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Decoding complex geometry for craftsmanship

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Abstract

The paper aims to bring forward two important aspects. First, that the design to production of shell structures is a close collaboration between the architect, engineer, and craftsman. And second aspect is the opportunity for the evolution of construction crafts with advancements in technology. Although the file to factory approach for the construction of complex geometry is well-known, the process differs in complex environments with low skilled labour, low-tech materials, limited access and experience in digital fabrication tools. This is the third freeform shell exemplifying the integration of computational design and crafts by the first author*. The first one was focused on funicular structures and Timbrel vaults. The second example developed topological modules with limited customisation and mortar-less construction system for funicular structures (Sheth and Fida [13]). This project demonstrates the construction of lightweight, scaffolding less, freeform steel gridshell. It is a visitor's pavilion (100 $\boldsymbol{m^2}$) of a stud farm located in Ahmedabad, India. The pavilion was designed and built as a prototype to train the local craftsman, calculate the construction cost and time. It was found that the cost of digital fabrication and time taken was estimated to be five times higher than the cost of craftsmanship, inclusive of training the craftsman. Hence, it was important to decode this geometry for craft based construction approach. The outcome of this prototype can be upscaled to the larger roof (1000 $\boldsymbol{m^2}$of animal enclosures in this case) and other freeform steel gridshell.

Keywords: computational design, digital crafts, ferrocement shell, form finding, free form geometry, optimisation, gridshell, metal spatial structures.

Figure 1: Freeform shell under construction

1. Introduction

Shell structures have been known through time for their infinite possibilities in form generation with the ability of accommodating loads efficiently as a result of their curvature (Adriaenssens et al [1]). The shape of shells and their thickness largely determine their structural capability. A multitude of methods were used over time to determine precise shapes in equilibrium either through physical models (hanging chain by Robert Hooke, hanging forms by Frei Otto) or computational modelling tools which began quantifying the 3-dimensional forces acting on the structure thus providing real time responses to the shape of the shell. This translation to the digital space established a higher-level control through TNA (thrust network analysis). This method forms the basis of the interactive design tool RhinoVAULT which provides the capacity for testing multiple parameters like edge conditions, supports, openings, peak while interactively generating corresponding form and reciprocal force diagrams which when subsequently achieved provide a result which is in equilibrium (Adriaenssens et al [1]).

On the other hand, design and construction of the shell structures is not only related to the geometry, structure and material, but it is also heavily dependent on the craftsmanship (Larson [8]). The versatility in form finding techniques coupled with the advancements in structural design tools have allowed for designing more complex shell structures. Further advancements in fabrication techniques in the form of CNC machining have allowed for more precision and control of their execution on site. However, when the complexity of such forms generated digitally are translated to reality of construction, the *force modelled forms* must be realistically rooted to the available technology and economy (Adriaenssens et al [1]). With this establishment of the present context, it is interesting to notice how this knowledge may be adapted in places like India where automation in construction industry is uncommon.

The project in discussion required the accommodation of animals in large semi-open enclosures, covering 1000 sqm, for which the lightweight shell was a suitable consideration.

Figure 2: Site Layout.

The design was generated using the computational tool, RhinoVAULT 1.3. Structural analysis and optimisation which is an iterative process used STAADPro. A range of materials such as clay tiles & cement mortar, customised concrete blocks, steel & ferrocement, bamboo & thatch, etc. were considered. The criteria for material selection were related to the available craftsmanship, while the structure was optimized for its weight. Figure 2 shows the site layout with functional distribution of the stud farm. Figure 3 summarises the design to construction process. Each step of the process is further explained in detail followed by a discussion and way forward.

