Gridshell as Formwork: Proof of Concept for a New Technique for Constructing Thin Concrete Shells Supported by Gridshell as Formwork

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GRIDSHELL as FORMWORK:

Proof of Concept for a New Technique for Constructing Thin Concrete Shells supported by Gridshell as Formwork.

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Abstract

This paper documents empirical experiment conducted in August 2014 as proof of concept for a new method of constructing concrete shells. An idea initially presented by the first author in 2012, it uses re-deployable gridshells onto which fabric is pre-stressed and concrete applied. Primarily, this system addresses key issues that led to their decline in use: construction methods/ formwork systems were not re-usable, nor were they easily customisable to create different shapes. Employing 27 man hours over seven days, two concrete shells were achieved using the same re-usable and re-configurable formwork. Lightweight (0.6kg) pvc gridshell formwork supported 106.92 kg of concrete to create a concrete shell that covered 1.11 sqm (floor area). The construction verifies a low-cost (£6.06/sqm) efficiency and material utilisation in the construction of very strong wide-spanning thin concrete structures. Detailed analysis of formwork behaviour during construction and detailed measurements of resultant shell the results prove this new method of deployable gridshells as re-usable and re-configurable formwork to construct very strong concrete shells very quickly. Whilst the emphasis of

the research focussed on the construction process, the vaults were tested and sustained a failure load of 4.2kN (4.32 times their deadweight), applied as a point load at the crown.

Fig. 1

1. Introduction:

This paper documents empirical experiment conducted in August 2014 as proof of concept for a new method of constructing concrete shells. An idea initially presented by the first author in 2012 (Tang, 2012a, 2012b, 2012c), it uses re-deployable gridshells onto which fabric is pre-stressed and concrete applied.

Concrete shells gain strength from their doubly-curved geometries to achieve impressive span to thickness ratios with relatively minimal material. For example, the Cosmic Ray Pavilion 1951 by Felix Candela registered an impressive span/ thickness ratio of 367:1 where its hyperbolic parabolic geometry provided clear spans without the need for intermediate supports (Garlock and Billington, 2008).

Fig 2

Concrete shells are popularly designed as communal venues such as sports stadia and even churches as they offer clear sight-lines and used little material to cover large areas. With many attributes to concrete shell's credit, the current state of concrete shell activity remains low. Recent examples in Japan, at Teshima Island Art Shells (by Ryue Nishizawa, 2010) and Kakamigahara Crematorium (by Toyo Ito 2006), demonstrate their architectural possibilities. Paradoxically, despite their potential as efficient structures with aesthetics and material economy benefits, concrete shell construction has declined.

The problem lies with the formwork - sometimes single-use and often time-consuming to prepare, the formwork negates environmental value offered by concrete (such as thermal mass in exposed interiors) and material economy derived from their double curved shaping. A survey of past and present concrete shell construction methods has identified concrete shell formwork as neither re-usable nor re-configurable. This new method resolves these problems by employing deployable gridshells as re-usable, re-configurable and intuitive-to-erect formwork.

2. Background : Challenges faced by Concrete Shells

2.1 Design difficulties

At the turn of the century, curved structures such as concrete shells and their curved formwork were difficult to design. In addition to spatial planning, pure shells acting in compression require force/form understanding. In the early days, this difficulty was overcome by shells designers developing through physical experimentation using models, as seen in the works of Eduardo Torroja (1899 - 1961) and Pier Luigi Nervi (1891-1979). Heinz Isler (1926-2009) also used physical models to find structurally appropriate free form shell geometries (Pedreschi, 2008).

Historically, structural design of shells involved complex mathematical analysis. However, with digital advancement, shell forms can now be form-found and analysed with computational analysis softwares. In the early days, these tools were specialised and difficult to use. However, current development in formfinding software such as Rhino-vault (Rippmann, Lachauer and Block, 2012) or Kiwi3D has made this process comparatively easier and more intuitive.

2.2 Formwork Challenges

Demanding a sound technical understanding of formwork construction, concrete casting and de-centring (formwork removal), concrete shell construction is intensive on formwork and labour. Hence, concrete shell design expects a good understanding of material behaviour and system assembly (i.e. both of concrete and formwork construction).

Difficulties in formwork fabrication, design methods and construction techniques also contributed to their decline. The consistent lack of construction ease, a limiting one-off form, and a system not immediately reconfigurable/ re-useable resulted in very cumbersome erection sequence/ procedure. In the quest to address these challenges, institutions such as TU Vienna’s pneumatic 2013 wedge system (Kromoser & Kollegger, 2015) and at ETH’s use of cable nets as formwork (Veenendaal, Bakker & Block, 2015) sought to address these difficulties in designing concrete shells.

2.3 Critical Analysis of Concrete Shell Formwork technologies

2.3.1 Timber Planks

Traditional shell formwork consisted of rigid timber planks arranged to produce a curved pourable surface. Timber formwork was suitable and effective in supporting the weight of construction workers as well as shoring concrete (Bechthold, 2008). The first concrete shell in 1922 by Franz Dischinger (1887-1953) for the Zeiss Planetarium in Jena, Germany with Walter Bausersfeld (1879-1959) used timber as a backing to prevent concrete from falling behind the shell (Addis, 2007). The exposed interior surface offers this option to be reflected in the imprints of timber planks. This characteristic is much valued by Felix Candela (1910-1997) as he retained them to express this process of their formation (Lee and Garlock, 2009). Candela designed his shells with hy-pars/ruled geometry. Ruled geometries are curved surfaces that are formed of straight lines. These are manifested through forms such as hyperbolic parabolas, conoids, hyperboloids, cylinders and cones. Candela was keenly aware that ruled geometries also meant loading could be calculated and analysed (Faber and Candela 1963). Most significantly, from a design point of view, ruled surfaces allowed Candela to simplify formwork as complex doubly-curved surfaces were formable from straight boards, which were also reusable, making them economical. For example, in his famous umbrella structures, falsework were reused several times. Specifically in the Rio’s Warehouse, Mexico, he concreted four concrete umbrella structures so that one week later he could decentre the forms and concreted another set of four (Garlock and Billington, 2008).

