Analysis of surface design and panel options for freeform building

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ABSTRACT: Roof and exterior wall are designed and constructed in a manner that prevents the accumulation of water within the wall and roof assembly in the formal building. However, in a freeform building there is no clear distinction between exterior wall and roof. In other words, the exterior walls and roof systems of the freeform building are integrated as a surface, unlike the formal building envelope. Therefore, freeform architecture needs a systemized envelope design method to perform functions of exterior wall and roof. However, in many cases, construction methods for roof and exterior wall are applied to freeform buildings without necessary alterations, which lead to incomplete design, leakage, cracks and other problems. Freeform architecture is thus designed and constructed differently from formal buildings. In order to more easily and inexpensively actualize freeform architecture, Building Information Modeling (hereinafter referred to as BIM) has recently been applied in the construction industry. The studies and case analysis are not sufficient to identify the implications and contributions of freeform buildings in future similar projects. Therefore, this research will study design and construction methods for freeform surfaces. This study attempts to analyze the pros and cons of each method for the concrete surface frame, and then presents the panel options for envelope system of the freeform architecture.

Key words: building information modeling (BIM), freeform architecture, envelope system, panel system

1. Introduction

The objective of this study is to develop a BIM-based virtual envelope construction model for freeform architecture that meets standards for design and workability. Freeform buildings are different from more typically designed buildings in that they integrate exterior walls and roofs into an envelope system.

Typically, exterior walls focus on aesthetic aspect, and the roof system is designed with drainage and water-proof functions. By comparison, a freeform building blends distinction between exterior wall and roof, and their respective functions are integrated into a building envelope. For this reason, freeform architecture requires a systemized envelope construction. Otherwise, applying traditional construction method to freeform architecture might cause problems such as leakage or crack. In case typical roof construction method is applied to an envelope system of freeform building without BIM analysis and consideration for grades, leakage might occur. The quality of design would be compromised as well.

This study aims to develop a BIM-based virtual envelope construction model for freeform architecture with sufficient workability. It is expected to be applied to design and construction of freeform architecture that grows more diverse and larger in scale. Detailed research objectives are as below:

1) Optimal BIM-based design for freeform building
 - Analysis of BIM design method
 - Optimal design for curved envelope system

2) Virtual construction model for envelope system of freeform architecture
 - Construction model for 1-way/2-way curvature
 - Construction model by structure types
 - Construction model by finish materials

The researchers have working experiences in academic or industrial settings or had conducted joint research, which rendered extensive human network and resources to this study. Researchers visited various sites to survey and analyze cases of freeform architecture, and interviewed experts in the field. Information gathering and research support have been efficiently undertaken on BIM-based design and construction.

2. Research Trend on BIM-based Design for Freeform Architecture

To date not many cases are found in Korea that used BIM-based freeform design except for the Nodulsum Art Center on the Han River, Dongdaemun Design Plaza and parts of the new City Hall building. In domestic construction industry, BIM technology is mostly used for 3D modeling for parts that are hard to render in 2D drawings to reduce design error and to enhance workers' understanding and examination of the work. The technology is also used to examine whether there are missing materials or whether there are conflicts among building materials.

Application of BIM technology has several difficulties as the construction company is often dissatisfied with design outcome of 3D modeling studio, and the studio staff is overloaded with work.[1] Several BIM-related studies on freeform architecture are underway to improve and address these problems.

Table 1. Studies on BIM for Freeform Architecture

Researcher	Subjects
Choi Soon-yong, Kim Jin-gyun[2]	Analyzes concept of digital master model and system information model; data should be converted to intellectual data system to apply BIM throughout a building lifecycle.
Park Jeong-wook *et al.*[3]	Comparative analysis of BIM examples; identifies related issues and proposes possible solutions
Kim Seon-hyo *et al.*[4]	BIM is currently applied to parts of a building or certain stages in design, and therefore lacks consistency in data; for freeform buildings, data conversion or coordination is difficult, which leads to conflicts over contract and claims.
Park Jeong-dae[5]	Demonstrates that freeform design can be realized by enhancing digital media
Park Jeong-guen, Lee Myoung-sik[6]	Provides design characteristics of freeform architecture and possibility of BIM application
Moon Sang-deok *et al.*[7]	Experimental use of laser scanning to freeform architecture for better construction and maintenance
Ahn Ji-yeon *et al.*[8]	Applies visualization technique based on augmented reality to construction and maintenance of freeform architecture
Park Jeong-dae[9]	Demonstrates generation of ruled surface and need for bi-directional parametric and associate modeling to design freeform architecture; suggests importance of reverse engineering correlation between generation factors and outcomes in design

In many cases, freeform architecture in Korea emphasizes visual aspects of design, while other elements remain weak such as drawing in full consideration of material's prototyping and panelization, design and manufacturing of construction materials, and construction management to assess precision of work.[10] The most challenging part is to design and construct the complex building envelope. Non-standard building materials and elements often cause problems in terms of air and water leakage, insulation, draft, thermal properties, and issues related with structural safety, efficient layout of materials and structures.[11] Thus, it is essential to develop BIM-based envelope system for freeform architecture that meets workability standards.

