ICE STEREOTOMY

A Case Study of Free-Form Ice Shell

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Abstract. The free-form ice shell is the most challenging type in the design and construction of free-form buildings due to the regional and temporary nature of its materials. This paper presents a case study of the integration of design and fabrication of free-form ice shell. Taking the computational design and robotic fabrication of the ice shell as the main object, we discuss that combines the form-finding of the shell structure of graphic static with the tessellation technology of stereotomy, and propose a new method and workflow for the integration of discrete free-form ice shell design and construction. In the end, we built a free-form ice shell consisting of 116 discrete ice blocks. Practice has proved the feasibility of the integrated method of discrete free-form ice shell design and construction in the article.

Keywords. Ice shell; Graphic statics; Digital stereotomy; Form-finding; Robotic fabrication.

1. Introduction

1.1. RESEARCH BACKGROUND

During the Renaissance, and due to the emergence of printing, Leon Battista Alberti believed that design drawings were the final output form of the architect's work, and the building was merely a repetition of that work. This triggered a change in how the work of architects was understood and drove the formal separation of architectural design and fabrication. Since then, architects have needed to rely on two-dimensional drawings to convey three-dimensional design information (Evans et al. 1997).

The development of computer-aided design has made it possible for architects to use parametric modeling and quantitative analysis to design non-orthogonal

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free-form buildings. The separation of design and fabrication led to the geometry of buildings becoming more complex, leading to problems such as long construction periods and the need for a large amount of construction material (Garcia 2013). When French architects built the church dome, they used the masonry surface as the reference surface from which the geometry was defined. This method was to allow precise cutting of construction materials (Plaza 2006). The form was also based on projection drawings executed throughout the process of design and fabrication. The generation mechanism of computer-aided design is able to reconnect design and fabrication.

1.2. PROBLEM STATEMENT

The free-form ice shell is the most challenging type of free-form building to design and fabricate because of the regional availability and temporary nature of its materials. In Figure 1a is the stretched nylon double-curved subsurface sprayed with water to form an integral ice shell at McGill University in 1975 (Sijpkes 2009). Figure 1b shows how the inflatable mesh rope fixed on the snow and ice foundation was then covered with a two-dimensional film bag to construct a three-dimensional template. A one-centimeter layer of ice and snow covered the film, and water was sprayed to make it freeze naturally to form an integral ice shell (Kokawa 2012). The methods commonly used for designing and building ice shells are the inflatable membrane method, the upside-down method, and the fluid form method. These methods have two shortcomings: artificial form-finding methods cannot accurately control the shape of the ice shell, and ice composite materials damage the original material properties of ice and snow-transparency. Both the Igloo and the Gothic masonry vault display the natural aesthetics of stone and ice (Figure 1c).

Figure 1. (a) Water sprayed on stretched double-curved subsurface (Sijpkes 2009). (b) Application of snow and water (Kokawa 2012). (c) Igloo under construction (Masterson 2009).

Stereotomy allows the natural aesthetics to be transformed from an artistic characteristics to technical realization. The application of stereotomy is extended to the design and fabrication of ice shells. With the aid of digital-fabrication technology, ice material can be cut to compensate for the error of manual shape finding. At the same time, the ice material is prefabricated in discrete units to retain the permeability of water freezing to become a real ice shell.

1.3. PROJECT GOAL

The ultimate goal of our research is to create an integrated method of computational design and robotic fabrication for free-form buildings. The scope of application of the design method is no longer limited to conventional materials such as concrete but is extended to ice and snow materials under extreme conditions. we work through the geometric origin and development of digital stereotomy and graphic statics. Digital stereotomy and graphic statics are integrated with computer technology tools to perfect the concept of projective cast proposed by Robin Evans and provide a theoretical basis for the integrated method of computational design and digital fabrication. And we propose a computational workflow, introducing it for the design and fabrication. In computational design, to realize the unity of the external shape and internal force of the shell, graphic statics is used for form-finding, and the duality principle guides the design of discrete elements. In digital fabrication, discrete ice blocks are prefabricated using the principles of digital stereotomy.

