DESIGNING CONTINUOUS COMPLEX CURVED STRUCTURES TO BE FABRICATED FROM STANDARD FLAT SHEETS

Sergio Araya Goldberg
Massachusetts Institute of Technology
Department of Architecture
Master of Science in Architecture Studies (candidate)
284 Vassar Street Apt. G1Cambridge MA 02139 US
sergio_a@mit.edu

Abstract

This paper explains how complex curved structures can be constructed from flat standard panels. The main objective is to link both design techniques and digital fabrication methods to solve a recurrent problem in contemporary architectural design, building double curved structures. Secondly, it achieves this by using regular fabrication methods and standard construction materials, available and affordable for Latin-American countries. It describes the processes of programming a set of computational tools to study and develop designs to fabricate continuous complex curved structures. I will describe this through a series of experiments, using parametric design environments and scripted routines for CAD software to implement certain techniques to fabricate these designs using rapid prototyping machines. I compare different fabrication methods using computer numerically controlled machines, used to process these flat panels to obtain certain properties, allowing them to bend, twist, fold or stretch achieving these complex forms.

1. Introduction

"We already had a digital revolution, we don't need to keep having it" (Gershenfeld 2005) The Director of the Center for Bits and Atoms, Neil Gershenfeld, points now to the imminent *Revolution of Making*, the programming and fabrication of the real world, not just the electronic virtual worlds. During the last two decades, computers and digital technologies have infiltrated our lives. Computer's power relies partially on its speed calculating complex mathematics. For architects this meant that complex geometries based on increasingly complicated equations, became possible design tools expanding the standard repertoire of shapes: whole family curved topologies, such as splines, and spline surfaces. Nevertheless, these tools while enhancing the design responses became too complex to be fabricated with traditional construction methods. As the relations and dependencies between geomtries are usually fixed by default in regular CAD applications, we cannot fully grasp the latent potency of such geometric constructions, neither can we understand them to fabricate them. In this paper I will describe two techniques to develop parametric designs of complex curved structures. I will explain this using both parametric design techniques and scripting, to study both approaches. I will show how these designs can be constructed using rapid prototyping and CNC methods.

1.1. Geometry in the background

Spline curves are traced using the vertices of a control polygon. Modifying the position in space of this poles alter the geometry of the spline. In the same fashion, surfaces can be traced by a grid of poles, resulting in complex curved surface. A spline curve, is always tangent to the first and last poles, but the rest of the poles remain external to the curve. While the continuity of the curvature is one of its main appeals, it is also a big problem. If a spline is cut in two each resulting segment changes, becoming tangent to the new edges and acquiring a new geometry. When this new splines are put together, there is no continuity on the curvature. Usually, when this happens in real construction works, the pieces are stressed to fit, almost always wrinkling and even breaking as a result of these forces. Another aspect of these continuous complex curved structures is that cutting them in pieces will result in large collections of pieces, almost all equal, but every single one slightly different. In regular CAD this operation is extremely time-consuming. Parametric environments are streamlined towards fabrication, facilitating processes like for example, unrolling ruled surfaces. But there is no possible unrolling of double curved surfaces. The technique that I developed for this research uses the unrolling principle to obtain a flat panel from an approximated double curved surface. This paper will examine how complex curved structures can be constructed from flat panels, borrowing a concept from mechanical engineering: "flexure structures".

2. Manufacturing curved structures

Construction industry is founded on standardization and modularity. Most construction materials come in flat sheets or panels. And casting materials that can acquire free forms also require molds that have to be made from flat panel materials. Therefore, the process of translating these continuous complex curved structures is always painful and usually requires translation to a more rational expression. This paper describes a procedure using "flexure" structures and developed in parametric environments, to fabricate partially double curved structures from rigid flat panel using rapid prototyping tools and CNC machining. In the larger perspective, this paper approaches the notion of generative design tools and their ability to use digital design fabrication logics and processes to extend the actual boundaries of constructability in contemporary design. Furthermore, this approach engages the reality of Latin-American construction industry and local economies, providing an affordable response to these complexities.

