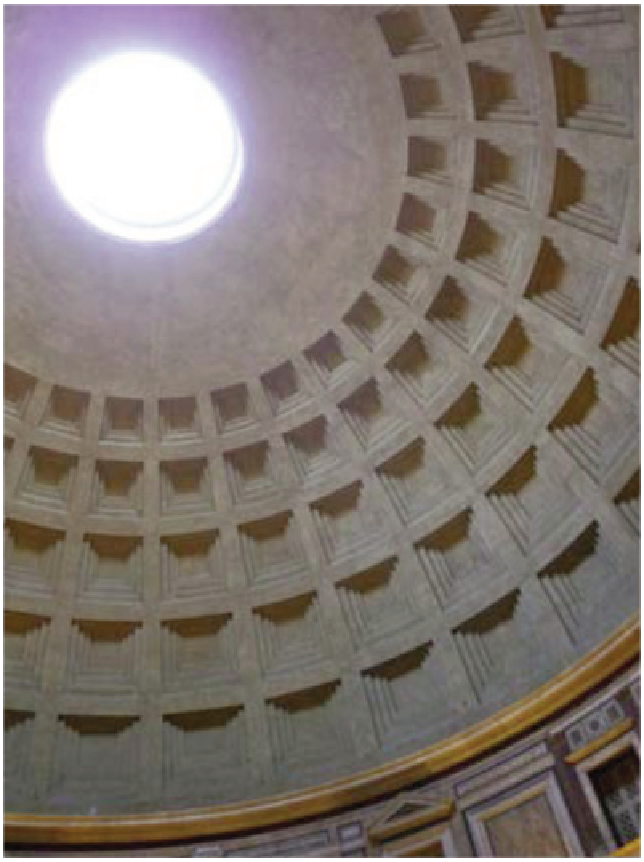

Figure 1. The concrete roof the Pantheon, Rome.

2. THE RISE OF CONCRETE SHELLS

2.1. Concrete is a material of possibility

The mouldability renders concrete an ideal material for shell construction. In theory, the perfect shell has 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 20th century when developments, accelerated by increased reinforced concrete use and raw exposed concrete or beton brut becoming more accepted as an architectural finish.

During the world wars, when building materials were scarce, concrete's availability led to its popularity as a building material for various construction purposes from concrete ships to plant pots. As it was cheaper than metal and steel otherwise heavily enlisted in patriotic war efforts, it was an ideal substitution for steel and timber. At a time when labour cost was low and supply plentiful, the conditions were conducive to concrete shell construction gaining popularity as a building solution. This was especially well-documented as the case in Italy whose battalion requirements had a major role to play in motivating

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

Nervi's creativity and inventiveness to combine pre-cast and cast-in-place concrete to build both cheaply and quickly (Huxtable, A. L., 1960 p. 24).

The war created building programmes that required 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. People saw concrete as a "light" material of thinness and filligree, and seemingly air-borne; as opposed to a heavier material that was akin to the ground, and of the land.

The war created new military functions which saw concrete take centre-stage. However, it was also responsible for the displacement of many key architects of the 20th century - many of whom left Europe to live and work in the *New World* where experimentation, hope and positivity prevailed in the architectural landscape. This epoch saw concrete structures become a symbol of a brave new sense of architectural adventure and optimism about the future with many designers embracing (reinforced) concrete as their material of choice, and a choice that offered morphological liberation.

After World War II – the curved organic forms re-gained popularity. The period 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. This was the age of the curve and curvilinear spaces. Together with new technological development in polymer plastics, concrete comfortably flowed into the mould as a material capable of producing futuristic shapes and forms. This may be perceived as a reactionary revolt against the primitive geometries of the squares, rectangles, perfect circles and cylinders, an imprint from the modern movement and 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 "bastilled" this latent desire to be free, to be adventurous, and most importantly, to be spatially expressive.

This spirit is highly visible in the works of Felix Candela in Mexico and also in the works of Oscar Niemeyer although not working strictly just on shells, they used curves in the design and concrete was employed extensively in the construction of the new Brazilian capital, Brasilia in 1960. (Andreoli and Forty 2004).

