Deployable Gridshells and their application as temporary, reusable and Flexible Concrete Formwork

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31 Deployable Gridshells and their application as temporary, reusable and flexible concrete formwork

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The laborious construction of formwork and the increased labour costs to create thin concrete shells is attributed to the demise of concrete shells. This paper presents and discusses the outcomes of a recent participatory workshop where timber gridshells were designed and constructed. These timber gridshells, made from deployable timber lattice mats, are capable of deformations that form structures observing double curving geometries. After weeks of public exhibition, they were taken down, collapsed and stored away for future use. The same lattice was then transformed by applying basic transformational tension and compression forces to bring about an alternative form. The possibility of reusing this deployable mat to achieve permutations of different forms resonates with the quest for construction efficiency, ease and sustainability.

With the intention to revive thin concrete shells with new structural intuition, ease of construction and sustainability, this paper speculates and investigates this method of shell form-finding and proposes it as an integrated system of reusable formwork for thin concrete shell construction. The paper interprets this method as fabric formwork but at a larger scale.

1 Introduction - Compression Timber Gridshells

Figure 1: Mannheim Gridshell, Mannheim Germany 1976 Frei Otto

The construction of structures by deforming a flat grid mat to produce double curving surface structures with mainly in-plane forces, has seen a come-back over the last decade.

This method was first investigated seriously at the Institute of Lightweight Structures at Stuttgart University where under the direction of Professor Frei Otto a number of experimental structures were built. Notably, the first engineered gridshell was constructed for DEUBAU, the German Building Exhibition at Essen, Germany in 1962. Following that, the two lath domes for the German pavilion at The 1967 World Expo in Montreal applied gridshell principles. This series of studies subsequently culminated in the publication of IL10 devoted solely to the gridshell (Nerdinger, W 2005).

The technique of construction by deforming a flat timber lattice mat into a three-dimensional architectural piece was most spectacularly used on an unprecedented scale in the construction of the roof of the Multihalle in Mannheim, Germany (Figure 1). Measuring 95,000 sqm, it was built in 18 months for the National Flower Show between 1974-1975 (Happold and Liddell 1975) using pioneering methods of structural analysis and construction processes. Otto used the term "gritterschale" (gridshell) to describe a grid of wooden slats that is curved twice over its extended area by the bending of the slats and angular twisting at the points of intersection.

After Mannheim, there appeared to be a "drought" of gridshell inactivity and it was not until 2001 with the strained/ compression timber gridshell constructed at the Weald and Downland Open Air Museum (Figure 2) that placed timber gridshells firmly into the architectural mainstream again. Today, many more are built, with examples of the 2005 Savill Garden Gridshell (Figure 3) by Glenn Howells Architects and the 2007 Chiddingstone glass orangery gridshell taking prominence.

Figure 2: Savill Garden Gridshell, Windsor Great Park, Windsor Glenn Howells Architects 2005

Figure 3: Jerwood Gridshell, Weald and Downland Open Air Museum, Chichester UK. Edward Cullinan Architects 2001

The design of compression timber gridshells, from an architect's point of view, require a sound understanding of the material and construction process. Timber gridshells belong to the family of surface structures. As such structures gain structural properties (become form-active) from their double curving morphology, the way they are constructed from a two-dimensional flat mat into a three-dimensional surface is a crucial point of understanding.

1.1 Gridshell - A Manuscript of Forces

Timber gridshells are intriguing structures with a powerful material sensibility. Timber gridshells showcase the material capabilities of timber. They also offer a spectacular visual expression of structural legibility –making them efficient in both expressing architectural tectonics and force transfers. Structurally, with grid densities affecting the stiffness and pliability of the grid mat, and as a response to structural design in statics, gridshells serves as a perfect manuscript of forces.

The design and construction activity of a timber gridshell was organised to teach and inculcate a cognitive understanding of timber as a material to students of architecture. This builds upon previous student workshops in timber structures carried out at various international establishments (Popovic, Tang and Lee 2010) that the author had been involved in.

2 In the tradition of the Physical model - Structural Intuition and Creative Play

In his 1966 book, Aesthetics and Technology in Building (translated from the original Italian text), Nervi talked about "intuition" in design (Nervi 1966). He also wrote about the importance of physical modelling to work out the most aesthetically pleasing form for a project design. He believed that aesthetics came from the imagination of the designer and should not be dictated and be compromised by sole concerns of mathematical static calculations.

