Shipping Complexity

Parametric design for remote communities

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Abstract. This paper presents a system for design and construction of a parametrically designed, structural shell for remote communities. It explains how, through the use of various digital software platforms, a single-layer, structural shell is designed and optimized and subsequently how a series of customized joints can be output for direct digital fabrication. As the customization is focused primary in the joints of the structure, standard dimension, locally sourced structural members can be used. By embedding assembly information onto the physical joints, the system has the capacity to simplify the construction of complex shell structures by workers with basic construction skills. Flat-packed joints can be shipped to remote sites without heavy structural members thereby reducing transportation costs and the overall embodied energy. By lowering cost and simplifying construction of large span structures, the project is intended to extend the benefits of digitally driven design to rural, remote or underprivileged communities.

Keywords: Parametric design, structural shell, remote communities, embedded intelligence, digital fabrication.

1 Introduction

Recent developments in combining modeling software with computer driven machines to generate and produce complex forms have expanded the practice and discourse of architecture as well as the traditional role of the architect. Digital fabrication processes allow architects to transfer information embedded in virtual models and drawings directly to building components. Parametric modeling software allows for complex models and systems to be easily changed with a series of adjustable controls based on a set of defined parameters. The combination of parametric tools and digital fabrication tools for the production of buildings offers many possibilities for new architecture. In recent years efforts by contemporary practitioners have been made to use these new digital tools to increase the complexity of form of new buildings. Projects that have actually been built using these tools tend to be for high end institutional or private use (i.e. Luxury housing, concert halls, museums). In other words, there have been relatively few applications of contemporary computational tools to assist underprivileged or impoverished populations.

In their work concerning digital design for humanitarian purposes, Yeung and Harkins [3] argue that “digital tools such as generative modeling are increasingly used in architectural design, but ironically their major applications lie in unbuilt proposals due to the cost-prohibitive nature of complex forms enabled by the software.” While their response to the proliferation of digital design to underprivileged populations in the Solomon Islands was to produce architecture with generative principles with a more basic geometry, we present another alternative to make complex forms simpler to build.

Like the Yeung and Harkins [3] work in the Solomon Islands, the authors have sought to find ways to use computational and digital fabrication technology for improving the built environment and social conditions of rural or remote communities. The objective is to find innovative ways to combine local building traditions with off-site digital tools and processes to provide efficient, flexible and high quality buildings at relatively low cost by workers with limited or basic construction skills.

As the construction industry is responsible for a significant part of the world’s energy consumption, this project seeks ways to make building production more sustainable in terms of transportation and energy use. Sourcing local materials for building projects within a 100km radius of the construction site can dramatically reduce the embodied energy of a construction process. Lumber can offer a relatively low embodied energy value if it is minimally processed and locally sourced [1]. We propose to use sustainably produced, locally sourced building materials such as bamboo and timber. The overall system combines low-tech building materials, with small kits of remotely produced, high-tech building components. The objective is to minimize transportation costs while maximizing the flexibility and efficiency that high-tech systems can offer.

2 Project Opportunities

Remote communities could benefit from being given the tools to create inexpensive and flexible buildings using locally harvested or produced materials. The project is intended to yield digitally designed fabrication kits that could be shipped to remote communities in small packages. Those packages would include building components that can be combined with local building materials and assembled by workers that already possess a traditional or locally developed skill set without complicated drawings or techniques. The result would be to upgrade the performance of structures by adding parametric methods of design, structure and assembly to local intelligence and know-how. This process would help to retain and improve local labor skill sets to help stabilize social environments that may be threatened by the negative impacts of mass industrialization and standardization.

The proposed system has the capacity to change the nature, type and scale of buildings normally built in rural contexts. Typically, impoverished communities often lack the resources to build larger structures for community use due to budgetary and technological constraints. By providing rural communities access to build new, low cost, large span spaces, communities could create new buildings for cultural events, civic meetings and agricultural storage, as well as other uses. The creation of new types of space would allow for the generation of new types of spatial production.

New types of relatively large scale buildings can have a big impact on the operational possibilities of smaller communities. The Green School in Bali by the design-build firm Ibuku is an entire community that is made possible by combining new geometries and new building scales with traditional craft (Fig.1) The project is a good example of how new types of communal space can impact the qualities and opportunities within a particular society [2]. Programmatically it works well because of the new scale of space available to the community through a new form of construction.