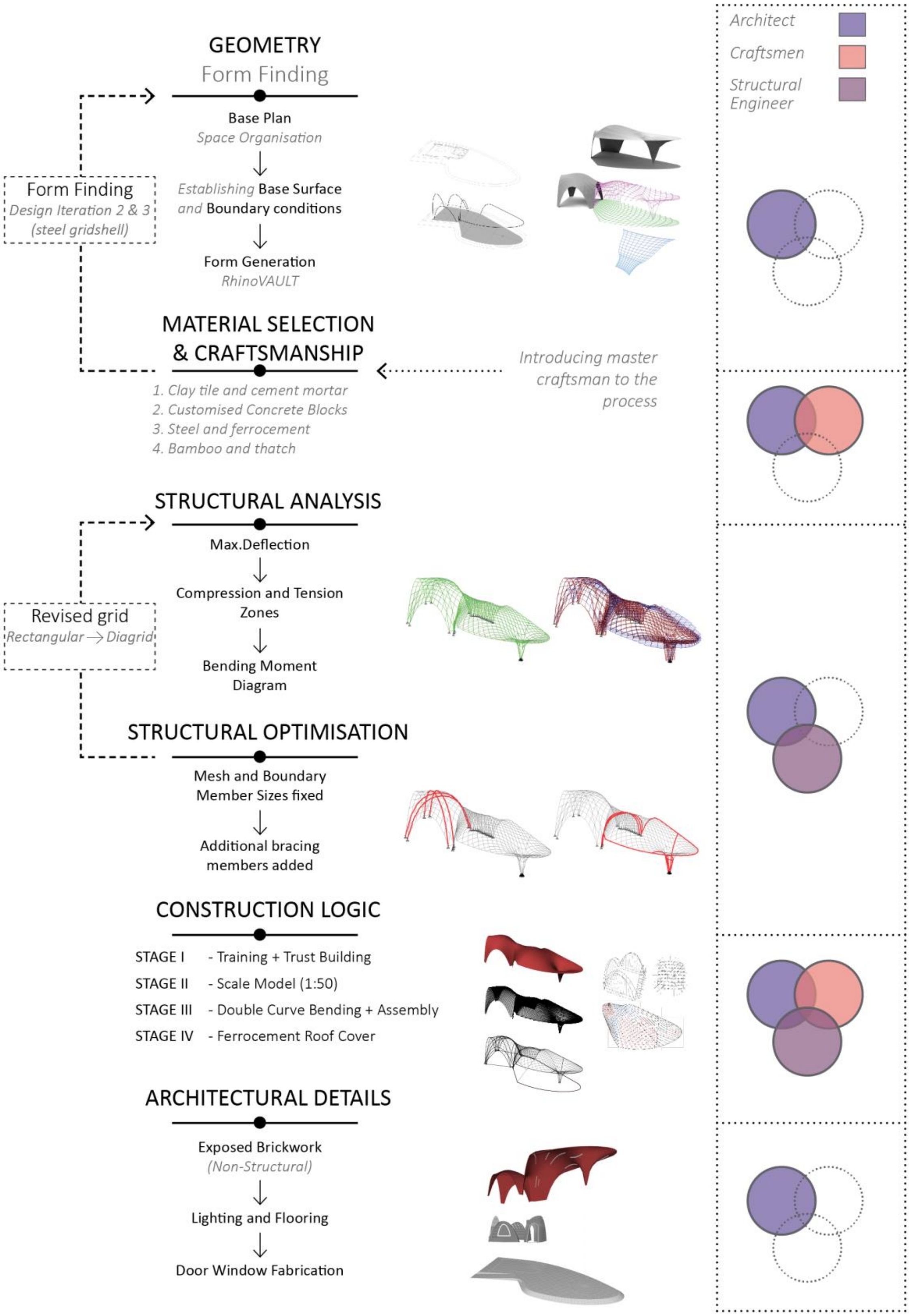

Figure 3: Design to construction process (Workflow diagram)

2. Form Finding

The pavilion was designed to house a room and a veranda. The location of visitor's pavilion is strategic, away from the animal enclosures and having maximum view of the horse rink for visitors (Figure 2). The roof was designed with the intention to be self-supporting and lightweight, covering 16.50 x 7.20m. The base area for the pavilion is defined to demarcate the closed and semi-open areas, bedroom with a toilet attached and the veranda, respectively. This was the input parameter for RhinoVAULT 1.3 [11]. There were three generative parameters considered: (i) minimizing number of supports, (ii) maximising view and (iii) restricting height to 4.5 m. These inputs determined the starting point for the form finding process.

2.1. Design Iteration 1

The first set of iterations were generated with varying support conditions, beginning with linear supports and ending with 5-points supports. A combination of linear and point supports were considered on the same base surface. Figure 4 shows the first set of iterations that achieved static equilibrium in the defined requirements. From these iterations, it was clear that the room was best suited with a 4-point vault. This allowed the architect to incorporate windows (view) on three sides. And the verandah functioned the best with a 3-point support, having nearly 180-degree unobstructed view of the farm.

From these inferences, the base surface was divided into two, one for the 4-point vault and the other for 3-point support shell. A decision was made that these two would be stitched at a common edge for construction (Figure 4). These were new set of input parameters for the next set of iterations.

