Shell Structures from Catalan to Mapungubwe

Lessons from Structural Efficiency for Sustainable Construction in Developing Countries

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1. INTRODUCTION

In a world moving towards a sustainable earth, the developing world is faced with the dilemma of rapid expansion of housing and infrastructure needs on the one hand and the constraints of sustainability on the other. However, a closer look at local strengths and technology elsewhere can lead to creative solutions.

Shells are a more efficient structural form than the widely used column-beam frames, which make use of bending strength and hence underutilize the structural capacity of materials. Superior structural efficiency allows for shell structures to be lightweight and thus reduce the material demand. The wide range of possible material solutions – from compressed earth to concrete - allow for an appropriate local material to be used in the realization of the structural form.

Shell structures are by no means a modern invention. Evidence of the earliest vaulted structures come from Mesopotamia in 3000BC; a 5000-year-old Mesopotamian burial chamber having a barrel vault of approximately 1 m span is in display at the Berlin Museum of Prehistory and Ancient History (Kurrer, 2008). The Roman arch, the bridges and cathedrals in Europe built during the renaissance, the modernisme movement in Barcelona and Guastavino vaulting, which spread in the east coast of the USA, have all left us with a rich collection of form-resistant structures. The more modern inclusions to this collection are Hassan Fathy's reinvigoration of Nubian technique, Heinz Isler, Frei Otto and Luigi Nervi's compression only shells followed by Jacque Heyman's safe theorem giving a systematic approach to design compression only shells.

The current study looks at both the traditional technologies (and adaptations thereof) and explores new frontiers in lightweight shell construction to scope out potential future growth. An understanding of socio-cultural impacts of these structures, technologies and materials give a better perspective on how technology can be appropriated to different local contexts.

This brief report includes knowledge gathered from travels to India, Europe and the USA; the former two being funded by the Pai Lin Li Travel Award presented by the Education Trust of the Institution of Structural Engineers, UK. The travels relevant to this report include visits to the following places.

- Auroville Earth Institute (AVEI), a partner institute of UNESCO chair of earthen architecture. They follow the Nubian technique as popularized by architect Hassan Fathy and fundamental structural analysis tools presented by Jacques Heyman.
- City of Barcelona is the home for many structures which stands true to the philosophy of form following forces. These include work by Antoni Gaudi, Lluís Domènech i Montaner and Rafael Guastavino.
- City of Boston and New York City houses many thin shell tile vaulted structures (Catalan vaulting) popularized in the east coast of the USA by Rafael Guastavino; both father and son.
- Block Research Group (BRG) at ETH Zurich leads the way in developing analytical tools and promoting the philosophy of structures without bending actions – i.e. compression only structures. They have provided architectural and structural engineering expertise to various shell structures around the globe.

  Furthermore, ETH is the home of late Heinz Isler and houses many of his scale models and many of his projects are within few hours travel from Zurich.
- Institute of Light-weight Structures (ILEK) at University of Stuttgart is chaired by Prof. Werner Sobek and holds a preeminent position in lightweight construction. They too have done interesting work on form-resistant structures (in contrast to compression only structures, they may allow some tensile stresses while minimizing bending). Both the rich collection of literature and their work on active control of structures shows a potential next step for form resistant structures.

The following report is written as a critique of different design philosophies (Section 2) and practices observed at the above places (design methods in Section 3 and construction practices in Section 4), supported by specific examples and case studies where applicable. Section 5 discusses a few socio-economic interplays as observed and discussed during the visits. This is followed by Section 6 which elaborates on possibilities with shell constructions and ideas for potential research, practical experimentation and applications within the realm of structural engineering.

2. DESIGN PHILOSOPHY: A CASE FOR SHELL STRUCTURES

Arch as a structural form was necessitated when beams were no longer able to bridge increasingly longer spans. Vaults and domes too may have been evolved due to such needs, but some historians and architects suggest that domical roofs used in cathedrals are suggestive of heaven or the realm of gods. Nonetheless, vaults and domes (the most common shell geometries from early days) were used for different functions and out of different materials in different places across the globe.

2.1. Nubian Technique

The tradition of earthen structures as practiced by the Auroville Earth Institute (AVEI) is not necessarily a traditional Indian technology but rather a mindful adoption of the Nubian technique, as popularized by Egyptian architect Hasan Fathy. However, significant improvements to design methodology, production of material and construction has taken place at AVEI during its 30 years of existence.

Nubian technique has originated from Nubia in south of Egypt and the famous vaults of the granaries of the Ramesseum at Gourna, Egypt are testament to the success of this technique. The basis of the Nubian technique is that the blocks adhere to each other with an earthen binder (Figure 2.1). The adhesion is achieved when the dryer blocks draws in water by capillary suction and the clay components of the soil acts as an adhesive to bind the blocks.

Traditionally, the Nubian technique requires a back-wall to mark the curve and ‘lean’ the first course of blocks. The vault is built as a sequence of arches slightly leaning on each other. The binder is a silty-clayey soil (from the Nile) and a binder layer of 10 – 15 mm is used with sun dried blocks.

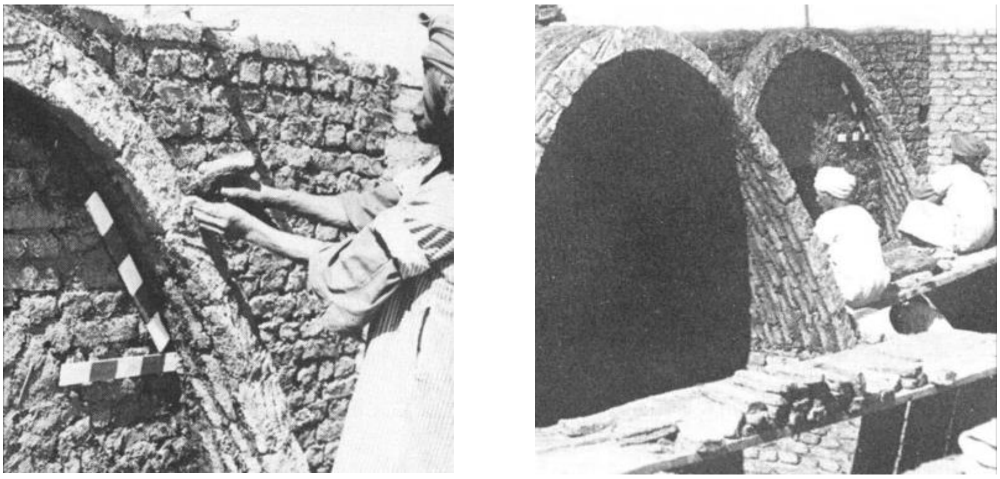


Figure 2.1 - Nubian vaulting technique. [Image source: Davis & Maini, 2016]

Figure 2.2 - Auroville Earth Institute.

Figure 2.3 - Auroville Visitor Centre.

Nubian technique can also be used to build circular domes with a compass to guide the geometry. At Auroville they have developed a series of compasses to be used with various geometries. A further development at Auroville is the ‘free-spanning’ technique. The premise here is to determine the sequence of construction in such a way that partially built structure always has a safe load path. This is further discussed in Section 4.2.

The designs and constructions done by AVEI include buildings at Auroville Earth Institute (Figure 2.2), Auroville Visitor Centre (Figure 2.3), Gayathri Dome in Auroville, Dhyanalinga dome and Sharanam conical vault.

2.2. Catalan Vaulting

In contrast to the heavy and thick masonry shells following from Nubian technique, Catalan vaulting (or Guastavino vaulting as referred to in the USA) uses multiple layers of very thin tiles (usually 3 layers of 15-20 mm thick tiles- see Figure 2.4).

Catalan vaulting too is a free spanning technique, using guides to define the geometry in space. This makes it an interesting technique to be used with free-form shells such as the one built in Valldaura Labs (Figure 2.5), by a group of students from the Polytechnic University of Catalonia, Barcelona. The first layer of Catalan vaults is built in space with a fast setting gypsum mortar. The subsequent layers are built with the first layer acting as the form work.

There are many examples of Catalan vaulting in both Barcelona and in the USA. The examples in Barcelona includes Teatre La Massa (Rafael Guastavino –Figure 2.6), factory building in Terrassa (Lluís Muncunill i Parellada –Figure 2.7), Palau de la

Música Catalana (Lluís Domènech i Montaner–Figure 2.8), Restaurant en Ville (Rafael Guastavino –Figure 2.9) and many other structures around the city (Figure 2.10).

The examples in Boston and in New York City include Boston Public library (Figure 2.11), patio of the Boston Coast Guards (Figure 2.12), Fariborz Masseh Hall at MIT (Figure 2.13), walkway at University of Massachusetts (Figure 2.14), New York Chamber Street City Hall Building (Figure 2.15), Queensboro Bridge (Figure 2.16), Oyster bar at New York Grand Central Station (Figure 2.17), a building at Vesey Street NYC (Figure 2.18). All these Catalan vaults in the USA were designed and built by the Guastavino company.

Figure 2.4 - Multiple layers of thin tiles in Catalan vaults.

Figure 2.5 - Free-form Catalan vaulted structure built at Valldaura Labs, Barcelona

Figure 2.6 - The Catalan vaulted spherical dome of Teatre La Massa in Vilassar de Dalt, designed and build by Rafael Guastavino.

Figure 2.7 - Catalan vaulted roof of the factory building at Terrassa (now Museu de la Ciència i de la Tècnica de Catalunya) designed by Lluís Muncunill i Parellada.

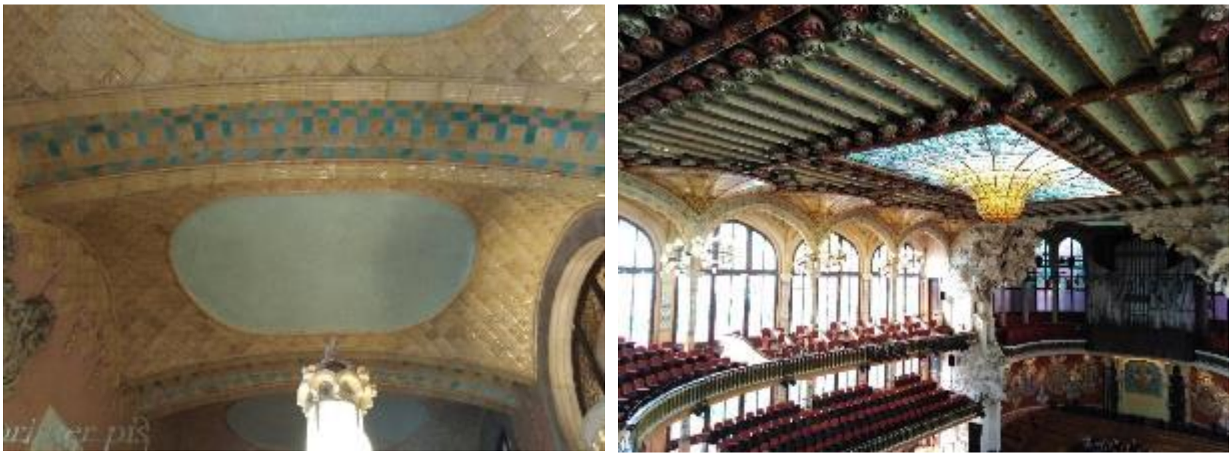


Figure 2.8 - Catalan vaulted ceilings of the Palau de la Música Catalana designed by Lluís Domènech i Montaner.

Figure 2.9 - Catalan vaulted roof of the Restaurant en Ville, Barcelona designed by Rafael Guastavino. The image on the left is an early example of the herringbone pattern being used in doubly curved Catalan vaults.

Figure 2.10 - Exposed and unexposed vaulted ceiling / floors around the city of Barcelona.

Figure 2.11 - Guastavino vaulted (Catalan vaulting) ceiling/ slab system in Boston Public Library.

Figure 2.12 - Guastavino vaulted ceiling at the patio of the Boston Coast Guards office.

Figure 2.13 - Guastavino vaulted ceilings at the Fariborz Masseh hall at MIT.

Figure 2.14 - Guastavino vaulted ceiling at the walkway leading to the chapel at University of Massachusetts.

