Design Production:
Constructing freeform designs with rapid prototyping

Lawrence Sass, PhD [1], Kristina Shea PhD[2] , Michael Powell[3]

[1] *Department of Architecture, MIT*

[2] *Arup R+D, Cambridge University Engineering Department (UK)*

[3] *Department of Architecture, MIT*

Abstract: Creative fields such as architectural design require the production of many candidate ideas for visual evaluation and redesign. This paper presents a method to design and manufacture a free form model at a specific architectural scale in less than a day. This paper presents describes methods to produce, measure and reuse data for new model manufacture with rapid prototyping, generative CAD and shape grammar notation.

Keywords Shape Grammars, Rapid Prototyping, Generative Design

1.0 Introduction

A method to physically produce free form designs with rapid prototyping (RP) and CAD scripting is presented. The purpose of this study was to discover a method to manufacture many free form designs with a specific topology with RP devices. Final models will be of physical sizes greater than 10” cubed: standard bed size of a 3D printer. Typical rapid prototyped models for architectural design are smaller than 10 cubed (Ryder, et al 2002) (figure 1a). We believe that high quality models built of assemblies at physical sizes greater that 12” in height will broaden a designer’s ability to make many design decisions with each artifact. This paper presents a method to build models of this type in a timely fashion with rapid prototyping and generative CAD methods.

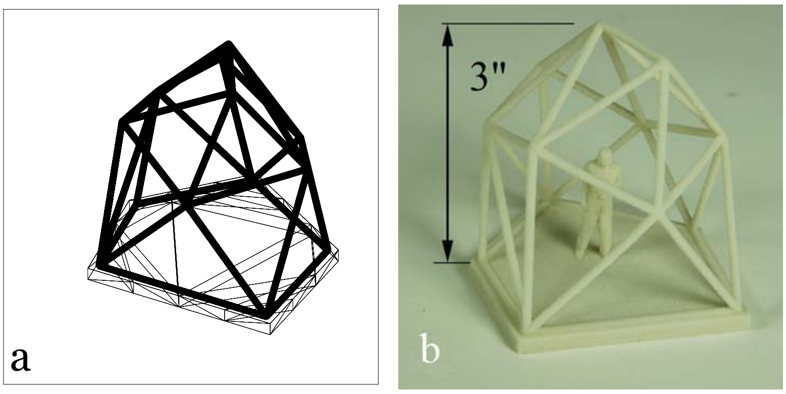

Figure 1 A 3D model generated from EifForm (a) and a 3D print of that model (b)

2.0 Background & Purpose of EifForm

EifForm is used to generate free form designs as surface models with triangular topologies. It is generative software that enables free form designs within specified sets of constraints based on shape goals. The program allows the generation many design concepts in a very short period of time. Although the program was built to optimized structural criteria design production can also match specified visual criteria such as shape or member size constraints. The limitations of EifForm is in fabrication where joint details and waterproofing possibilities are not resolved as part of the design generation. Model generation produce a cloud of points or points with cylinders linking each point (figure 1a). EifForm is a software demonstrator for generative structural design and optimization based on a method called Structural Topology and Shape Annealing (STSA). This method combines structural grammars, performance metrics, structural analysis, and stochastic optimization via simulated annealing. STSA supports exploration of discrete structural forms in relation to engineering and architectural performance for both routine and challenging scenarios. Compared to published results, the method is capable of generating multiple design alternatives for planar truss, single-layer spatial truss, e.g. domes, and full-scale transmission tower design tasks that are innovative yet efficient (Papalambros and Shea, 2002). More recent advances have included development of new 3D structural grammars for single and systems of truss-beams, e.g. stadium roofs (Shea et al., 2005). The generative nature of EifForm and geometric complexity of the designs that emerge and rapid generation of different design alternatives will greatly enhance the use of eifForm for creative design.

3.0 Research Question

EifForm can generate a free form surface model of many points in a matter of seconds to minutes. The goal here is to build a physical model in one day by translating an EifForm model from a cloud of points to information for manufacturing in CAD (see Figure 8a). The research question here asks is it possible to manufacture models that capture aspects of real world construction as assemblies of discrete parts in design. Where joints are manufactured with 3D printing of assembly parts and acrylic sheets are cut with CAM laser cutters to simulate glass. Past attempts to manufacture free form designs have resulted in computer models for structural evaluation, rendered models (Papalambros and Shea, 2002) for visual evaluation and a 1:1 structure built of wood, metal and plastic (Shea 2003) for real world spatial evaluation. Here an attempt is made to build desktop models as a representation that stands between real world 1:1 models and sketch models (figure 1b). This new design representation is similar in nature to models built after schematics commonly referred to as design development models (DDM) (Cuff 1980). The benefit of working with a DDM model is that it incorporates issue of scale, material fundamentals and functional aspects.