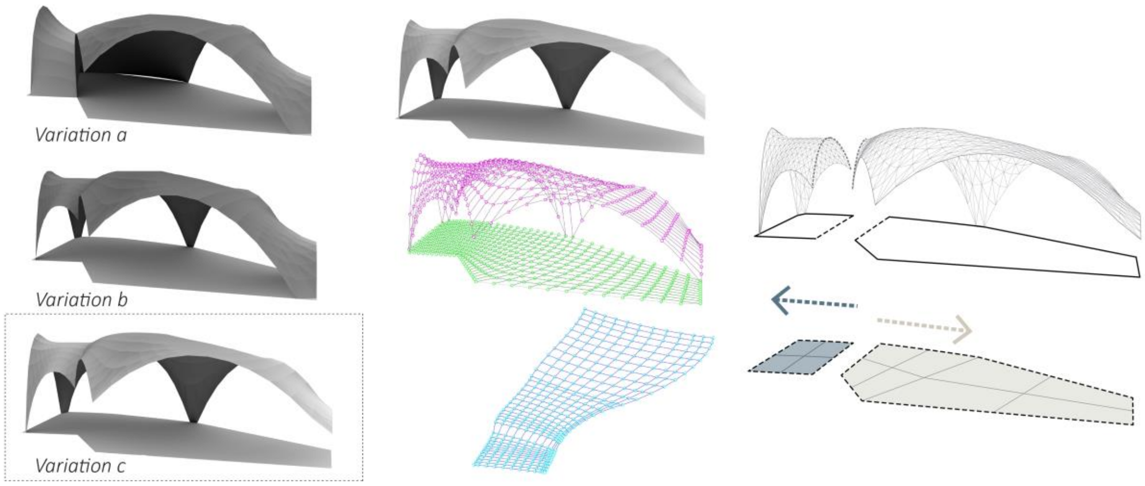

Figure 4: Diagram showing selected variations of Iteration 1

2.3. Design Iteration II and III

For the 4-point vault, spanning 3.00 x 4.50m, catenary arches provided stable boundary conditions in Iteration 2. However, the 3-point shell spanning 11.60 x 7.20m (cantilevered), induced an acentric load, resulting in the structure being unstable. Hence, the support located in the periphery was brought to the center, making it a tripod support in place of the long cantilever. This led to Iteration 3, with the introduction of a teardrop column to be able to distribute the loads equally (Figure 5). So far, the self-weight of timbrel vault was considered to generate the form. Both the forms had vertical equilibrium with rectangular grid.

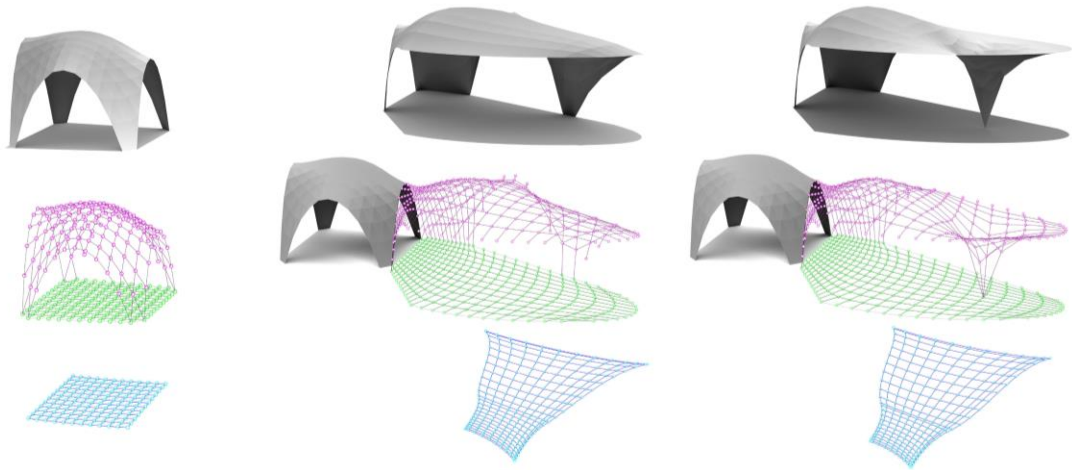

Figure 5: Form and force diagrams of the 4-point vault and iterations of the free form shell

3. Material Selection

Design generation began with the idea of a funicular shell being constructed using clay tile and cement mortar in timbrel vault technique. This was based on the earlier experience of building a free from shell. Both, material and craftsmanship, were tested at a smaller scale (Sheth [12]). The other consideration was that this pavilion had the potential to test the ongoing research on limiting the customisation of topological assemblies in constructing funicular vaults and freeform shells (Sheth and Fida [13]).

Towards the end of the form finding stage, the design brief was updated. The structure was required to be temporary in nature, hence, the need of thinking alternative material occurred. As per Indian Standard Building Codes, it had to be light in weight and materials like mild steel, timber, bamboo, textile membrane, etc. were the options considered. Table 1 shows the material comparison till this stage.