Figure 2.15 - Guastavino vaulted ceiling at New York Chamber Street City Hall Building.

Figure 2.16 - Guastavino vaulting in the Queensboro Bridge, New York City.

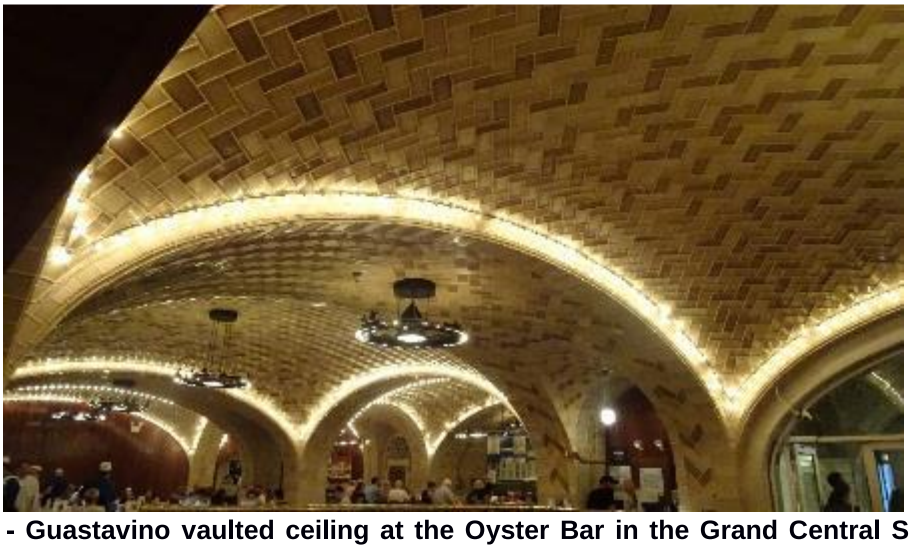


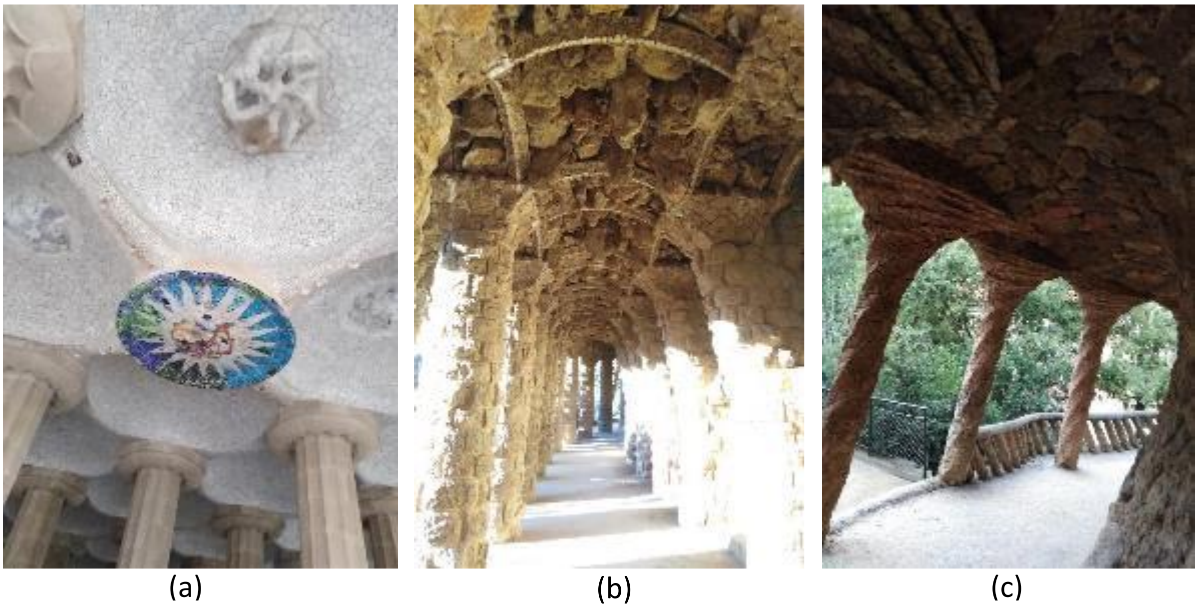
Figure 2.17 - Guastavino vaulted ceiling at the Oyster Bar in the Grand Central Station. This survived a major fire in 1997 with delamination of some tiles being the only damage caused.

Figure 2.18 - Guastavino vaulted walkway in a building in Vesey Street New York City. This structure is directly opposite to the World Trade Centre and survived the impact from debris during the collapse of the twin towers in September 2001.

2.3. Gaudi's forms following forces

With an understanding of flow of forces, gained from his physical models, Antonio Gaudi was able to use the full canvas of the three dimensional space and produced some wonderful structures in doing so.

Park Güell houses simple examples of forms following forces (Figure 2.19), whereas La Sagrada Familia (Figure 2.20), Colonia Güell (Figure 2.21), Casa Milà (Figure 2.22) and Casa Batlló (Figure 2.23) depicts more elaborate expressions of forms following forces.



(a) (b) (c)

Figure 2.19 - (a) a domed roof slab, (b) a vaulted viaduct and (c) tilted columns - all forms following forces- at Park Güell by Antonio Gaudi.

(a)

(b)

(c)

(d)

Figure 2.20 - (a)The passion façade, (b) vaulted entrance way, and (c) (d) the tree like columns supporting the main spire (not yet completed) and the roof structure, at La Sagrada Familia designed by Antonio Gaudi.

Figure 2.21 - Ribbed and vaulted roofs of Catalan tiles at the crypt in Colonia Güell, designed by Antonio Gaudi.

Figure 2.22 - Ribbed and vaulted roof structure at the attic of Casa Milà, designed by Antonio Gaudi.

Figure 2.23 - Ribbed arches in Casa Batlló, designed by Antonio Gaudi.

2.3. Similar yet different

All three types of technologies of shell structures discussed above does the same fundamental thing; they carry loads primarily in compression. However, there are interesting differences in (i) how they account for variable loading and (ii) how the lateral thrusts at supports are resisted.

2.3.1. Accounting for variable load

The heavy Nubian vaults have a much higher self-weight in comparison to variable loads. Also, these shell structures are typically used as roof structures rather than slab systems. Thus, the self-weight itself is the significant loading and the effects of variable action can be reasonably accounted for by having a safety margin on the thickness of the shell.

(a) (b)

(c) (d)

Figure 2.24 - (a) Catalan vaulted slab system in an old weaving mill (currently being renovated as a museum) in Vilassar de Dalt, (b) a cross section of the Catalan vaulted slab, and (c) (d) a partially demolished part of the slab showing the vertical stiffeners in the hollow slab.

Catalan vaults are used as slab systems (Figure 2.24) and have a much thinner shell. As such the variable loading is a significant factor for the safety of the structure. It is observed that the Catalan vaulted floor slabs account for the variable loading by having vertical stiffeners (see Figure 2.24c and d). Furthermore, Rafael Guastavino has extensively used doubly curved thin shells as slab systems (Figure 2.11) to give robustness to the shell structure. The doubly curved shell is extremely stiff and is capable of safely carrying asymmetric loadings due to its multiple load paths.

Figure 2.25 - A prototype of doubly curved Catalan vault built in front of Teatre La Massa in Vilassar de Dalt, Barcelona

In more modern work by the Block Research Group (BRG), they assess the structure under the different load cases envisaged. Such a procedure can be viewed as a more ‘engineered’ solution than the intuitive solutions discussed above.

The next stage of ‘engineered’ shells is observed at ILEK Stuttgart; the SmartShell (Figure 2.26). This 40 mm thick timber shell of 10.28 m span and 3.57 m rise is supported on three supports which can be actively controlled and one stationary support. The shell is sized to resist only the permanent actions. The variable loads are resisted by the active control of the structure via the supports (Figure 2.26b). A 0.4 kN/m^2 additional load on one quadrant gives a maximum stress of 11.2 MPa and by adjusting itself through active controls the shell would reduce the maximum stress to 3.2 MPa.

The hand-off point between mass resistant system and active control system (i.e. the material utilization factor) is determined based on energy; the embodied energy of the material that resist permanent loads and the actuation energy required for active control of the structure. Further improvements are necessary for rapid assessment of the existing stress state of the structure as this currently is the bottle-neck in the active control systems. Once the current state of stress is determined the optimal shape and the actuation sequence can be found within milliseconds.

(a) (b)

Figure 2.26 - (a) Stuttgart SmartShell and (b) its actuator system, constructed at ILEK, University of Stuttgart.

2.3.2. Resisting lateral thrust

The heavy masonry structures observed in Auroville (Nubian technique) and Barcelona use masonry buttresses (Figure 2.28) to safely carry the large horizontal thrusts created. In contrast, light weight Catalan vault systems use steel tie rods (see Figure 2.24 and Figure 2.27) to carry the horizontal thrusts.

Figure 2.27 - Steel rods taking the horizontal thrust of Catalan vaults in a restaurant in Vilassar de Dalt.

Figure 2.28 - Making use of buttressing to resist the horizontal thrust (in absence of tie rods) of Catalan vaulted structure, at University of Massachusetts.

These tie-back techniques are observed in more modern projects done by BRG. The Armadillo Vault uses steel support plates tied back with steel rods (Figure 2.29) so as not to damage the historical floor of the exhibition hall. The ETH Zurich Pavilion for the 2015 Ideas City festival in New York did not use any tie back (Figure 2.30). The lighter weight of the vault (due to it being built of hollow blocks made from compressed tetra pack panels) meant that the stability of the stack of timber pallets supporting the vault can be guaranteed by weighing down the timber pallets with ballast loads. Additionally, the pallets were bound together to act as a single unit.

Figure 2.29 - Armadillo Vault designed by BRG. [Image source: BRG http://block.arch.ethz.ch/brg/content/project/armadillo-vault-venice-italy]

Figure 2.30 - Pavilion designed by BRG for the Ideas City Festival in New York 2015. [Image source: BRG http://block.arch.ethz.ch/brg/project/eth-ideas-city-pavilion-new-york-ny-usa] .

Antonia Gaudi takes a different view of transferring the thrusts from the heavy shells. Instead of traditional buttressing which tries to stay true to the concepts of walls and rectilinear spaces, he used inclined columns to support the random rubble vaulted viaducts at Park Güell in Barcelona. These columns are oriented to have the columns primarily resist axial loads and minimize bending moments. Many examples of these were evident in Park Güell (Figure 2.31). Similar observations can be made in Gaudi's other creations including in La Sagrada Familia (see Figure 2.20 and Figure 2.21).


(a) (b)

Figure 2.31 - Inclined columns (a) supporting a viaduct and (b) a walkway at Park Güell in Barcelona, designed by Antonio Gaudi.

2.4. Prinzip Leichtbau: Lightweight Principle

The principle of lightweight presented by Frei Otto compare masses and how they are able to transmit forces. The ability to transmit forces (Tra) is quantified using the force that can be transmitted (F) and the length of the load path (s). This extend the concept of form and forces to include masses. With masses brought in to the mix it is now possible to relate form and forces to energy and cost – which are much easier parameters to comprehend for layman public and policy makers. In ILEK publication IL 24 he presents a parameter called Bic (with units g/Nm), which is the ratio of mass to 'Tra', where 'Tra' is the ability to transmit forces as presented above (Tra = F x s). An interesting observation from his study is that tension systems (e.g. a cable nets) would always give a lighter weight solution than a compression only solution (e.g. compression shell) although the latter still gives a positive Bic value.

This stand to show that compression-only shells are not the end of the path for optimizing material usage- there can be lighter weight solutions if one intends to look for. However, considering the material at hand (e.g. materials with low tensile capacity) or other constraints, compression-only solution will be the best one can aim for.

3. DESIGN METHODOLOGY: FROM INTUITION TO INFORMATION AGE

The structural analysis of compression only forms have evolved through the years. But all the methods of analysis observed during this study were based on one fundamental idea; Robert Hooke's observation of hanging chain – "as hangs the flexible cable, so but inverted stands the rigid arch".