The opportunities provided in The Green School project stem from the availability of bamboo as a local and natural resource. Due to its flexibility, lightness and scale, bamboo allows for easy spans of great length. The relatively small scale lumber proposed by the authors in this project is widely available in most places, whereas bamboo is not. The social benefits that The Green School has made possible are a goal of this project and could be achieved through variations in material with the system proposed.

Fig. 1. The interior of the Green School by the Ibuku design group in Bali.

3 Embedded Intelligence

One large question posed by this research project has to do with building complex forms without complex drawings. How can one single component of a building structure, in this case connective joints and nodes, be used as an organizing system that reveals the instructions for assembly as the building is being built? In this project there was a strategic choice to embed all the digital intelligence for an entire structure in the joints only. Flat packed, foldable metal joints are inherently easier to ship and require less material to cut than heavy structural members. By proposing a combination of customized, CNC cut elements and standardized, structural elements, the project alleviates the dependency on digital production methods for the entire structure.

4 The Building System

The system is designed to require minimal input from the building site to generate architectural structures. To create and output a structural shell, the system needs only a simple single curve, or set of curves that define a building perimeter to start. Perimeter curves may be planar or non-planar and may have varying degrees of curvature. As the original geometry can be constructed from 3 dimensional curves and paths, the system has the advantage of being able to conform to uneven landscapes. Potential building sites could be measured with simple analogue tools and transferred easily to digital information off site. The ability to build structures on existing terrain would mean that communities could avoid possibly large site preparation costs such as grading and leveling. The proposed lightweight system is able to rest on simply constructed footings around the perimeter of the structure.

4.1 Digital Techniques

As a basis for further development and specific materialization, a generic digital setup was defined. As mentioned, the process for designing a structure starts with a simple two or three-dimensional curve that represents the desired perimeter of a floor plan for the structure. Using a combination of modeling and scripting platforms, the computational process focusses on the joints generated at the nodal intersections for the multiple structural members of the triangulated surface. These unique joints, which contain all geometric information required to reconstitute the surface, are unfolded onto two dimensional cut sheets and are labeled with important information for positioning and assembly.

Using a specific combination of digital interfaces including Rhino, Grasshopper and Kangaroo, a geometrical mesh is modeled. By using Kangaroo‘s real-time physics engine, an equilibrium surface shell is generated by applying virtual forces to a surface. Forces can be adjusted parametrically to adjust the overall height and volume of the shell (Fig. 2).

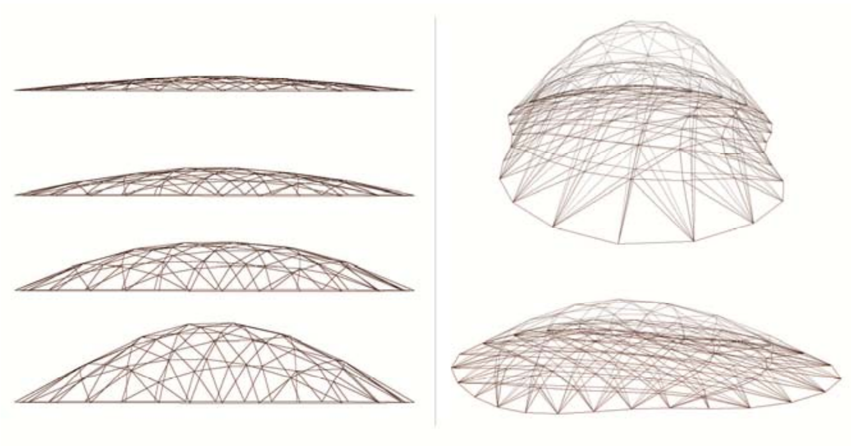

Fig. 2. Applying different forces on the shell can create varying height and volume.

In this test case scenario, NURBS geometry was used to generate the shell with adjustable U and V values to control the density of the mesh. A tighter mesh will create more nodes and therefore more joints and structural members. Increasing the density of the mesh will increase overall smoothness of the mesh, but will increase overall building components and add to the complexity of assembly and construction (Fig. 3). A key part of the design of structural frames would be to balance architectural and geometric desires with an understanding of local constraints of time, material and labor force skills.

