COMPUTING & MATERIALIZING NON-UNIFORM SHAPES

An evolutionary approach to generate and digital fabricate non-uniform masonry walls

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Abstract. A novel evolutionary system used for the production of design information for digital fabrication is presented. This program generates information for physical construction as architectural models of double-curved walls built from unique masonry units. We present a series of computer programs and physical models as examples of straight and curved walls generated from an evolutionary system built for design. The wall examples here are built of non-uniform, interlocking units. This project is an exploration of evolutionary design tools that construct double-curved structures in CAD for fabrication with a 3D printer.

1. Introduction

he integration of computing into current architectural design processes requires non-conventional solutions for the generation of information and ultimately, fabrication. Designing and computing curved forms have become common practice for architects as rendered images, but difficulties are presented when considering fabrication and assembly as a desktop model (Figure 1). This paper explores a few issues when computing non-orthogonal form for design evaluation and fabricated using digital fabrication processes. The architectural offices of Frank Gehry, Rem Koolhas, and Norman Foster are littered with physically large representations of proposed orthogonal and curved building designs. These models are produced by hand techniques and rapid prototyping. Physical models empower designers to demonstrate and study the details of space, light, and form. However the difficulty in working with physically large models is that manufacturing components and assembly require many hours of labor in translating information from drawing to physical materials. In return the process illuminates many properties at full scale construction with the benefit of physical reasoning within the design space. Reasoning with physical materials introduces new constraints in computing which are explored in this paper. The vision is to explore design systems for constructing physically large curved surface representations with rapid prototyping.

This paper introduces a design system that analyzes and decomposes curvilinear form in CAD into non-uniform components ready for assembly at any desktop design scale. The system enables visual and physical evaluation of double-curved structures for construction by form deconstruction, fabrication and assembly. Our investigation is exploration into a system that can generate and evaluate curvilinear shapes or form for creating discrete non-uniform component. Form and shape investigation built by architect Eladio Dieste demonstrated the complexity of using masonry units as the elements of construction. Current leading architects such as Frank Gehry and Bernard Cache have attacked the problem of non-uniform construction of curved shapes with computer modeling and CAD CAM fabrication. Their work demonstrates ways to physically construct buildings of glass and metal from computer models, and displays the continual design intention to experiment with more provocative forms. Short comings of these designers' work are in the final constructed building. Higher level questions are centered on methods to design these shapes as physical models from rapid prototyping devices and redesign based on changes found while exploring the design. Based on published information design evaluation and redesign was a virtual process, physical methods to reason with design shapes and assembly strategies were not until the end of the process.

Figure 1. A complex computed design shape

2. Physical Evolution

This system considers evolutionary methods that dictate physical solutions by dividing curvilinear form into sub-units with embedded assemblies from a seed. It is an alternative approach to typical evolutionary design by considering manufacturing as part of the generative process versus virtual evaluation and final output (Bentley, 1999). Manufacturing and assembly constraints are introduced early in the process versus typical methods of generating surfaces then translation to solid objects for manufacture. Design evaluation is by physical testing of tolerance, structure, assembly and aesthetics. Most important, the work explores the issue of redesign of new curved surface models (as desktop models) based on evaluation.

There are two challenges in this work: generating models as unique components starting with a curved surface and the fabrication of 3D models; managing component strength and assembly tolerance. Modeling and 3D printing non-uniform double curved surfaces is a challenge for any modeling program. The problem is exacerbated for models built larger than the volume of a typical 3D printing machine. Models larger than 10” square must be built and printed as individual components. Conventional modeling of unique shapes for individual manufacture in standard 3D modeling software is time consuming and laborious.

3. Background

This work resides in evolutionary thinking in relation to design and fabrication.

3.1. FABRICATING MODELS FROM GENERATED DIGITAL MODELS

Wang and Duarte’s (2002) demonstrates that geometrically complex designs too difficult to produce by hand can be manufactured from rules. A computer program generates forms through shape grammars. Their designs were fabricated using a Stratasys FDM 3D printer. Their approach generated solid objects as physically small models (approximately 4” square) of the complex shape relationship. Models of this type and size are not convincing as architectural solutions mostly because they do not allow for spatial study as well as formal study.