2. Digital stereotomy and graphic statics

2.1. THE GEOMETRIC DEVELOPMENT OF STEREOTOMY AND GRAPHIC STATICS

Stereotomy is the art and science of cutting three-dimensional objects into specific shapes (Sakarovitch 2003). An arch building of stone and wood materials with high spatial complexity is constructed by defining the geometric rules, and corresponding relations between the arch system and the discrete units (Andrusko 2014). Giuseppe Fallacara first proposed “Digital stereotomy” and three invariants in 2003. This research lays a solid foundation for the design and fabrication of digital stereotomy (Fallacara 2006).

The research on graphic statics and architectural design methods in the last twenty years is the basis of the rise to the emergence of the field of architectural design. In 2009, Philippe Block of MIT used the characteristics of projection geometry to analyze the limit state of masonry structures using thrust lines (Block 2009.). Block has since established the Block Research Group laboratory at ETH Zurich to continue to study the free-form design of graphic statics (Block 2014). This research was combined with the force density method for form-finding to develop RhinoVault, which has developed into an effective tool for designing arched space structures.

2.2. INTEGRATION OF STEREOTOMY AND GRAPHIC STATICS

The concept of projective cast was originally derived from the work of Robin Evans, who believed that architects design and depict buildings in a projective way, where the diagram and space project each other. Space is perceivable by people. The projected object, the map, and the building bear the task of expressing space in two-dimension and three-dimension (Evans 2000). Although he provided an extensive formal analysis of architecture, he did not propose a clear method for design and fabrication based on geometry.

Stereotomy is a method of drawing and geometric cutting in the first of these projection relationships from imagination to picture to architecture. The method for drawing between horizontal and vertical sections is considered to be the embryo of descriptive geometry. Theories about drawing methods have gradually improved since the second half of the 18th century. Descriptive geometry makes designers pay attention to the drawn expression of abstract concepts. Jean-Victor Poncelet summed up projective geometry as based on descriptive geometry (Calvo-Lopez 2011). Jacques Hyman initiated the study of structural performance-based design based on the duality principle of projection geometry and the invariable cross ratio (Garcia-Ares 2015). Graphic statics is a typical representation of structural geometry. However, since the second half of the 18th century, descriptive geometry made designers pay more attention to architectural-perspective drawings and other drawing expressions. Ignoring the positioning and description of shapes in actual construction through a series of geometric operations led to the stagnation of stereotomy. Technology in actual construction has stagnated. The development of computer technology, stereotomy, and graphic statics, fused with computationally aided design and parametric-design tools, addresses the separation of architecture and structure and promotes the integration of design and fabrication.

3. Methodology

3.1. COMPUTATIONAL WORKFLOW

Figure 2 describes the integrated process of free-form architectural design and fabrication based on the projective cast concept. The fusion of graphic statics and stereotomy provides theoretical support for computational design and digital fabrication. Computational design includes form-finding, reference-plane geometric division, and discrete element design. Digital fabrication includes two techniques of discrete unit prefabrication.