2.1. Flexures

Compliant structures are those who can change its shape when a force is applied to them, and that will return to their previous state if the force is taken out, for example springs. There is a type of compliant structures that behaves similarly to springs, called *flexure*. These structures deform elastically depending both on material properties and on its geometry. This paper describes how to create complex curved structures from flat rigid panels through the flexion of these structures. According to Larry Howell, it is a special kind of mechanism, "a mechanical device used to transfer or transform motion, force, or energy" Typically they are made of "rigid links connected at movable joints." (Howell 2001).

A compliant mechanism or flexure, however, while still performs the same basic functions of transferring or transforming energy or force, gains at least part of its mobility "from the deflection of flexible members rather than from movable joints only" (Howell 2001)

Flexure structures have several advantages as they reduced the number of pieces involved, reducing the assemblies required, and therefore reducing its costs. But more important for this investigation, is that they can be developed from single pieces. Flexure structures are frequently used in machines that require very precise movements, as they have a reliable displacement precision. They can effectively isolate their movements to the axis where the maximum flexibility has been provided from other lateral movements, "reducing the vibration natural to hinged joints, eliminating the friction between movable parts and the backlash from their rigid body and hinged counterparts"(Howell 2001). Applying this notion of flexure in this investigation provides a method of material transformation, where solid rigid flat boards can be developed into partially flexible structures. This process was conducted through experimentation on different geometrical patterns and the performance obtained from them when applied to a solid material. The fabrication process chosen was material removal by cutting these designed flexure patterns onto the rigid boards.

3. Parametric features, scripting, and fabricating

Two different strategies were explored to model these curved designs, creating a parametric feature in Generative Components, and populated an unrolled approximated double curved surface. The other approach was by writing a script in Visual Lisp to create a parametric flexure pattern. In Generative Components (GC) I created a flexure pattern feature, based on an array of points supported by a basic quadrangular shape. The feature is populated over a point grid placed on a spline surface. A global variable controls the number of points used to subdivide the surface, adjusting the *resolution* of the flexure surface. The shape grid used as vehicle for population is unfolded in a different model. After reimporting it to GC, the unfolded shape array can be promoted to GC and can then be used to reconstruct a shape grid. Finally the flexure pattern feature is applied to this unfolded surface, obtaining the cut sheet which can now be exported as a regular 2D CAD drawing to be machined.

The second strategy developed a Visual Lisp script that draws simple flexure patterns. Two variables control the size of the cut figure, and another two secondary variables control the spacing between them. This first script works only in two dimensions, but allowed me to test different material behaviors, manipulating the variables, studying the tolerances required for a machine, and a specific material. A second script, still in progress, works on three dimensional curved surfaces. The first step was to create an approximated spline surface, because autocad does not have spline surfaces or nurbs. So I wrote a script that uses splines as inputs. Then I used a spline subdivision function written by Takehiko Nagakura (2005), to create lists of points which are used to create another series of splines, going in the opposite direction, connecting the first point on one of the original splines, with the first point on the second original spline, and so on. This second list of splines provides the resolution on U direction on the future spline surface. See Figure 1.

This list is subdivided again , obtaining the resolution on V direction, creating a dense point grid in 3D space. Based on this script, I wrote a couple of functions that create ruled surfaces between the splines obtained, producing an approximated spline surface, even though, each segment is a developable surface. Based o this properties, each of this segments could be unrolled or developed, and then used as a base for reproducing a two dimensional flexure pattern. See Figure 2.

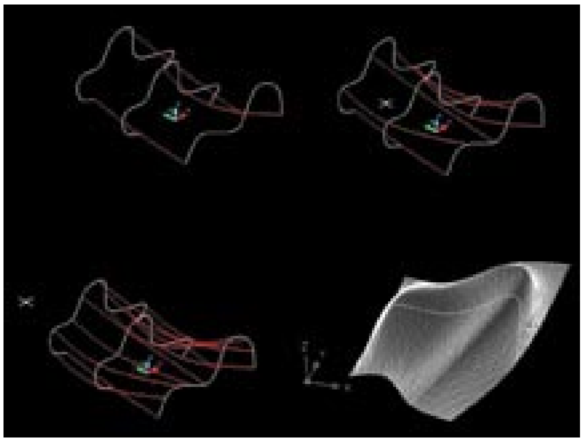

Figure 1: Spline subdivision script to create an approximate spline surface in autocad.