> *"….How to develop in students a static sense, an indispensable basis of intuition of structural imagination, and how to give them a mastery of rapid, approximate calculations for purposes of orientation….." Nervi, 1966.*

The use of the physical model was also strongly advocated by the late Heinz Isler, renowned for his inverted hanging shells form-finding methodologies. Isler, who formally expressed this sentiment in his 1997 IASS paper "Is the Physical Model Dead?", favoured the physical model as a way of appreciating, understanding and ultimately creating forms (Chilton, 2000). In fact, he liked touching the models and occasionally found weak areas in the structures by doing so (Ramm 2011).

The model is capable of simulating structural behaviour which mathematical calculations so crucially misses. The model is much more intuitive in the cognitive understanding of behaviour, and of how the structure reacts to forces. For example, in gridshell design, it is much easier to observe how areas with low curvature could lead to buckling by "poking and prodding" a physical model.

This "Creative Play" (Chilton, 2000) approach was the educational driving force behind this week long activity where design workshops were enhanced by real scale construction activities. To reinforce learning, invited speakers delivered lectures on innovative timber shell design and construction.

This builds on the educational premise of structures/ technology education for architecture students in the gridshell design and construction workshops developed by Douthe, Bavarel and Caron at The Navier Institute Paris and Deregibus and Sassone at Il Politecnico di Torino in Italy.

3 Timber Gridshell Workshop at Sheffield Hallam University, March 2011

The students of Sheffield Hallam University participated in a life-size workshop to learn about this type of structures by designing and constructing timber gridshells during a week of material explorations in timber. A flat site opposite Sheffield Central Train Station was chosen for the week-long construction workshop.


Figure 4: The completed gridshell entitled THE SWELL, Sheffield Hallam University March 2011

3.1 Scaled paper gridshell model and grid mat deformational behaviour

Prior to building the structure at full scale, the participating students explored the construction sequence and form-finding by using 1:50 models made from 5mm wide paste-card strips. These were first crossed and pin jointed together at their intersections to form a gridded mat. (Figure 5)

The joints replicated the swivel action that allowed the deformation of the grid to take place. With this grid ability to deform from square to diamonds, the overall mat itself was able to lengthen and shorten. The material remains two-dimensional, although the mat changes shape and area coverage on plan.

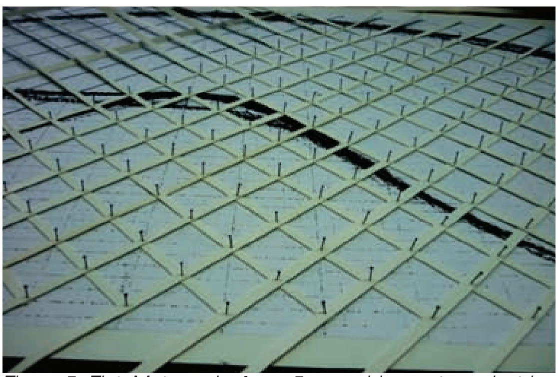
Figure 5: Flat Mat made from 5mm wide pastecard strips pinned at their intersections

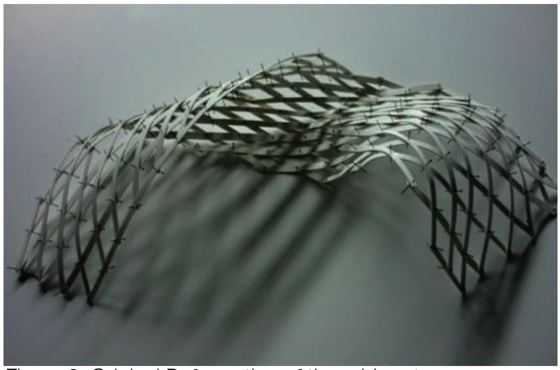
Figure 6: Original Deformation of the grid-mat

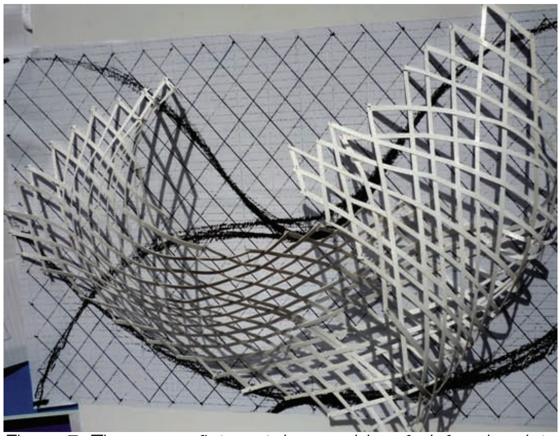
Figure 7: The same flat mat is capable of deforming into different forms demonstrating reusability as concrete shaping formwork.