Designing constructible shapes opened up form possibilities. Construction complexity could now be managed by varying and repeating the hy-par form. Candela led the way in developing shells in responding to analytical limitations at that time. His design process and concrete shell forms were therefore developed using method and technology available at that time and he succeeded with great acclaim.

2.3.2 Glulam timber formwork

Whilst the stable weather of Mexico allowed concrete shells to stay uninsulated and impressively thin, concrete shells in areas with harsh winters required thermal insulation. In Switzerland, Heinz Isler used insulation panels as permanent shuttering. In the 1962 Wyss Garden Centre shell, thin timber boards were placed at regular intervals across the timber trusses. Over this, insulation boards were positioned and served as permanent shuttering onto which concrete was poured.

Isler's work used bespoke timber formwork, precisely profiled to follow bespoke curvatures. Having built up a long-standing working relationship with his long collaborating contractor, W. Bösiger, to achieve economy, he adapted his designs to recycle pre-used timber sections for new designs with similar geometries (Chilton, 2000). Evidently, the more successful shell builders were resourceful in addressing constructional economics by varying the way they were built. Any successful system should also address challenges of cost, amongst many other factors. Clearly, Isler was aware of building economics and was effective in addressing these concerns.

Historic photographs of Candela's shell construction depicted complex scaffolding-intensive method where dense "forests" of timber scaffolding supported a casting surface. The following decades saw concrete shells gaining popularity in Mexico (1960 GDP per capita: US$342) where labour and building material was cheap. One wonders how shells constructed this way would perform in a more developed economy such as Switzerland (1960 GDP per capita: US$1787.40). External social and economic factors such as the low labour cost in Mexico provided fertile testing ground to encourage an architectural acceptance but the Swiss also seemed to embrace new shapes in the construction of concrete shells in cities and along motorways.

2.3.3 Fabric

In 1955, James Waller patented a method of constructing concrete shells by using fabric as formwork by applying concrete manually or by spray application (gunite). Using this method, shells were constructed easily and quickly. The system relied on fabric being draped to form stiffening corrugations between pre-fabricated and reusable rigid arches conforming to funicular curves. This allowed Waller to eliminate complicated and difficult use of metal mesh reinforcements. Unfortunately, cracking was reported at the top of the shell (anon, 1963) and observed poor thermal quality (Naidu, 1963) which consequently led to this technique's decline.

2.3.4 Moveable and Repeated Formwork

In 1942, concrete shells were designed as a double hangar at the airport of Marignane, France. The two units were covered by six 101.5m waves, 9.80m in width and 12.10m for the sag. They comprised concrete shells, each 6 cm in thickness, with steel reinforcement. The pre-fabricated pivoting timber sections were attached on roller rails pushed along rolling blocks. To create a continuous surface for concrete pour, these arches were pieced together and craned into position. In these hangars, wire netting also served as reinforcements. The first roof of 60m x 100m was constructed in 38 days (including overtime and Sundays) whilst the second hangar was constructed in 23 days. (Motro and Maurin, 2011).

2.3.5 Pre-cast concrete panels

Seen earlier, the innovative use of precast panels stemmed from the need to construct with speed and efficiency. Similar to Heinz Isler, Pier Luigi Nervi (1891-1979) was aware of post-war construction economics. His construction innovation responded directly to the economic situation of the inter-war period in Italy. A contractor working in war-time Italy, he designed and built eight aircraft hangars by pre-casting concrete trusses instead of casting them in-situ. To simplify structural analysis and to make their structural behaviour more predictable, Nervi made these hangar supports symmetrical (Billington, 1983).

Nervi’s construction method involved concrete panels known as *travelloni* pre-cast with *ferrocemento* on ground level, then raised piece by piece and set into position. With reinforcement bars tying them together, concrete was poured into the grooves to secure individual pre-cast panels. Not only did this method used readily available materials, it was also fast, making it affordable and expressing structural logic. His Salone Agnelli in Turin (1947-1954) and the later Olympic buildings in Rome remain strong affirmations of this ethos (Billington, 1983). Although his idea of repetition was progressive and aligned with mass production at an industrial scale, Nervi's shells, celebrated this on the inside exuded attractive aesthetical tectonics. His shells were highly economical. In particular, the repeated hemispheres and barrel-vaults encapsulated that exact spirit driven by economy and construction speed.

2.3.6 CNC-Milling Technologies

CNC-milled foam formworks for reinforced concrete shells were investigated by Professors Dombernowsky and Asbjørn Sondergaad of Aarhus School of Architecture and other researchers including Professor Arno Pronk at The University of Technology in Eindhoven. Large-scale architecture projects constructed from these technologies included Der Neue Zollhoff in Dusseldorf by

Frank Gehry Architects (Kolarevic, 2001) and CNC-milled timber moulds used to form the floor/ roofs of the Rolex Learning Centre in Lausanne, Switzerland by SANAA (Scheurer, 2010).

2.3.7 Earth Mounds:

Earth mound formwork was experimentally by Heinz Isler in early projects (Chilton 2000). This method involved the preparation of earthworks to the shape of the shell upon which concrete was poured. Once set, the earthwork was removed to reveal a self-supporting concrete shell.

Ulrich Muther's (1934-2007) shells used earth mounds to reduce cost. For the Binz lifeguard rescue towers (1975 and 1981), sections of the shells were cast in sand. The shell halves were then lifted and positioned on location and mounted on the main columnar support.

More recently, the Tokyo-based architect Ryue Nishizawa designed the Teshima Art Museum shell at Teshima Island in Japan used this method in 2010.