3.1. Physical models

3.1.1. Antonio Gaudi

Physical models are the most fundamental manifestation of Robert Hooke's observation. Antonio Gaudi has extensively used physical models (Figure 3.1 and Figure 3.2), which are daring in their size and complexity, as are his realized structures. Hanging chain models are more complex manifestations of Robert Hooke's hanging chain. Different weights are attached to nodes to represent the loadings on the structure, due to self-weight or otherwise. Unlike the Heinz Isler's models described later, the hanging chain model is not rigidified, but the inversion is done on paper with geometry measured from the hanging chain model. A glass mirror was used to look at the inverted shape to get a sense of the shape generated.

3.1.2. Heinz Isler

Heinz Isler's physical models are much simpler. The scale model in Figure 3.3 is a hanging chain model rigidified in plaster of Paris (gypsum plaster) which also includes cables to resist the horizontal thrusts. The simplicity in his models made sure that these structures can be repetitively used in different projects. The model was built as a form-finding model for the Norwich Sports Centre roof structures. This roof structure was used for many tennis court and swimming pool roof structures by the architects

Haus + Herd of Herzogenbuchsee (Chilton, 2000). The tennis court complex in Solothurn has a similar roof structure (Figure 3.4).

The model in Figure 3.5 is a plastic shell prototype used as a load testing model for the design of concrete shell roof structure of Dübendorf Air Museum. The model in Figure 3.6 is used to show the effect of shear deformable nets in giving clear doubly curved surfaces, whereas a cloth which has some shear resistance will show wrinkles.

Figure 3.1 - Hanging chain model of La Sagrada Familia.

Figure 3.2 - A replica of the hanging chain model of the crypt in Colonia Güell.

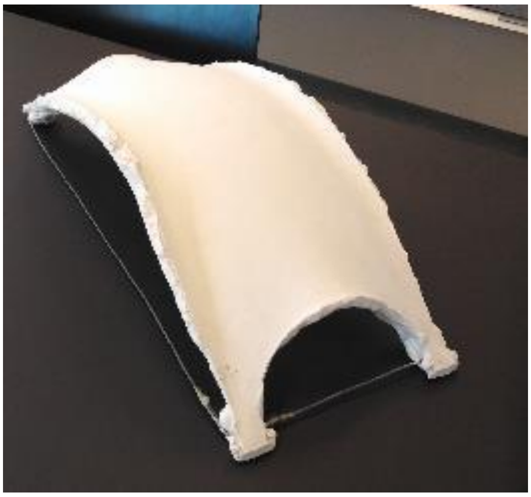


Figure 3.3 - Heinz Isler's scale model for the Norwich Sports Complex tennis court.

Figure 3.4 - Tennis court at Solothurn, Switzerland built by Haus + Herd.

Figure 3.5 - Isler’s model used for the scale model testing of the roof shell in Dübendorf Air Museum.

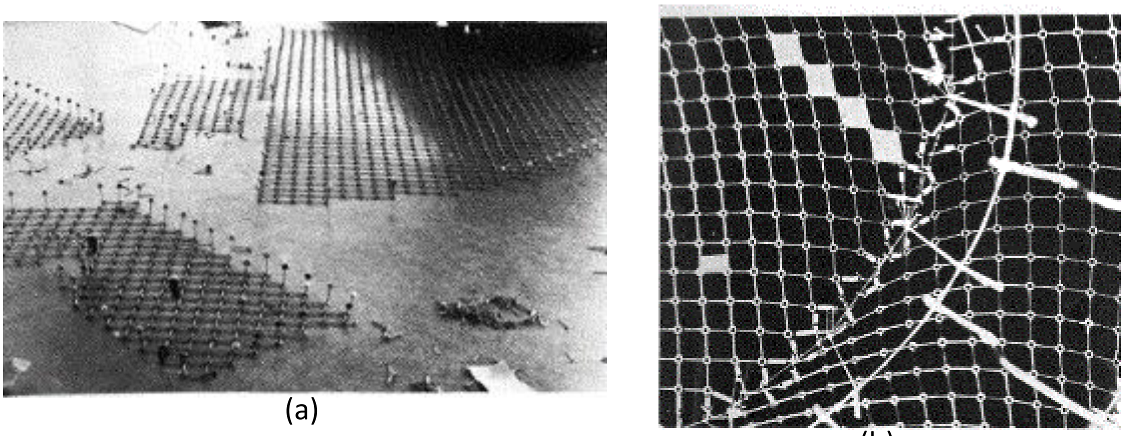
Figure 3.6 - Isler's hanging net model, with unstiffened free edges.

3.1.3. Frei Otto

ILEK – under Frei Otto’s guidance- has developed a systematic approach and an expertise for using hanging chain models for form-finding of compression only structures. These approaches were developed for projects such as Multihalle Manheim (see Figure 3.7) and the Munich Olympic Stadium (the former is a timber grid shell and the latter is a cable net structure). Note that grid shells, although not fully solid are considered shell structures and are designed to have minimum bending forces.

A 1:500 scale model (design model) is first built to get a sense of the size and the form of the structure. A 1:100 scale model (form-finding model) will then be built to carry out a rigorous form finding exercise and determine the final geometry. Playing around with these scale models gives a better understanding of the force flows and the final geometries were adjusted based on the understanding gained. Separate models were used to extract geometry and member forces.

These suspended models (hanging chain models) give a unique equilibrium solution for a given (i) pattern of cable net (ii) support conditions and (iii) loading system. As such the mesh patterns is of significance. One primary impact from the mesh pattern is the chain segment sag. This indicate a low tensile area in the net which lacks stiffness. In the inverted compression only state this is a stiffer region and would indicate that the compression elements would tend to buckle. These can be adjusted in the suspended model by adjusting the supports or the mesh itself. A rectilinear mesh (i.e. a net which in its fully relaxed state lays flat) would almost always produce segment sag – and would violate the uniqueness of the equilibrium solution. In contrast, a uniform triangulated mesh (or any other kinematic mesh) would not produce segment sag. However, considering construction restraints uniform square meshes (which are not kinematic) are usually used for form-finding of grid shells.


(a)

(b)

Figure 3.7 - (a) Assembly of the chain net and (b) the construction of the hanging chain model for Multihalle Manheim. [Image source: IL 13 Multihalle Manheim]

These models are built of chains and the mesh is representative of the elements of the realised grid shell structure. Different techniques were used to represent the edge supports. Proper representation of the stiffness of the edges is critical as this affects how the hanging chain model take its shape. In the hanging chain model built for the Multihalle Manheim, plexiglass strips were used to simulate the foundation concrete strips and thin brass wires were used for double ropes along the perimeters.

Different types of meshes were used based on the usage of the mesh: fishnets/ textile grid fabrics or knotted thread nets were used for design models; woven chains nets, knotted chain nets and element nets were used for form finding models. The chain nets are made of specially made Tombak (a brass alloy) wires of 0.25 -0.45 mm diameter. A woven chain would have 577 links/m and a knotted chain 1400 links/m. The former is of a higher weight (3.28 g/m) than the latter (1.81 g/m). The assembly of chains and nets is a manual process and would take about 150 man hours to assemble a 59 cm x 81 cm mesh. The same footprint made from element meshes (hook and ring) would take 8-10 man hours but would not give as much detail as a chain net.

Three methods were developed at ILEK to take measurements of geometry from a hanging chain model. Measurement table with a pointer to drop a plumb line was the most basic method used. Measurements of precision of ±0.1 mm are possible with this method. Aerial photogrammetry for cartography adjusted for close range (developed in IAGB, University of Stuttgart) is an advance method used (see Figure 3.8). This too can achieve similar accuracies, but the technology at the day meant these were time consuming and costly. Parallel light measurement was another option available.

Separate models need to be built for force measurements as the force measurements were made using coil springs or rubber bands attached to the supports. This method would only allow the measurements of forces at the supports as deformation of the springs would alter the geometry.

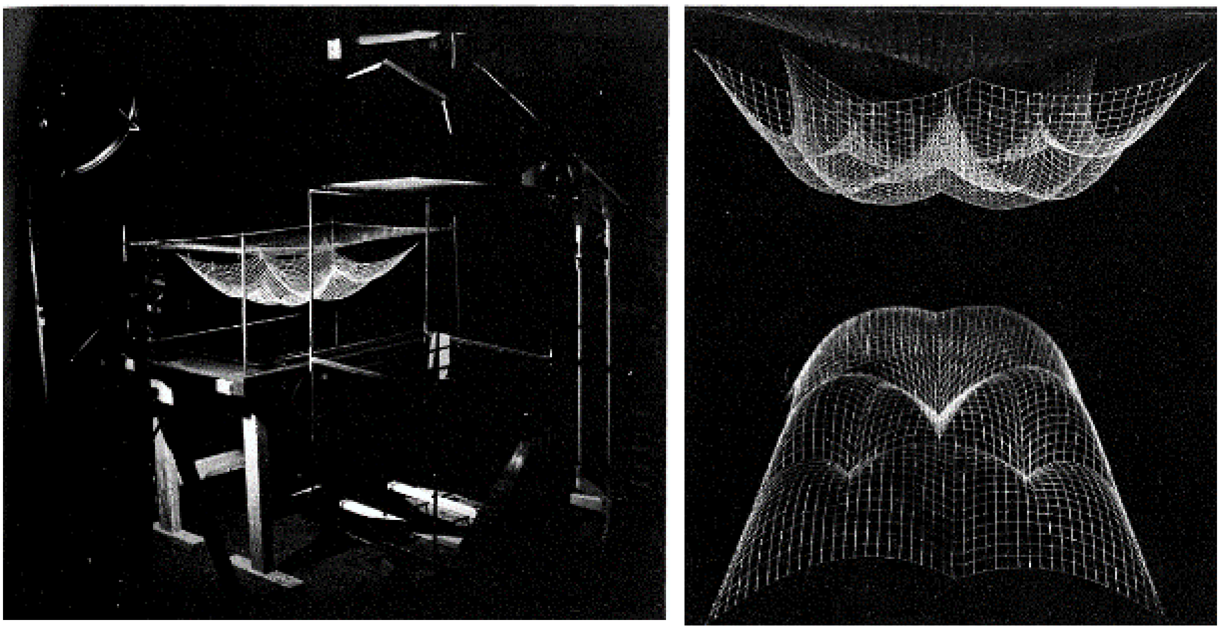


Figure 3.8 - Use of photogrammetry (using the analogue-stereo-comparator developed at IAGB, University of Stuttgart) to extract geometry from a hanging chain model. [Image source: IL 10 Grid shells]

3.2. From line of thrust to thrust network

The concept of a line of thrust (or thrustline) was presented by Thomas Young (1817), Franz Joseph Ritter von Gerstner (1789), Méry (1840) and Henry Mosely (1835) – and different text books would attribute it to one or many of these people.

Figure 3.9 - hanging chain models used as a tool to understand optimization of vaults, as used at Auroville Earth Institute.

Heyman’s safe theorem is the formalization of Hooke’s observation and concept of the line of thrust in to the realm of limit state analysis. Heyman’s safe theorem states that “if a set of internal forces in a masonry structure can be found that equilibrate the external loads, and which lie everywhere within the masonry, then the structure is safe – safe in the sense that it cannot collapse under those loads.” In his seminal work presented in the publication titled ‘the stone skeleton’ (Heyman, 1966) he describes the above safe theorem and notes the corresponding uniqueness theorem with the additional requirement of the thrust line allowing ‘… the formation of sufficient hinges to transform the structure into a mechanism’.

At AVEI, they use the Heyman’s safe theorem with Karl Cullman’s graphic statics and James Clerk Maxwell’s force and form duality to generate lines of thrusts. With years of experience in design and construction they have developed the AVEI optimization method. This is an empirical set of rules that can be used to optimize the thickness of vaults constructed of known regular geometries (e.g. segmental arch, pointed arch, equilateral arch, Egyptian arch). The optimization procedure relies on the fundamental understanding of hanging chain models (Figure 3.9): If the line of thrust moves out of the middle third near the crown, increase the thickness near the support . Since they are using a 2D canvas as their design space this methodology is only applicable to vaults – i.e. extrusions of 2D cross-sections.

A 3D geometry as in a dome would have a three-dimensional force flow. In a 1921 text book on graphic statics, William S Wolfe describes a graphical analysis method to analyse the equilibrium of domical shells by considering both meridional and hoop forces (Figure 4.13).