3.2. EVOLUTIONARY PROCESSES AND COGNITION IN DESIGN

Peter Bentley describes the intersection of disciplines for creating designs in an effort to emphasize the process of evolutionary solutions. He expresses, with the use of examples, the creativity that computers instigate as they introduce possible design solutions or options that were non-existent before applying evolutionary procedures. This study illustrates designs created by algorithms within a 3D software environment which uses design computing as a way for aiding design decisions.

An example of an evolutionary method generates tiles of various colors using grammar rules as the basis for the emergent of tetrahedron shapes (Kristina Shea, 2004).Generated results demonstrate tetrahedron of various colored topologies for visual evaluation. The generative program does not capture connection or the constructability of individual units for physical evaluation, therefore resulting shapes require a second transformation for fabrication as a 3D printed model.

4. Assembly and Block Design

Traditional masonry wall construction is composed of a standard manufactured unit assembled in a variety of ways to build one wall (Figure 2(A)). Variation is not in the masonry unit but, is achieved by the experience and skill of the mason. Depending on the construction goals, the mason’s process would involve the placement of mortar at the top, bottom, and sides of a unit dictated by the condition of each unit. For example mortar is needed between units to assure adhesion, mortar is not needed at an exposed wall edge where a wall turns a corner or ends.

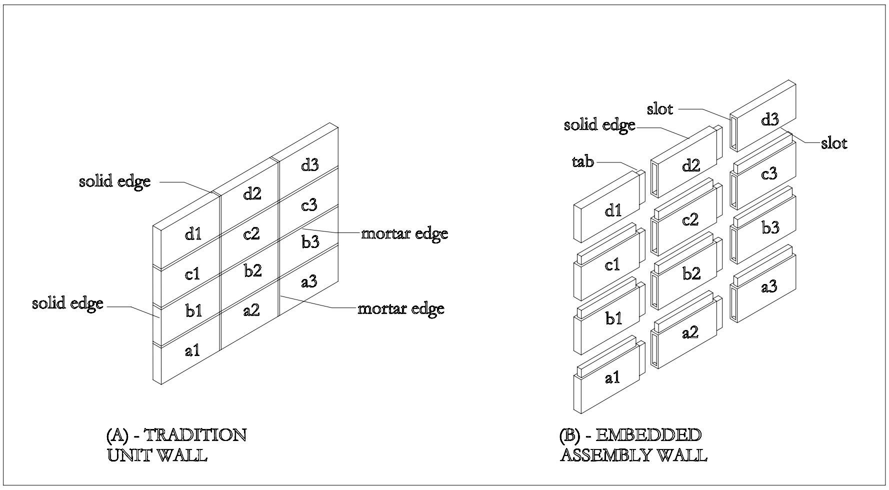

Figure 2. (A)Traditional wall with mortar joints between blocks (B) wall with embedded assemblies

Digitally fabricated units consider the assembly embedded into each unit eliminating the need for mortar between each block. The benefit is the reduction in assembly time in particular when considering walls with curved geometries. For the full scale construction of a wall using curved units, a mason will need form work or scaffolding to support physical assembly. The assembly process using a unit with embedded connections considers the tab, slot size, and curvature of the tab and slot as part of the generative process.

Assignment and ordering of assemblies are part of the generation of each block with varying slots and tabs depending on the block’s location. The program starts with a surface then subdivides the surface into rectangular blocks for 3D printing. Each with primary parameters for general block description and secondary descriptions identify block edges. Each block edge is a slot, tab, or solid edge depending on the previous edge. The starting block (a1) is built of two tabs and two edges; intermediate blocks contain a variation of slots and edges; and the final key block (d4) is built of slots and solid edges only (Figure 2(B)).

5. Walls

In this paper, three computer programs illustrate walls generated by evolutionary methods for fabrication at any scale with any 3D print device. Each model is a sample of a wall once assembled is larger than the typical envelope of a 3D printer. Starting with a surface model the programs subdivide the surface into individual units in CAD with embedded assemblies. Each unit is organized for manufacturing using 3D printing devices and assembly by hand. Many variations can be generated and printed in 3D from a starting shape.

5.1. STANDARD WALL

The first program (Figure 3) generates uniform blocks complete with a tab and slot for assembly. The program subdivides a rectangular surface (starting shape) as the seed element into evenly shaped units.