2.3.8 Vacummatics

In the Netherlands, Dutch architects and engineers are developing vacummatics formworks for the construction of thin concrete shells. Developed by Huijben, van Herwijnen and Nijesse by creating a vacuum in an enclosed membrane envelope with unbound particles within, three dimensional forms are created to form temporary surface formwork for concrete (Huijben, van Herwijnen and Nijesse, 2012).

2.3.9 Pneumatic formwork

The principles of pneumatic formwork are based on a formwork which is supported by air. With membrane tightly fastened to the ground, air is pumped to inflate the formwork. Variations and development on this have evolved over the years with varying success as exemplified by Dante Bini (1932-) (Bini, 1969) and David and Bary South (Bechthold, 2008).

In 2014, TU Vienna developed a system to create concrete shells from flat plates. The Pneumatic Wedge Method of shell construction consists of a concrete slab resting on a pneumatic cushion. The flat formwork tray slab was wedged with spaces in between the segments so when the middle section is lifted, the segments will fit together perfectly. A shell of a height of 2.9m could be achieved within a lifting period of 2 hours (Kromoser & Kollegger, 2015).

2.3.10 Cable Net as concrete formwork

Researchers in The Netherlands and Switzerland are also exploring ways to construct concrete shells using cable nets as formwork. This is based on cable nets concrete upon which concrete is poured. The use of tensile formwork to support a fabric surface was explored for the construction of the NEST Hi-LO project at ETH Switzerland (Veenendaal and Block, 2014) where a shell concrete roof constructed by applying concrete on a fabric stretched over a net of tensile cables. Although constructions to date have been successful as proof of concept, the primary need for a frame to be constructed to suspend the cable net remains a key critique.

3. Hypothesis: Gridshell as Formwork

The demise of concrete shell is hence a result of construction, design method and formwork shortcomings. Primarily, they are often single-use to particular geometry, and become less economic. Deployed and actively-bent gridshells are proposed as a new formwork system to offer re-usability and re-configurability, something past and present construction methods lack.

Gridshells can be largely categorized into two main families: Deployable (actively-bent or strained) ones or non-deployable ones (Adriaenssens, Block, Veenendaal and Williams, 2014; Chilton and Tang, 2017; Tang, 2018).

Fig 3

3.1 Non-deployable Gridshells

These are rigidized by fastening discrete straight members or bespoke pre-curved and/ or rigid two-dimensionally curved sections together to form a three-dimensional structure. Accurate sections, some with precise curvatures developed through CAD/ CAM/ robotic milling timbers, are assembled together. Examples include the Pompidou Metz (2010), Haesley Nine Bridges Golf course (2010) both by the Japanese architect Shigeru Ban. Others include the Kreod Pavilion, London (2014) and the SUTD marine plywood gridshell in Singapore. More details about these examples can be found in Timber Gridshells: Architecture, Structure and Craft (Chilton and Tang, 2017).

3.2 Deployable Gridshells

Deployable (actively-bent/ strained) gridshells are based on the idea of deploying a lattice grid allowed to slide, deploy, deformed and braced into shape. These have appeared since the first engineered timber gridshell in 1962 measuring 15m x 15m developed by Frei Otto for The German building exhibition in Essen, Germany (Otto, F., Schauer, E., Hennicke, J., & Hasegawa 1974). This technology developed into increasingly sophisticated forms culminating in the Mannheim Multihalle 1976 (by Carlfried Mutschler and Partner with Frei Otto), Weald and Downland gridshell 2003 (by Studio Cullinan with Buro Happold) and Savill Garden gridshell 2005 (by Glenn Howells Architects with Buro Happold). Bending-active deployable gridshells however posed practical construction problems such as:

- jointing of timbers
- intersection joints without excessive removal of timber material or weakening fibre severance
- structural deterioration through weather and water attack
- roof covering and enclosure
- knots which weaken the structure (Chilton and Tang, 2017)

Non-wood-based material such as flexible glass fibre reinforced plastic (GFRP) with active bending was used by Olivier Bavarel for the 2011 Solidays pavilion et al (2010, 2012) and Cretail pavilions (Tayeb, Baverel, Caron, & Du Peloux, 2013). This re-configurable nature of deployable gridshells is useful and could fill in a gap in the construction of concrete shells. Actively-bent gridshells constructed from GFRP and carbon fibre also offered re-usability and a return to flat mat readily. These are intuitive as a design tool for designers not familiar with specialist software or complicated force mechanics.

Deployable gridshells are flexible and responsive to loading conditions. Deformation is difficult to control and will depend on materials. Mannheim Multihalle timber gridshell (1976) initially experienced vertical displacement of 200mm (2.2%)between 9m temporary supports during construction (Liddell and Happold, 1975). The 2003 Weald and Downland gridshell experienced a deviation of +/-50 mm (4%) over a 15 m span and 8.5m height (Harris et al, 2003). The vertical displacements of loading tests on a gridshell constructed of GFRP glass fibre reinforced plastic registered a range between 5mm (symmetrical loading) and 135mm (asymmetrical loading) when braced representing a comparatively smaller deflection of 0.0624% to 1.69% (Douthe, Caron, & Baverel, 2010).

4. Methodology

This hypothesis is tested out by physical construction experiments as a means to prove the concept and understand the construction process

Fig 4

Realistic prototypes were developed. Analysis is not limited to the finished concrete shell, but the construction process is also recorded and studied. Three key aspects are investigated:

1. Construction Process – formwork behaviour and movement
2. Aesthetic/ geometry (Concrete shell) – dimension, upper and lower surface geometry, shell thickness and edge conditions
3. Structural Performance (Concrete shell) – static loading loading to failure.

5. Construction

Concrete shells were constructed at the architectural research workshop at The University of Edinburgh in August 2014. These were scaled to suit the space and facilities of the workshop. The gridshell was developed and proportioned using previous experience of larger scale prototypes (Tang) with timber lathes. Simple plastic tubing was found to be appropriate for the curvatures necessary in this study.

