

Soft Skin Skyscraper: Digital Design and Fabrication for Tall Building Façade

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ABSTRACT

Digital design and manufacturing have profoundly impacted and transformed building industry. By focusing on the effectiveness of CAD/CAM technologies in the design and development process, we utilized digital fabrication for designing and automating assemblies for the soft skin skyscraper. Different scale mock-ups with creative design of each compartment were fabricated by using the advent of rapid prototyping machine. Connection system for multi-scale fabrication was tested, and Ethyl Tetra Fluoro Ethylene cushion for novel façade structure was evaluated from fabrication process and discussions with professionals. This paper will identify the effectiveness of CAD/CAM in design processes and address several advantages and disadvantages of two-dimensional fabrication machines and three-dimensional machines from this design practice.

Author Keywords

ETFE, Digital Design, Fabrication, Rapid Prototyping Machinery, Skyscraper

INTRODUCTION

Rapid prototyping tools have been getting enormous attention to architecture field recently for its usefulness in structure analysis and visualization. However, many researchers and architectures tend to focus more on the designing overall shapes than considering details of the building in mock-up scale. In this project, we focused on the concept that any small-scale details and structures, if designed carefully, can be applicable to the large-scale mock-up, or real scale fabrication step. If this is the case, we should be able to get more useful structural information from the small scale mock-up using rapid prototyping machines.

Another focus was integrating Ethylene Tetra Fluoro Ethylene (ETFE) cushion system into the tall building façade. The successful architectural part of the ETFE is the panels of the Eden Project. To examine these two concepts, we chose the existing building structure “Swiss Re” as our model. Modified façade shape, different joinery system, and membrane structures were tested using Z-corp machine, Waterjet, and Laser cutter. During every fabrication step, several design problems were created until the final design was successfully integrated to the tall building system.

DESIGN IMPLEMENTATION

FIRST PHRASE:

ETFE cushion and connection compartment

1. ETFE cushion

The Ethyl Tetra Fluoro Ethylene (ETFE) cushion is the technological and ecological envelope. This material was first developed by DuPont for NASA in 1938 and was used extensively in the Eden Project designed by Nicholas Grimshaw & Partners[4]. ETFE has an elastic capacity which can be stable with a high insulation value. The transparency of this material can be equivalent to the double glass facade or better. The flexible covering system can minimize shadow and maximize the absorption amount of sun light. Besides these tremendous potentials, in terms of manufacturing and construction, ETFE cushions use less storage space and can be easily replaced and transported.

To evaluate the ETFE layer in small scale mock-up, we used several tools to fabricate cushions. Zip lock bags were used as a substitution for the real material due to its local availability. Zip lock freezer bag (4x6 inch, 1.75 mil.) were selected by the durable and quality of the material and the closest size to the designed triangular pillow model. Figure 1 gives

overall fabrication steps of ETFE cushion. The zipper part would be cut to let the air in, and then the triangular shape would be roughly drawn on the bag. Using one side of the pre-sealed Zip lock bag, the second side would be folded and heated with the Hot plate to seal the two layers together. The stainless steel ruler was used to close the gap between each layer and maintain the air inside the bag. The third side was made by the same method but left the small gap at the corner for air injection. After that, the Hot Plate was used to seal the open part again. Once these triangular shaped air pillows were done, they would be hooked to the frame system that was already prepared as shown in Figure 2.



Figure 1. ETFE cushion fabrication process. After drawing specific patterns on the layer (a), Hot plate (b) was used to bond two polymer layers (c).



Figure 2. ETFE cushions attached to the large scale mock-up system with connection part.

Problem encounter during the pillow making:

- The punctured pillow is difficult to be repaired.
- The pillows are made by heat sealing method. It is difficult to control and maintain air volume while making the pillow because it requires constant heat and specific timing. Moreover, it is very difficult to perfectly heat sealed the material manually.
- Air inside the ETFE cushion constantly leaks because of an uneven heat seal.
- The size of the triangular pillows is unique and different for each change in radius and frequency. [4]

2. Connection compartment

Designing a unit connection part was one of the most critical steps for the façade structure. To meet the criteria for the rapid prototyping, we focused on fabricating every part using only two dimensional fabrication tools; Laser cutter and Waterjet. Based on the original Swiss re façade, each connection compartment needs to connect 60 degree triangular and diamond membranes. Figure 3 shows the unit connection fabricated by laser cutter tools.