Material	Components	Weight of structure *(Dead Weight)*	Maximum deflection	Total cost *(Material + Craftsmanship)*	Roof Thickness
1. Tile Vault	clay tiles + gypsum mortar + cementitious mortar	-	-	-	80mm
2. Customised Bricks (Topological assemblies)	customised bricks + minimal reinforcement	-	-	-	100mm
3. Reinforcement bars/ hollow MS steel pipes with ferrocement	hollow MS pipes/ reinforcement bars + chicken mesh + ferrocement	Mild Steel - 1881kg Cement- 60 bags Sand - 6 tonnes	60mm	MS steel pipes: Rs 1,12,860 Cement: Rs 18,900 Sand : Rs 2,880 Chicken mesh: Rs 1,56,076 Craftsmen: Rs 69,965	50mm

Table 1: Material comparison

At this point, the selection of material was dependent on the cost of material and the availability of craftsmanship. Based on these criteria, steel and ferrocement was chosen. It is important to notice that the change in material implied the change in structural behaviour from membrane to gridshell. Both, 4-point vault and 3-point free form shell, were fine-tuned for their grid pattern when structurally analyzed at a later stage.

4. Structural Analysis and optimisation

4.1. Structural Analysis

First iteration of the structural analysis was done by importing the rectilinear grid from Rhinoceros 5.0 to STAAD pro as wire frame, followed by testing the structural stability of varying member sizes, starting from CHS 19 mm to 45 mm; 3.2 mm wall thickness. This was followed by a quick relay to the architect regarding the stability of the 4-point vault and workable member sizes. However, even with the 45mm diameter pipe, the 3-point free form shell was unstable. It was advisable to change the grid in a way that the members passed through the column otherwise deflections were high.

Hence, a diagonal grid along the lines of forces passing through the tear drop column was developed for the 3-point shell. This was the input parameter for the second iteration (Figure 6). Dead loads including the self-weight of the members, the weight of 50mm thick ferrocement and live load of 25 Kg/m^2 were considered. Analysis showed a maximum deflection of 60mm. This was in the permissible range. Additionally, this value was expected to reduce due to the stiffening from ferrocement in reality.

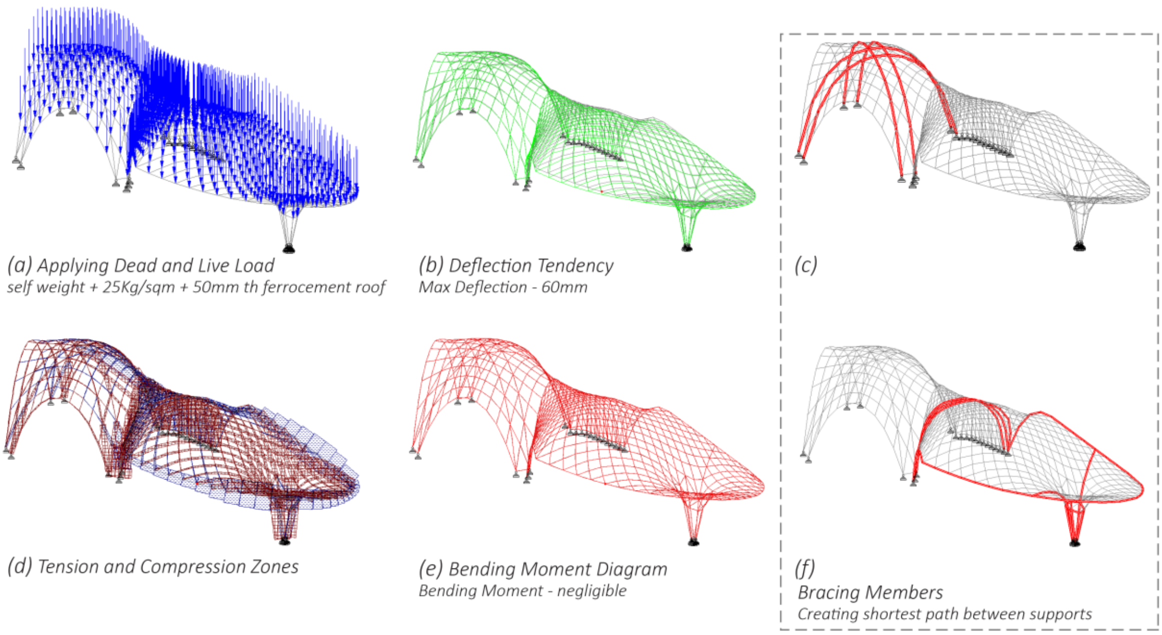

Figure 6: Structural analysis using STAAD Pro for hollow pipes with ferrocement.

4.2. Structural Optimisation

The third iteration was done to optimize the weight of the structure. For the 4-point vault, CHS 21.3mm OD 3.2 mm th. was proposed for the overall grid. CHS 33.7mm OD 3.2mm th for the boundary members and an additional diagonal bracing was proposed having member size, CHS 48.3mm OD 4mm th. (Figure 6c).

For the 3-point free from shell, CHS 33.7mm OD 3.2mm th. was finalized for overall grid. Boundary members were CHS 48.3 mm OD 4 mm th. Additionally, by stiffening the 3 members which connected the tear drop column and the 2 other supports would form the shortest load path which further reduced deflection. Therefore, these members were CHS 48.3 mm OD 4mm th. (Figure 6f).