When pushed or pulled within this plane, the newly constructed mat was able to twist and deform.

When lifted out of the board, it comes alive. It is this 3 dimensional deformation that gives the mat the ability to define space, to rise from a 2-d to a 3-d form. The same mat is capable of creating many permutations of forms. (Figure 6a,b)

Axial forces acted within the mat to create “structurally correct” forms. It was also easy to “feel” the stiffness of this structure by handling the shaped mat.

Playing with the grid-mat, it was also noticed that the deformation depended on the pattern and arrangement of the grid. If a mat was constructed such that grid patterns are parallel to the mat edges, the deformation creates a narrowing effect where the deformed mat tapers into a point. However, to achieve a mat with a useful length and breadth dimension, the grid pattern needs to be set at a diagonal to the dimension of the mat.

It was also noted that by pre-deforming the mat, e.g. the action of lengthening and shortening the mat, loosens the mat and helps in the proceeding forming process.

Figure 8: View of Shell from interior space

After shaping, the three-dimensional paper grid mat was then secured into position by model pins onto a foamboard base.

After much simulation tests, discussions, experimentation and explorations, the final design was finally arrived at.

THE SWELLS, as the piece was eventually entitled, was constructed from a rectangular grid mat measuring seven units wide and 17 units long. With each grid unit measuring 900 x 900mm square, the mat laid flat measured approximately 9m by 18m.

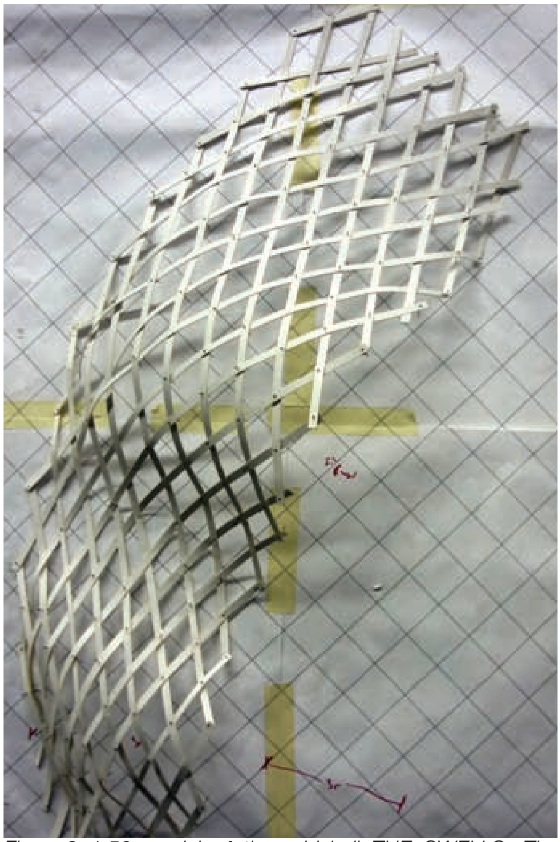

Figure 9: 1:50 model of the gridshell THE SWELLS. The smaller crest is on the bottom and taller crest on top.

4 The Eventual Design: THE SWELLS

The designed gridshell consists of two swellings to the structure (Figure 9)- the smaller baby swell appears at the bottom end and with the front edge leaping out of the ground to a height of 1.2m.

The mat then dives into the ground again before rising to create mother swell, this time taller, to a height of 3.5m, again with only the front edge rising out from the ground. All the back edges are anchored to the ground. The geometry is reminiscent of the Gaussian vaults found in many of Eladio Dieste's work in Uruguay.

4.1 Sequence of erection

The mat is deformed in a specific sequence of erection. Like in the model, firstly, the mat was constructed with the grids completely square. It was then completely shifted (without deformation) to the correct orientation. After that, the mat was elongated (deformed two-dimensionally) by pulling, so that the square grid pattern become diamonds. The middle section between the two crests is identified and anchored down to the ground using metal chairs.