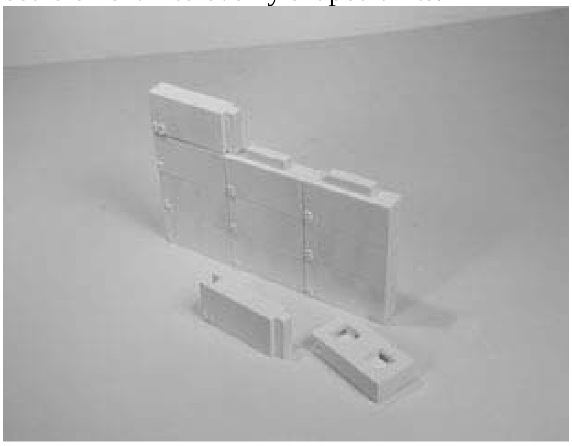

Figure 3. Results of orthogonal wall system

5.2. NON STANDARD WALL

The second program generates non-standard units from an irregular starting shape as the seed (Figure 4). This program works with a four sided non-orthogonal shape (quadrilateral) as input. Subdivision of the shape creates non-orthogonal units that are transformed to a 3D shape with tabs, slots, and a void in the back. The novelty of this approach is that the tabs and slots are angled based on the shape of the block.

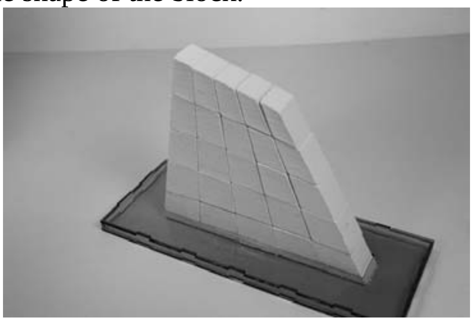

Figure 4. Results of non-orthogonal wall system

Figure 5. Results of double-curved wall system

5.3. NON-STANDARD CURVED WALLS

The third program subdivides curved wall forms into non-uniform components manufactured with 3D printing (Figure 5); a process far more complex than the previous two. The program (Figure 6) starts with two curved lines as the initial seed (a). The program evaluates and subdivides the seed and offsets the shape for unit thickness. Next, the program subdivides the solid shape into smaller units along the initial surface isocurves (b). Subdivision size is specified by user. After, slots and tabs are built into each unit (c). Results of the Non-Standard Curved Wall program are 3D units as part of a larger curved surface with interlocking assemblies built into each unit (d). This process addresses the difficulty architects face when considering designs as organic shapes and the need for methods to subdivide curved surface models for evaluation as desktop models as well as full construction. In this paper, starting with a curved surface, non-standard curved units are generated for manufacture with embedded assemblies as part of the generative process. For assembly and appearance tabs and slots incorporate surface curvature as part of unit generation.

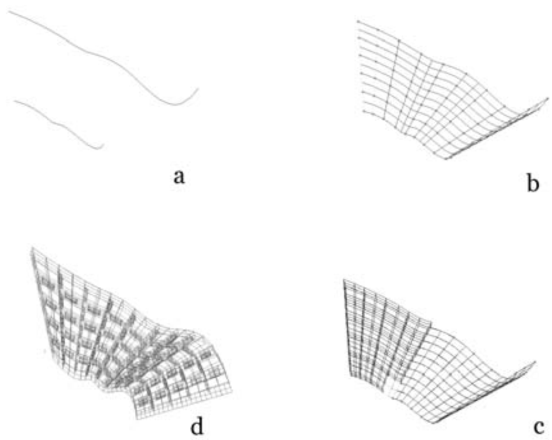

Figure 6. Non-uniform generative program starting with lines as the seed shape

6. Contributions

This paper elaborates on the conversion of computed form to tangible constructible artifacts for physical and visual design evaluation. The contribution made within this paper is the computational process for deconstructing complex form to constructible forms from straight or curved input. The evolutionary process introduces a more tangible fabrication constraint for use by architects as evaluation. The fabricated model allows the designer to evaluate the design based on evaluation mechanisms such as: structural implication, space relationship between forms, and aesthetics of the physical form itself. The design solution allows the designer to formulate questions about the wall's shape and proportions that can be altered in the original design file. The process then becomes a cyclic process which potentially drives the designer towards more provocative forms and the opportunity to evaluate designs physically.

Future studies will investigate larger walls built of higher levels of curvature and materials other than plaster. Investigations will explore means to generate the initial form as an evolutionary program and to subdivide the form as part of the evolution of the initial design shape.

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