DESIGNING AND FABRICATING CONTINUOUS COMPLEX CURVED STRUCTURES FROM FLAT PANEL MATERIALS USING A FLEXURE APPROACH

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Abstract. This paper describes a procedure that combines scripting and modeling in a parametric environment to design and manufacture complex double curved structures from rigid flat panels using rapid prototyping tools and CNC machining. It engages generative design techniques and programming while extending the digital design and fabrication possibilities for curved structures.

1. Introduction

Construction industry is founded on standardization and modularity. Most construction materials come in flat sheets or panels. Casting materials can acquire free forms but require molds that also have to be made from flat panel materials. Therefore, the process of translating continuous complex curved designs into built form is always painful and usually requires a reduction to a more rational expression. This paper describes a procedure using “flexure” structures developed through scripting and parametric design, to fabricate partially double curved structures from rigid flat panels, 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.

2. Design for fabrication

The computational algorithm utilized, was to abstract and fragment the complex 3D geometry of the surface in order to process it as smaller flat 2D shapes that could be used as fabrication models. Then specific functions developed according to particular manufacturing procedures and machines are applied. This first procedure turns a bspline surface with double curvature into a parametric faceted surface by applying a triangulation method via a script. The script locates a series of points on the surface based on its UV values. These points sampling the surface are translated, rotated and aligned in another plane, effectively unfolding the points.

As each facet is created by grouping four non collinear UV points on the surface, the resulting facets are quadrangular, which can be reduced to two triangles sharing a side in common. The first triangle is translated into a plane, then the second triangle, takes the common edge of the first unfolded triangle and aligns its third vertex to be coplanar with the vertices of that first triangle. The result is the unfolded quadrangular facet. An optional procedure is included to unfold the second facet, using the common edge with the first facet, either in the U or V directions, creating a continuous facetted strip. *Figure 2*

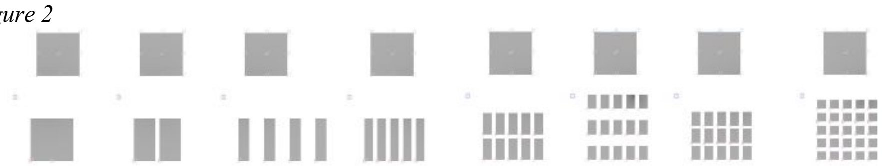

Figure 2. The abstraction function transforms the surface into a series of flat quad-patches optimized into a nested layout for fabrication.

According to different materials and design requirements, this procedure of decomposing the surface into quad-patches could be useful, providing a precise layout for each facet to be fabricated out of a flat panel. In other cases, it might be better to decompose the surface into strips to be cut from larger panels. As the objective of this research is to enable possibilities for design, through the embedding of fabrication logics, these options were kept as parameters in the script. By facilitating the unfolding of the bspline surface points into a flat bidimensional representation, this procedure transforms the design geometry into a fabrication layout, but at the same time, allows to conceive, adjust and perfect such design according to the procedures that would be later involved in its construction. *Figure 3*

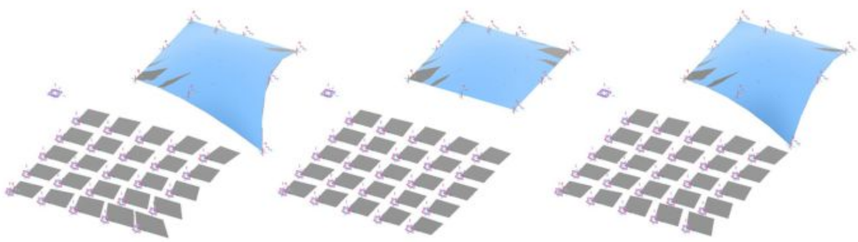

Figure 3. Being a parametric reproduction of the bspline surface, any adjustments on the geometry of the surface is passed its unfolded and subdivided version.

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 flection of these structures. According to Howell (2001), 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”.

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.

2.2. PATTERN SCRIPT

The strategy explored to model these flexure pattern designs consisted of creating a parametric feature in Generative Components (GC), and populated an unrolled portion of the surface with it. The creation of the flexure pattern "*feature*" was based on four points, supporting a basic quadrangular shape. The feature is populated on a shape grid placed over the bspline surface. The shape is used as a vehicle to group and order sets of 4 points in order to insert the parametric feature on the surface, or in the unfolded version of it in this case. A global variable controls the number of points used to subdivide the surface, adjusting the resolution of the flexure surface. The shape grid used for population is unfolded in a different model. Finally the flexure pattern feature is applied to this unfolded surface. Global variables were exposed to be able to control the nesting of the unfolding shapes as a cutsheet, optimizing the material use and reducing the cutting time.

2.3. TAGGING

A common difficulty when dealing with large number of different pieces to assemble is how to match the pieces, usually requiring an assembly diagram. The script includes a tagging feature that labels each quad patch obtained and unrolled from the original surface. The tag also works as registration mark as it is located always in the lower left corner of the piece, facilitating its alignment. Furthermore the tag can also be applied to the subdivided surface, which acts itself as assembly diagram explaining where each tagged patch goes. *Figure 4*

Figure 4. Assembling the pieces together to reconstruct the double curved structure.

2.4. SCRIPTED JOINTS

If a design is to be fabricated as parts or components to be assembled, careful consideration has to be given to the way these components will be joined. The algorithm proposed for the series of exercises conducted for this research uses a common starting join concept, which is developed and adapted according to each specific fabrication method. I started using the common dove-tail joint detail, usually used in carpentry and woodwork. I use this detail as it provides an efficient yet simple press fit joint which could be later modified to different extents as different designed assemblies would require.