Once the location is determined, the *baby swell* was created first. The short western edge of the mat moves southwards to push *baby swell* out from the ground. Once created, rebar chairs peg the grid mat into the ground.

To create *mother swell*, the other edge of the mat is similarly moved to push it out from the ground.

According to the 1:50 model, the two swells performed most shell action, they felt taut, presumably with in-plane forces acted upon. By handing these areas physically, the forces within the shell is understood readily by the architecture students- they could see what was “right” and what was not.

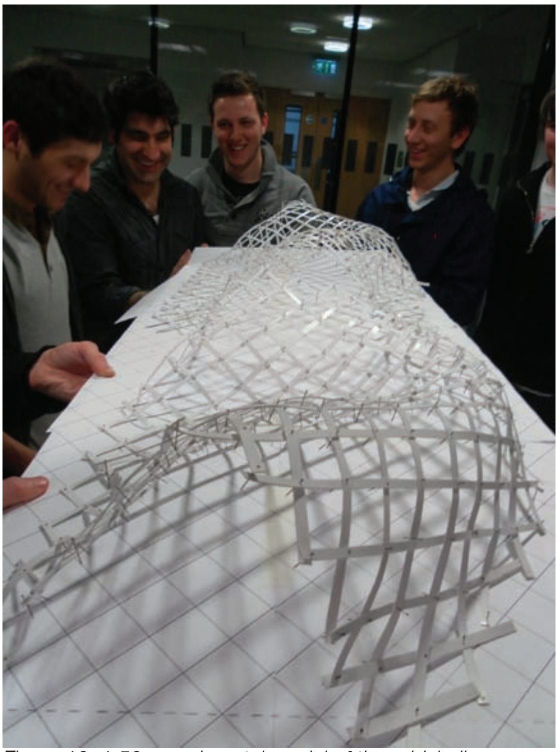

Figure 10: 1:50 experimental model of the gridshell

4.2 The Construction

The final timber gridshell was constructed using 2.1m long pieces of timber pine battens of profile section of 35 x 12mm arranged in a 900mm square grid. Each piece of timber was pre-drilled to create a couple of 5mm diameter hole at each end. They were then spliced together using nuts and bolts to create longer members. At the intersections, long flexible members were cross-bolted at intermediate pre-drilled points to form swivel joints, replicating in-plane swivel action as simulated by pins in the paper card model.

Figure 11: The simple testing timber battens

Timber testing was carried out using a simple rig test. (Figure 11) This required all the timber battens to be subjected to a bending test in which each softwood batten was bent to a calculated curvature before it fails. Breakages occurred at 40%. As expected, timber battens mostly failed at weak points specifically at knotted sections.

Figure 12: The flat mat is carefully lifted and moved to correct orientation.

As simulated using the physical model, the timber mat was first constructed laying flat on the ground. To do this, battens were spliced and bolted together at their intersections. The card model proved a very useful tool to communicate to the student teams about the sequence of erection (Figure 12). Before construction, each student knew their stations and whether they are

a) stationary

or

b) moving - and if they are moving, in which direction. The sequence was carefully choreographed using the model in team meetings throughout the week.

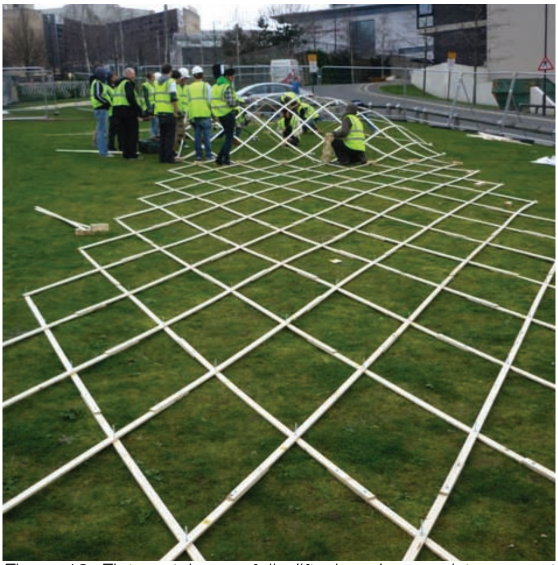

Figure 13: Flat mat is carefully lifted and moved to correct orientation.