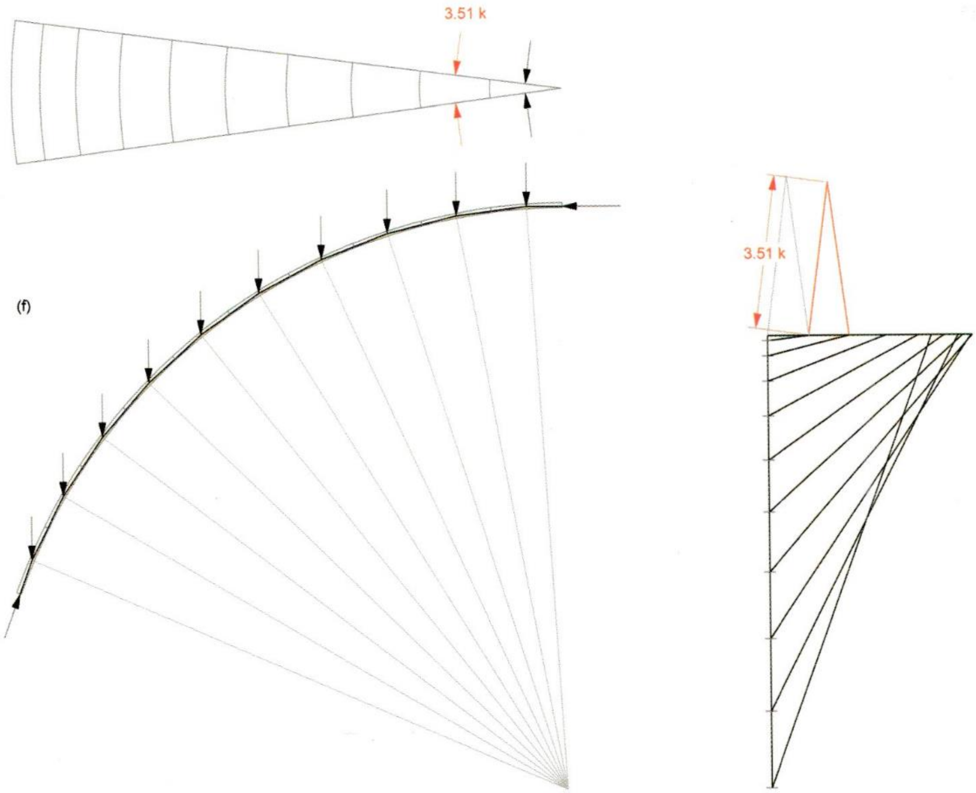
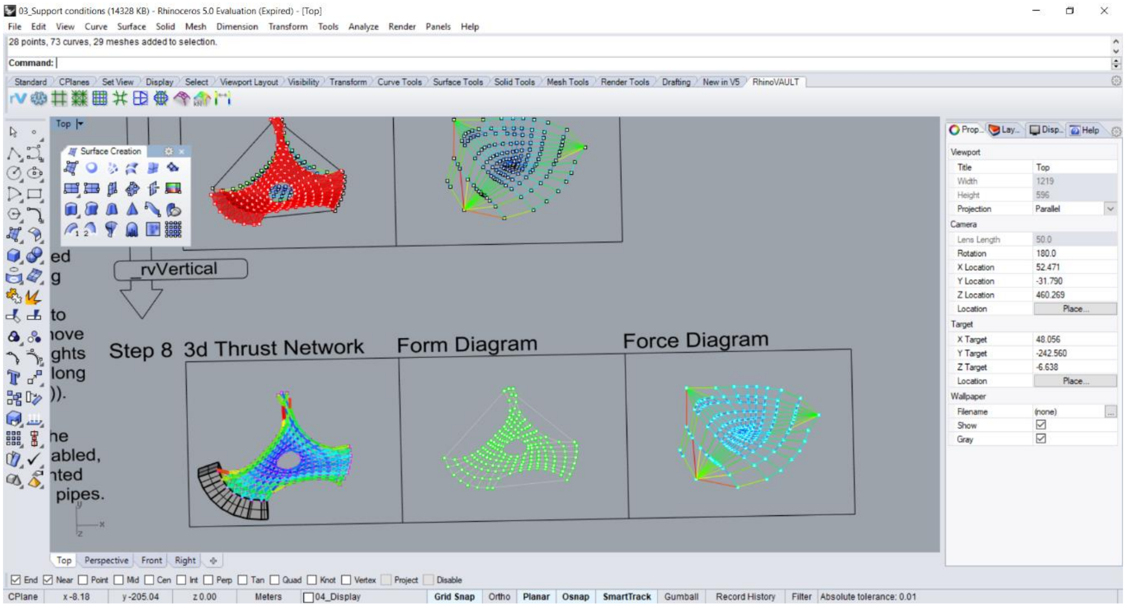


Figure 3.10 - Graphic static method developed by William Wolfe for the analysis of the equilibrium of spherical domes. [Image source: Reese, 2010]

A set of two and three dimensional hanging chain models of the Pantheon - built at ILEK Stuttgart -nicely presents this idea of three-dimensional force flow and what is missing in a two-dimensional analysis of a three-dimensional force flow. Figure 3.12 shows the hanging chain representing only the meridional forces of a lune of the spherical dome (the length of the chains represents the weight of the masonry) and this does not lie within the cross section of the masonry structure. Hence, this violates the Heyman's safe theorem. But we know that this structure stands safely. Thus, there need to be some other force taking care of the equilibrium. Figure 3.14 shows a three dimensional hanging chain model of the same structure. Here, both the meridional and hoop forces are represented. The ‘diamond’ in the junction of meridional and hoop chains (Figure 3.14) are representative of the relative contribution from hoop and meridional forces- an open diamond represents a larger hoop forces and vice versa. The measured size of this diamond can be used to make an adjustment to the 2D hanging chain model (Figure 3.13) to include the horizontal force contribution from the hoop forces. The additional short chain connects horizontally to the hanging chain (meridional forces) and the orientation of the other end is the angle of opening of the diamond. This is a visual proof of the three dimensional load bearing effect of a domical shell.

A full three-dimensional analysis considering Heyman’s safe theorem (and improvements thereof) is only possible using computers. The idea of line of thrust then become a thrust network in the three-dimensional case. In fact, the cable nets used by Gaudi (Figure 3.2) and Isler (Figure 3.6) are physical representations of force networks.

In his PhD thesis Prof Philippe Block presents thrust network analysis, which is a form exploration tool where he merges Heyman’s safe theorem and Clerk Maxwell’s reciprocal diagrams. At BRG, thrust network analysis is implemented as a plugin for Rhinoceros CAD platform – RhinoVault (Figure 3.11) - and in the computation platform developed at BRG - COMPAS. Both these tools facilitate analysis of three dimensional shells via evaluation of the equilibrium of a three dimensional force network representing the shell.



28 points, 73 curves, 29 meshes added to selection.

Command:

Viewport
Title Top
Width 1219
Height 596
Projection Parallel
Camera
Lens Length 50.0
Rotation 180.0
X Location 52.471
Y Location -31.790
Z Location 460.269
Location Place...
Target
X Target 48.056
Y Target -242.560
Z Target -6.638
Location Place...
Wallpaper
Filename (none)
Show ☑
Gray ☑

☑ End ☑ Near ☐ Point ☐ Mid ☐ Cen ☐ Int ☐ Perp ☐ Tan ☐ Quad ☐ Knot ☐ Vertex ☐ Project ☐ Disable

CPlane x -8.18 y -205.04 z 0.00 Meters 04_Display Absolute tolerance: 0.01

Figure 3.11 - RhinoVault plugin for Rhinoceros CAD platform for the form finding and static analysis of free form shells.

It is important to note that thrust network analysis is developed as a form exploration tool, and as such is not only capable of analysing existing shell structures but also coming up with free form compression-only shells – e.g. the Armadillo Vault (Figure 2.29), the MLK pavilion (Figure 3.16), NYC pavilion (Figure 2.30).

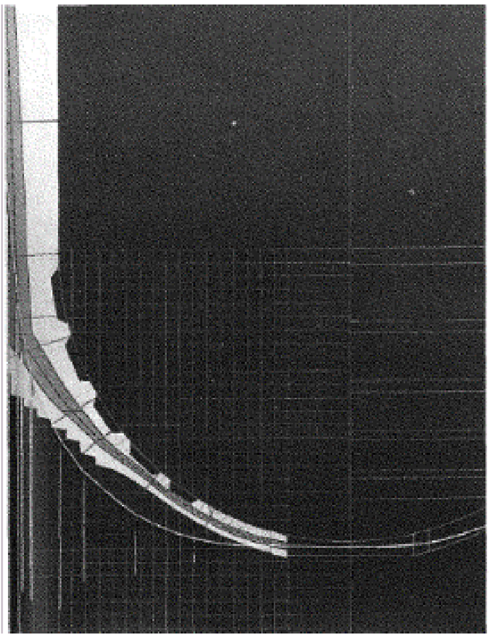


Figure 3.12 - 2D hanging chain model of the Pantheon, only considering the meridional forces. [Image source: IL 25 Experiments]

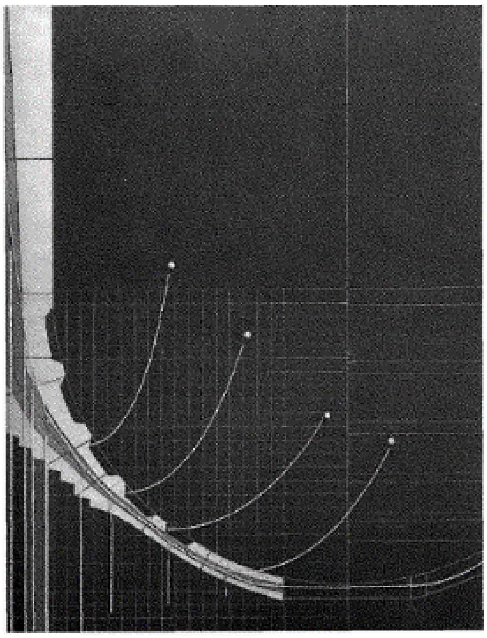


Figure 3.13 - 2D hanging chain model of the Pantheon, considering both meridional and hoop forces. [Image source: IL 25 Experiments]

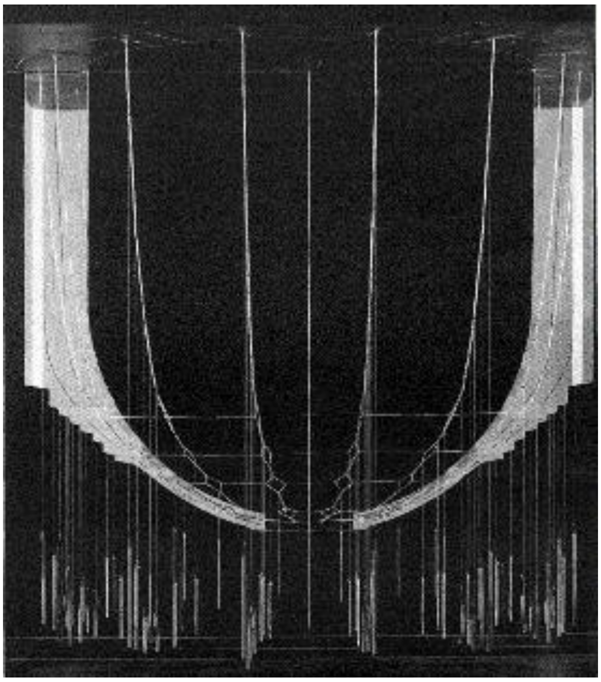


Figure 3.14 - 3D hanging chain model of the Pantheon, considering both the meridional and hoop forces. [Image source: IL 25 Experiments]

Although we can safely use thrust network analysis, the structure may resist higher loads as formation of tension cracks may not have formed a three dimensional collapse mechanism – i.e. the thrust network provides a lower bound estimate of the load capacity and the uniqueness condition needs to be satisfied to determine the collapse load.