The joint detail was scripted as another parametric feature in GC, which could be nested on top of the series of other features to provide a complex modular component design yet maintaining control over the individual features that control the component. The points used to drive the dovetail detail are placed using the planes defined by the triangles obtained by the subdivision function. Every dovetail tenon has a correspondent dovetail mortise. For the joint to work on different materials and with different machining processes, a tolerance value was included, reducing the tenon in size, in a ratio that can be controlled globally. Global variables were exposed to control the size and shape of these details.

Another concern was the location and frequency of these joints, therefore the parameter that controls the number of joints populated on each side of the quadrangular patch was exposed as a variable, redrawing the bspline line that defines that particular edge of the patch to take any number of tenons or mortises. This method provides a flexible solution that ranges from individual joint details for each quad patch up to a continuous joint seam. *Figure 5*

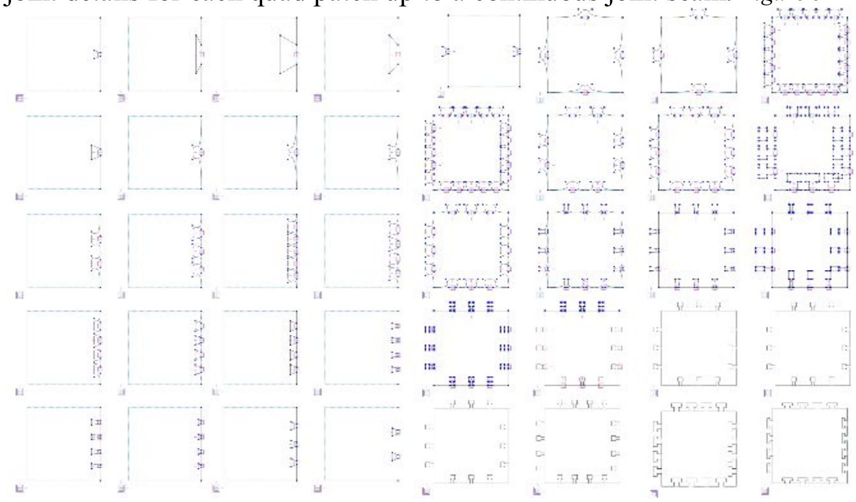

Figure 5. Parameters control the geometry, size, location and number of joint details per piece.

3. Machining

The actual fabrication of the components required adjustments according to the machines and the materials utilized. These adjustments were granted by the variables scripted in order to control the tolerance of the joints and the nesting of the shapes in the cutsheet. The tolerances for the laser cutter had to be bigger than the other machines like the waterjet, where given the toolpath it is possible to specify the side of the cut, requiring only small adjustments in the tolerances to obtain pressfit precision. The ratio between the speed of the machining and the cutting power was used to provide a smoother or rougher finish, which can also be used to increase the friction between components ensuring a better assembly. It was hard to calibrate the tolerance when pieces to be matched were processed in different machines. In general the strategy that proved to work best was to provide at least on one of the pieces, a rough edge in order to help the press fit assembly.

4. Conclusions

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

The script files developed prove that the geometrical logics of parametric design environments can be used to drive fabrication models.

The tests performed for this research were at model scale, and further testing is required at real scale with real materials. Nevertheless the results obtained from the model tests, prove that this techniques could be performed using standard materials. 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 scripting to previous tests achieved by modeling, the performance of the script is several times better. Scripting in GC combines the speed and performance of programming and the adaptability and flexibility of parametric design

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 out flat again for transportation advantages. *Figure 6*

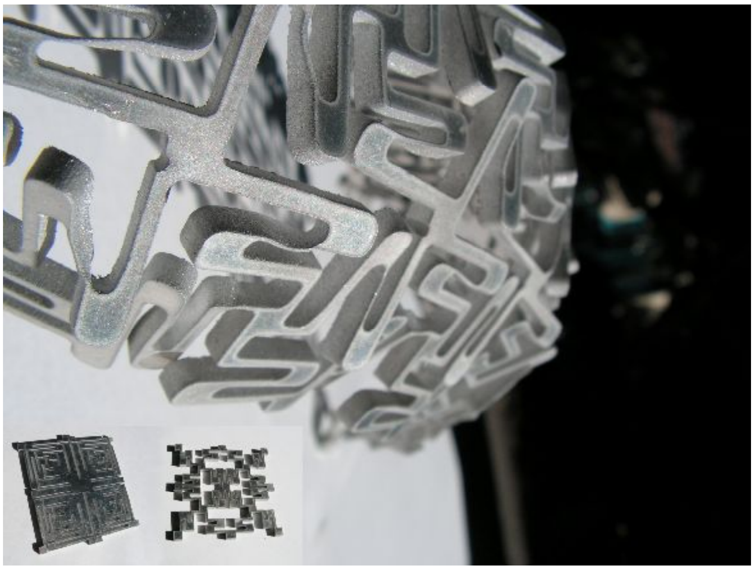

Figure 6. Pictures of flexure structures cut from 4 mm aluminum

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 further functionality of decomposing complex features into 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.

6. Acknowledgements

All my gratitude to Robert Aish for inviting me an letting me take part of the GC community and for his continuous support, always stimulating this research and other projects.
Sincere thanks to my advisors Ann Pendleton and Lawrence Sass for their support and insight during the development of this research.
Thanks to the RPL and Media Lab at MIT for making this research possible.

7. References

[1] Howell, Larry L, 2001, *Compliant Mechanisms*, New York: John Willey & Sons.