4.0 Method

4.1 Parametric Models

For this study DDM modeling was a bottom up approach where the details are modeled as parametric objects later attached to a data point (from EifForm). In order to manufacture a model in a day model production is divided into phases.

The first phase of the process was to design model assemblies at the junction between the glass surface and structural members. Four demonstration assembly models were built and evaluated for assembly strength and appearance. Assembly test model #4 was selected for final model production mostly because it was most compatible with CNC fabrication methods for metal (see Figure 2a & b). The selected joint was tested for strength and assembly methods. The ultimately assembly goal was a strong design with self assembling components fabricated of unique geometries with no liquid adhesives (Sass 2002).

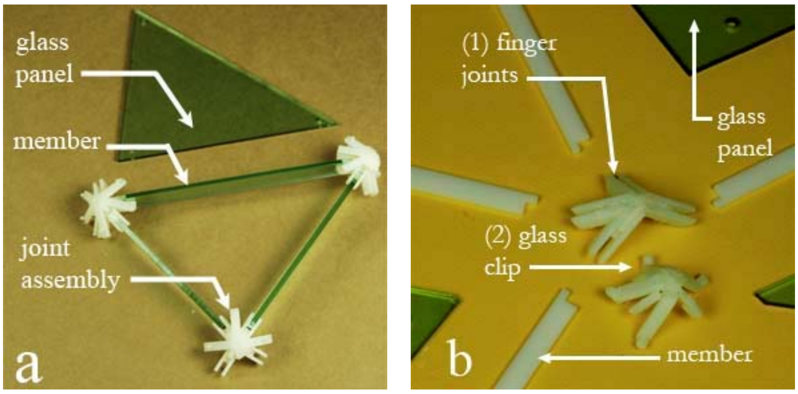

Figure 2(a) Assembly case study #4 members here are flat structural "members" versus round members in EifForm and glass panels are attach to the members with a special (b) glass clip which is attached with a post to a channel in the finger joint.

The second phase was the development of a production strategy to attach assembly joints to points data in the right sequence and the right alignment. Shape grammar schemas were used to present rules as schemas later translated to CAD scripts written in a variety of programs (see Figure 3). Points data generated in EifForm was translated to CATIA V5 from which parametric joint assemblies were generatively assigned. Second, scripts were written in Rhino v3.0 to flattened structural geometries to horizontal positions for laser cutting and FDM 3D printing.

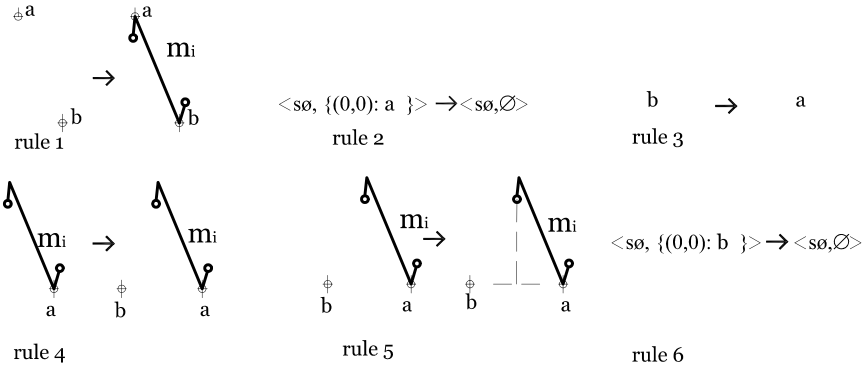

Figure 3 Rules 1 – 6 used to transform eifForm data points cloud to a representation of member assemblies

4.2 Measures

The next set of questions centered on time to produce objects with rapid prototyping. Laser cutting for any model proved to not be an issue due the fast nature of 2D cutting. The greatest issue was joint assembly manufacturing where each joint had to be 3D printed in less than one hour at a scale of 1:12 or 1" = 1'. Joint assemblies of this scale, with the proper orientation in the device printed in less than one hour per joint assembly. In order to build a model in a day a free form model had to contain fewer than 24 joints.

4.3 Procedure

Generative CAD model production was a 5 part procedure starting with a generated model or cloud of points from EifForm. The process ends with physical assembly and design evaluation. A summary of the process is described as follows:

i. **Cloud of Points:** Generate points with EifForm software (24 joints or fewer). Each point in the model was assigned a number. For early stage 3D printing of a free form design with cylinders between each point was built at a scale of 1” = 48’ (see Figure 1a & b)

ii. **Model Base**: Model generation starts at a point on a ground plane with a generated base, later the base will serve as a platform to start physical assembly of the model.

iii. **Application of Assemblies**: Joint assemblies with glass clips are applied to each data point. The application of assemblies is a three step process presented as abstract rules 1-6 (see Figure 4) First is to apply and align structural members between the first and second data points (rule 1). After rules 2-5 are applied a new joint is assigned to the second point and aligned with the third data point (rules 1). Glass clips for the first and second member are aligned perpendicular to opposing structural member (rules 4 & 5). A new member is applied and rules 4 and 5 are repeated until all points in the cloud are assigned joints and all clips align to opposing structural members (see Figure 4).