3. Digital Technology for Building Envelope System of Freeform Architecture

3.1 Curved Envelope System of Freeform Building

In freeform architecture, the design process for envelope system involves design concept, site selection, coordination, manufacturing of envelope structure and components, and construction. To provide measurable data for the freeform envelope system, its design should be visualized and provided in numerical data to build structure, facilities and architecture. For the research purpose, BIM is understood as information providing to manufacture and install an envelope system to develop a virtual model for freeform architecture, which enables to design building envelope in consideration of material properties.

3.2 CAD/CAM Technology

CAD and CAM revolutionized architectural design, manufacturing and construction by providing precise numerical analysis and control of mechanical work. Interactive design system makes it possible to produce a highly accurate digital model, surface and 3D modeling. With data on dimensional properties, it assists optimal design and manufacturing of particular building elements, such as curved exterior panels. Based on data on dimensional properties, design programs can be integrated into a single system or an independent package program. Products and molds can be manufactured with CNC milling machine, drill, saw, laser cutter, water jet, or welder controlled by numerical data.

Moreover, physical models can be scanned digitally and converted into a digital model through reverse engineering. To make a prototype, layers of slice data can be accumulated to a 3D model by using 3D printing technique, freeform design and rapid prototyping.

3.3 CATIA-based Envelope System Design for Freeform Building

Frank O. Gehry pioneered the field of freeform architecture since 1991. Yale University discovered the use of CATIA in 1986 that was being used at Ford car company, similar to how Jim Glymph, architect partner of Frank O. Gehry, came to discover the use of the technique in the early 1990s. Glymph began to use CATIA that was traditionally used in automobile and aviation manufacturing. Based on complete numerical control, CATIA defines irregular 3D curves of a building exterior in multiple equations and mathematical functions, and provides coordination of points on a building envelope.

Gehry repeatedly conducted precision measurement of 3D building model to establish a digital CATIA model, and produced spatial coordination of exterior points and joining parts of steel structures. Based on these data, the architecture firm SOM produced structural design, and an Italian firm Permasteelisa manufactured building parts.

3.4 Use of CNC Milling Equipment in Freeform Architecture

There are several methods to design an envelope system for freeform buildings, and CNC milling equipment is widely used to produce various forms of building parts and materials. Pre-digital technique largely involves digital molding and mold manufacturing. Building materials are cut and shaped with CNC equipment, and digital molds are made. In mid-1990s, Gehry started to use CNC milling to cut curved stone panels to cover the exterior of the Walt Disney Concert Hall. CNC milling was also used for the Nat West Media Center by Future Systems, and for Bernhard Franken's bubbles and dynaform.

3.5 Digital Molding for Envelope System of Freeform Building

Digital mold was first used in Gehry's DG Bank's Planum project. The exterior of the Planum was supported by pre-treated stainless panels that were shaped through extension and compression. It resulted in a space encased in panels with large curvature. While small curves can be shaped through simple bending, the Planum's Horse Head had to be made by manufacturing complex metal panels that went through stretching and pressing under particular temperature and pressure, in consideration of the metal properties. Sometimes reverse engineering is used for design of freeform architecture. The 3D model is converted into digital data through digitizing by 3D scanner (FARO, CAT) and rapid prototyping by 3D printer (STL). The same technique can be used in restoration of historical buildings.

3.6 Rapid Prototyping for Envelope System of Freeform Building

The technique began to be used since the 1970s, based on preliminary geometric modeling system and CAD. It was developed to produce a physical model from the system-based geometrical data on architecture. Rapid prototyping uses equipment such as LOM, FDM, SLA and 3D printer. The Guggenheim Museum was the first project that adopted reverse engineering into architecture, using FARO and CAT scanner. The former is used to scan vertebrae in a medical surgery, and the latter to take and edit detailed section images of a brain to produce 3D digital model.

Reverse engineering was also used for the Turbulence House designed by Steven Holl. The house model was cast and then the curved exterior panels were divided into small parts to be pre-fabricated using a CAD/CAM program Pro-Engineer. The panels were put together on the project site.

At this point, architecture is faced with new challenges for geometric design, to produce panels for building envelope and supporting beams. The key issue is to produce panels for free-form curves of a building envelope at a reasonable cost, which requires advancement of building materials and technology. In the meantime, architecture geometry, for example, a variety of disparate geometry, is likely to develop into new research topics in the field of geometric computing.