Rafael Guastavino seemed to have understood the greater load carrying capacity in double curvature shells and have extensively used them. However, it seems he did not properly understand the load carrying mechanisms. In an 1892 essay titled 'the theory and history of cohesive construction' he claims that Catalan vaults carries load due to the bond between the tiles and mortar, which allowed it to resist tensile stresses and therefore did not thrust on the supports (Ochsendorf, 2010). It is self-evident that this is not the case and in fact he provided mechanisms (buttresses and tie-rods) to resist the horizontal thrusts. Rafael Guastavino's explanation on how Catalan vaults worked was neither based on calculations nor engineering theory, but purely on his intuition. But drawings from their later work – St. Paul's Chapel in New York (1906 - see Figure 3.15), Cathedral of St. John the Divine in New York (1907), St. Francis de Sales Church in Philadelphia (1908) – shows graphic statics being used to size the shell.

3.3. Non-structural design aspects

The design requirements also include non-structural aspects. Possibility of building free-form structures – as opposed to the rectilinear foot prints and elevations we are so used to - is one advantage of the shell structures. In contrast the acoustic performance of shells – reverberations and echo- could be either beneficial or problematic.

The MLK Jr pavilion (Figure 3.16), the vault at Valldaura lab (Figure 2.5) and the Armadillo vault (Figure 2.29) are but a few examples of free-form possibilities of shell structures. All the above projects were evolved from BRG. One primary reason for this is the form exploration capabilities of the RhinoVault software developed there. Maya Somaiya Library for the Shri Sharda English Medium School in Maharashtra, India designed by Sameep Padora and Associates is an example of RhinoVault being used by a group independent of BRG to design a free-form shell structure.

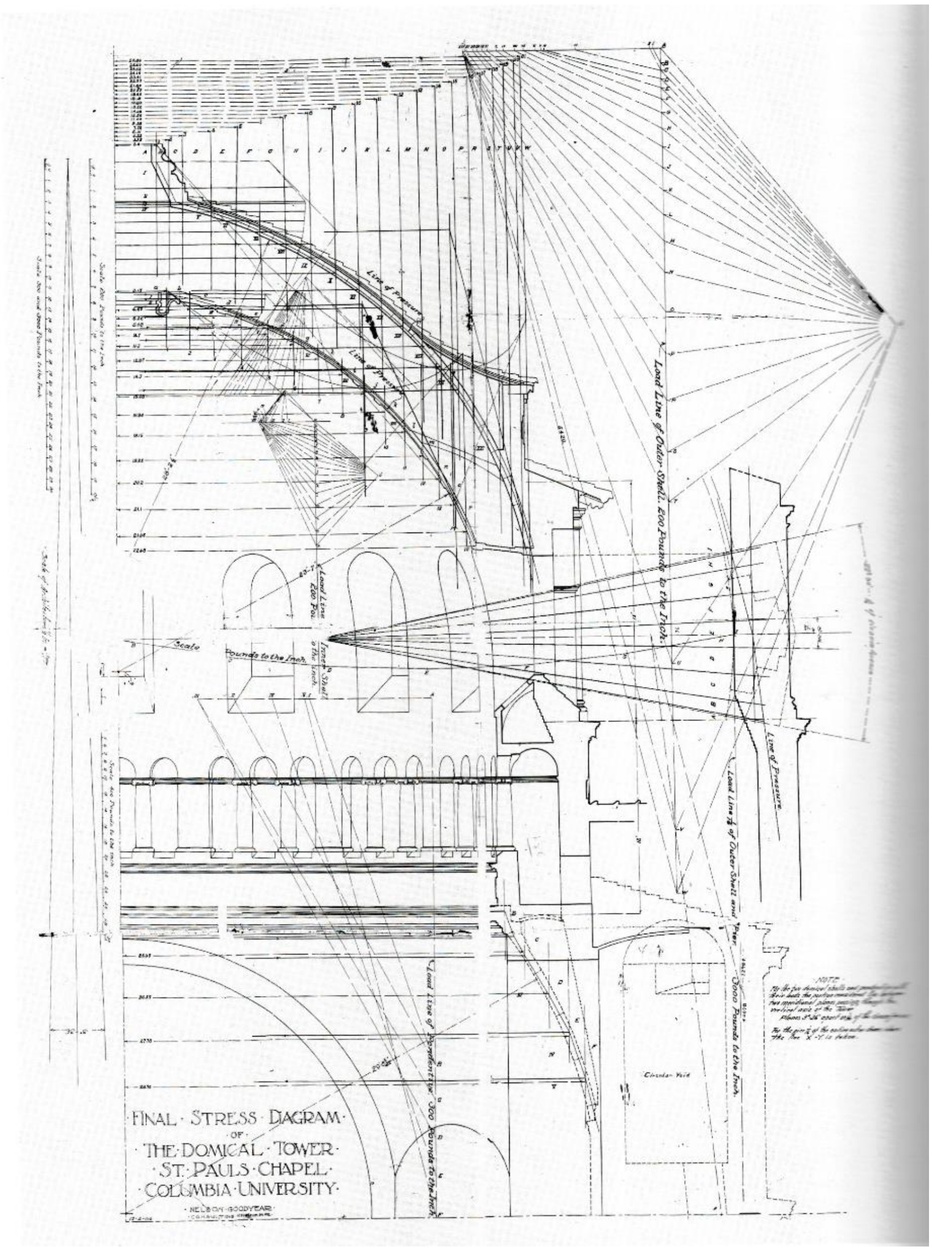


Figure 3.15 - Drawings for the dome of the St. Paul's Chapel in Columbia University, produced by Guastavino Company indicating the graphical analysis of the shell. [Image source: Ochsendorf, 2010]

Guastavino Jr. was interested in acoustical architecture and along with Wallace Clement Sabine – A professor of physics at Harvard- improved the acoustics of the Catalan thin tiles and produced six patents related to acoustical innovations. The aim of these developments was to reduce reverberations by absorbing sound rather than reflecting them. This sound absorbing worked too well and was thus a problem in Churches where the reverberation of sound is an important character.

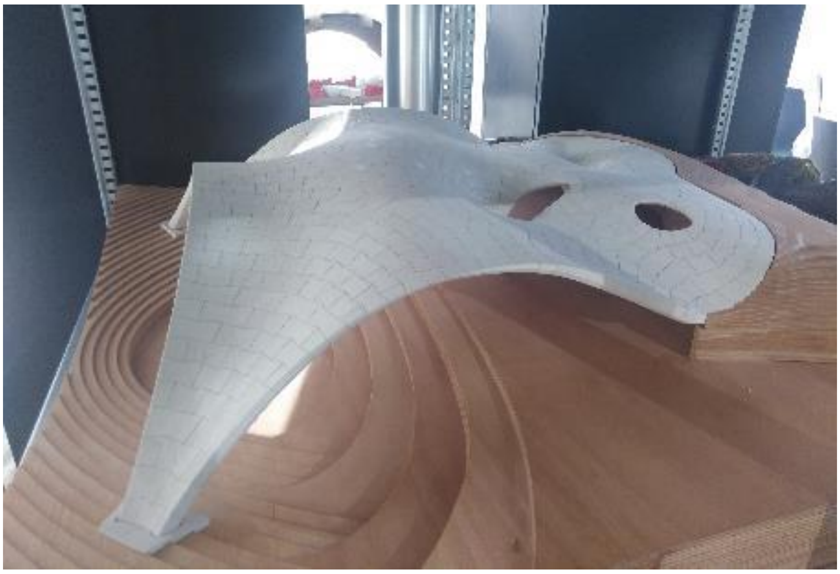


Figure 3.16 - A model of the proposed MLK Jr Pavilion in Austin, Texas.

Auroville Earth Institute has also studied this problem. They have identified three reasons for the high level of reverberations in vaults and domes.

1. The large volume created by the vaulted structure, which is larger than adjacent volumes
2. The propensity of the shape to reflect sound
3. Surface quality of materials of shell interior

They use Helmholtz resonators (single resonator absorbers) to absorb sounds. They are using simple solutions such as PVC pipes or clay pots as the volume of the resonator absorber (Figure 3.17). This further account to reduce echo in spherical domes. Echo is a problem in spherical domes (and segments thereof) and is rarely an issue in other types of domes (e.g. pointed domes, groin vaults).

(a) (b) (c)

Figure 3.17 - An example of a clay pot being used as a resonator absorber: (a) during construction, (b) the hole of the resonator, once completed and (c) resonators to absorb 3 frequencies. [Image source: Davis & Maini, 2016]

BRG is also addressing the issue of acoustics and are developing techniques for acoustic optimization of funicular shells. They are incorporating their techniques in there COMPAS computational platform which is a free and open software platform.

4. CONSTRUCTION: FROM EARTHEN MASONRY TO CONCRETE AND BEYOND

The material plays an integral role in compression-only structures. In fact, the need for a compression-only shell stems from the masonry itself not being able to carry significant tensile stresses.

4.1. Construction Material

4.1.1. Unbonded Stone

The early arches during Roman times were made of unbonded dressed stones. BRG in two of their projects showcases the possibility of thin shells with unbonded dressed stones. The proposed MLK Jr Park Pavilion in Austin, Texas was to be built of unbonded dressed stone to show case a local material technology. However, due to financing issues the project did not come to fruition and this technology was later showcased at the Venice Biennale (2016) with the design and construction of the Armadillo Vault.

This not only show case the ability of the shell structures but also the material technology involved. The shell was discretized to blocks considering the principal stress directions from the FE model. Interlocking of the blocks was also considered in this discretization, specially so for the edge blocks. Fabrication and assembly process also need to be considered in the discretization; smaller blocks would mean a longer construction time and a larger block would mean heavier blocks which are difficult to handle. The block sizes were decided such that the maximum weight of a block near supports did not exceed 135 kg and 10 kg for that at the top.

A 5-axis CNC (computer numerical controlled) machining process was used to cut the limestone blocks to the required geometry. The digital stereotomy process developed for the MLK Jr Pavilion project included brackets to maintain a reference point once the block was flipped. In the Armadillo vault project, considering the time restraints the geometry was so selected that the extrados face was planar, hence cutting being required only in one face. This meant that the extrados surface of the shell had a stepped feature. Further, all the contact faces were maintained as planar surfaces to enable a single cut with a circular saw. The curved intrados surface was formed by CNC cutting of grooves at close spacings and then hacking away the resulting stone fins to give a rough intrados surface (see Figure 4.1). Finally, profiling tools were used to make finer adjustments to make the blocks have the required 0.4 mm tolerance. The cutting of the keystone rows was only done after a test build of the remaining shell and taking measurements of the built section. Having been able to do this was very important as any slight offsets in block sizes at first rows can introduce large errors at the top. This way the geometry of the keystone blocks was decided considering those errors.

Sandstone cutting for both Armadillo vault and the MLK Jr Pavilion project were done by the Escobedo Group in Texas, who are local specialist in stone cutting.

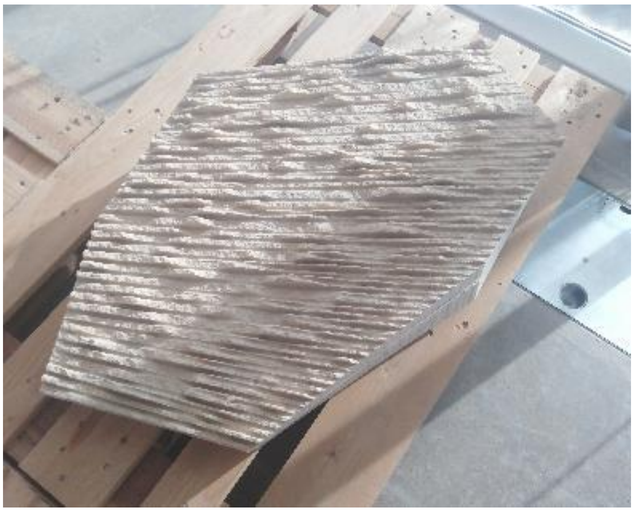


Figure 4.1 - A cut sandstone block from the Armadillo Vault.

4.1.2. Bonded Masonry

Bonded masonry is used in both Catalan vaulting and Nubian vaulting technologies. But the blocks and the binder used are different and stand testament to the possibility of adopting a local material for construction of compression only shells.