When the mat was ready, the flat mat was pushed into shape by students holding on at important points. (Figure 14) Each student either walked towards each other or away from each other to bring about the 3D deformation of the flat mat in accordance with the simulations of the scaled paper strips model.

Figure 14: The baby swell takes shape and was fixed by pegging down using rebars chairs.

Once the form of the gridshell is arrived, longer bracing elements of these timber members were drilled and bolted together to "fix" these shapes by triangulating the quadrilateral grids to give rigidity. (Figure 15) A simple system of metal chairs and timber blocks were used to peg the gridshell in place. Rope was also used to tether the structure to the ground to prevent wind uplift.

Figure 15: Bracing members are fixed to triangulate grids to lock in form.

The structure allowed visitors to interact, walk, stand and sit under during lunch-hour and drew much interests from the media including local newspapers and the BBC radio.

A short time-lapse film of the construction can be viewed online using the following url link:

http://vimeo.com/21348054

Figure 16: The completed gridshell on display. The bigger crest (left) rises to a height of 3.5m.

5 The Advantages of the System

The exhibit was left on-site for a two week period, inviting the public to view and interact with the structure. It was then disassembled and kept for future re-erection. During the taking down, the gridshell flipped back into its original two-dimensional mat form when the bracing pieces were removed. The flattened mat was then collapsed, taken apart in sections and stored away.

It was the intention to reuse the mat again. It is possible to re-form it into another shape by splicing the sections together again. Explorations made using the paper model proved it to be a feasible idea as numerous forms, although of varying degree of stiffness were made from the same mat as shown in Figure 17 and Figure 18).

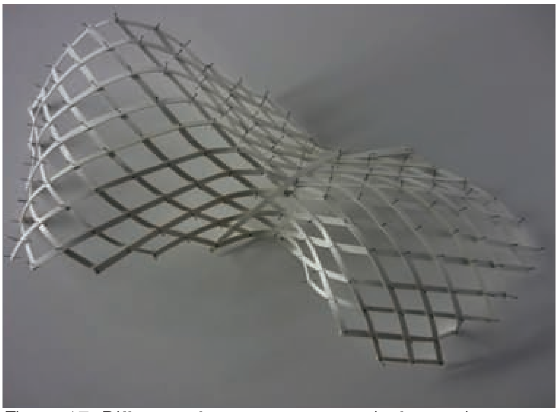

Figure 17: Different forms constructed from the same deployable grid mat.

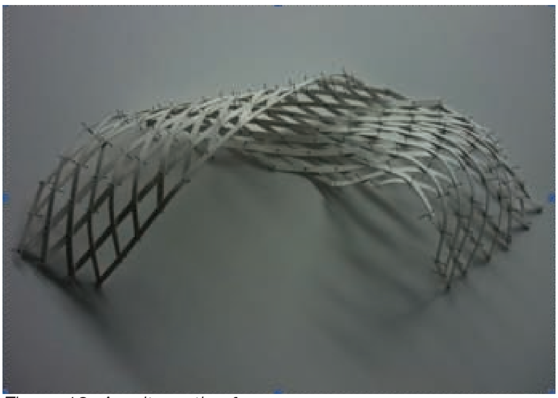

Figure 18: An alternative form

The idea that such a deployable system is reusable is very attractive and indeed full of potential.

Not only has this workshop illustrated a system suitable for erecting a small-scale open air enclosure, creatively, this method may offer an alternative way of building concrete shells without complicated scaffolding and ladders leading to cost economy.

6 Evaluation and Limitations of the Timber Gridshell

Indoor grade pine sections were used in this project. The structure remained intact with the good fortune of dry weather in the weeks of outdoor display. In inclement weather, the structure may suffer from moisture deterioration and possibly fail. An alternative material such as plastic or carbon fibres, could be trialed and explored to offer a weather-proof solution.

The weakest points of the gridshell structure were observed to be at the regions of contraflexion – areas where a change of geometry occurs ie when the shell changes from anticlasticity to synclasticity which demonstrated most deflection. Careful stiffening need to be considered to the design of these regions.

Although the project was successful in focusing on the cognitive instinct of the architectural designer, structural analysis, calculation and finite element analysis may be useful to confirm/ testify/ enhance the design to complete the learning experience and to create a structure with mathematical soundness, yet imbued in creativity.