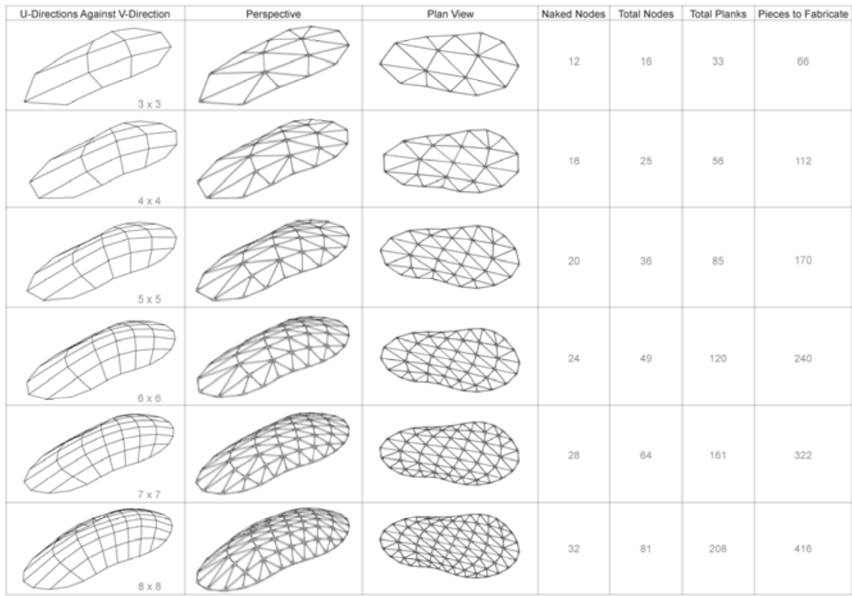

Fig. 3. Sample shell structures with varying degrees of grid density.

The digital script developed in Grasshopper focuses on the nodal intersections of the structural mesh. The script is used to measure angles between the multiple linear structural members at each node. As the intersecting lines creating each node are not necessarily planar the script calculates the precise angle of each member from a reference plane.

From this surface-specific model, procedural techniques are used to generate material-specific structural geometry for the shell. In this project, sectional dimensions of standard 1x4 inch timber framing were used as a test profile. Based on this structural profile, the surface is given realistic depth and dimensions to match the actual material that will be used for construction on site. The script is programmed with a parameter that is able to control maximum structural member length. For example, if locally-sourced timber comes in a maximum length of three meters, the program can generate a structural shell grid that uses no member longer than three meters in order to accommodate that particular material constraint.

Profiles of the structural members are automatically extruded along the mesh lines of the surface. The alignment of the profiles with the lines of the structural mesh has significant implications for the geometry of the joints. In the project case study, various options and for the alignment of the profiles at the top, middle and bottom of the structural mesh were examined. The final conclusion was to align all structural members below the surface of the mesh so that planar conditions at the top of the surface could be maintained. To avoid intersection of structural members, and to help resolve the non-planar surfaces at the bottoms of the timber beams, the ends of the members are trimmed away based on a set distance from the nodal intersection at the centre of the joint (Fig. 4).