Catalan vaulting uses a thin burnt clay tile of 15-20 mm thickness (see Figure 4.2). The shell is typically of three layers giving a shell thickness of less than 100 mm, with a 10 mm mortar layer between courses. The thinness of the tiles is essential to making full use of the optimal shape of the shell. The construction process does not involve any formwork and the first layer of tiles acts as the formwork for the subsequent layers. A system of guides is used to mark the geometry of the first layer (discussed in section

4.2). The first layer is built free standing and hence require a fast setting mortar. A gypsum mortar – which is readily available in Catalunya – is used as the fast setting mortar. In contrast good quality gypsum is not easy to come by in South India (and many other places) and finding such would accrue significant costs. As such the Nubian vaulting practiced in Auroville (in South India) uses a completely different construction system, which is also a formwork-less construction.

(a) (b) (c)

Figure 4.2 - Catalan tiles from (a) AVEI (b) Valldaura Labs and (c) Teatre La Massa.

The thin tiles have seen many improvements by Guastavino's. Their innovations - leading to as many as twenty four patents - were relating to features such as fireproofing, soundproofing, decorative effects as well as improvements relating to construction process and manufacturing of tiles. Their flanged tiles (Figure 4.3), which reduce the amount of gypsum mortar in the first layer, was patented in 1895. The same year a manufacturing technique for manufacturing a block of six tiles was patented. This technique allowed for reduced damage to tiles during transportation, and once on site a slight blow of hammer could easily separate the six tiles.

Nubian technique practised at Auroville uses cement stabilised earth blocks with a cement stabilized clay mortar. The construction proceeds without formwork. The clay mixture is applied to the block to be fixed and the surface to which it attaches is wetted. Then the block is placed. The block is pressed on with a repetitive left to right to left sliding motion. This is done till a scratching noise is heard. During this most of the clay mortar extrudes out of sides. An excessive amount of mortar is initially used to guarantee a void-less bond. Once the scratching sound is heard the block can be let go and it will stay in place. To a skilled brick layer this process would take less than 30 seconds. If the position of the block is not correct, the brick and the binder must be removed, and the surface cleaned before the block is re-laid. The block should not be tapped in to place as is done with regular masonry work.

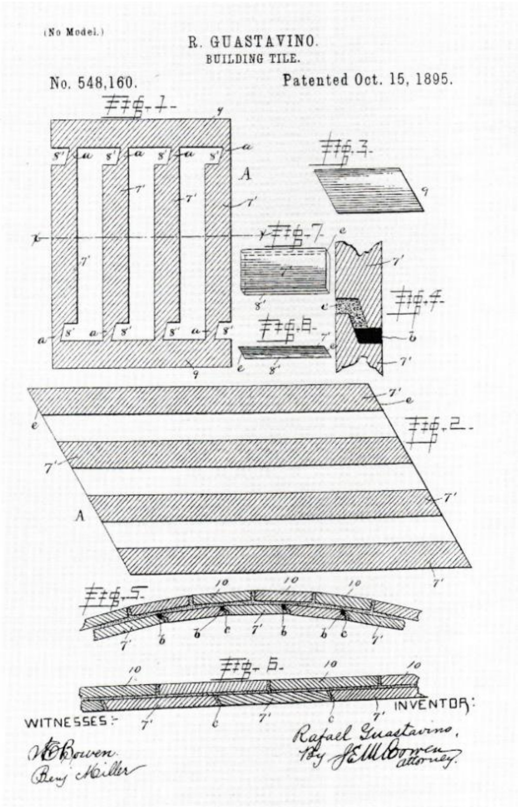


Figure 4.3 - The patent for flanged tiles developed by the Guastavino company. [Image source: Ochsendorf, 2010]

The blocks used with projects designed and constructed by AVEI are produced using the Auram Press 3000, which is an earth block press designed and developed in Auroville. The block sizes range from 190 mm to 390 mm. Table 4.1 gives the dimensions of the blocks produced using Auram 3000 block press.

Table 4.1 - CSEB block sizes produced at Auroville Earth Institute.

Block Designation	Nominal size (l x w x h) in cm
390	39 x 19 x 9
290	29 x 14 x 9
240	24 x 24 x 9
190	19 x 9 x 9

The blocks are 5% cement stabilized. The above is recommended for sandy soils, and lime stabilization is recommended for clayey soils. The blocks are cured under a shade for two weeks and then for further 4-6 months in open before they are ready for use in construction.

The embodied energy of the blocks is shown to be less than 10% of that of fired bricks (6,122.54 MJ/m^3 for a fired brick and 548.32 MJ/m^3 in CSEB bricks produced in Auroville). They also claim this to be 15 -20% cheaper than fired brick- however note should be taken that these calculations are based on a context where labour is cheap and good quality soil is readily available.

Three basic principles are presented for the cement stabilized earth mortar used.

1. Stabilise 1.5 times more than the blocks, to achieve the same strength.
2. Add sand to reduce shrinkage when drying. The larger thickness at extrados of arches, vaults and domes (as opposed to uniform mortar thickness in walls) call for sand additions in the mortar.
3. The mix need to be plastic.

The mix proportions (sand percentage) and the fluidity of the mix depends on the characteristics of the soil and the usage of the mix. A structure which has an earthen vault or a dome would essentially have earthen walls supporting them. Thus, it is typical to relate the mix proportions to the corresponding mix for the walls (assuming soil form the same source is used for the entire project). For an example 1:4:8 (cement: soil: sand) mix for the wall would suggest a 1:6:3 (cement: soil: sand) mix for the vaults and domes, giving a clayey mix but with considerable sand inclusions.

Vaults would require a very liquid binder to have a thin bond of 1-2 mm, specially near the intrados where the blocks are touching each other. Building of a spherical dome out of cuboids will leave large gaps (relative to bond thicknesses in the dome) and hence thicker paste of binder is used. The consistency can be tested by letting the well mixed binder flow along a trowel held vertically; the liquid paste will leave a film of 3-4mm, the thicker binder will leave a thick layer of 7-8 mm (Figure 4.4).

There are other important points to consider when constructing with masonry, which are common to any type of masonry work – e.g. wetting of bond surface, bond pattern not allowing vertical joints to align across multiple layers. Care should also be taken in laying the keystone block. The final block (or multiple blocks, if necessary) is laid dry. The blocks may need some dressing to fit the intrados perfectly. Stone chips are used to wedge the keystone perfectly. A thinner clay mix is then poured in to the crevice to fill the space near the intrados. A thicker clayey mortar can be used to fill the gap near the extrados.

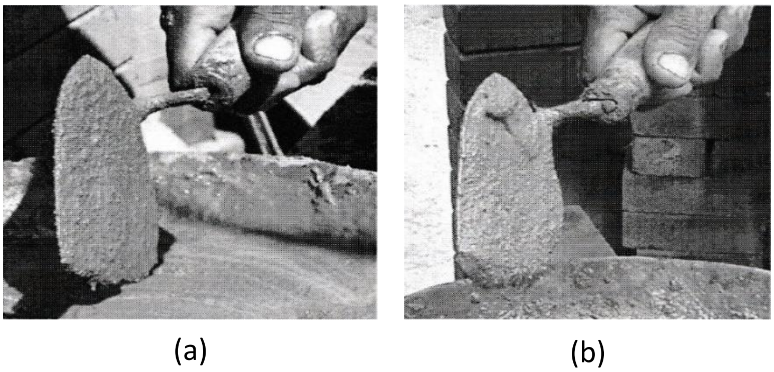

(a) (b)

Figure 4.4 - An on-site consistency test for the clay mortar; (a) liquid paste and (b) thicker paste. [Image source: Davis & Maini, 2016]

4.1.3. Concrete Shells

Heinz Isler's shells are classic example of thin concrete shells. The Wyss Garden Centre in Solothurn, Switzerland was built in 1962 (Figure 4.5). This is a geometric shell with a surface area of 650 m^2. The 70 mm thick shell has a cantilevered edge with a maximum cantilevering length of 3.5 m to stiffens the edges. This was used instead of a bulky edge beam and mimics the upturned lips observed in hanging chain/cloth models. During testing it was observed that the structure would experience some tension cracking, hence the exterior was painted (in contrast to other Isler shells) as an extra layer of protection for rebars.

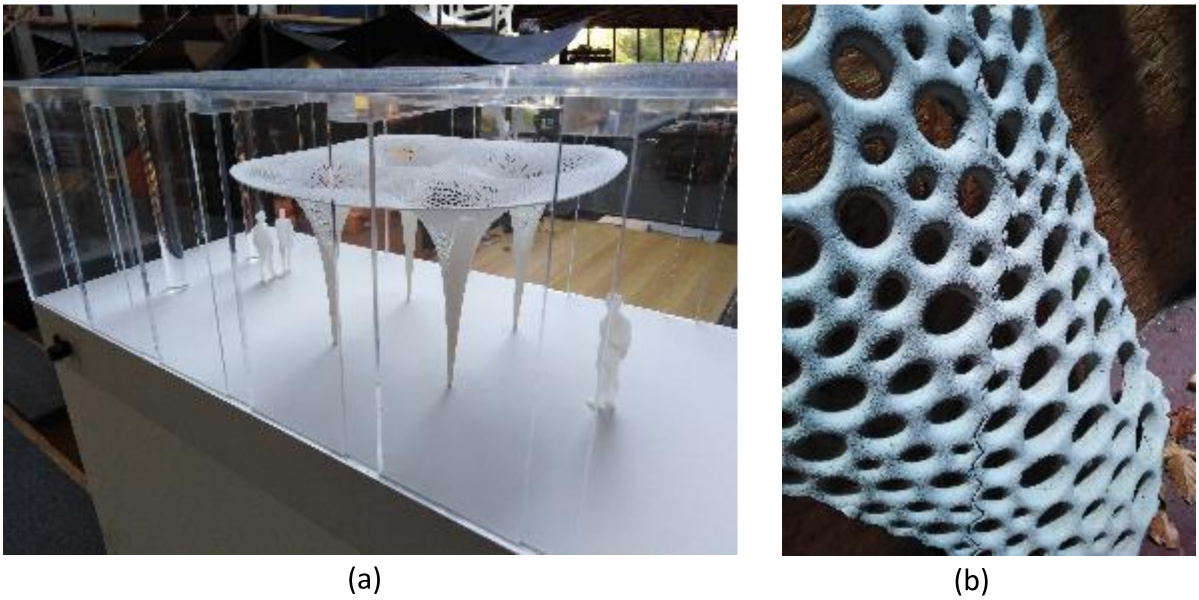
Figure 4.5 - Wyss Garden Centre in Solothurn, Switzerland, designed by Heinz Isler.

Figure 4.6 - The twin concrete shells at the Deitingen service station, designed by Heinz Isler.

The twin 31.6 m long 26.0 m wide three point supported prestressed concrete shells at a highway service station in Deitingen (built in 1968) is another classic Isler Shell (Figure 4.6). This shape was derived from a hanging cloth model. The shells are 90 mm thick and the doubly curved nature gives it a high load capacity.

A segmental concrete shell was built at ILEK Stuttgart as a proof of concept (Figure 4.7). The porosity in the shell was to give an illusion of translucent surface but can still be identified as a shell. The shell thickness is 3 cm. The need for segmental shells came out of the limitations in constructing the shell as a single unit. Pre-cast sections are bolted using M4 bolts along the connecting edges. The compression-only shell (under self-weight) guarantees that the bolts do not have to carry any bending. This shell was made of concrete and the complex geometry of the shell was to be achieved by casting the concrete in a frozen sand formwork. However, due to issues with local climate it was finally done using Styrofoam formwork.

The concrete shell floor system developed at BRG is a 2 cm thick unreinforced doubly curved ribbed slab. The complex rib pattern is to activate the compression shell action and external steel ties are used to resist the tensile forces. This system is found to result in 70% cost reduction compared to the conventional concrete slabs. However, the complex formwork required to achieve the rib pattern makes it more suitable to a repetitive floor foot print.



(a) (b)

Figure 4.7 - (a) a prototype and (b) a segment of the segmental shell constructed by ILEK, University of Stuttgart.