The erection process relied heavily on effective communication and teamwork. This required the careful maneuvering of a large fragile timber mat, susceptible to fracturing prior to gaining stiffness before deformation. As such, there may be limitations to how large this grid mat can be, to enable it to be erected without any support. Although PERI scaffolding can be used to lower the mat into shape safely over a sustained period successfully in the Weald and Downland Gridshell, their use may negate the scaffolding-free benefits of this “push up” system. This is an avenue of investigation.

It is not difficult to observe similarities between this structural method and the use of suspended fabric formwork. Both are highly responsive to gravitational forces and result in structures which are an imprint of force transfers logic. The tectonics of the gridshell as a support matrix on a bigger scale can be easily seen as a form of force fingerprint.

7 Future Work and Development: Potential as Reuseable Formwork for Concrete Shells.

This method of building small scale gridshells can have an impact of the revival of shell construction.

Concrete shells, as a building typology suffered in popularity over the last 30 years because of cost concerns due to their ineffective formwork systems and rapid development of competitive systems such as membrane and lightweight constructions.

In recent years, computer advancements has resurrected shell structures into the vocabulary of 21st century architecture seen most recently in the walkable shell surfaces at The Rolex Learning Centre at EPFL, Lausanne, Switzerland designed by SAANA completed in 2011.

7.1 Application

The hypothesis of treating this deployable gridmat as a temporary reusable and flexible formwork is an interesting notion in a time when innovation and shell building is making a return to the architectural landscape. This system of shell construction, reuseable in our sustainability-conscious environments is an important point of consideration.

The idea is for the deployable mat, not necessarily of timber, to be pushed and erected into a desired shape with sufficient axial loading capacity and be locked in place by simple triangulation is seemingly straightforward. Fabric membranes can then be laid/ stretched onto this structure before concrete or other composites such as glass fibre reinforced concrete sprayed onto this surface. In such a way, the compressed gridmat acts as a frame for which fabric formwork can sit on.

Using geo-textiles and membranes to suspend between the grid laths, shotcrete can be applied onto the surface to form the shell. The vocabulary of shell aesthetics is apparent and draws references to the sensibilities of structures cast from fabric formwork. (Figure 19). The use of a flexible membrane to create undulations, creases, cuts on a curved surface in these instances is a very attractive possibility. This have the potential to contemporarize this technology and introduce it into the technological mainstream to revive the concrete shells again.

Upon the new concrete shell being cured, the deployable gridshell can be removed from under the newly formed shells to another location to create shell form of another geometry and be reused.

7.2 Limitations

Concerns and other practicalities are very real in this proposition. This idea, in my opinion, offers opportunities for further exploration that include:

- What is an appropriate shell size for this application?
- Thermal insulation,
- Form “locking” mechanism and release of gridshell
- Loading conditions of the heavy concrete-shotcreting techniques
- Issues with movement and tolerances whilst concrete is curing
- How the formwork will be released/ removed
- Edge conditions

7.3 Related works

The use of timber gridshells as formwork is obscure with limited precedents documented. An office and house in Hirituka City, Kanagawa in Japan is roofed with a similar system. In this 1988 project designed by Shinji Yoshino, Tokyo and engineered by TIS & Partner, a latticed timber gridshell supported the formwork that formed 5 shell roofs. However, as the timber lattice gridshell was fixed, the lattice shell became permanently visible from the interior. (Herzog *et al.,* 2004)

Figure 19: Experimental shell encased in modroc

Figure 20: Interior view of "concrete shell" formed atop a deployable gridshell

Figure 21: The patterning of the "concrete shell when the gridmat is removed

This is an ongoing research on the feasibility by the author as part of a PhD studies program at The University of Edinburgh.

8 Conclusion

The workshop presented in this paper proposes an exciting way of constructing shell forms and geometries using the scaled model as a starting point of structural investigation. It also exemplifies the creative pedagogy advocated by Nervi and Isler, that intuition and an understanding of material and their structural properties is an important component of architectural design in education.

The collapsible and deployable nature of this gridmat renders it suitable for re-use and its application as formwork.

Its suitability will be determined by ensuing research and development by the author. This idea of a new formwork and process of creating concrete shell is postulated to further propel the use of shell construction in contemporary architectural application with the aspirational outcome of sound structural logic, economy and sustainability.

9 Acknowledgement

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