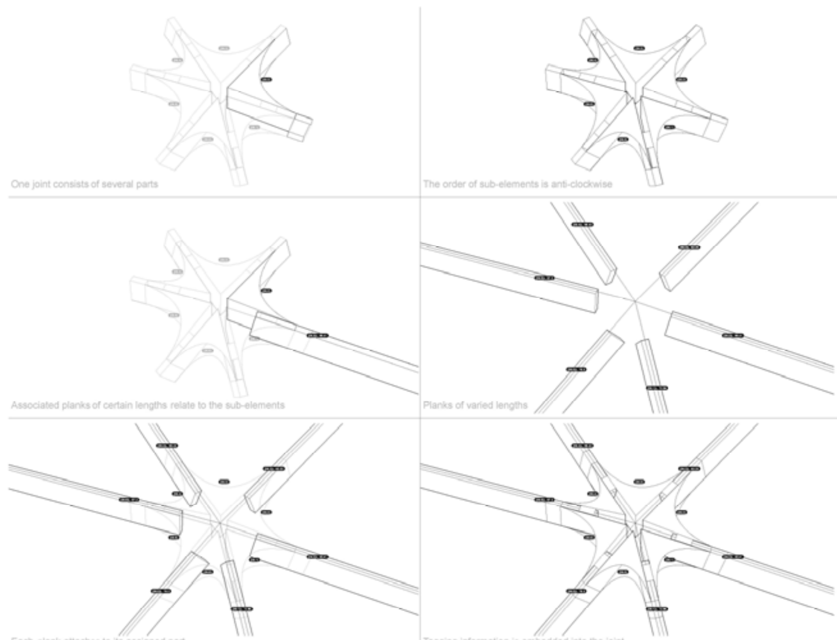

Fig. 4. Joint formation and information labelling.

Using the clustered ends of the timber members as a base geometry, another series of surfaces and webbing is offset from each timber face to form the geometry for the folded sheet metal joints. Surfaces are unfolded into flat plates and arrayed to form two-dimensional drawings that can later be used as cut sheets for CNC driven cutters (Fig. 5). As some joints are quite complex, unfolding often causes single joints to split into several pieces. Flattened plates use the perforating and tabbing logic of folded paper origami or cardboard boxes to ease folding and re-connect separate plates to form contiguous surfaces for the joints.

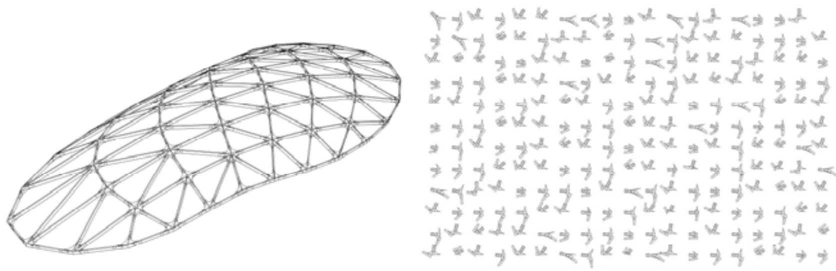

Fig. 5. Sample grid shell with unfolded, 2D joints ready for CNC cutting.

The ability of the joints to perform as instructions for assembly depends on information that is gathered in Grasshopper and scribed onto the actual plates using CNC driven cutters. By scribing item numbers onto each plate, they can be organized and joined on site. In addition to alpha-numeric codes that identify families of plates and positions within the overall grid shell, the plates also carry information for cutting of the lengths of adjacent timber members. In this way, the joint carries enough system information as to function as a cut sheet positioned in specific space. This system of coding and numbering eliminates the necessity for a secondary, associative code to identify member to joint connections. By embedding cutting and assembly information into the joints themselves, traditionally printed instructions, long cut lists and complex assembly diagrams can be removed from the construction process.

The project presented in this paper is a single iteration of a system of assembly that has the potential to make use of many types of material as structural members. The customized joinery of the system is highly flexible in regard to structural member depth, profile and shape. In the example described herein it makes use of the standard, dimensional timber often found in lightweight, wood frame construction (Fig. 6). By changing the script to adapt to other profiles, the system could accommodate steel, aluminum, wood or potentially even bamboo beams and columns.

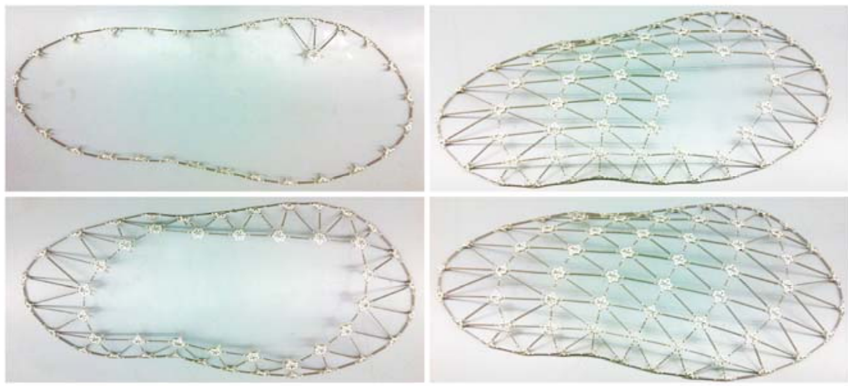

Fig. 6. Model photos showing assembly process of the structural shell

5 Conclusions and Future Opportunities

This research project has sought to develop a prototype for the production of low cost, customized structural shells with foldable, shippable components. The innovation of the project is not in the development of the form per se, but in how building assembly and construction complexity can be reduced by using digital scripting to embed assembly intelligence directly onto the building components. There are a number of ways in which the project can be further developed.