4. Analysis and Construction of Envelope System for Freeform Architecture

4.1 . Structural Systems of Freeform Architecture

Typically, an envelope of freeform building and the supporting structures are joined to establish the envelope system. This requires secondary structures to connect primary structure and the curved exterior. Pak (2005) [12] classified such structural systems into six types: steel frame truss, curved shell, curved truss, portal frame, rib and monocoque.

Table 2. Structural Systems of Freeform Architecture

System	Type	Load Distri-bution	Joining Method	Notes
Steel frame truss	Vector	2 way	Use of secondary structures	-Typical truss is used as secondary structure to support complex curves -Use of curved materials to simplify joining with secondary structure
Rib	Plane	2 way	Partial use of secondary structures	-New type of structure - Structure is defined along the outer shape of the curves; most advanced type of technology
Curved truss/ wall	Bending	1 way	Primary structure directly connected to building envelope	-Applied truss system that uses straight materials along the curve axis -Applicable to curves that has ruled surface
Portal Frame	Bending	1 way	Primary structure directly connected to building envelope	-Curve shapes can be completely shaped in portal frame -Structural frames support the envelope along the long axis
Curved shell	Plane	2 way	Primary structure directly connected to building envelop	-Advanced form of continuous structure and applicable to structural analysis of orthopaedic curves

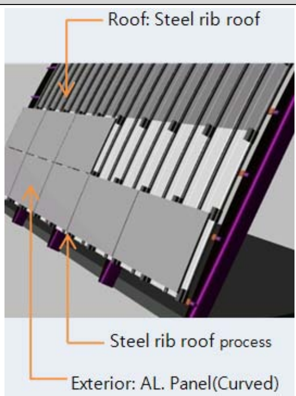
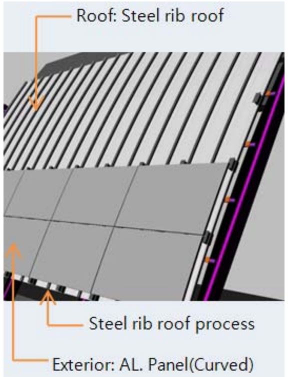
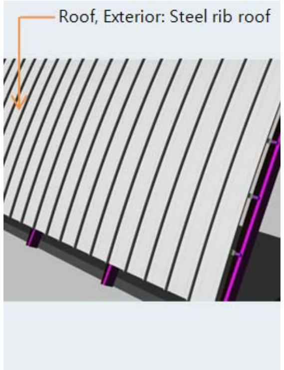
			e	
Monocoque	Vessel structure	2 way	Primary structure directly connected to building envelope	-Envelope and primary structure both play dynamic role -The application is limited to a certain scale; large curve requires manual construction

4.2 Panel Design for Envelope System of Freeform Architecture

Some of the recently built freeform buildings have structural problems due to an incomplete system.[13] It is hard to implement BIM because special contractors are operating each construction by subcontracting in domestic system. To build freeform buildings, BIM should be applied to both design and construction processes, but in practice, 3D models are hastily made in a construction stage.

The BIM-based design proposed in this study is expected to meet workability standards in constructing envelope system for freeform architecture. It is important to develop various types of envelops systems to address current issues and promote design of freeform buildings. Panels used in envelope system of freeform architecture can be largely grouped into three options in terms of materials, cost and design.

Table 3. Panel Options for Envelop System of Freeform Architecture

	Option 1	Option 2	Option 3
Perspective			
Cost	High	Medium	Low
System	Roof: AL and rib Exterior: AL. curved panels, steel rib roof	Roof: steel rib roof Exterior: AL. curved panels, steel rib roof	Roof and exterior: steel rib roof
Characteristics	Excellent anti-corrosion and durability; costly	Optimal system to build curved exterior at reasonable cost	Minimum cost; relatively low design quality and monotonous building elevation

5. Conclusion

In designing envelope system for freeform architecture, full attention should be given to drainage, water-proof quality, stretching and shrinking of materials, maintenance and repair. For example, trenches should be built at the edge of roof and exterior walls to drain rain, which also marks a border to produce separate shop drawings for the roof and exterior walls. For exterior walls, aluminum panel open joint and steel rib roof system should be effectively used to build the designed curves at reasonable cost. In addition to aesthetics, freeform building projects should consider construction cost, feasibility, water-proof quality, and easy maintenance and repair throughout the life of a building.

In particular, rain drainage and water-proof function is highly important and should be thoroughly prepared in a design stage. More systematic method and technique should be developed to design an envelope system for freeform architecture to reduce construction period, save cost and facilitates maintenance.

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