Bechthold (2008) posits that the history of rigid structural surfaces in architecture is described in 2 periods – The first period from 1912 to 1939 where the design and construction was derived from the tradition of vault and dome construction with a beginning 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 16 m and only 3 cm 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 developed, improvised and perfected during this period. The quest for wide spanning concrete shells peaked in Nicholas Esquillan's Parisian CNIT exhibition hall in 1958 measuring 218 m 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 which prevented the structure 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 factories, warehouses, metro stops, grandstands, theatres, cinemas, churches, restaurants, bars and houses roofed with concrete shells around the world.

During this period. concrete shells had a world-wide appeal and influence. There was a frenzy to build in concrete shells. It was, however, not restricted to Europe, the United States and the west. Many designers in the east shared the same vision of this kind of structures with many applying the vocabulary of shells in concrete; in the decade from 1980 to 1989 (Mungan and Abel 2011). Famous proponents in the eastern world included Professor Yoshikatsu Tsuboi, holder of the prestigious IASS Torroja Medal in 1976, Professor Yasuhiko Hangai who was instrumental in inspirational education of students in the structure and design of concrete shells. Additionally, Professor Mamoru Kawaguchi, holder of the renowned Torroja Medal 2001, also reinforced concrete shell activities in the east, having most famously worked on a suspended stadium roof with the architect Kenzo Tange in 1964.

Most recently, and prolifically Professor Mutsuro Sasaki was also influential in concrete shells being used as a building solution in his collaborations with architects such as Toyo Ito in the design of many concrete shells such as the 2006 Kakamigahara Crematorium and Grin Grin Park concrete shell roof in Fukuoka, Japan. Professor Sasaki also worked with the Japanese firm SANAA Architects on the Teshima Art Museum where the use of earthform formwork was investigated as well as the structure of the walkable concrete shell structure at The Rolex Learning Centre in Lausanne Switzerland.

In India, the thriving concrete shell building by architect and engineer R. Sundaram is evident. Mr Sundaram, since 1963, has designed numerous thin shell concrete roofs ranging in geometry, and for a variety of architectural functions (Sundaram, 2010; Mungan and Abel 2011).

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
EladioDieste (1917–2000)

However, as noted, there are also many other influential names that deserved honorary mention. They include Prof Buckminster Fuller, Prof Alfred Parme, Prof David Billington as well as writers and authors of important relevant works such as Prof Ramaswamy, Prof Y. Tsuboi, Prof M. Kawaguchi. Prof Jack Christiansen was also a notable proponent of the concrete shell being successfully designed and constructed long spanning shells in concrete, with the last 2 shells completed in 1990 (Mungan and Abel 2011). Additionally, numerous shell theorists such as Vlasov, Goldenweizer, Ulrich Fünsterwalder, Wolfgang Zerna and Flügge were also responsible for the influential rise and popularity, accessibility and understanding of the concrete shell as a commonplace buzzword in architectural vocabulary.

3. THE FALL OF CONCRETE SHELLS

This section below outlines the reasons that led to the disappearance of concrete shells, namely:

- the passing of the great masters
- changes in fashion
- cost of labour
- building physics
- “impractical” morphology of shells
- complex analysis
- material opacity
- building codes
- competing materials

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 all need to be assessed. Cassinello, et al (2010) reasoned why concrete shells lost favour in the architecture world of today.

Fashion

First and foremost, the aesthetic sensibility is an important factor of consideration when designing and using shells; architects and 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 has affected architecture over time - most distinctly so in the periods of the Baroque, the Regency, the Rococo, the Greek and Classical revivals. These changes in preferences of architectural fashion sees particular architectural trends being discarded and reinstated again over time.

In the same vein, following 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 societal values, economic concerns and political outlook of the times.

Cost of labour

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 developments in pneumatic formwork, the repetitive use of straight planks or even modular formwork 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 Grötzingen Performance shell of 1977 (Chilton 2000).

Building physics

The requirement for 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 structural steel with infill construction or even conventional reinforced concrete. Concrete shell construction required highly skilled labour as tolerances for formwork are tight.

Impractical morphology

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

Complex analysis

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 a mathematically tedious process, but it also gave calculation results which were difficult to interpret, apply and improve shell understanding. Analytical tedium had caused the design process to become specialist, expensive and thereby lose their appeal to other comparatively straightforward structural systems.