The bent pipes were overlaid in both directions of the gridshell, hence, forming overlapping junctions that were required to be permanently welded after mounting. 8mm thick base plates were used to anchor the superstructure to the plinth. The completed gridshell was covered with chicken mesh followed by the application of ferrocement, the construction method of which is discussed the next section.

5. Construction Logic

From the previous research, it was established that construction without scaffolding would save on costs to a large extent. Hence, this became the basis for defining fabrication and assembly logic. If all the pipes were bent in the required shape, when assembled, it would form the designed geometry. CNC pipe bending machinery were an obvious choice, however, this was not possible to implement due to limited budget of the project. CNC pipe bending was estimated to cost five times more than the total cost of manual pipe bending, its assembly and training the craftsman in the process. It was decided to bend the pipe manually on site.

5.1. Stage I (Single curve bending and assembly)

The construction began with the 4-point vault due to its simplicity in construction logic. It was also used to train the craftsmen and ensure their seamless transition from single curve bending to double curve bending involved in the 3-point shell at a later stage.

Each curve from 4-point vault was extracted, and perpendicular distance was given from each nodal point. Both horizontal and vertical dimensions were given to craftsman as shown in the Figure 7. Each curve was drawn on ground by following these drawings and bent precisely by the craftsman. The boundary curves were first bent and mounted. This was followed by the regular grid members. Finally, the diagonal bracing was mounted above the grid.

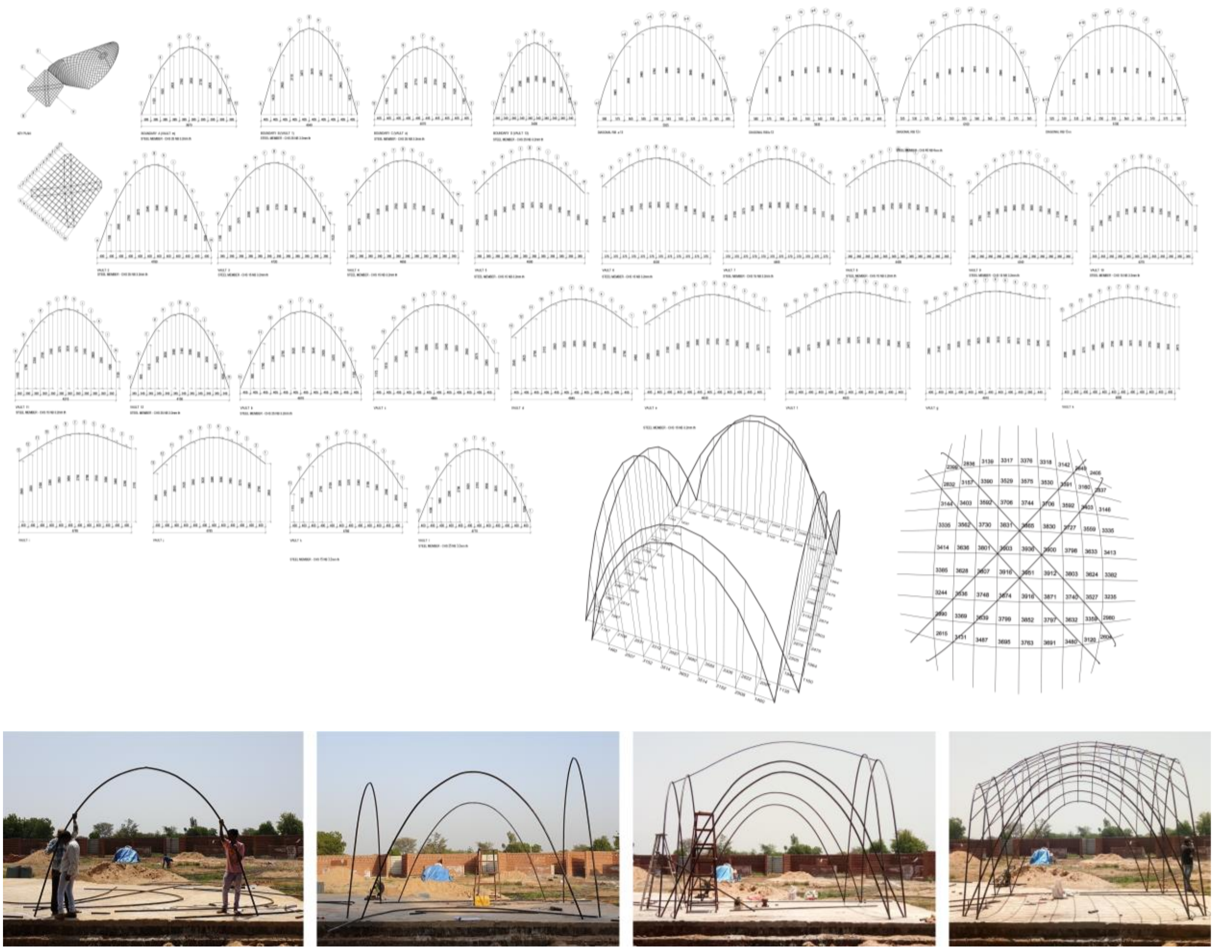

Figure 7: File to Fabrication – 4-point vault.