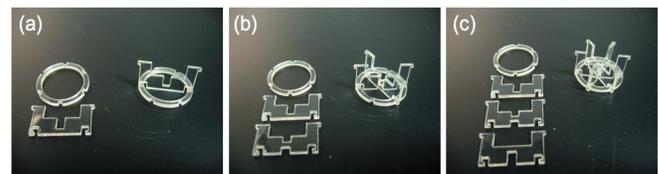


Figure. 3. Each part of the connection compartment and the assembled unit. Three rectangular parts connect to the circular ring by material flexibility. The number of the vertical parts and the notches of the ring change to adapt the different number of the membranes meeting at the joint.

Vertical rectangular parts connect the water jet cut 1/16 inch thick aluminum membranes by geometric constraints. Circular ring with notches were made of 1/16 inch thick PEG polymer. PEG was chosen rather than Polymethyl methacrylate (PMMA, Acrylic) because of high flexibility in its material property.

In designing step, we considered the possible variation for different shape of membranes, thereby different number of node for each joint. In case of even numbers of membranes N meeting at the node, the number of vertical parts will be simply dividing N by 2. If N is odd, it necessitates an additional vertical part with different shape that has only one notch for the membrane connection rather than two notches.

Therefore, the necessary number of vertical parts N_V is given by

$$N_V = \left\lceil \frac{N+1}{2} \right\rceil \quad (1)$$

Angle θ between each vertical part, necessary for indicating specific notches of the circular ring part, is simply given by

$$\theta = \frac{\pi}{N_V} \quad (2)$$

If each membrane of the façade is tilted respect to the other membrane by angle θ_m , it can be also considered by changing the angle at the end of the joint of each vertical part by θ_m . Specific data such as N and θ_m can be extracted by parametric modeling; direction of the vertical to double tangential lines. Figure 4 shows the successful connection between façade and the main building struts by the novel joinery system. Simple triangular and diamond membranes were used for the mock-up, but variable geometry of the façade is possible using same concept of the joinery system and adapting data from the parametric modeling as described above.

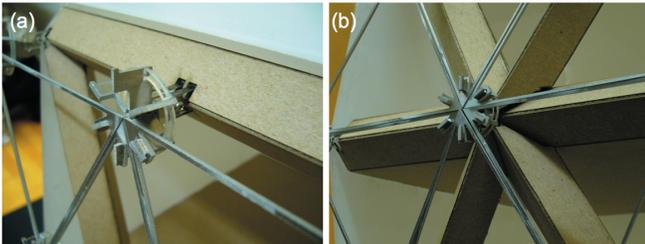


Figure 4. Detail of two story building mock-up using the novel joinery system. Each joint compartment successfully connects each membrane of the façade structure without using any adhesive or three dimensional fabricating tools.

SECOND PHRASE: Design and Development

1. Component Modeling

In connection part, the model had to be re-designed by simplifying all the connection part applicable for manufacturing each design components, because the second mock-up was smaller in scale than the first one. Figure 5 shows simplified connection part for small scale mock-up. In over all structure, Z-corp machine was used to print the based part of the model due to the structure tolerance and stability. However, for the upper level such as lobby and office area, we decided to fabricate the model using both 2D and 3D fabrication machine. The 2D cutting model was done by Laser cutter using 1/16" plexiglass as a raw material while the 3D printing model was done by Z-corp machine.

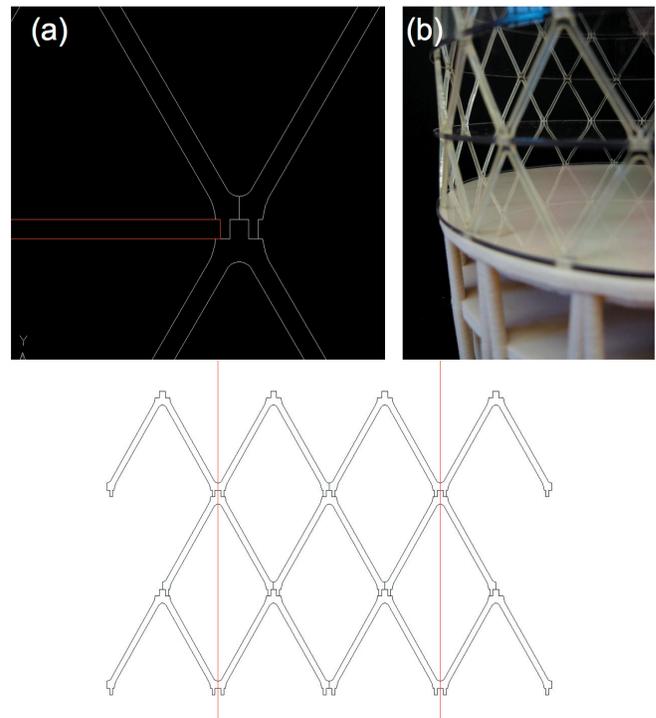


Figure 5. Schematic design of the simplified connection part for small scale building (a) and mock-up fabricated by Laser cutter (b).