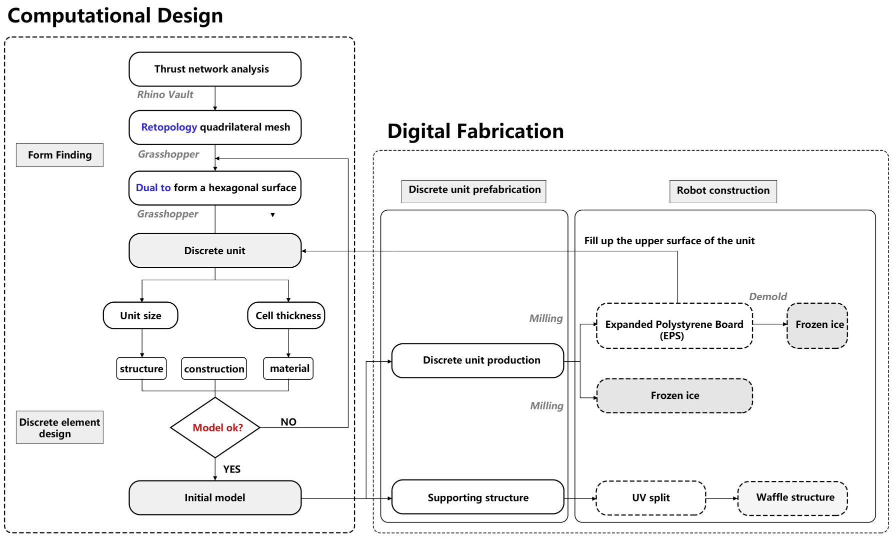

Figure 2. Computational Workflow.

3.2. COMPUTATIONAL DESIGN

3.2.1. Form finding

The ice-shell is a gathering place where the three directions of people flow are gathered. Its planar shape is shown in Figure 3a. The direction of the horizontal thrust in the RhinoVault thrust grid is derived from three-dimensional target geometry and structural features. The form diagram (Figure 3b) and the force interaction diagram (Figure 3c) are used to find the equilibrium state of the shell structure on the horizontal projection (Block et al. 2007). In the form-finding process, the stable shape produces a static balance that requires horizontal loads to ensure that all loads are transferred to the base. The vertical load is applied to make the thrust grid appear three dimensional. The generated thrust grid can be converted into a grid surface, which can then be used as the middle surface of the ice shell.

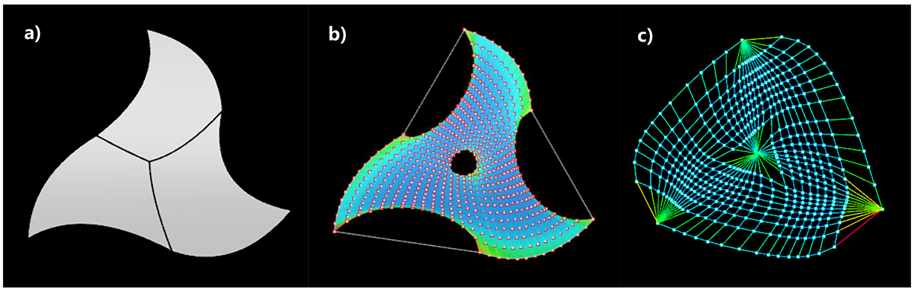

Figure 3. (a) Plane form. (b) Form diagram. (c) Force diagram.

3.2.2. Discrete element design

After the computational form-finding design stage, the digital stereotomy method is used to geometrically divide the thrust-grid reference surface just generated. This is done to construct the three-dimensional shape and precise proportions of each component of the shell before the actual construction and implementation of robotic processing. The mesh surface (Figure 4a) is retopologized into a triangular mesh surface (Figure 4b). Using the dual algorithm in projection geometry, the triangle-mesh faces evenly becomes a polygon; the number of sides is determined by the number of triangles connected to a vertex. The advantage of using triangular meshes for duality is that the generated polygons are extruded to form a compression-only structure (Figure4c). The stress flow of the triangular surface is internalized to the shape itself.

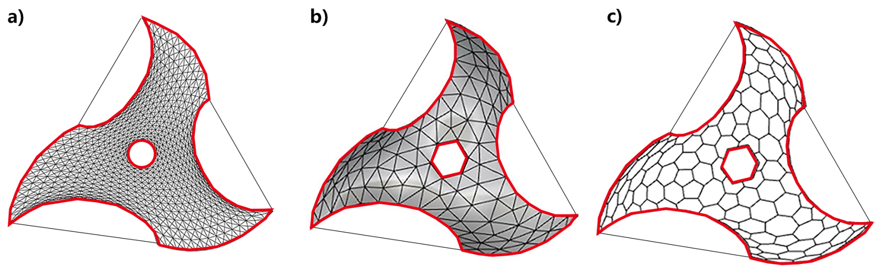

Figure 4. (a) Quadrilateral grid. (b) Triangular mesh. (c) Polygon.