It was also observed that thin concrete shells are by their fragile virtue, very unstable. Concrete shells may buckle if there was insufficient curvature within the shell. As they are so fragile, wind vibrations and unexpected live loading may cause it to buckle and fail easily. The collapse of the aircraft hangar at Cottbus, Germany in 1934 served as a sobering illustration to the fragile nature of concrete shell structures at their infancy (Hines E, Billington D, 2004).

Opacity

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 in not just structural terms but further complicates detailing 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).

Building physics

Shells are not compatible with modern building physics. Many of the examples of thin concrete shells were either built as outdoor shelters (hangars, outdoor warehouses or outdoor garden pavilions) or in warm climates. These scenarios negate the need for thermal insulation. They can therefore afford to be thin. To increase their global appeal and application, a new technique of building insulated concrete shells or new insulated concrete will need to be discovered without a loss of shell thinness. This issue is addressed in some of Heinz Isler's shells in Switzerland. Isler incorporated insulation within the shell build up but designed a tapered and upturned edge detail to give an illusion of thinness and to increase form stiffness. Without sensitive design and understanding, insulation bulk would easily eradicate the aesthetical attraction of a concrete shell - that of 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.

Building codes

As they are unusual structures with specific structural qualities and particular behaviour, 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.

Other developments

Competing materials

Developments in other lightweight building systems have 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 of emphasis of building function also meant that materials with superior structural properties such as glass and steel 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.

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 why the concrete shells are no longer built commonly 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. Through understanding this, issues and factors affecting concrete shells can be tackled and designed out in reviving this type of structures.

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

A) Timber formwork

Straight timber formwork

The use of timber shuttering was commonly used to create the shell formworks by the Spanish engineer/ architect Felix Candela (1910–1997) who lived in exile in Mexico. His signature concrete shells largely observed ruled geometries – appearing in the forms of hyperbolic paraboloid, 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.

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 minimum thickness of 1.5 cm. (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.

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

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

Curved timber formwork

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 in the plane of the shell.

As well as this, he has also produced compression bubble shells based on the principle 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 laminated timber beams defined by complex geometries. 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, was able to retain and use them again.

The warm climate of Mexico enabled shells to be single-layered 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.

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).

B) Pre-cast elements

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 invention of ferro-cemento was a big step in concrete thinking and had a big impact on how concrete shells are made. Nervi used ferro-cemento where layers of fine steel wire mesh (0.02–0.06 inches diameter, set 0.4 inches apart) were incorporated into concrete to achieve shell structures of impressively thin profiles. 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

Figure 5. Torino Exposition Hall, Italy by PL Nervi (1947–1948).

become instrumental in the development of pre-cast panels in forming concrete shells.

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) The design dexterity in structural and detail thinking is revolutionary to the process and material of construction using concrete.

To further reduce cost and increase the 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 of the various stages of shell erection.

Nervi's use of precast panels did not eliminate formwork; in fact, there was substantial falsework/scaffolding. However, what Nervi's method did achieve was it heavily reduced the need for timber shuttering on site and the moulds were re-used off site.

Figure 6. Palazzetto dello Sport, Rome, Italy by PL Nervi (1956–1957).

Figure 7. Y-shaped columns on the outside of Palazzettodello 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 Palazzettodello 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.

The invention of using thin precast ferro-cemento panels and cast-in-place concrete cleverly made more efficient use of timber formwork and metal, both of which were materials 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.

Pneumatic (inflatable) formwork

The principles of this is based on a formwork supported by air. With the membrane tightly fastened

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

to the ground, air is pumped to inflate the formwork. Variations and development on this principles have 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 (as shotcrete). As one might imagine, it is difficult to fix reinforcement bars onto a smooth pneumatic membrane. Attributed to Dante Bini, the Bini system breathed new life into shell construction although with limited form variation.

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 30–60 m are common and spans up to 300 m 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 designed to be made with sprayed gypsum/loam mixture or gypsum/cement mortar they were next built. 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. Although its design was based on pneumatic form-finding, the Balz house was built on conventional scaffolding timber formwork. It was noticeably difficult to place traditionally shaped furniture in the house and many had to be commissioned especially. (Chilton, 2000).