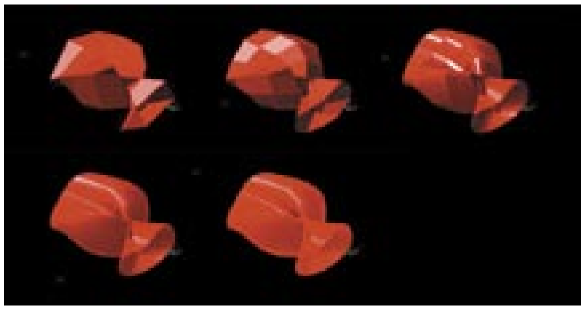

Figure 2: A subdivision factor is set as a variable, adjusting the smoothness of the resulting approximated spline surface.

3.1. 2D cutting

Removing material from a flat board weakens its structure. If this operation is performed according to the material flexibility of the panel, it is possible to obtain degrees of flexion from it, even from the most thick and rigid panels. Different patterns can be applied to cut and or remove material from flat panels to be able to flex them and obtain curved geometries. Furthermore, I will show how different patterns can be applied to obtain different performance from the original panels and therefore, different surface effects. Two different materials have been tested for this purpose, to investigate the incidence of the material properties in relation to the material removal process.

I used 2 mm plywood on a laser cutter to test different results derived from a script. The wood panels were

Figure 3: Different results obtained from processing equal panels with the same script but with different variable values

semi rigid, allowing to be slightly bent along the longest dimension, but completely rigid (for hand applied force) in the short dimension. The cut sheets were imported directly from the dwg file where the script was executed. The speed and power of the cutting were related to the resolution of the pattern, so they had to be adjusted every time to avoid burning the wood and creating flames. Even though the script was very simple, the results obtained were very different, depending on the values of the variables that control the script. The wood acquired the desired material elasticity in order to bend not just in one direction, but in both, obtaining double curved structures, from original, semi rigid panels. When the deformation force was ceased, the panels return to its flat state.

A second test was performed on an Omax Water Jet machine, to cut flexure patterns on 4 mm aluminum. This panel was absolutely rigid in both dimensions. Several test using different patterns were conducted to study the results of varying lengths and thicknesses, comparing removed material percentages and elasticity acquired. See Figure 4.

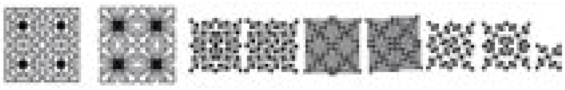

Figure 4: Several flexure patterns were tested to study performance according to materials and machine processes

A more complex but still regular 2D pattern was applied. See Figure 5. The result is that material elasticity was achieved, although the ranges of plastic deformation

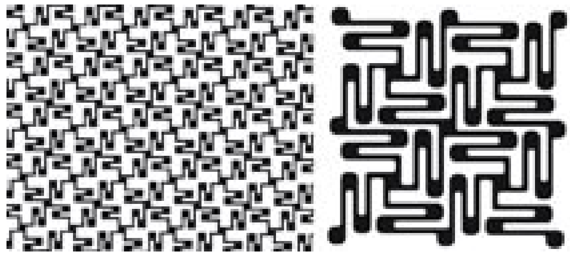

Figure 5: Flexure pattern propagation and final pattern developed, with rounded edges avoiding fracture points

were several times smaller, given the material properties. See Figure 6.

Nevertheless, the aluminum panel became ductile enough in order to be shaped by hand into a double curved structure. The flexure pattern applied, gave enough elasticity to the material to allow plastic and non plastic deformation. When the plastic threshold is overcome, the structure does not go back to its original state. See Figure 7.