The full scale prototype of HiLo roof shell was constructed at ETH Zurich using a fabric formwork supported on a cable net. Node markers of the cable net was used to monitor the geometry of the cable net, and to adjust the net if necessary. The adjustments are not straightforward as the nodes of the cable net does not move independently. Hence a control algorithm was developed to determine the adjustments at boundary such that the differences of node geometry (from planned to observed) is minimized. A reinforcement net is provided and grade C90 concrete was used, both considering the possibility of shrinkage cracking. Sprayed concrete was used to give the desired thicknesses of 3-12 mm, as required. Once the concrete has set both the cable net and the fabric formwork was removed. The cable net is prepared for this specific project and hence is not readily reusable. But this method allows for greater control of shell geometry.

4.1.4. Glass Shells

A few experimental shells were done at ILEK Stuttgart using glass as the construction material.

The glass dome built in 2004 is a segmental spherical dome of 8.5 m span and radius of 6 m, giving a 176 cm rise (Figure 4.8). The glass is of 1 cm thickness giving a slenderness ratio of 1:850, making its relative thickness smaller than that of an egg shell (0.3 mm thickness). The float glass was chemically tempered to 2 mm on one side. A 10 mm thick stiff adhesive ($E \approx 1000$ N/mm^2) is used to bond the 44 glass panes making up the shell. The glass shell is supported in a titanium ring fixed to a base by 32 stainless steel supports. Titanium was used to avoid issues with differential movements due to temperature (coefficient of thermal expansion for glass and titanium are $8.5 \times 10^{-6} K^{-1}$ and $8.6 \times 10^{-6} K^{-1}$, respectively). The settlement of the highest point after decentring was less than 0.1mm.

Figure 4.8 - Glass dome at ILEK, University of Stuttgart.

The glass arch bridge (Glasbogen I) residing at ILEK is made up of eight flat glass panels (making up the bridge deck) that are stabilized by means of a contact framework and a truss-like underslung (Figure 4.9). The bridge is of 10 m span, 2 m width and 2 m height. The structure consists of eight 2 m x 1.35 m untreated float glass panels. The four middle panels are reinforced with a wire mesh. The arch is bearing on fixed steel supports.

Figure 4.9- Glasbogen I at ILEK, University of Stuttgart.

Figure 4.10 - The blocks made of recycled tetra pack boards, used for the BRG Pavilion for the Ideas City Festival 2015 in New York City.

A pretension of 10 kN is applied to keep the glass arch under compression. Primarily the load is carried by compression of the glass arch and the stainless steel truss-like structure carry the tensile forces generated by additional loading (in its free state the steel frame is not under stress).

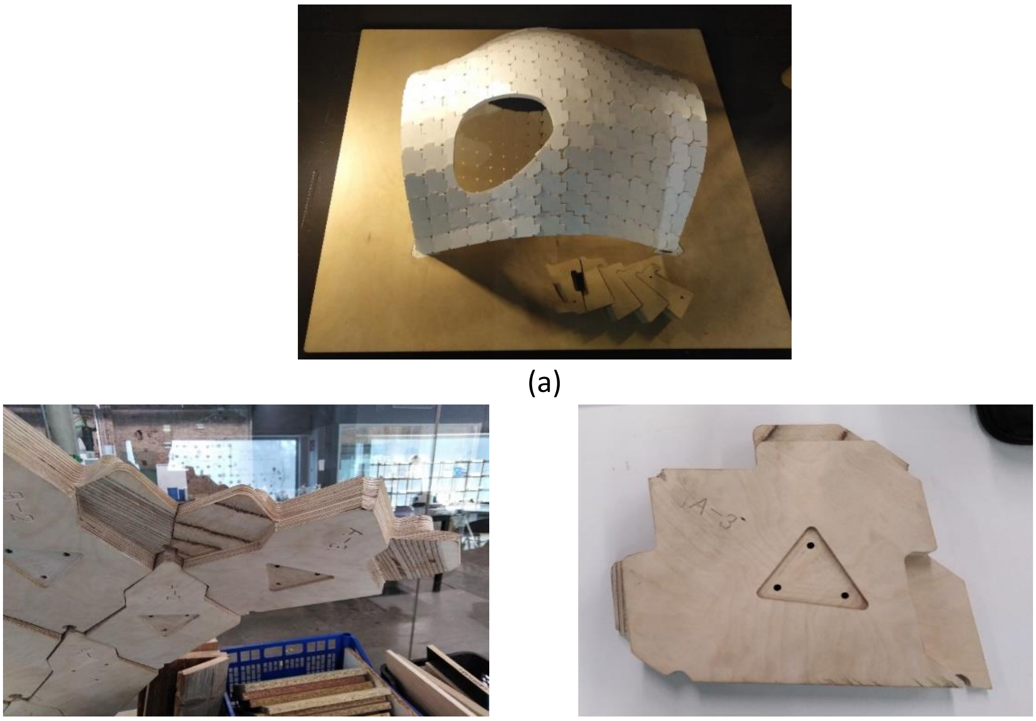
4.1.5. Recycled Waste

There are more modern views on what materials can be used with compression-only shell forms. BRG had done a project using hollow blocks made of recycled tetra packs.

The temporary pavilion was built for the 2015 Ideas City Festival in New York City (Figure 2.30). The doubly curved shell covers an area of 20 m^2 and consists of 34 arches of 13 blocks each. The arches span between two sets of ballasted wooden pallets. Triangular prismatic blocks made from 9 mm thick compressed tetra pack boards produced by ReWall® were used (Figure 4.10). The boards were produced by compressing shredded tetra packs, without any binder. The doubly curved nature of the shell meant all 442 blocks were of different sizes and shapes and thus CNC cutting was used to cut the blocks and then was manually assembled and strapped. The purpose of the project was to showcase the potential of building with a waste material, which is also not intended to be a structural material.

4.1.6. Timber Shells

The Institute for Advanced Architecture of Catalonia (IAAC) is a research institute in Barcelona, and they conduct research on structural forms and construction materials, among other topics. They too have developed a formwork-less construction system for shells with interlocking timber blocks (Figure 4.11). The timber pieces are made by gluing together layers of plywood boards – cut in different shapes. The notches (or cuts) are to facilitate interlocking and to prevent blocks knocking on each other at edges.



(a)

(b) (c)

Figure 4.11 - Surface expanded joinery system developed at IAAC; (a) a prototype model of the shell, (b) a segment of timber block assembly and (c) a single timber block.

4.1.7. 3D printing

The compression only shell floor system designed by the BRG is first cast using concrete. This was subsequently tested with 3D printing using a silica sand bonded by phenolic binders (Figure 4.12). However, this technology is still in its infancy (at least with regards to building of structures) as the strength of the printing material are limited and integration of steel reinforcement during printing is observed to be a difficult task.

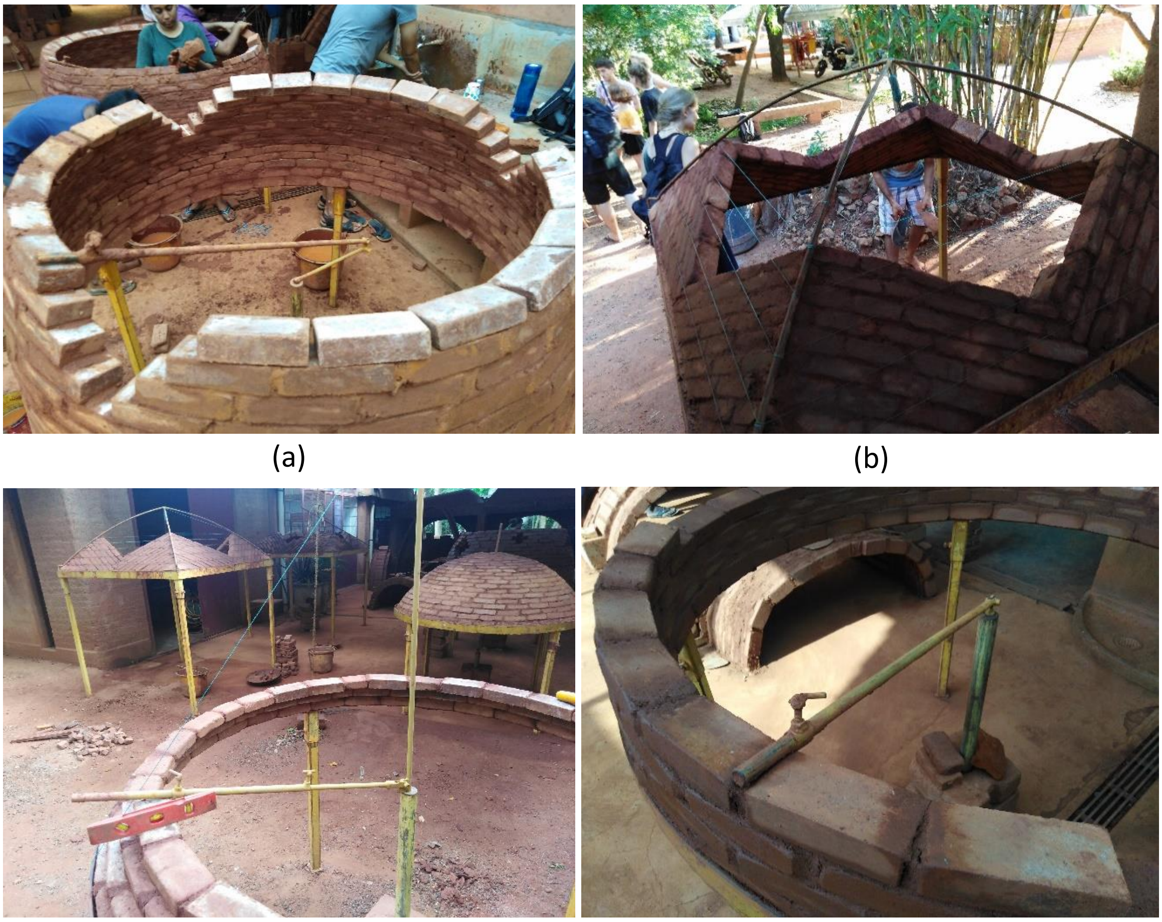
Figure 4.12 - 3D printed slab system developed at BRG.

4.2. Formwork, false work and free-spanning

Some type of formwork or falsework is required to keep track of the geometry of a shell during construction. Free-spanning construction techniques such as Nubian technique and Catalan vaulting does not require any formwork, but guide works are required to keep a check on the geometry. Building free-form shapes with irregular geometries would require elaborate guide systems. But, in some cases formwork is unavoidable as there is no intermediate stable geometry and the stability comes from the whole system working together (e.g. the voussoirs making up an arch).

Figure 4.13 shows guide work developed at AVEI for construction of prototype domes. The same technique has been used in various projects carried out by AVEI. One such project is the Dome of the Dhyanalinga Temple (1999). The dome has a diameter of 22.16 m and has a cross-section of a segmental ellipse of 22.16 m span and 7.9 m rise. The dome was built around the existing Lingam – the relic- hence it was not possible to place a compass at the centre. Thus, the dome was built with an elliptical cross-section, having two focal points. An elaborate system with telescopic compasses made of GI pipes were devised but excessive sag due to the weight of the pipes meant inaccurate results. Due to time constraints 15 m measuring tapes were used (instead of a redesigned telescopic compass out of Aluminium). This along with the irregularities with local bricks made significant errors to the shape of the dome. At the 57th course (of 240 courses) the dome shape was found to be 5 cm off. The shell geometry was re-calculated for the existing geometry and the shell was completed for this new geometry. Regular checks with height surveys and extreme care with tape measures ensured that dome was completed successfully with an accepted tolerance of 2-3 mm from the defined geometry.

A free spanning technique is developed in AVEI, taking inspiration from Nubian technique. This technique distinguishes between horizontal and vertical courses. Horizontal courses are where the blocks are laid in length by width surface of the block. Blocks are laid in breadth times height surface in the vertical courses. This is allowed by the various block sizes manufactured at Auroville and the vaults generally having a wider base and a thinner crown (see Figure 4.14b). Each vertical course adheres to the one before and may not be fully closed in one go. Hence the first vertical course would require a side wall to adhere to or a temporary formwork to support its load. The subsequent courses can be built incrementally to provide safe load paths to the intermediate stages of construction. The construction sequence needs to be decided during the design stage as in the one hand the decision is based on the equilibrium analysis and on the other the number and size of the blocks need to be determined well before construction begins.