Two concrete shells of different dimensions were built using the same deployable gridshell as proof of concept. Specifically, this provided empirical insight to:

- understand formwork behaviour and concrete shell behaviour of a single curvature
- verify reusability and re-configurability of gridshell formwork
- understand behaviour of gridshell formwork i.e. formwork movement when concrete is applied.
- understand structural behaviour, within elastic range and loading capacity of the shell
- explore tectonic and structural implications of undulating surface developed by construction methods.

5.1 Materials and relevant mechanical properties:

1. Type Q3323 woven polyester fabric supplied by JD Wilkie Ltd (weight 232g/m2. nominal thickness 0.35 mm with tensile strength 3750 N/50mm in the warp direction and 2350 N/50mm in the weft direction)

2. 20 m length PVC plastic piping oval profile (16mm x 10mm 3m lengths) with 1.5mm walls, normally used for electrical installations.
3. PVC binding screws (5mm in 20mm, 30mm 40mm lengths), usually used in bookbinding.
4. 12mm thick plywood base upon which shell was constructed and raised from the floor for manoeuvrability.
5. Concrete was mixed at 1 part cement to 2.5 parts coarse sand. Synthetic fibre reinforcement, Strux 90/40 was added. The concrete was mixed in batches of 25kg cement, 62.5kg sand and 150g of 40mm of Strux 90/40, and nominal 8.4 litres of water (modified slightly for each batch to ensure adequate application. A number of concrete cubes and cylinders .Test samples were taken. The average density of the concrete was 2100 kg/m^3, cube strength 38.1 MPa, cylinder strength 30.5 MPa and tensile strength 6.4MPa.)

5.2 Construction Principles

Fig 5

A. A gridshell is made from PVC pipes bolted together with plastic binding screws to create free-rotating scissor joints allowing the flat mat to deform/ expand. Once the required form is obtained, geometry is locked in place by adding additional struts to triangulate the gridmat to temporarily restrain the gridshell formwork.
B. This flat mat is now bent and propped against 2 prefabricated abutments affixed to a pre-made timber platform base. The magnitude of displacement during concrete loading for the gridshell will be recorded to understand the degree and nature of movement during concrete loading.
C. A poly-propylene woven fabric was then stretched over the gridshell to support concrete.
D. Concrete was then applied in layers directly to the fabric by hand using steel trowels.
E. Once the concrete has set, the gridmat was then removed from under the concrete shell.
F. To create the next shell, the bracing that triangulates the structure and therefore fixes in their dimensions were removed from the gridmat. With the joints free again, the same gridmat was deformed into a flat mat with different geometry to produce a shell that was longer and narrower than the first. The second taller shell was constructed on a different set of

abutments. After this, the steps of casting and assembling and dissembling are again repeated to test the viability of this method of construction.

5.2.1 Baseboard

Each shell sits within its own baseboard raised off the ground with timber struts for access and transported with a pallet truck when necessary.

5.2.2 Abutment

Abutments are needed to attach the gridmesh and contain the horizontal thrusts of the concrete shell, The detail of the abutments were carefully considered to allow the gridmesh to be lowered once the concrete had hardened and angled to effectively collect the thrust from the vault. The abutments were bolted to the base board, which acted as a horizontal tie. The abutments were cast in prismatic moulds using 5mm thick acrylic plastic sheets taped together. The concrete for the abutments consisted of three parts10 mm aggregate, two part sharp sand and one part cement.

5.2.3 Fabric

A woven polyester geotextile manufactured by JD Wilkie was used. It was sewn and hemmed to the width of each shell with a piping detail to thread pvc pipes through easily and prestress the fabric when attached onto the gridshell frame.

5.2.4 Edge Detail

The ends of the formwork have to follow the geometry of the gridshell and rating the concrete to the required thickness. An edge detail was developed using pvc sewn into hem in the fabric. Attached with pvc binding screws, an additional pvc conduit pipe on each side acted as side rails and formed a neat edge with a consistent depth.

Fig 6

5.3 Constructing the grid-shell:

Fig 7

5.3.1 Gridshell Preparation

The pvc conduits were drilled with 5mm diameter holes spaced 200mm apart. Using 20mm long pvc binding screws, the flat deployable grid-mat was assembled.

This gridmat was then pulled to an overall extended length of 1640mm. This elongated gridmat was temporarily locked into position by securing cross bracing in position at intersection points. At each intersection, 30mm long binding screws secured the gridmat through pre-drilled holes. This triangulated gridmat was propped between the concrete abutments to create an arching formwork.

5.3.2 Casting Test Shell 1

A 10mm concrete coat was first trowelled onto the fabric working upwards from abutments, towards the apex. Concrete was gradually pushed from the apex towards the quarter spans until they met. Following a couple of hours curing, a further top concrete coat was applied in the same sequence. Concrete filled in the lenticular spaces between braced gridshell formwork to produce an undulating cushion-like surface on the underside.

5.3.3 De-centring

After 2 days, the gridshell formwork was removed, following that, side rails were removed, followed by timber props (which prevented concrete from flowing out at the concrete and abutment interface). Lastly, the fabric was removed in a process taking 15 minutes from start to finish.

5.3.4 Casting Test Shell 2

Casting and Decentering

De-centered from shell 1, to cast shell 2, the gridshell formwork was re-assembled onto a second base board and abutments. This second shell (width 846mm) was longer and narrower than shell (width of 470 mm). The shell was then cast following the same order but in one single cast.

5.3.5 Labour

Table 1: Time scale and schedule of construction

The construction of two concrete shells took 27 direct man hours in a period of 7 days including 2 weekend days for concrete shell curing.