3.2. Printing bricks

Even though the purpose of this paper was to explore

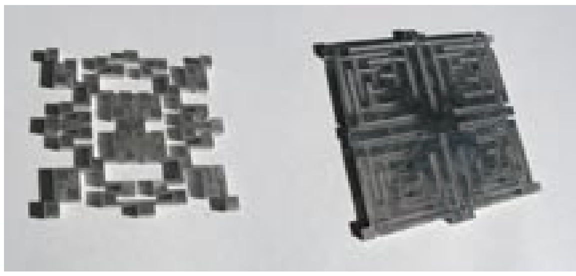

Figure 6: Flexures fabricated with a CNC Water Jet machine on 4mm aluminum

Figure 7: Double curved structure fabricated from a rigid flat aluminum panel

fabrication on flat panel, I detoured from the original line studying other fabrication methods that could be implemented from the development of the scripted routine. I wrote a function to create solid extruded modules using the pointgrid obtained from the previous script. Global Variables were defined to control the height of the extrusion. More functions included in the final script were developed to provide a hollow module, and control on the number of sides that the module would have, I tested pyramidal and cubic modules. This result was fabricated using 3D printing process on a ZCorp machine. This line of research has the potential to develop as a separate study, developing complex structures using a non standard modularity approach. See Figure 8.

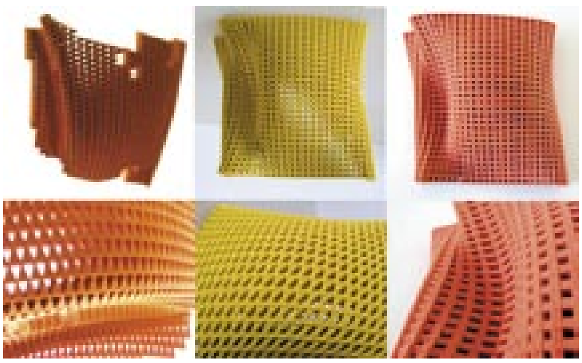

Figure 8: Double curved structures developed through solid module scripting and 3D printed using a ZCorp Machine

4. Conclusions

The research described in this paper is still in progress, but the result obtained so far are interesting and promising.

The first exploration using parametric design environments, demonstrates a technique to obtain unfolded flexure patterns, which retain the geometrical information of its curved state. Fabrication tests have to be done to confirm that this technique provides accurate double curved structures.

The script files develop, prove that the geometrical logics of parametric design environments can be applied to regular cad applications, which are widely spread and a common platform in Latin America. These scripts also had better performance in relation to parametric features, which could be an advantage for large-scale full-resolution implementation of these techniques.

Although the test performed for this research were at model scale, and that further testing is required using real scale and real material, the results obtained from the laser cut wood tests, prove that this techniques could be performed using standard materials and two dimensional CNC processes. The Water Jet test in aluminum shows that it is even possible to obtain complex curved structures form rigid materials, through these techniques.

Comparing the results from parametric design and scripting, it is important to notice that the performance of the script is several times better in terms, but it lacks the realtime manipulation of a parametric system. The script would have to run again, the parametric component can be modified on the fly. The script variables are set a priori, while the variables for the parametric component can be adjusted during the design process.

Finally it is promising to note that large structures could be develop by this way, reducing the number of pieces required to be assembled, providing a range of deformation to adjust in place the continuity of the curvature between assembled pieces. They could be eventually, while performing with plastic deformation, be unstressed and laid flat again for transportation advantages.

5. Further research

The results shown in this paper are preliminary and further research should be done to accomplish more precise and universal results.

In depth exploration using parametric components should be performed to demonstrate the functionality of decomposing complex features cut sheets for fabrication. This opens a wide spectrum of possibilities for architectural design and building technologies, providing a technique to streamline the production of complex components.

Additional investigation regarding the parametric Visual Lisp scripts should be done. Scripting the unrolling function and the laying out function are still pendant, and would prove to be crucial to pack the script as a new tool. A graphic interface with optional functions should be created in order to act as a standard "plugin" for Autocad.

As a side product of this research, I discover the potential of using such parametric techniques to develop a masonry-like approach to develop complex structures. This requires a study on its own, testing different computational approaches and results from different processes. I will extend this research in the future.

Further investigation using large scale panels and CNC machines should be performed in the very near future, to have scalable result for realtime fabrication and implementation.

Above all, these explorations would prove that complex curved structures, and other complex components, could be designed and manufactured using parametric techniques and digital fabrication methods, with standard materials, and with affordable budgets.

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Sergio Araya Goldberg
Architect Pontificia Universidad Catolica de Chile, Magister in Architecture Pontificia Universidad Catolica de Chile, Master of Science in Architecture Studies (candidate) Massachusetts Institute of Technology.
Areas of interest: Kinetic Architecture, Responsive Systems, Parametric Design, Digital Fabrication, Design Computing.