Unfortunately, pneumatic formwork did not take off since their innovations as the resultant shells remain limited in forms as they are always domed or are a variation of this form. Associated with domed morphology are problems of awkward furniture placement, making space planning and space usage difficult. To inhabit a space in this shape, special furniture had to be made. As it becomes challenging to produce a usable space for habitation on a small scale, they have always been applied on a large-scale basis almost always restricted for storage buildings such as grit stores, or recreational facilities such as swimming pools and tennis courts (Meyer and Sheer, 2005).

D) Fabric Formwork and other developments

The use of fabrics as formwork has been explored and investigated in depth by various institutions, most prolifically by Prof Mark West and his associates in Canada (Bechthold, 2008 p153). When filled with concrete, these fabric formwork produces gravitationally expressive forms, and sometimes eerily beautiful. All these innovations are impacting on how we view concrete as a material and also the way that concrete can be shaped.

The use of fabric as formwork to create shells was used most extensively by James Waller (1884–1968) in a process called Ctesiphon Construction, named after the Ctesiphon Arch he saw in Iraq, which allowed the fabric to sag between the formwork to form the corrugations which gave the structure stiffness. This method of using cement-stiffened hessian draped over inverted catenary arch ribs minimised the amount of reinforcement required to construct the shell of the building. This was a very appealing form of construction method in the time of steel shortage. As it was a simple method of construction, the structures required only unskilled labour, and this system was very efficient time-wise.

During the war, there were 50 such concrete shells built with spans between 6 m and 12 m. A variation of this came in the form of granary domes in Cyprus, called the Cyprus bins. A patent was granted in 1955 for spans of up to 150 m.This technology was applied in applications between the 1940s and 1970s, in housing, storage and factories around the world in countries such as UK, Ireland, Zaire, Zimbabwe, Tanzania, Nigeria, Kenya, Australia, Spain, Greece and India (Veenendaal, D., West, M., Block, P. 2011).

The application of fabric as concrete formwork is applied excitingly and recently in the casting of an outdoor staircase by Sandy Lawton of ArroDesign to address issues of cost, maintenance and durability having been designed originally in steel across a steep site (Lawton and Miller-Johnson 2012).

Recent technologies in CAD/ CAM manufacturing has meant that computer generated forms can be manufactured by milling foam into suitable shapes using a CNC mill. This method of construction has been used in the production of complex shaped elements in an office building in Düsseldorf. To withstand weight of the concrete pour, the foam surfaces can be treated specially. (Bechthold 2008).

When assembled together, the mould act as concrete formwork with the possibility of combining formwork and shuttering. Some of these ideas researched by Prof Dombernowsky and Asbjørn Sondergaard of Aarhus School of Architecture (Dombernowsky and Sondergaard, 2011) in their construction of a concrete canopy.

3D CAD/ CAM was employed in the extensive formwork manufacture of the Grin Grin Park in Fukuoka, Japan by Toyo Ito and Prof Mutsaro Sasaki. Following digital formfinding and shape analysis, a free smooth surface was sent to be fabricated from plywood where the plywood framework was cut into 1m x 2m pieces and transported to the site where approximately 2000 cubic metre of concrete was cast by 400 workers. This method was again employed to create the formwork for the Kakamigahara crematorium roof designed again with Toyo Ito and Prof Mutsaro Sasaki where plywood formed the extensive smooth surface upon which concrete was cast (Sasaki, 2010).

5. SHELL RESURRECTION

5.1. A concrete re-naissance

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

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, Jörg Schlaich professed numerous reasons why there would be a future for the concrete shell. In the 2010 paper in memoriam 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.

Another improvement is better shotcreting technology that reduced rebound 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.

6. CONCLUSION

Only through understanding the reasons to what caused its demise and fall from favour can designers be equipped with the skills to create and apply this form of architectural vocabulary appropriately and sustainably, as they have so much to offer in structural and tectonic terms. Through modifications to the design processes, construction stages, material understanding and relevant formwork improvements will architects and designers be able to meet the demands of the 21st century and beyond.

To understand why the concrete shells are no longer built commonly 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. Through understanding this, issues and factors affecting concrete shells can be tackled and designed out in reviving this type of structures. Very importantly, concrete shells are not the only way to build, but their construction, structural efficiency, tectonics and thermal qualities should be 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 is important. The understanding of this relationship can act as a starting point to method and technique innovation exemplified by the pre-cast construction method pioneered by Nervi and other shell designers.

The 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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