Table 2: Breakdown of labour (time) over duration of 7 days excluding curing time) to nearest half hour

Fig 8

5.4 Gridshell movement during casting

To understand loading behaviour during the casting process, steel plumb lines were hung at 18 points 50mm directly above corresponding measuring boards (datum). 18 corresponding measuring boards A1 to C6 (fig 9) were made from laser cut 2mm MDF boards. Displacements in 3 axes define movements at specific points in the shell to denote point movement of the structure during concreting.

Fig 9.

5.4.1 Results of movement study for Shell 1 during casting

Fig. 10

Fig. 11

5.4.2 Results of movement study for Shell 2 during casting

Fig 12

5.4.3 Discussion

In both test shells, resultant movement exhibited similar movements during the casting process –, areas A in both shells lowered (-0.98% drop for shell 1 and -1% for shell 2), whilst areas C rose (+0.3% for Shell 1 and +0.1% for Shell 2). The apex (B) rose too. As the two shells were designed as singly-curved structures, the vertical movements of points along transverse line A, B and C was averaged for expedience.

Notably, the movement corresponded with the concreting sequence– area A, area C, then area B in both cases. The method and sequence of applying concrete onto a free-standing gridshell framework is significant on the eventual curvature of the resultant concrete shell.

Fig 13:

5.5 Dimension

Fig 14

Table 3: Span to rise ration of Shells 1 and 2

Shell 1 spanned 1300mm and 492mm tall giving a span to rise ratio of 2.64. Shell 2 spanned 1350mm and 620mm tall, giving a span to rise ration of 2.17.

6 Aesthetics

6.1 Geometry and dimension

Although appearing to be symmetrical, a visual inspection uncovered a lowering across the transverse apex line. To fully understand the significance and implication of construction sequence on shaping the resultant shell, without expensive photogrammetry, a jig was set up to measure and plot the top surfaces directly and precisely.

6.2 Patterning

A distinct and unique appearance of festooning concrete cushions was created by concrete suspending on the polyester fabric between grid laths on the underside of the shell. Deeper dominant lines were observed to run in the direction of the uppermost grid laths. These ridges imply the sectioning of shell into diagonal bands of increased thicknesses and indent lines of weakness, suggesting zones assumed most prone to structural failure.

Fig 15

6.3 Edges

Shell edges are crucial in giving an illusion of shell thinness. The artful treatment of the free edges imparts a visual reading of shell thinness - a key concern of Felix Candela. At the 1960 Bacardi Rum

Factory he pulled back structural stiffening arches from the edges to make the shell appear thinner and more elegant. This is an improvement from his earlier work such as Bolsa de Valores (1955) where stiffening arches were thickened at their edges giving an impression of solidity and heft.

In this experimental construction, the use of a gridshell from elliptically profiled hollow pvc tubes allowed the edges to appear sharply-defined. The use of pvc pipes of the same dimensioned profiles fashioned a crisp and sharply-defined free edge thus illustrating what could be achieved at this scale. Liken to how Candela expressed timber board-markings, the smooth upperside surface contrasted with the under surface imprinted with casting material and cushions.

Fig 16

Fig 17

Fig 18

The undulation of the shell is not expressed on the outer and upper surface. Measurements showed cushions thickest at the abutments whilst cushions at mid-span apex are less pronounced and even. A small concentration of air pockets and pvc reinforcement strands were visible, suggesting air not escaping sufficiently from fabric surface, partly due to a dryer concrete mix used.

Fig 19

6.2 Upper Surface: Dimensional variation

Fig 20

6.2.1 Measuring procedure:

To take accurate measurements of the upper surfaces, a steel frame was welded from 25mm x 50mm rectangular tubular sections straddles along the shell clamped to a wooden railing secured to edges of the wooden base on the short sides. A Leico disto D510 laser meter was used to measure the distance from the steel rail at 25mm intervals projected onto the shell on plan, yielding distances with high accuracies. The steel frame was moved to record the next data row. These data were then entered into Excel and FE software to understand the exact upper surfaces of the 2 concrete shells.

Various shell section measurements confirmed the deviations of the upper surfaces in both concrete shells.

6.2.3 Results

Fig 21

Fig 22

Fig 23

Fig 24

Fig 25

Fig 26

6.3 Discussion:

Relationship Between Shell Shape and Gridshell Formwork movement.

The measurements of geometry and movements during construction suggested a strong relationship to concreting sequence. The upward movement of gridshell formwork has resulted in the concrete shell displaying a corresponding rise in geometry.

The process of concrete construction involved "depressing" concrete onto area adjacent to the abutments first, followed by concrete at the apex of the gridshell which was stiff in both shells, then forming regions that joined the two quarter span regions. In both cases, a dryer concrete mix used to prevent slumping and slipping on the smooth fabric. This resulted in underside surfaces appearing heavily pock-marked. Pressure applied was increased as well, resulting in the upper surface being uneven.

Fig 27

Furthermore, fabric formed "air pockets" in the concrete shell as it gets filled with concrete. The height difference showed the upper surface of concrete shell falling away (-60mm) before rising to (+40mm) below datum. The movement at Quarter 2 for the gridshell formwork moved upwards on average. Across Shell 1, significant variations were observed to vary between 4mm and 81mm. Shell 2 differences ranged from 2mm to 64mm. Both upper surfaces of the concrete shells exhibited saddle shapes, with Shell 1 more pronounced. In both shells, there appears to be minimal differences at mid-span i.e. at the apex. Mid-span apex had the least difference, resulting in a flat top region. The largest variation is observed at the quarter span region, corresponding with most gridshell movements. This area is least stiff and was most responsive to hand pressing concrete onto the gridshell formwork. As the quarter span areas were the last sections to receive concrete, much concrete was trowelled in a downward motion from higher areas and others were applied upwards from the lower areas. The quarter spans were most difficult to control, resulting in biggest height variations across the concrete shell.

