

## **DIGITALLY DESIGNED ARCHITECTURAL FORM BUILT USING CRAFT-BASED FABRICATION**

*Weaving a Complex Surface as a Bamboo Reticulated Shell*

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**Abstract.** This paper outlines a methodology that enables the construction of complex surface forms resulting from computational design processes by manual means using non-industrial materials. The methodology is based on the craft process of weaving whereby a three-dimensional form can be produced using a flexible, linear material. Construction information from a three-dimensional digital model is communicated to craftsmen through a set of two-dimensional drawings outlining the sequence of construction and requiring only linear dimensions.

**Keywords.** Digital-physical; craft; non-industrial materials; weaving; reticulated shell.

### **1. Introduction**

The physical manifestations of digital designs are most often realised through digital fabrication. This is in part because digital design and fabrication research has taken place in the developed world where skilled labour is expensive and automation is a financial necessity (Bechthold, 2004). Digital fabrication technologies require highly processed, homogenised, materials to maintain their high levels of accuracy and high tolerances and such materials are difficult and expensive to produce (Risatti, 2007; Kamath, 2009; Enns, 2010). Both the technology and the materials of digital fabrication are often financially out of reach for a majority in the developing world, but craft skills and non-industrial materials, on the other hand, are abundant. This paper outlines a methodology whereby craft based fabrication may be used to construct digitally designed forms.

## **2. Craft, Design, and Computation**

While design and craft both start with an idea and result in the creation of a functional object, Risatti (2007) argues that a designer operates in abstract and creates a set of instructions by which to make something, rather than creating anything physical. The subsequent execution of the design to create a physical object may use either human workmanship or machines. The human workmanship involved in executing a design, according to Risatti, is not craft. While a design may be completely original, its execution must follow the set of instructions set down in the design, and every time the design is executed the resulting object will be the same. The kind of workmanship involved in executing a design may be described as the “workmanship of certainty” to use a term coined by David Pye (1968). Pye explains that when the “workmanship of certainty” is taken to its logical conclusion, the result is mechanised industrial production where the outcome of the production process is completely controlled and there is no room for variation. Instead, craft – “the workmanship of risk” – involves the making of objects in a dialogical process between the craftsperson, their hand and mind, and physical material. While a craftsperson needs to exercise precise, often repetitive, skill and control, every object made by this process is still unique and different from every other object made.

In illustrating the parallel histories of computation and industrialisation, Dutta (2007) terms the variation inherent in craft objects to be “felicitous error” (p.212) that is a “variation from the programmed” (p.212) and the craftsperson as a source of “fecund miscomputation” (p.212) in the craft process where every move “bears the possibility of an incomputable deviation from the norm” (p.212). The source of this variation originates in the dialogue between craftsperson and physical material, as described by Risatti (2007). Kamath (2009) shows that the reason that variation in craft is incomputable is due to the inability of any algorithm to predict either the outcomes of human action or the outcomes of the natural processes that create the raw materials of craft, to a degree of dimensional accuracy that is needed to describe the variation between similar craft objects.

## **3. The Advantages and Disadvantages of Craft and Design**

The advantages of industrial mass production over craft are obvious – industrial production allows a large number of objects of a consistent quality to be produced cheaply, as opposed to craft which involves workmanship of risk. The process of design prescribes the form and shape as well as the material specifications of a manufactured object. Even if a design is completely unique (as is often the case in architecture), Risatti (2007) explains that a

given design specifies a single object and has no room for variation built into it.

The disadvantage of uniformity and standardisation inherent in mass production has been overcome through the digital control of manufacturing processes that enable mass customisation (Pine, 1999). The emergence of mass customisation has gone hand-in-hand with the digitisation of the design process.

Risatti (2007), Dutta (2007), Kamath (2009), and Enns (2010) point out that another disadvantage of industrial production is its dependence on input materials having uniform physical properties. Enns states the problem with reference to contemporary trends of digital design and fabrication in architecture:

“Such practices constitute an unnecessarily inefficient production circuit that moves from nonstandard input such as a tree to standardised stock material such as plywood or dimensional lumber, and back to nonstandard forms through digital fabrication.” (Enns, 2010, p. 118).