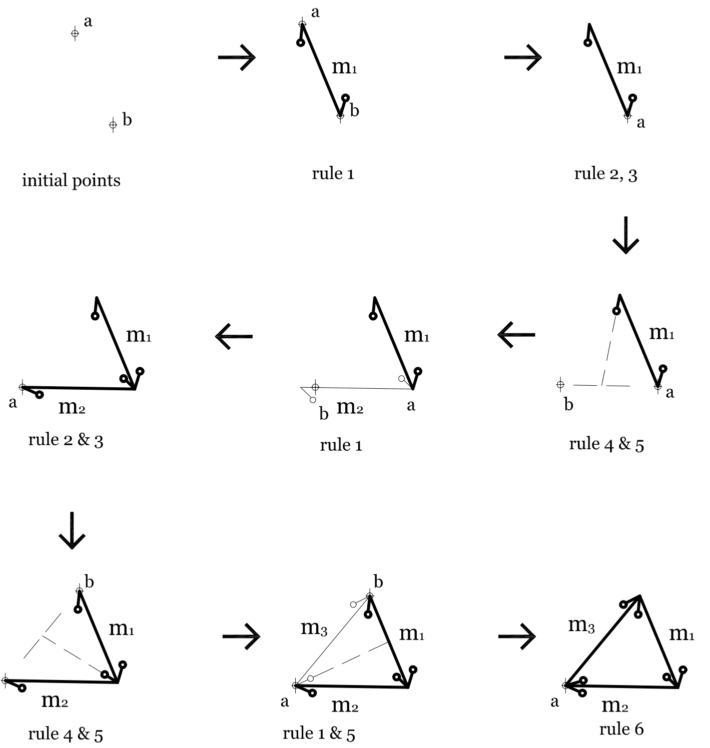

Figure 4 derivations of rules starting with an initial set of data points

iv. **Application of Glass**: Triangular glass panels are assigned to 3 joint assemblies at a time resulting as a 3D parametric model (see Figure 5a & b)

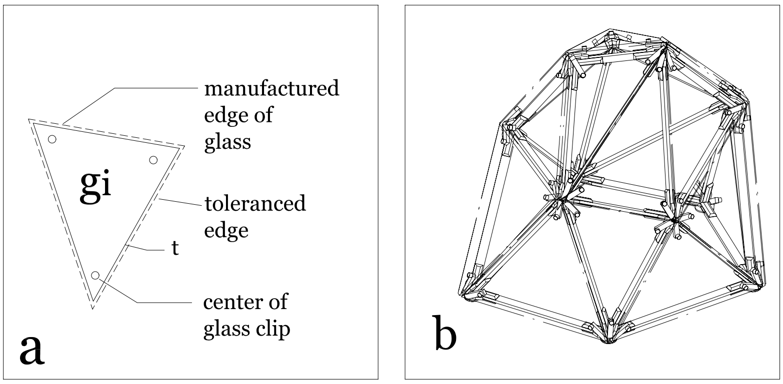

Figure 5 Parameters for glass panel (a) and a fully installed model of assemblies, structural members and glass components(b)

v. **Translation of Joints**: This is a two step process where each joint is copied from the data point to a flattened position within a 10” square boundary (3D printer boundary). After translation joints attached to structural members are separated from the glass clips (see Figure 6a & b)

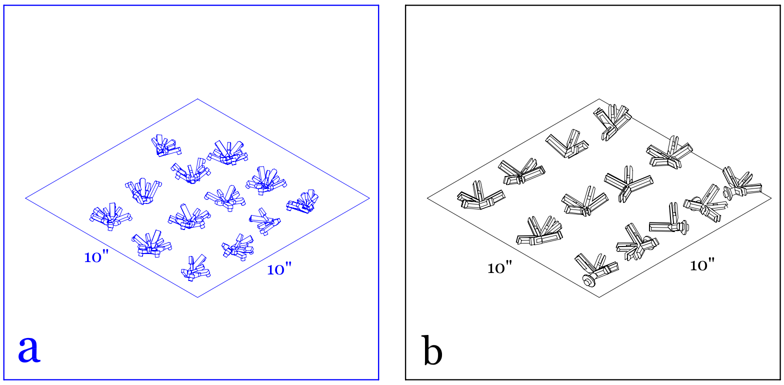

Figure 6 (a) finger joints on print bed, (b) FDM printed finger joints with no support material above the printed joint, parts are positioned flat to the print bed

vi. **Translation of Glass Shape**s: The surface for each glass profile is copied and translated to a flatten position for fabrication. After each surface translation triangles are packed within a specified boundary for laser cutting (see Figure 7a & b).