5.2. Stage II (Scale model)

The free form shell was challenging as it required doubly curved bent members. The scaled model was used to understand the fabrication technique that would be employed on site (Figure 8). The boundary member was projected on the ground plane. A jig was made by marking perpendicular distance at regular intervals on this boundary. This would be secured first followed by the members connecting three support points and finally the regular grid members. It was clearer from the prototype that each member of regular grid would be bent in a plane that passes through the two end points and the point of maximum height (Figure 8). This logic was determined for the fabrication drawings and subsequent construction.

Figure 8: Scale model (Scale 1:50).

5.3. Stage III (Double curve bending and assembly)

A stepwise process of decoding double curve geometry for manual bending is explained below.

Step 1: Single Curve (Primary) Bending

A two-dimensional plane passing through the start (A), end (B) and mid (C) points of each curve was established. The curve was projected onto this plane and a planar elevation was obtained for primary bending of the member (Figure 9).

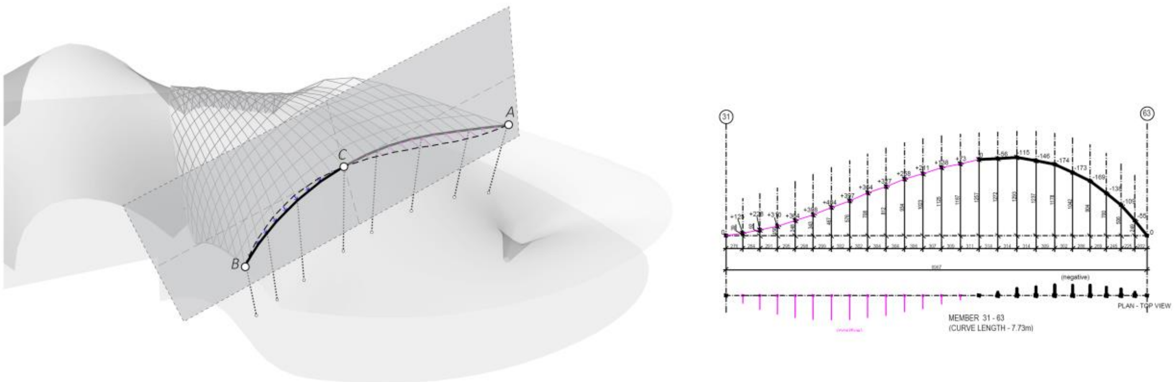

Figure 9: Fabrication logic for double curve bending of the regular grid members.

Step 2: Double Curve (Secondary) Bending

The deviation of the curve with respect to the plane was determined in the positive and negative direction perpendicular to this plane and this was indicated in magenta and blue, respectively. The start, mid and end points were at 0m, and the positive bending was indicated with a '+' sign and the negative bending was indicated with a '–' sign (Figure 9). With this logic, fabrication drawings for the free form shell were generated. (Figure 10).