#### **4. Digital Craft**

Kamath (2009) looks at the dialogical process between a craftsperson and their material medium as an iterative cycle where each step in the cycle can be broken down into three parts – “sensing” (where the craftsperson studies the material and its inherent variations), “evaluating” (where the craftsperson thinks of ways to negotiate these material variations with the set performance criteria required of the object being produced), and “shaping” (where the craftsperson gives a form to the material that takes into account its non-uniformity and the performance criteria required of the object). Kamath shows how each of these three steps – “sensing”, “evaluating”, and “shaping” the material – can benefit from existing technologies such as 3D scanning, parametric design software, and digital fabrication respectively. While this transfer of technology from design processes to craft processes may be theoretically possible, it is still at a very nascent stage as may be seen in the work of Christian Feibig (2011).

Instead of looking at craft and design as two mutually exclusive processes, this paper illustrates a workflow that allows existing technologies of digital design to be used in a collaborative manner with craft processes so as to integrate the respective advantages of craft and design discussed above while overcoming the limitations of each.

## 5. The Digital Design and Fabrication of Complex Surfaces

This paper describes the design and construction of a complex roof surface in bamboo-crete using a permanent bamboo reticulated shell formwork. Bechthold (2004) outlines a tectonic strategy to construct the complex forms of equilibrium shells involving sub-dividing the shell into non-standard components that are CNC pre-fabricated and subsequently assembled on site to create some manner of temporary or permanent formwork. This formwork is used to give shape to a variety of materials such as ferrocement or strips of wood. According to Bechthold, the advantage of such a method compared to other, non-digital, methods of construction, is that digitally fabricated formwork

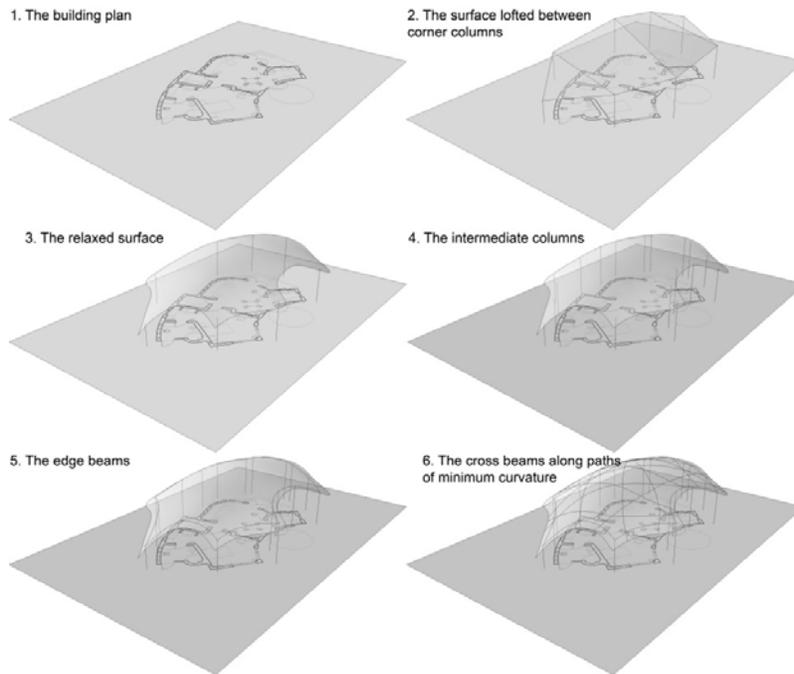
“liberates designers from restrictions to regular geometry or repetitive use of identical shells for the sake of economy. The process is designed such that there are no disadvantages to uniquely shaped shells and shell segments. A maximum complexity is embedded in, and maximum value derived from the rib network that is directly generated from the digital model.” (Bechthold, 2004, p. 96.)

While Bechthold (2004) refers to the construction of complex surfaces in the context of equilibrium shell structures, others such as Griffith and Sass (2006) extend this method of sub-dividing a surface into CNC fabricatable parts to other structural systems such as block walls.

## 6. The Digital Design of the Permanent Formwork

This paper describes a methodology by which a digitally designed complex roof surface is built manually through a craft based weaving process. The roof is to cover a living unit for visiting scholars at an educational research campus. The roof was envisaged as a hybrid reticulated shell structure (Paoli, 2007) where a funicular equilibrium surface is supported by a series of edge columns and beams. A detailed discussion of the structural system, however, is beyond the scope of this paper.

The plan of the residential unit determined the profile of the roof (Figure 1, step 1). Columns were created at the corners of the roof and a lofted surface was created to span between the tops of the corner columns (Figure 1, step 2). A commonly available, open-source, surface-relaxation algorithm was customised for this project and used to create the funicular surface of the roof from the lofted surface (Figure 1, step 3). Further columns were added along the periphery of the funicular surface between the corner columns (Figure 1, step 4). Edge beams were then created by connecting the tops of the columns along the funicular surface (Figure 1, step 5).