The discrete element of the free-form surface is transformed from a plane figure to a thick polyhedron by using the method of translating the thrust grid along the normal vector (Oval et al. 2019). The enclosing of the body occurs through inlay processing. First, the span of the ice shell is 7.1m. The thrust line is calculated along the axial direction of the curved surface using the compressive strength of the ice material and the relationship between volume and weight. The optimal ice thickness under this scheme and scale is obtained. The thickness of the support is 6cm, and the thickness of the highest point of the unsupported arch is 4cm. Second, this measurement is fed back to the offset grid surface ice, and a three-dimensional boolean operation is carried out to enclose a composite body in the form of a discrete unit body with a corresponding thickness. This unit body realizes the internal shape of the ice crust and unity of force. Third, each discrete unit body generated is placed on the datum plane according to the uniform coordinate, and the units numbered from west to east.

3.3. DIGITAL FABRICATION

3.3.1. MCT milling of EPS template

MCT technology is mainly applied to the milling of templates for the discrete units. The position, processing speed, processing path, and other parameters of each ice-unit model are set using the SprutCAM platform (Dunn 2012). The simulation module includes automatically optimized motion-path and collision detection. By transferring the NC-code output to the KUKA robot for the fully automatic milling process, the discretized EPS unit template is realized.

Furthermore, the expansion coefficient of ice is 52.0 (Fukusako 1990). In the preliminary experiment, water was directly poured into the EPS-unit template to freeze. It was found that the ice and EPS could not be separated after freezing. We learned from the concrete demoulding method, and plastic was poured into the EPS template plastic filmand fixed all around with paper clips (Figure 5). Before pouring water, one side of the paperclip was removed to ensure that the plastic wrap remained completely attached to the template under the action of water flow.

Finally, the processed discrete unit molds are placed uniformly outside at a temperature below -20°C according to the label, and frozen under natural conditions for more than 40 hours. No water flow inside was observed, indicating that the ice was completely frozen and can be used as a unit to build.

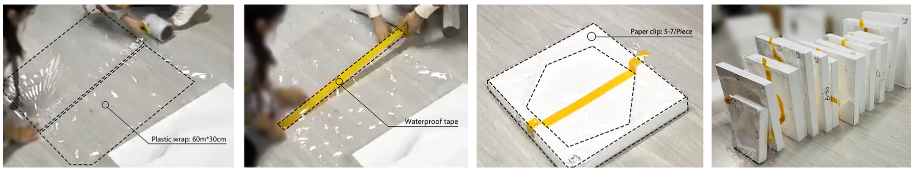

Figure 5. (a) Plastic film. (b) Waterproof tape for bonding plastic film. (c) Paper clip fixed to EPS. (d) Sorted by serial number.

3.3.2. *MCT milling ice*

The key to MCT milling of ice blocks is the fixation of the ice blocks. Preliminary attempts were made using two fixing methods: the suction cup and the physical shield fixing methods. The advantage of the suction-cup method is that there is only one contact surface between the suction and the ice block, the processing constraint is 1, and the other surfaces can be processed directly. However, in the actual milling process, it was found that the sucker was controlled by the air compressor and that the pulling force of the milling speed, stepping width, cutting depth, and bit speed on the ice block was greater than the friction force of the sucker on the ice block, which made the ice block offset 15° counterclockwise. The sucker-fixing method was not applicable to the milling ice block. The second, shielded physical fixation method, can only provide processing on one side, and the processing constraint is 5, which is suitable for milling ice blocks (Figure 6).

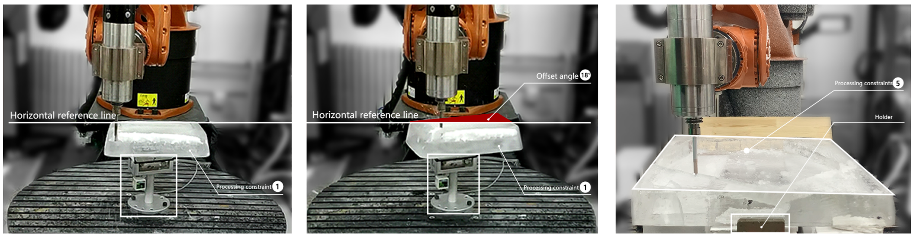

Figure 6. The suction cup fixing method and the shielding physical fixing method.