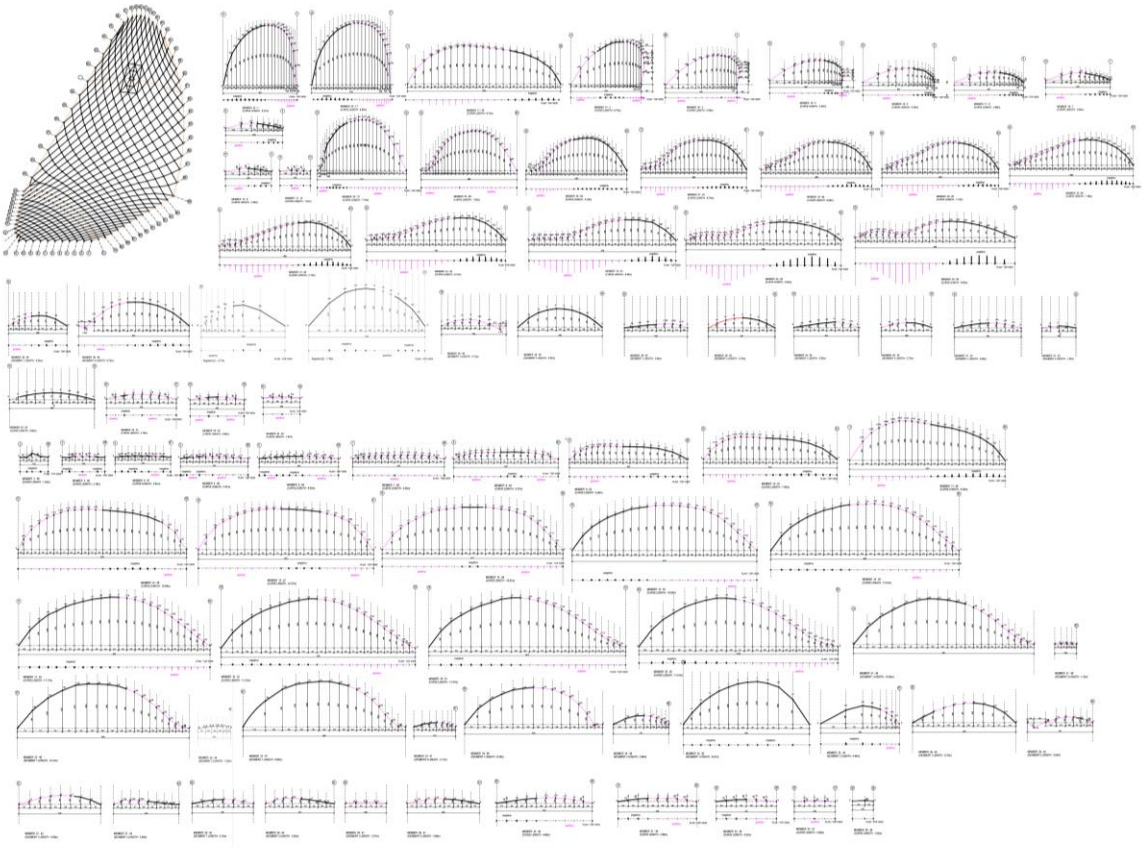

Figure 10: File to Fabrication drawings of free from shell.

Figure 11: Steps of fabrication and assembly of the free from shell on site. (a) Boundary and bracing members, (b) Double curve bending of a single member, (c) Temporary jig to cross check height of each member, (d) Assembling members from the tear drop column, (e) Fabrication and assembly of second layer of the grid, (f) Permanent welding of all overlapping joints.

Step 3: Assembly and Cross Checks

The boundary members and the bracing members which connected the 3 supports were mounted first followed by the first layer in the u-direction and then the 2nd layer of members in the v-direction. These members were held in place by temporarily welding them at the nodes. The midpoint of each member was cross checked for its height and inclination with the help of a jig at critical points. On completion of the gridshell the joints were permanently welded (Figure 11).

5.4. Stage IV (Ferrocement Application)

A total of six layers of chicken mesh were affixed over the completed structure. Three layers above and three below the MS gridshell (Figure 12A, 12B and 12D). Ferrocement, made in cement - fine aggregate ratio of 1:2 was then applied manually above and below the chicken mesh (Figure 12E). A second layer of ferrocement, mixed with a 4% brick pigment, was then applied on the outer and inner surface of the shell. Finally, the top surface was treated with a water proofing agent (Figure 12G).