*Figure 1. Steps in the design of the permanent formwork.*

## **7. Weaving as a Method to Create a Doubly Curved Permanent Formwork**

Having determined the shape of the roof using the established form-finding methods, the next step was the design of the woven permanent formwork spanning across the edge beams. The process of weaving was chosen as a means to communicate the design to the craftspersons constructing the structure and enable them to construct the complex, doubly-curved reticulated shell in a manner that enabled its manual fabrication.

Weaving involves the laying of intersecting, flexible, linear members to create a form that may be a flat sheet (like a mat), or a singly or doubly curved surface (like a basket). It is the flexibility of the individual members held along a curve by their intersections with other members that allows the overall woven surface to curve. The relative positions of the intersections in space, and the lengths of the flexible members between the intersection points determine the curvature of the surface. The only measurements required to specify the doubly curved woven surface are the distances between

intersection points along each member and the positions of the end points of the members.

For the following model (Figure 2), a doubly curved surface was constructed in a 3D modelling software (Figure 2, step 1) and iso-curves in two directions were drawn on the surface. The iso-curves were modified to take into account the thickness of the plastic tubing (Figure 2, step 2) and the lengths between intersection points were measured along each curve. A simple script was created to automate this process (Figure 2, step 3). The distances between intersection points along each curve were read off the digital model and marked along the tubing material. The resulting members were then woven by pinning intersecting tubes at the marked points to make the surface (Figure 2, step 4).

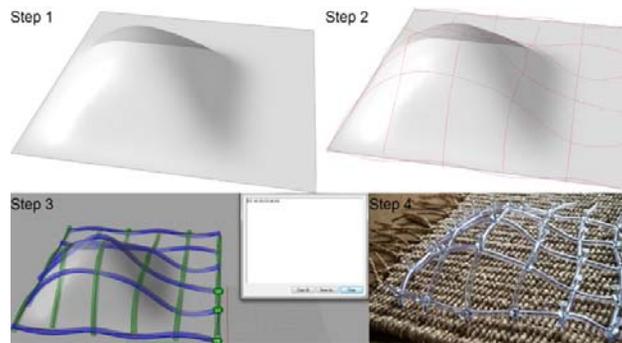


Figure 2. Weaving a doubly curved surface from a 3D digital model.

## 8. The Design of the Woven Permanent Formwork

The material chosen for weaving the permanent formwork for the roof was bamboo. The larger the diameter of a culm of bamboo, the stronger and less flexible it is. Iso-curves and regular grids mapped on to the funicular surface resulted in members with very great curvature which would have required very thin, and therefore very weak, bamboo to construct them, making the structure unfeasible.

An algorithm was therefore devised to find the path of minimal curvature through any given point along a surface. This algorithm was used to find paths of minimal curvature along the funicular surface passing through selected points on the edge beam (Figure 1, step 6). Weaving members along these paths of minimal curvature allowed the use of the strongest possible bamboo members with the largest diameter since the curvature required of the members is a minimal.

The single-line 3D model including the column centre lines, edge beam centre lines, and cross beam centre lines obtained from the paths of minimal curvature, was used to analyse the structural behaviour of the roof by ST.AR. Consulting Engineers. The results of the structural analysis determined that the average bamboo diameter required was 200mm with a wall thickness of 12.5mm, and that the edge beams and the cross beams along the paths of minimal curvature were required to be 600mm deep.

Based on some rudimentary physical tests on bamboo of the required specifications, it was found that half-round bamboo members would be able to achieve the curvatures required of the cross beams following the paths of minimal curvature along the surface. The edge beams, on the other hand, had been derived by connecting the tops of the columns along the funicular surface and were therefore not necessarily paths of minimal curvature. The greater curvatures required for the edge beams necessitated the use of quarter-round bamboo members for their construction. In order to achieve a beam depth of 600mm as specified by the structural analysis it was decided that the edge and cross beams would be built up with multiple layers of quarter-round and half-round members respectively. The weaving sequence for the roof (which determines which member goes over and which member goes under in an intersection) was then decided.

Having determined the weaving sequence and the thicknesses of members required, this information was used to create a set of drawings for construction. The construction drawing set (Figure 3) consisted of a series of plans showing the sequence of construction based on the weaving sequence. Each drawing in the sequence provided the information needed to weave one member of the roof. The drawing gave the lengths between the intersection points along the member and whether the member would go over or under at each intersection point.