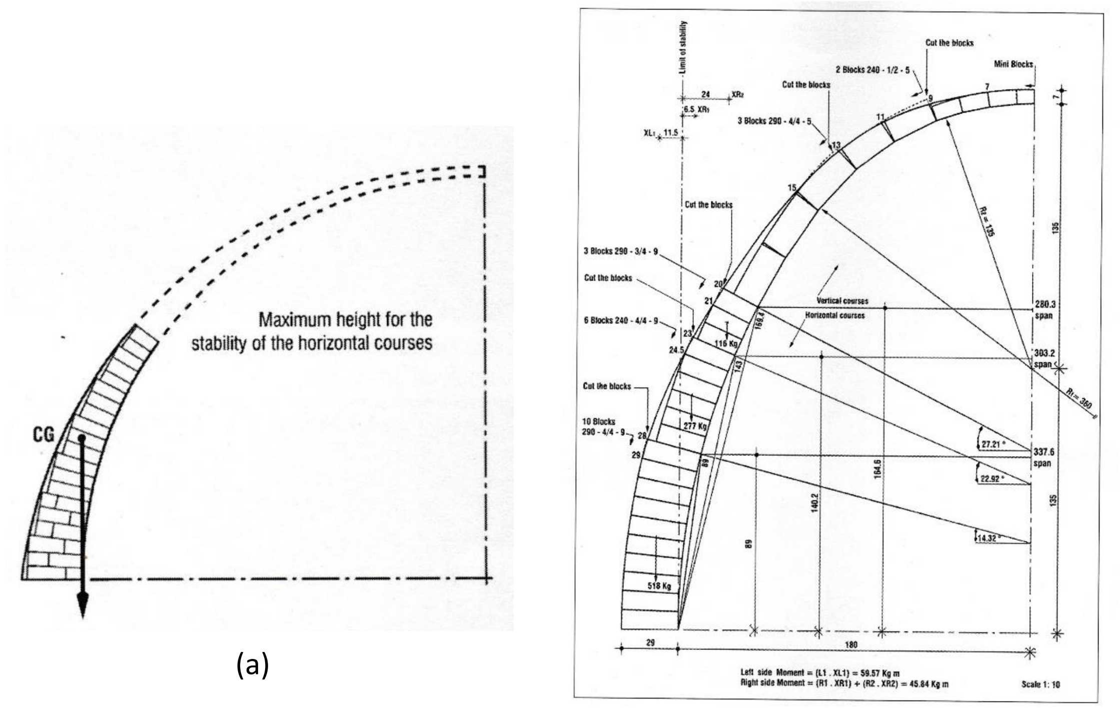

(a) (b)

(c) (d)

Figure 4.13 - Compasses developed at AVEI for (a) segmental pointed dome, (b) cloister dome (c) conical dome (d) spherical dome.

The horizontal courses are built in essence as leaning walls and the stability of the wall under gravity dictates the maximum height of horizontal courses (see Figure 4.14a). Beyond that height the vertical courses are used, and the latter achieve stability (in a formwork-les construction) using the adhesion between blocks and the clay mortar – which is the basis of Nubian technique.

Different types of guide work have been tested by the BRG (and their members affiliated to other institutions) in the various free-form shell construction projects. Simple guide work has been used for vaults (which are essentially extrusions of arches). Two steel frames are placed at either end of the longitudinal axis of the vault and guide strings are run between the two guide frames. This system was used in their urban housing project – SUDU- in Ethiopia. The spacing of guidelines are based on the workmanship of the masons; a skilled mason has a better spatial sense and can work with a coarser guide work. For a free-form shell a closer grid of guide work are required. For the two Catalan free-form shells built at Valldaura and at UPC Barcelona (for an exhibition) a skeletal structure made of freely bent rebars was used as the guide work.



(a)

(b)

Figure 4.14 - (a) The limit on height of horizontal courses and (b) design of horizontal and vertical courses of a vault considering varying block sizes. [Image source: Davis & Maini, 2016]

In some cases, it is not possible to avoid form work. In the NYC Pavilion project, they used a temporary guide work supported on a moveable industrial lift to support the blocks. Once settled under self-weight, the thrusting between the blocks can keep them in place. An additional tensioned cable was sent through the blocks (along the axis of the arch) as additional support.

The Armadillo vault used a timber skeletal formwork to support the stones till the keystone was placed and the shell was able to carry its own weight. The block placement was assisted by grooves in the blocks (not in the keystone blocks) and scratch marks made during the test build. A total station was used to locate the exact positions of the blocks. Wooden shims were used to adjust the height and inclination of the blocks.

However, the shell would start to carry its own weight only after the formwork decentred and the blocks settle into their final positions. Thus, the decentring process is critical for shell construction with formwork. To assist with this, formwork for Armadillo vault was placed on elven independent scaffolding towers which allowed for a gradual and sequential decentring. The decentring sequence is crucial as the decentring is equivalent to applying a large asymmetric load to the shell. Decentring was done in a circular pattern with stiffer parts decentred first. The scaffolds were lowered in stages of 0.4 mm in each cycle. Shims falling indicates that the shell is no longer supported by the formwork but is supporting its own weight. A final maximum settlement of the shell (i.e. deviation from defined geometry) of 4 mm was measured.

5. SOCIO-ECONOMIC DIMENSIONS

The structural efficiency or material technology alone does not contribute to the successful adoption of a technology. There are social and economic reasons that would force out certain technologies as evident by many historic events.

The rise of thin tile vaulting in east coast of the USA was mainly due to the fire resistance characteristics of this construction. At the time, construction in the USA was timber based and many large fires (e.g. Great Boston fire of 1872) called for fire resistant structures. This was the time when Rafael Guastavino introduced Catalan vaulting to the USA. The rapid adoption of the technology was not due to its load carrying capacity but due to the superior fire performance. In fact, in early days Rafael Guastavino Sr. did not have any calculations to validate the load carrying capacity of the structure but they conducted load testing to demonstrate the superior load carrying capacity of these structures. Before taking on the construction of vaults in the Boston Public Library, Guastavino Sr. was requested to build a prototype vault and load test it. The 4 feet by 5.5 feet (1.2 m x 1.7 m) vault safely carried 12,200 pounds (5,500 kg) of load- i.e. about 27 kN/m^2. This would not have been possible in an age of rigid design codes.

In a similar vein, the down fall of the Guastavino company and thin tile vaulting in the USA was not due to the introduction of a superior material or a structural system. In 1940’s concrete was being introduced to the construction industry and people viewed concrete as ‘the material of the future’, although thin tile vaulting was a far superior load carrying system.

In the current world of hyper-connectivity, the same can be observed in the developing world. People view concrete and steel construction – which are primarily from materials and technology imported- as ‘modern’ and views earthen construction to be of inferior ‘quality’. This view neglects both the economies of using local material and the local climatic conditions under which the earthen constructions are likely to perform far better (in terms of creating liveable spaces).

Auroville is an exception to this- or rather a case study on how people’s mind set can play a role in wise adoption of technology. Auroville is a global village founded in South India in 1968 and aspire to live by the four main ideas in the Auroville Charter; (i) Auroville belongs to no one in particular; (ii) a place of unending education; (iii) a bridge between past and the future; and (iv) a site of material and spiritual research. This environment has created an ideal platform for the development of earthen construction technologies and successful implementation of the same. Many structures in Auroville are earthen shell structures of Auroville’s take on the Nubian technique. Elsewhere in India – as is in many parts of the developing world – earthen construction is looked down upon.

In contrast Casa Milà is an example of structural efficiency and architectural beauty dictating the terms regardless of people’s perceptions. It is said that the people mocked this ‘strange’ house built for an elite family. 100 years down the line it is one of the main tourist attractions in the city of Barcelona. The MLK Jr Pavilion project in Texas is an example for showcasing a local material being a primary reason for the choice of material. Although, these exceptions may exist – especially so for marquee projects- people always look to have new things – novelty is perceived as an indicator of quality.

6. THE FUTURE: OPPORTUNITIES, POSSIBILITIES AND CHALLENGES

The projects I had the privilege of observing closely - as well as the projects I have heard of through various media - showcase the potential of shell structures in producing aesthetically pleasing, efficient and sustainable structures. However, in many cases – apart from probably Auroville - these have been used mostly in landmark structures rather than everyday public spaces or domestic dwellings.

It remains a possibility – and a need in view of the call for a sustainable construction industry- to make shell structures a more common structural form; from domestic dwellings, public spaces to landmark structures. The Stuttgart SmartShell successfully demonstrate the possibility of using shells in the next generation of structures: active control structures.

However, there remains key challenges in using shells as structural systems. One of the main issues is the rigorous development of material technologies and simultaneous development of codes of practices. The analytical tools currently in use to analyse compression only structures have produced safer structures. The variability of material properties and the vast range of possible material solutions would be a challenge in developing relevant codes of practices.

One of key missing pieces in fully earthen construction is the slab system. Catalan vaulting has showcased the potential of shells to be the structural component for an earthen slab system. As was seen earlier, Catalan vaulting may not be possible everywhere in the world. Other local material technologies need to be developed and tested, with earthen slab systems based on shell forms.

But the greatest challenge of all would remain to be how to convince engineers and general public on the merits of using the structural efficiency of shell structures. It would be a challenge to convince people that shells are not just a part of the history but the future as well.

7. IN CONCLUSION

In conclusion, it is recognized that;

1. There are very many local traditions in building shell structure, developed with different materials. This not only include traditional techniques such as Catalan vaulting or Nubian technique but also Guastavino vaulting spread in the USA in the early 1900s and the many concrete thin shells designed by Heinz Isler in the 1960s.
2. The tools used for analysis of shell structures include physical models, graphic statics as well as intuitive understanding of the behaviour of shells. But the fundamental basis of all these methods can be related to Robert Hooke's observation of hanging chain.
3. The different material technologies used with shell structures include unbonded and bonded masonry, concrete, glass, timber and even recycled material and 3D printed materials. These different materials have their own construction challenges and advantages and as such allied construction methods have also been developed.
4. There is a real interest among researchers in showcasing the benefits of using shell structures in moving towards sustainability and using modern techniques such as computer aided manufacturing and active control structures.
5. However, the bigger challenges towards using shell structures more commonly in construction seems to be both people's perception and the design freedom given in rigid design and building codes.

BIBLIOGRAPHY

Block, P., van Mele, T., Rippmann, M., & Paulson, N. (2017). *Beyond bending; reimagining compression shells.* Munich: DETAIL.

Burkhardt, B. (1976). *IL13: Multihalle Mannheim.* Stuttgart: ILEK.

Chilton, J. (2000). *The engineer's contribution to contemporary architecture: Heinz Isler.* London: Thomas Telford Publishing.

Davis, L., & Maini, S. (2016). *Building with arches, vaults and domes: Training manual for architects and engineers.* Auroville, India: Auroville Earth Institute.

Heyman, J. (1966). The Stone Skeleton. *International Journal of Solids and Structures*, 249-279.

Kurrer, K.-E. (2008). *The History of the Theory of Structures.* Berlin: Ernst and Sohn.

Lopez Lopez, D., & Rodriguez, M. D. (2015). *Tile vaults. structural analysis and experimentation: Guastavino Biennial 2015.* Barcelona: Ajuntament de Barcelona.

Maini, S. (2011). *Dome of Shanalinga Temple.* Auroville, India: Auroville Earth Institute.

Ochsendorf, J. (2010). *Guastavino vaulting: The art of structural tile.* New York: Princeton Architectural Press.

Otto, F., & Weidlich, W. (1990). *IL25: Experiments.* Stuttgart: ILEK.

Otto, F., Satak, K., & Grobner, G. (1974). *IL10: Grid Shells.* Stuttgart: ILEK.

Reese, M. L. (2010). *Structural analysis and assessment of Guastavino vaulting: Guastavino Biennial Prize 2010.* Barcelona: Ajuntament de Vilassar de Dalt.