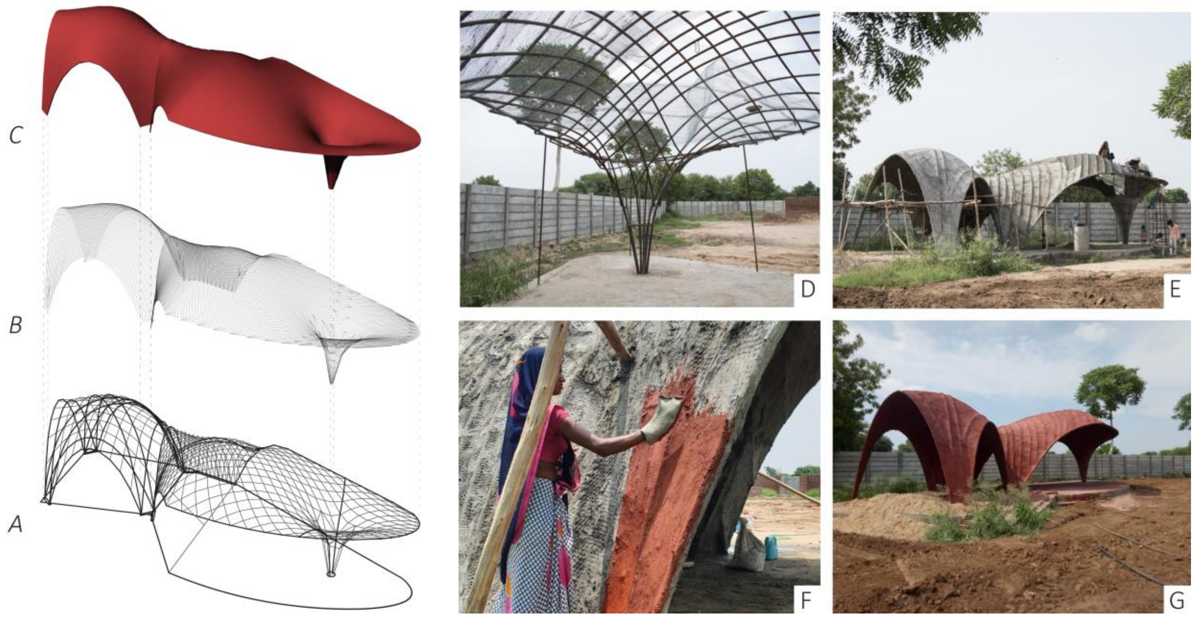

Figure 12: Ferrocement application.

6. Discussion and Way forward

6.1 Digital tools for form finding and structural analysis

With the advancement in computational design, numerous software provides tools for the form finding of free form geometry. The choice of a particular software is always critical and specific to each project. As mentioned earlier, RhinoVAULT 1.3 was used here to generate the form, as the starting point for the project was a funicular structure using timbrel vault construction or limited customisation of topological concrete blocks. If it were a gridshell to start with, the form could have been generated using Kangaroo physics by Daniel Piker (Piker [9]) and analysed in Karamba3D by Clemens Preisinger (Preisinger and Heimrath [10]). It is when these tools are used in conjunction with expertise of craftsmen who have acquired knowledge over time that the project becomes more rooted to its context. Contemporary design practices like craft based IBUKU reiterate this further with the amalgamation of long-established bamboo craft with 3D software that can be used to structurally analyse and test the stability of the structure. Physical models are made with bamboo sticks (to scale) which is then transferred to design software to further analyse the structure and check its adherence to codes [4]. This give and take adds value to the project through the precision of the software enhanced by the expertise and the years of acquired knowledge of the makers while also sourcing their material locally.

6.2 Structural optimisation through material selection

For materials, one deviation was the choice of MS circular pipe over the reinforcement bars. Standard ferrocement construction uses reinforcement bars and Hussain Doshi Gufa was one such example studied by the team (Doshi and Hussain [5]). A comparative structural analysis was done for both the materials. It was found that for the geometry of this shell, the total weight of the steel for 21.30mm dia. reinforcement bars were higher than the total weight of pipes. This became an important factor to choose MS pipes over bars as there was a reduction in the material used and the overall weight of the structure.

As said by Bill Baker, "Never design anything unless you have at least one idea of how to build it." From design to construction, decoding the geometry for craftsman is a key stage. As described in Frei Otto: Thinking by modelling (Vrachliotis et al [14]) and prototyping for architects (Burry et al [3]), physical prototypes always remain a tool to work out construction logic, sequence, and details.

6.3 Collaborative process

It is essential that the building crafts are understood through the acquired knowledge of the craftsmen while also finding new approaches to the craft by the means of the technology available to design and construct. This requires close collaboration among architects, engineers and craftsmen who can bring their respective expertise to the table while also exchanging ideas that can bring about novel forms of construction. This project had involved craftsmen in the design stages of the visitor's pavilion (Figure 3), and this helped us gain their inputs on material details, manual bending of the pipes and its limitations. The structural engineer had accommodated these limitations while issuing boundary member sizes in the structural optimisation stage. The involvement of architect, structural engineer and craftsman was essential during the construction phase while devising the fabrication logic, training, translating drawings on site and assembling the gridshell.

6.4 Empowering craftsmen with technology

As manual pipe bending required fabrication drawings for each member (Figure 7 and 10), handling these drawings on site was cumbersome for the craftsmen. Throughout the fabrication process, one person from the design team was working closely with the craftsmen to make sure that the drawings were followed correctly. Hence, training the craftsmen for mixed reality tools like (Fologram [6]) would help simplify the translation of the design from digital to physical space by extending their capacity to visualise the shell (in this case) in real time. This further expands their potential to develop crafts in conjunction with the advances in technology.

However, there is a limitation of manual bending as one can bend a maximum of CHS 48.3mm OD, 4mm thick MS pipe. Any size bigger or thicker than this would not be possible to bend manually and this needs to be considered while thinking about upscaling this method of construction. The constraints of craftsmanship shall be used as design parameters while upscaling. Both architectural design and structural optimisation for weight should take feedback from craftsmanship hence being an inclusive process through all the stages.

In the present day, the advances in digital tools to determine fabrication methodologies should be recognised while also understanding the necessity of contextualising computational complexity of design to the region of its execution. This concludes that a necessary coexistence of both is essential for the construction industry in India. It is only with time that this novice integration will feed into each other, create a unique inventory of construction techniques, and expand on its possibilities.

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