The logic of milling ice blocks is that the original ice blocks are inverted. A circle of contour lines is drawn on the original ice blocks with a drill bit, and the excess ice blocks milled out. The milling surface is the lower surface, and the upper surface is the plane. The milling logic of ice blocks is opposite to that applicable to EPS boards. The problem introduced to the process of milling by the shielded physical fixation method is that the processing constraints are too high and the method inflexible. Therefore, it is necessary to manually detach and remove the ice from the milling part in time to prevent the ice from coagulating with the standard ice. The advantage of directly milling ice is that standard ice can be used, which saves time on freezing ice. Therefore, the ice blocks with H>11 in this experiment were made using MCT-milled ice blocks.

4. Results

The on-site assembly of the ice shell takes place in sequence in three stages: the base, the support grid, and the discrete unit body. The base is positioned using the 1:1 drawing method, with the accurate CAD drawing being printed on white paper and then covered with a transparent plastic protective film. Six standard ice bases with a size of 0.75m*1.55m*0.5m were placed by forklift on the positions corresponding to the drawings. Wooden planks were used to define the boundary area, and water poured into the area to freeze the base and the ground as a whole and to prevent the base from being displaced during the construction process.

The discrete unit ice blocks were placed on the support grid in a spiral manner and directly in contact with the wooden board; there is no other material between the two. The precise machining by the robot makes the inner surface of the discrete unit a curved surface, which has the same curvature as the support grid, and achieves a precise fit if there is accurate positioning. The gap between the first layer of ice and the ice base was filled with crushed ice, slag, and snow, and water poured in after filling. After the first layer of ice blocks and the base were frozen into one body, the ice blocks were placed layer by layer and frozen with water after every two layers of ice blocks were attached. When the discrete units were prefabricated, a layer of plastic wrap was laid in the EPS template to make the inner surface of the ice block smoother. The increase in smoothness has a negligible impact on fabrication, and the use of plastic wrap makes it very convenient to demold the ice. The EPS template can also be reused.

5. Conclusion and discussion

This article combined stereotomy and graphic statics to develop a free-form shell-design method and process that was applied to the ice shells. A discrete unreinforced ice shell design was constructed using architectural geometry and digital fabrication. An experimental building process accommodated the precise positioning of the free-form ice block and the permeability of the material while expanding the application range of stereotomy and graphic statics. Using the concept of projective cast proposed by Evans and taking advantage of the evolution of the architectural-drawing method, stereotomy, and graphic statics were recombined. The projection mold from Evan's concept was transformed into a practical principle and design method, and the theory of projective cast advanced (Figure 7).

Figure 7. Real view of the ice shell during the day.

The combination of computer-aided design and parametric tools allowed for the emergence of a parametric design method for free-form buildings based on the projective cast. Traditional design methods and fabrication techniques were combined with computer-aided design and parameterization tools to take advantage of and develop traditional theories in the context of digital technology.

In cold climates, ice and snow are used as local materials, and water is easy to fetch and transport. As the temperature rises, temporary ice and snow buildings melt into water and then re-enter the natural water cycle. Materials are easy to obtain and sustainable. In digital fabrication, the robot milling template and ice respond differently. One approach to this is to use templates that can be recycled. The other approach is to cut standard ice directly, which is suitable for large-scale ice fabrication. These two different digital fabrication methods and the previous computational design form a set of precise fabrication and allow the recycling of the model of the ice-shell structure. This model provides new ideas for people living in severely cold areas to quickly build ice and snow buildings with short-term wind and cold resistance and to be able to easily model and view those structures. The model also provides more diversified directions for development in the construction of ice and snow buildings in the more severe climates of the Arctic, and Antarctic.

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