5.1 Skinning

While the projected has focused on the development of a digitally adaptable structural frame, the digital model may also help communities to clad the structural shell. In regions and situations where plastic tarpaulins and fabrics can be used for quick surfacing and waterproofing, digital models could be used to unfold outer surfaces to create precise cutting patterns for fabric skins. Workers on site could use patterns to cut large rolls of fabric custom fit to the structural frame. In other contexts, building skins could be easily constructed from local materials like thatching, plywood, corrugated plastic or sheet metal. The triangulated frame of the shell creates planar surfaces that can be easily clad with sheet material.

As a component of ongoing research for the development of this project, the research team is investigating full scale mock-ups of skinning techniques with actual materials. The joint components can be adapted, through folding, to act as clips to receive and attach a waterproof fabric surface. Surface unrolling and unfolding techniques will use the same shell geometry as the structure. As proposed materials are thin and relatively lightweight, there is an opportunity to ship them to remote communities along with flattened, unfolded joint materials.

5.2 Real-Time Structural Analysis

Structural analysis of the shell constructions will of course be necessary for insuring personal safety and building longevity. The ability to analyze structures in real-time, during the design phase would significantly advance form flexibility and overall work flow efficiency. Pairing digital design techniques for structural analysis with local or vernacular building methodologies would offer several advantages.

Vernacular architecture uses empirical methods to define rules for their building system based on material performance. The rules-of-thumb following this empirical process are often very conservative resulting in often over-dimensioning of structural members. Real-time structural analysis of designs using locally sourced materials allows for a more informed and optimized outcome and therefore a more efficient use of resources.

For the development of the project, the authors are working with engineers to develop real time structural analysis tools for the project. If local, vernacular materials are known in advance, shell design could be adapted in terms of structural member length and overall grid density. Furthermore, there is an opportunity to adjust the robustness of the connection nodes through the selection of different sheet metal types or thickness.

5.3 New Geometries

The case study modelled in this project uses basic NURBS geometry to form the structural grid and determine the placement of structural members. The UV subdivision of the generic equilibrium NURBS surface has large implications for the construction of the final buildings. Combining the physics engine with flexibly and strategically sub-dividable meshes informed by specific material choices, would allow for a more specific definition of the final geometry and more control over project complexity.

The project has used a single layer shell as a test case. The single surface thickness poses a significant restriction on the spans possible. A development of the digital model, where, from the same nodal concept, a double structural layer is possible, would dramatically increase the spans possible. This could potentially be automatically integrated in a script that follows the structural example of early renaissance dome construction where the centre is built as a single layer and the structure doubles up at the periphery.

5.4 Optimization and On-going Research

The overall building complexity remains a goal in terms of building form and a challenge in terms of construction and assembly by unskilled workers in remote communities. The authors are in the process of building 1:1 scale models in which the code can be adapted to further reduce the amount of varied lumber pieces and number of unique joints that are required. This further level of optimization would seek reduce the complexities on site even further to make the system more valuable.

The project team is working on a full scale test model of the shell system with a metal fabricator in the Pearl River Delta region of China. The fabricator has a range of CNC driven cutting and folding tools that will be tested with various types of sheet metal material. The authors will seek to test various ways of cutting or scoring the sheets so that they can be hand folded on site. Test nodes will be used for empirical structural testing to compare with digital structural analysis. Embedding simple instructions for assembly is a critical part of this research project. The authors will work with teams of workers to find simple ways to remove complexity of assembly from an otherwise complex structure.

References

1. Calkins, M.: 2009, Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials, John Wiley & Sons, Inc., Hoboken, 271-326.
2. Chow, T.: 2011, Earth Angels, *Perspective Magazine*, March 2011, Hong Kong, 90-93.
3. Yeung W. and Harkins J., Digital archi for humanitarian design, *CAADRIA 2010*, Hong Kong, 413-422.