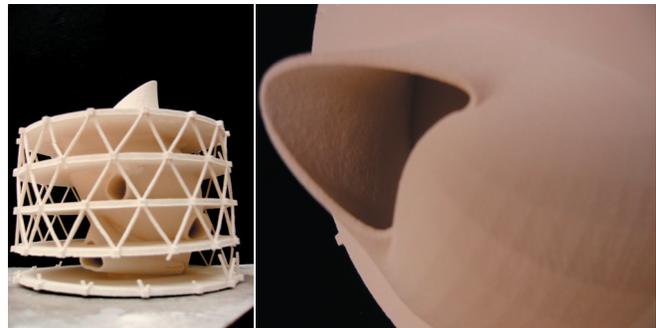


Figure 6. Overall (a) and detailed (b) images of mock-up fabricated by Z-corp Machine. Inner core model was done by clay studio (3D MAX) creating double curvature structure.

The differences between both models can be identified as follows:

- 2D cutting requires less time consuming but need to be modeled in detail. Since each component part determines tolerance between each member for the whole structure stability by interlocking and cross-referencing each other, it has to consider about relationship and the geometrical constraints of each components. Moreover, this model will require extra time to assemble the final product.

- 3D printing took 7 hours for printing and 2 hours and 30 minutes for excavating. However, it does not require extra time to assemble the component part. It can be roughly modeled but consideration about the gravity and force distribution of the design structure is necessary. 3D machinery might be more suitable for printing complex shape or double curvature surface.

2. Applicability of ETFE layer to the façade system

Regarding the information from visiting Grimshaw's office in New York, there are several problems to be considered in the use of this material; how to solve the acoustic problem, increase surface strength, and adjust and control the air pressure inside the ETFE cushion. In Eden project, ETFE cushion functions as the panel covering for the whole garden space. However, the Eden project is located in the suburb, so the acoustic and transparency does not impact much. Moreover, the air channel system was introduced to control the air volume inside the ETFE cushion.

Several ideas to solve potential problems were discussed in our group. Unlike the roof cladding ETFE pillows, the ETFE cushion for wall structure need to consider the pressure and support of the panels. The recent research done by OMA for Los Angeles County of Modern Art has shown the different configuration of ETFE pattern for investigating the tensile capabilities of the material. Figure 7 shows possible variations of ETFE layer design.

Based on this research approach, ETFE cushion can be geometrically treated to reduce external noise by using heat welded at the edges forming a cushion segment. A third interstitial layer can be added to reduce the vibration for noise reduction and strengthen the geometrical structure. As the air pressure provides the pretension and initiates curvature of the surface, different ETFE shapes can result in different surface and structure stability. Moreover, by printing to one or both sides of the pillow, it will function like a shading device and reduce the light levels on the area beneath it. The density of the pattern and application will define the exact amount of light transmitted by the printed area.

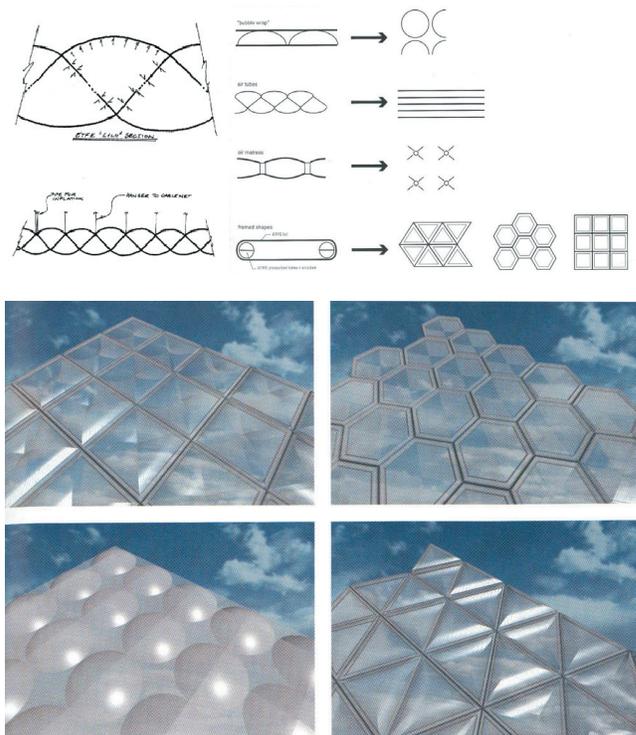


Figure 7. Different configuration and shapes of ETFE pillows taken from references [5] and the interstitial layer added to reduce acoustic problem.