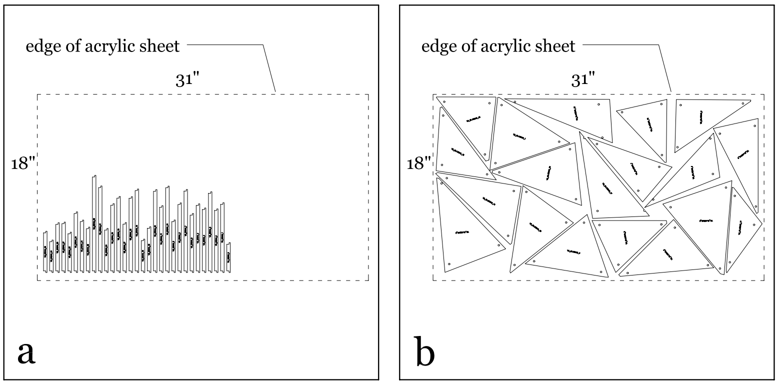

Figure 7 (a) file for laser cutting member (b) file for laser cutting glass panels

5.0 Results

The completed model was a 14” high assembly of laser cut glass (acrylic sheet) panels and 3D printed joints (see Figure 8a). Total production time from design to final assembly was approximately 18 hours for a model built of 18 joints. Architecturally the space did not have a clear purpose the design goal was to build a water proof space of glass panels aligned at non orthogonal angles. The goal of model assembly was that friction fit connections between objects meant no glue was needed to hold parts in place. Also because parts were friction fit disassembly was possible for model storage. Finally, as part of the process two models were manufactured from the same parametric file. The second model was fabricated as a parametric variation of the first (see Figure 8b). Through the work we discovered that the manufacturing process does not scale. Larger models require more part manufacturing and production time. Models of the same design style built of more than 18 joints require many days to manufacture versus hours.

Figure 8 Final models assembled of laser cut acrylic sheets, laser cut members, FDM finger joints and glass clips printed of abs plastic.

6.0 Discussion

This research supports a means to build a free form models in a day with a limited number of components. On average one hour was needed per joint assembly. Although the paper presents a method to fabricate designs as architectural models at a scale 1:12, a similar process can be used to build 1:1 representation of 3D printed metal parts and glass panels. The process supports methods to generate CAD models and fabricate as identified by past methods to combine shape grammars and forms of CAD modeling (Heisserman and Woodbury 1993) (Wang and Duarte 2002). The difference here is that models are a complex assembly of generated parts, previous research models results were single solid objects. A benefit of this way of working is that the method allows manufacturing as part of the design process, not an after thought. The limitations of this study were difficulties in tracking production in terms of people time and machine time. Students participating in this study were also learning software and machine manufacturing methods while generating schemes. An accurate way to analysis the method would have been to repeat the design and manufacture process many times over with the same geometry. The next step in the process will be to fabricate models with more 30 joints and of a variety of sizes and with multiple floors. For example this method could be used to generate an office tower.

Acknowledgements

We would like to thank Gary Atkins for modeling and digital fabrication work.

References

Cuff, D. (1992) "*Architecture: The Story of Practice*" MIT Press, Cambridge

Heisserman J R and Woodbury R (1993) "Generating languages of solid models" in *Proceedings of Second ACM/IEEE Symposium on Solid Modeling and Applications*, May 19-21 pp 103-112

Papalambros, P.Y., and Shea K. (2002), "Creating structural configurations", Chapter 4, Formal Engineering Design Synthesis, Antonsson, E. K. and Cagan J., eds., Cambridge University Press, pp. 93-125.

Ryder G, Bill I, Graham G, David H, and Bruce W "Rapid design and manufacture tools in architecture" *Automation in construction* Vol 11 (2002) pp 279–290

Sass, L, (2004) "Design for Self Assembly of Building Components using Rapid Prototyping", Architecture in the Network Society, 22nd eCAADe Conference Proceedings Copenhagen (Denmark) 15-18 September 2004

Shea, K., R. Aish and M. Gourtovaia (2005), "Towards integrated performance-driven generative design tools", Automation in Construction, Volume 14, Issue 2, eCAADe 2003, Digital Design, U. Hirschberg ed., pp 253-264.

Shea, K (2003) "Digital Canopy: high end computation/low-tech construction" Architectural Research Quarterly, Vol 6 (3)

Wang, Y. and Duartes J, (2002) "Automatic generation of fabrication of designs" Automation and Construction 11 pp. 291-302