Whilst the smallest height differences across the shell were observed at the apex, the largest differences appeared at quarter span regions for both shells. Manual hand trowelling, without propping at key points, the production of a perfectly symmetrical surface was challenging as the gridshell was constantly moving with each stage of concrete application. The use of the flexible gridshell facilitates removal of the formwork but may lead to increased variation in final geometry. In this study it was important to consider the full effect of the grid-shell itself, Additional props at the quarter points would reduce the dimensional variation significantly.

6.4 Shell Thickness

6.4.1 Cushions and indents

Measuring the cushions and thickness

An aesthetic feature is the patterning of the shell underside with noticeable thickness variation. Shell thickness was further accentuated by the difference between the upper and under-surfaces of the shell. The under-surface exhibited cushioning effects resulting from the sagging fabric under wet concrete. Thickest sections were located in the middle regions of each diagrid and indentations occurred at gridshell positions cutting into the fabric. A visual inspection also showed the regions near the abutments as being thicker, a result of concrete slipping towards the abutments exacerbated by trowelling movements. A further differentiation of concrete depth was observed: deeper lines were created by gridmat in direct contact with the fabric; shallower lines which were marked by bracing members attached at the lowest level.

Fig 28

Fig 29

Direct measurements were taken using a bespoke double-sided calliper was made from laser cut mild steel. Bolted at the centre, the callipers could reach 600mm from the edges adequate for this purpose. With one end of the calliper measuring the thickness at specific positions, the dimension is reflected at the other end and recorded using a micrometre. This procedure required the co-ordination of two persons – the first measuring and the second, reading and recording the dimension. The measurements were taken by points moving across the shell. This method was simple and accurate.

Fig 30

6.4.1.1 Shell 1

Measurements showed large variations between the thinnest and thickest parts of the shell between 9mm and 63mm, representing 7 times difference, highlighting the sensitivity of the construction process, also representing a 4% variation of the span. The first third and the final third averaged 62mm and 63mm respectively whist the middle third recorded an average of 41mm. The regions near abutments (first third and final thirds) are thickest, measuring 60-67mm (table 3).

The thickest sections appearing at the abutments highlights the sensitive nature of construction through deflections experienced by the gridshell during casting. It is necessary to have thicker abutments to ensure concrete could be built up.

Fig 31

Table 4. Shell 1: Summary of Thickness variations (courtesy of Walejewska, 2015)

6.4.1.2 Shell 2

A variation between 11-67mm at the maximum was recorded i.e. the thickest cushion of more than 6 times between the thickest and thinnest indentation shell thickness with a difference of 56mm, representing a variation to span ratio of 4%. Like shell 1, thickest cushions occur near the abutments measuring a maximum of between 60-67mm. The middle section is comparatively thinner (max 40mm).

Table 5. Shell 2: Summary of Thickness variations (courtesy of Walejewska, 2015)

6.4.1.3 Discussion

Following structural testing, fragments of the concrete at various positions various points were cross-checked with data obtained from the callipers. By measuring particular pieces of the broken shell with thickness measurements produced highly similar results with small discrepancies of less than 3mm. Examining the averages for Shell 1, a symmetrical thickness pattern was exhibited. The shell was thinnest at lines 337.5mm and 1037.5mm at an average thickness of 19.1mm and 19.4mm respectively. Average thicknesses for Shell 1 (cushions and indentations combined) are tabulated below:

Fig 32

Table 6 Average dimensions for effective distances away

At the cushions of shell 1, again, studying the average figures for shell thickness measured 23.2-28.5mm. Atypically, the thicknesses of the cushions at the ends adjacent to the abutments displayed a larger figure at 39.2mm and 34.5mm. The thickest points occurred at the abutments.

For shell 2: Average thicknesses for Shell 2 (cushions and indentations combined):

Fig 33

Table 7 Average dimensions for effective distances away

Averages for shell 2 described an asymmetrical thickness pattern. The shell was thinnest at lines 300mm and 1000 mm with an average thickness of 19.0mm and 17.5mm respectively. Like Shell 1, the thickest sections were near the abutments measuring 55.1mm average at 0mm span and 45.6mm average at 1238mm at the opposite end. These thickness observations coincided with the meeting of concrete between the apex and the lower sections nearer the abutments.

7. Structural behaviour

7.1 Distributed Load Testing

Method

Distributed load tests were carried out to understand shell stiffness. At mid- and quarter- spans, holes were drilled and weights hung at evenly spaced points along mid- and quarter span lines across the shell. Careful drilling was carried out slowly to minimise and avoid vibrating and disturbing the structure.

Fig 34

12 mm thick mdf boards were cut into 40mm square blocks, with 8mm diameter holes drilled to pass wires through. Each wire wrapped around a wooden dowel at the top, passing through the same hole to form a ring at the bottom for weights 10kg, 20kg and others which were placed onto 0.5kg and 1 kg hooks.

Shell Deflection and Displacement at Point

To check for deflections displacement gauges were attached to specially welded frames clamped to the bottom of the bases to minimise errors during taking of measurements.

Fig 35

Loading began with hooks at mid span, first Q2, then Q1 where each position was loaded at 2kg increments. Due to unevenness of the upper surface, beam loading was deemed inappropriate and subsequently point loading at described points used instead.

An initial total loading weight of 234kg for shell 1 and 130kg for shell 2 was applied. Gauge positioning are illustrated in fig. 38. The loading conditions did not result in structural failure and soon, even with all available weights at the workshop used failed to produce significant deflections.

Results

Fig 36

Shell 2

Fig 37

Discussion

With the limited amount of load available, the data displayed a linear load to displacement relationship implying constant stiffness and elastic shell behaviour with small movements. The measurements for Shell 1 ranged from -0.82mm to 0.56mm, representing a variation of 1.38mm equating 0.1% of shell span. For Shell 2, deflection ranged from -1.44mm to +0.51mm representing a deflection range of 1.96mm (0.145% of shell span).