Project Results

Two different scale mock-up building structures were successfully fabricated using rapid prototyping tools; Z-corp, Waterjet, and Laser cutter. Invaluable information was given from each scale mock-up.

We focused on designing the variable joinery system and ETFE layer system in $1/2" = 1'$ scale. Several restraints in two dimensional fabrication and variability of the membrane shape gave us a challenge, but the final joinery system worked properly. Regarding the ETFE layer, the demonstration of the bubble system was quite successful. However, after several discussions with the professional architects at Grimshaws office and others, we noticed that more careful examination of new system to the existing building structures is necessary and came up with several ideas.

In $1"=25'$ scale, we designed the different joinery system because of the constraints in fabrication tools. As a part of designing the novel core of the building, we tested Z-corp three dimensional printing tools also.

EVALUATION AND FUTURE DEVELOPMENT

1. Fabrication: a measurement of material

Difficulties in fabrication are considered as follows: Organization and tracking of components and individual elements, limits of material choices, and connection points. This limitation has been challenged by technological improvements, especially in 3D modeling systems. By being able to track, locate and position the proper element at the proper angle and position can change the way building practice is done [3]. Components can be easily modified again, fabricated in a controlled environment, and properly managed the entire process to run smoothly. Moreover, as there is no rapid prototyping machine for fabricating the ETFE cushions, the quality of the mock-up is very difficult to control. The development of the fabrication machine that is applicable to different kinds of material can improve and expand the design feasibility. The manufacturing and design process intersected throughout the project process to ensure the design feasibility. It also determines which design should use other technologies such as the molding technique rather than standard fabrication procedure.

2. Parametric Modeling: a representation of information

Parametric design plays a significant role in the design process. Utilizing constrained inputs in a 3D environment, it allows designers and engineers to create parametric models based on functional constraints such as material availabilities. The design rules that are influenced by manufacturing constraints add another level of efficiency to parametric design and affects design approach decisions, material selection, design and fabrication schedule, assembly, and even suggest formal and aesthetic choices[3]. A major challenge is the integration of diverse software environments through the common data model and its associated file format. By enabling an information exchange between CAD and CAM, the efficient collaborative design process of customized construction elements can be conducted in a reasonable time with consistent quality [1]. Since it provides an access for re- designing each compartment through numeric system and automatically updates the change to the whole model. In this project, the mixed use of 3D modeling software was introduced to the design and fabrication process. Rhinoceros software was used for initial form finding and analysis of the controlled element before imported to CATIA for the parameterized process.

3. Manufacturing: a consumption of time

The close integration of CAD/CAM and the advent of rapid prototyping machinery can be used to facilitate product design and development process increasing the product quality. In this project, rapid prototyping machinery was used differently for each design purpose and material usage. Rapid prototyping tool provide not only design representation, but also design analysis for fabricating model. 3D printing machine such as Z-corp is more suitable to the complex shape and form finding. 2D printing machine such as Laser cutter and Waterjet is more suitable for the detail analysis and design evaluation.

CONCLUSIONS

This workshop started with challenging designs and assembly problems. Many applications of digital design and manufacturing techniques have been utilized for fruitful produces. Digital design and fabrication technologies offer the possibility for design innovation as well as for improved design quality. CAD/CAM, Rhinoceros, and CATIA do not dictate a certain type of design approach, but allow a new design vocabulary to be explored by designers [2]. We demonstrated an alternative that these technologies not only support extremely useful visualization, but also give various kinds of quantitative evaluations such as detail analyses and simulations. Our findings have provided a principle way for the incorporation of CAD/CAM and Rapid prototyping Machinery that can support the automatic emergence of a comprehensive design process. Accuracy and precision is another advantage offered by digital technologies, and it marks a distinguish design capabilities and product qualities between traditional fabrication and digital fabrication.

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REFERENCES

1. Bechthold, M. (2003). Customization in Building Construction. Design and Technology Report Series, 2003-2, 91-96.
2. Chin, R. (2000). Product Grammar (Master dissertation, MIT, 2000). Cambridge, MA: MIT.
3. Koolhaas, R. (2003). LACMA/Los Angeles County Museum of Art Los Angeles. *Architecture and Urbanism*, 398, 99-101.
4. Gray, R. (n.d.). *Pillow Dome Project overview*. Retrieved May 9, 2006, from <http://www.rwgrayprojects.com/rbfnotes/pillow/pillow.html>
5. RIBA. (2004). *Barbarian at the Gate*. Retrieved May 9, 2006, from http://www.architecture.com/go/Architecture/Debate/Sustainability_4831.html?q=etfe