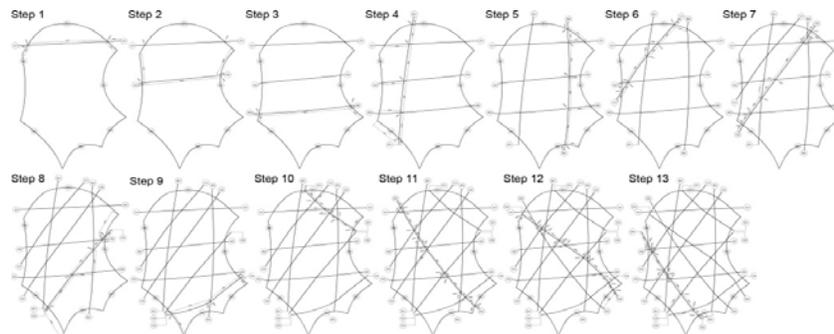


Figure 3. The construction drawing set.

### 9. The Construction of a 1:25 Scale Model of the Formwork

Before embarking on the construction of the roof, a physical construction model at a scale of 1:25 was built (Figure 4). The purpose of building the construction model was to check if the information provided in the construction drawing set was sufficient to build the roof and if the craftspersons building the roof would be able to make use of this information as they worked. The construction model was built by members of the team that would eventually build the roof. The material chosen for the model was hand-split slivers of bamboo representing the half-round and quarter-round members of the roof. After being briefed on the project and the notations in the construction drawing set the craftspersons were able to successfully build the model.



Figure 4. The Construction model.

### 10. The Construction of the Formwork

While following the linear dimensions given in the construction drawing set, the craftspersons (Figure 5) on the site were free to negotiate the unpredictable variations in the bamboo during construction.

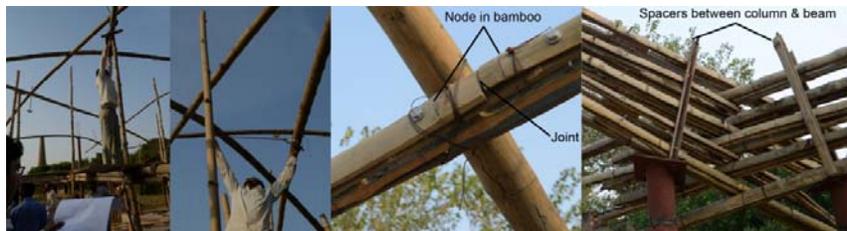


Figure 5. Reading linear measurements while negotiating variations in material.

For example, culms of bamboo that were thinner (but within the structural requirements) were used where greater curvature was required or where spans were smaller, and thicker culms were used for larger spans and members with lower curvature. Also, where members were longer than the longest length of bamboo available, two culms were joined at the nodes. At the points where the edge beams of the roof rest on the columns, bamboo spacers fill any gaps between the beam and column. Since the exact size of the bamboo can not be determined, the spacers have to be cut to fit each unique joint. Yet, following the linear dimensions provided in the construction drawing set enabled the craftspersons to build the formwork for the digitally designed doubly-curved surface.

The bamboo beams were woven, 20mm average diameter bamboo were laid out across the beams as reinforcement and permanent formwork for a 50mm thick layer of cement micro-concrete (Figure 6). The only steel reinforcement in this bamboo-crete roof spanning 19m X 12m will be a 16 gauge welded GI mesh with 25mm spacing which prevents the cracking of the micro-concrete.



*Figure 6. The woven bamboo permanent formwork ready to receive the bamboo-crete.*

## 11. Conclusion

While this methodology involves both designers and craftspersons, it is not simply the manual fabrication of a designed object. In this process a design informed by craft and material feeds back into a craft process and contributes what is impossible to achieve through craft alone – namely the form-finding of a complex, doubly curved surface, and paths of minimal curvature along this surface. The digital design process thus enables efficiency in the use of a non-industrial material that is impossible through a completely craft based process. The craft based construction was essential because a com-

pletely industrial or digitally driven process will not be able to negotiate the variations naturally present in a non-industrial material like bamboo. The importance of the craft based process can be seen by realising that if another roof were to be constructed using the same construction drawing set, it will not look the same because the bamboo members will be different and the way in which the craftspersons will negotiate these material variations will be different.

This methodology therefore opens up the advantages of digital design to those without the access to technologically intensive digital fabrication tools and expensive industrially processed materials, as well as opening up non-industrial materials to digital design processes.

### Acknowledgements

The author would like to thank the members of Kamath Design Studio, the clients, structural engineer, contractor, and most of all the craftspersons who were involved in this project.

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