7.2 Load test to failure

The vault was tested to failure using a line load applied at the crown of the vault with a hydraulic ram, Line loading of a shell is particularly onerous compared with the application of distributed loads, more suited to its geometry. However it does provide an insight into the strength, Stiffness and failure mode of the shell.

Load is applied along the crest of the shell by hydraulic ram. Load spreaders were custom-made to distribute loads between four equally spaced points described in fig. 41 and fixed mid-span. The load spreader sat on 40mm square mdf pads attached atop the shell with plaster to spread the loads.

Results

The steel frames were positioned at quarter spans with 2 gauges secured at each of them. Loading was applied slowly in 0.5kN increments and displacements were recorded at each increment until the shell collapsed. To record and study this displacement, two cameras were set up either side of the shell to record the displacement.

Fig 38

A crack at quarter span Q2 (possibly made when it was moved) was observed before the start of the may have influenced failure behaviour. The crack was repaired by gluing epoxy glues to adhere it together.

Shell 1

Four deflection gauges were positioned on the shell two at quarter span 1 and the other two at quarter span 2. This was set up to further record deflections whilst load was applied at the apex. All the recordings showed the shell moving downwards with downward deflection of the upper surface to 1.11mm before the shell cracked and collapsed. These measurements were taken within the elastic range. When the first crack was observed, the gauges and steel frames were removed and the behaviour of collapse was documented in the photo series below. The data, charts and diagram illustrate the findings of this exercise.

Fig 39

Collapse of Shell 1

Fig 40

Shell 2

Four gauges were positioned on the shell for the failure test similar to shell 1. The data collected showed the shell deflected downwards at both positions for Quarter 1 but one of the two gauges, the shell gauge 2 moved upward consistently reaching +1.31mm before collapse. For gauge 1, this position moved upwards to 2.75mm before it collapsed. Photos of a time lapse video presented here records the collapse behaviour.

Fig 41

Shell 2

Collapse Stills of Shell 2

Fig 42

7.3 Summary and Results:

The critical collapse load was recorded to be 4.2kN i.e. 420kg for Shell 1 which is very high failure loading for a shell 1 (106.92kg) representing a collapse load to self-weight ratio of 393%. Critical collapse load for Shell 2 was recorded at 2.7kN (270 kg) for Shell 2 (62.4kg) which is also high representing a collapse load to self-weight ratio of 432%, demonstrating that strong shells can be constructed using this simple method.

8. CONCLUSION

8.1 Deflection / Movement

Construction of test shells demonstrated the flexible nature of the casting process. The formwork was dynamically responsive to the action of applying concrete. The movement/ deflection of the gridshell and sequence of applying concrete affect the concrete shell shape, with greatest movement at the quarter points, the concreting sequence in both cases resulted in asymmetrical shells being formed. Therefore, props at quarter span are suggested as vertical supports to reduce this movement.

8.2 De-mountability

All tests and construction verified the possibility of a new construction method. Test shells construction evidenced the reusability and reconfigurability of the formwork. Additionally, it clearly demonstrated the ease by which the formwork was demounted.

8.3 Variation of Forms

Although this exercise concentrated on two shells of similar geometries (largely single-curved parabolic shape), this method had been used successfully to create shells of more complex double curved geometries, of varying synclasticities and anticlasticities presented in greater detail in (Tang, 2018).

8.4 Thinness

Edges are important expressions of shell thinness and require careful design. Test shells 1 and 2 demonstrated different ways of forming edges to accentuate this thinness. This construction method further exemplifies fabric formwork use, adding to their application as surface and filled moulds, extrapolating fabric formwork applications as an emergent architectural technology (Hawkins et al, 2016). The evenly sharp concrete edge achieved by the use of PVC tubes (which were also used to make the gridshell) defined edges in shells 1 and 2 with a tectonic consistency. Shell thickness of the cushions and indentations can be difficult to check. One possible way of controlling thickness is by inserting pins into the soft concrete during casting.

Table 8: Material Summary of Test Shells 1 and 2

8.5 Cost

The proposed system offered many benefits that past and contemporary methods could not. Although expensive at the outset, cost will reduce with each shell cast through formwork re-use. Their ability to be re-used and re-configured reduces the cost in the life cycle of a deployable GFRP gridshell formwork. This is particularly useful in comparison with rigid curved timber glulam planks (Heinz Isler's shells), bespoke CNC milled foams or temporary OSB casting tables (used in Rolex Centre by SANAA and Kakamigahara Crematorium by Toyo Ito), or timber planks formworks for Felix Candela's shells. An alternative method will be to apply concrete in layers with gunnite (sprayed concrete), of equal thickness such that undulations of the fabric concrete would become visibly expressed on the outside. However, with concrete sprayed onto a flexible matrix, formwork rebound may become an issue. With this, the rigidity of the fabric formwork and other methods of applying concrete would become further improvements.

8.6 Surface Quality

Surface quality depends on factors such as concrete mix, casting technique and textiles type. This concern can be addressed through technology and construction knowhow. The need to vibrate the concrete to smoothen after application (to reduce blow holes and improve concrete quality) may exacerbate deflection movements during the casting process and cause the concrete to slide away. This in turn may disrupt the eventual shell geometry which may be resolved by vertical props to stabilize the shell during vibration/ smoothing suggested earlier.

8.7 Reuse and Recycle

The system is proposed with re-deployability and re-configurability in mind. Upon decentering, the gridshell could be re-configured or re-erected to the same form and prepared for casting. When the system is not in use, they can be collapsed safely and be stored away.

8.8 Performance: Structural Failure

Test 1 has a failure load to self-weight ratio of 393% whilst Shell 2 has a ratio of 432%. The exercise proves that shells cast this way can be very strong with high failure loads.

Re-using and re-configuring the gridshell framework, concrete shells of different dimensions can be built quickly. Primarily, this system address key issues that led to their demise: that previous concrete shell construction methods/ formwork systems not being re-usable, nor easily customisable. In seven days (27 man hours over 7 days), two concrete shells were successfully built using the same re-usable and re-configurable formwork in August 2014. In these experimental exercises, lightweight formwork weighing 0.6 kg was capable of supporting 106.92 kg of concrete to create a concrete shell covering an area of 1.11 sqm floor area. The construction verifies unprecedented cost (£6.06/sqm) evidencing a high rate of material efficiency in the construction of very strong, very thin and wide-spanning concrete shells.

Movement analysis of formwork behaviour during construction, measurements of resultant concrete shell geometries and a tested failure load 4.32 times their deadweight again serves to prove of concept as re-usable and re-configurable formwork to construct very strong concrete shells very quickly.

8.9 Scalability

The purpose of these prototypes was to test the concept and obtain insight into the use of a flexible gridshell as formwork. The system presented using the PVC tubes could be developed directly for application in domestic scale buildings say 4-5 metre spans, using larger diameter pipes of perhaps even bamboo. This may find particular benefits in low coast housing. Larger scale constructions should also be possible with further development. Large timber gridshells have been constructed and the structural design is understood. The behaviour and strength required of the textile will be dependent on the geometry and pattern of the grid shell. The nature of fabric formwork is such that the fabric deforms to carry the concrete in the most efficient way. The construction sequence is important and pre-tensioning of the fabric will help reduce sag. With a pattern based on a two metre grid and maximum sag of 5 cm the fabric used in these tests could carry an initial layer of 5-7.5 cm of concrete easily and comfortably. The potential for new fabric to be developed specifically for formworks was discussed in Brennan et al (2013). The feasibility of larger scale construction was considered in Tang 2018.

8.10 Insulation and cushioning control

The shells could be insulated by a number of ways. Once the shell is cast, spray foam insulation can be sprayed onto the upper side of the shell before being covered with a suitable roofing material of choice. This retains the thermal mass benefits and exposes the aesthetics of this unusual cushioning. Alternatively, should there be a requirement to eradicate these cushioning, rigid insulation boards can be placed over the gridshell in sections prior to concrete pour, as Heinz Isler has done. However, this would negate the thermal mass property of the results but offers a preferred aesthetic that may require further work and finishing.

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Fig 43

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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LIST OF TABLES

Wednesday	**Thursday**	**Friday**	**Saturday**	**Sunday**	**Monday**	**Tuesday**	**Wednesday**
Assembling materials to make the plastic gridshell	Fabric stretching and preparation of recording	Casting of concrete Completion	Concrete Shell Curing	Concrete Shell Curing	Stripping and removal of formwork. Preparing of recording instruments	Concrete Shell Curing	Concrete Shell Curing

Table 1: Time scale and schedule of construction

Gridshell formwork construction	6 man hours (2 technician x 3 hours)
Fabric preparation	2 man hours (2 people x 1 hour)
SHELL 1	
Abutment construction/ preparation	3 man hours (2 technicians x 1.5 hours)
Casting including concrete mixing	9 man hours (3 technicians x 3 hours)
Decentring	0.12 man hours (1 technician 10 mins)
SHELL 2	
Abutment construction/ preparation	3 man hours (2 technicians x 1.5 hours)
Casting including concrete mixing	3 man hours (2 technicians x 1.5 hours)
Decentring	0.06 man hours (1 technician x 5mins)
TOTAL MAN HOURS	27.18 hours

Table 2: Preparation and building times

Shell	Span/ mm	rise/ mm	Span to rise ratio
1	1300	492	2.64
2	1350	620	2.17

Table 3: Span to rise ration of Shells 1 and 2

section of a shell (mm)	average (mm)	minimum (mm)	maximum (mm)	Section of a shell
Entire shell	29	9.3	62.9	entire shell
Sec. 1 (0-450)	33	9.3	62.9	first 1/3
Sec. 2 (450-900)	25	9.4	40.9	middle 1/3
Sec. 3 (900-1350)	30	11.4	61.6	last 1/3

Table 4. Shell 1: Summary of Thickness variations (courtesy of Walejewska, 2015)

section of a shell (mm)	average (mm)	minimum (mm)	maximum (mm)	Section of a shell
Entire shell	31	11	67	entire shell
Sec. 1 (0-425)	34	16	67	first 1/3
Sec. 2 (425-850)	23	13	36	middle 1/3
Sec. 3 (850-1300)	33	11	60	last 1/3
Sec. 1 (0-100)	48	22	67	thickest line of cushions near abutment 1
Sec. 2 (100-1100)	23	11	46	middle section
Sec. 3 (1100-1300)	42	17	60	thickest line of cushions near abutment 2

Table 5. Shell 2: Summary of Thickness variations (courtesy of Walejewska, 2015)

0mm away from right hand free edge	46
75	43.8
200	31.9
337.5	***19.1***
500	20.9
675	25.2
875	23.6
1037.5	***19.4***
1162.5	25.1
1287.5	36.3
1350	48.2

Table 6 Average dimensions for effective distances away

0	55.1
75	41.7
175	29.0
300	***19.0***
450	20.6
650	18.6
850	19.2
1000	***17.5***
1125	33.9
1238	45.6

Table 7 Average dimensions for effective distances away

	Test Shell 1		Test Shell 2	
	weight	cost	weight	cost
Pvc tube 20m	0.32 kg	£2.73	0.32 kg	£2.73
binding screws	0.05kg (nominal)	£1	0.05kg (nominal)	£1
fabric	0.2kg	£3	0.2kg	£3
	area	Formwork Price/ sqm	area	Formwork Price/ sqm
Floor area	1.3x 0.846m = 1.11 sqm	£6.06/ sqm	1.35m x 0.47m = 0.63 sqm	£10.51/ sqm
Concrete shell weight	106.92 kg	97.2 kg/ sqm	62.4 kg	98.34 kg/ sqm
Collapse	4.2 kN		2.7 kN	

Table 8: Material Summary of Test Shells 1 and 2