TOWARDS A FRAMEWORK FOR CAD/CAM DESIGN AND CONSTRUCTION PROCESS IN FREEFORM ARCHITECTURE: A CASE STUDY

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Abstract. This research aims to analyze the design and construction process of the built freeform architectural projects and understand deeply the applications of the CAD/CAM media tools, and come up with a preliminary framework of an executable general CAD/CAM design and construction process in freeform architectural design.

1. Introduction

Since the start of the 21st century computer-aided design (CAD) and computer-aided manufacturing (CAM) have been developing as separate fields following the advancement of computer technology. CAD drawing software such as autocad, 3Dmax, formz, maya, and so on, as well as CAM technology such as computer numerical control (CNC), rapid prototyping (RP), laser cutter, 3D scanner, were mainly used in other fields than architecture during the early days. These included industrial design, shipbuilding, aerospace and the movie industries (Groover and Zimmers, 1984; Callicott, 2001). However, 1992 marked the start of a revolutionary trend in computer-aided technology as CAD/CAM started making waves in the architecture and construction fields as well. At the time, Frank Gehry applied CAD/CAM digital techniques in the design and construction process of his Barcelona Fish sculpture, in effect digitising the whole design process (Mitchell, 1998; Linsey, 2001). With the aid of CAD/CAM, there has been greater freedom and liberty in the design form as the design process has been progressively digitised (Rahim, 2000; Kolarevic, 2003).

In recent years, increasing numbers of researchers and architects have started probing the ways CAD/CAM technologies are supplementing the design process, culminating in the study of digital fabrication (Kloft, 2001; Wang and Duarte, 2002; Breen et al, 2003; Chiu and Chiu 2003; Kolarevic,
Currently, a lot of attention is being focused on CAD/CAM fabrication within the field of architecture. This is because computer technology has not only influenced and changed the design process, but has also impacted the approach to and process of building construction (Ryder et al., 2002; Simondetti, 2002).

2. Problem and Objective

Digital design tools have become familiar to those in the architectural design field and are now an integral part of the design media, especially employed in design and construction processes (Luca and Nardin, 2002; XX, 2004; Seely, 2004; Schodek et al., 2005). The application and utilisation of CAD/CAM media are gradually becoming essential in architectural education and practice. At its current stage of development, digital fabrication using CAD/CAM media has been applied in many freeform design cases in the field of professional architecture (Leach, 2001; Ryder et al., 2002; Ceccato, 2004). Moreover, professional standardised CAD/CAM systems have also been developed, for instance by Gehry Technologies (GT), SmartGeometry, and so on, in order to realise complex freeform architectural designs.

CAD/CAM technologies have become the crucial design media in freeform architectural design in the digital era. However, most designers are not familiar with this new media. Although the GT professional standardised system is available, its operation is high-tech and its use is restricted to high budget projects, and it is therefore difficult to implement in low-tech, low budget environments in Asia. Therefore, this research aims to identify an executable digital design and construction process that lowers the GT high-tech threshold and allows CAD/CAM media to fit our existing design environment. The objective of this research is to integrate an executable general CAD/CAM design and construction process for freeform architecture.

3. Methodology and steps

A case study approach was utilised as the research method of this study to analyse and integrate a preliminary design and construction process using CAD/CAM media. There are three steps, as described below:

Step 1. Previous study: Based on previous study of the design process framework proposed by Lee (2005), in which the process is analyzed for domestic freeform design cases and with more focus on the fabrication process, however the present study attempts to re-integrate the whole process, from the early architectural program to the conceptual design stage,
design development stage, detailed design stage, and finally the digital fabrication stage.

**Step 2. Case Study:** Relevant case studies are integrated throughout, taken from the freeform architectural work of the internationally famous architects Frank Gehry and Bernard Franken. Based on the books, portfolios and publishes data, four significant freeform architectural design works on different scales (building design and interior design) have been chosen for analyzed:

- a) Guggenheim Museum Bilbao, 1991–7, Frank Gehry
- b) Conde Nast Cafeteria, 1996–2000, Frank Gehry
- c) BMW, Wave Pavilion, 2000, Bernard Franken
- d) BMW Dynaform Pavilion, 2001, Bernard Franken

**Step 3. Discussion:** A preliminary design and construction process using CAD/CAM media is re-integrated based on the case analyses of Step 2.

4. Analysis

4.1. PREVIOUS STUDY

From several small interior design projects, including Reception Lobby of Bcom Electronics Inc, New Art Center for Ming Chuan University, Digital Pavilion for Far East Architecture Award in Taipei Fine Arts Museum, and Reception Lobby of Jhubei Office, Lee (2005) first inferred, tested and then verified a ‘small freeform design and construction process’. On the basis of this he then carried out a mid-sized interior design project, Lobby in Headquarter Office of GreatLink Corporation, in order to test, verify and revise the steps in the process. Owing to the fact that he participated in the design and construction process of these projects, he could proceed with analyzes of the complete and abundant data and he eventually produced a ‘preliminary freeform design and construction process’ (Figure 1).

However, this process focuses more on the operational steps in the fabrication stage, and only projects in Taiwan and China are integrated. The purpose of this study is to propose a complete process from design to construction (architectural program, conceptual design stage, design development stage, detailed design stage, and digital fabrication stage) in which CAD/CAM media are applied. Therefore, in this study, several international projects in which the CAD/CAM technology has been utilized to assist in the freeform design and construction process will be analyzed.
4.2. CASE STUDY

4.2.1. Case 1: Guggenheim Museum in Bilbao

From the analysis, we can learn that Gehry still used the sketches and handcrafted models (Figure 2a, 2b, 2c) as main design media in architectural program and conceptual design, a stage of non-digital design process. Not until the stage of design development did he adopt lots of applied digital media. He viewed the design by examining repeatedly virtual models created with CATIA, and physical models of various scales manufactured with CAM equipment (Figure 2d, 2f). Once the design is complete, CATIA master model (Figure 3e) will be delivered to the contractors who will review and develop the detailed design and shop drawings (Figure 2g) (detailed design stage). Then, in the stage of digital fabrication, the complicated 3D model is divided into two units: frame and skin. Proceed with drawing analyses (structure and curve analysis) and rationalize them into a standard unit process (Figure 2h, 2i). Meanwhile, 1:1 mockup is manufactured to test structure, wind and so forth. After the analyses and tests, start the mass unit production, and assemble it on the site in the end (Figure 2j). During the whole process, the data of CATIA model are exclusively utilized so that architects and contractors can keep good communication. Also, the digital construction process is so precise that the construction time and budget can be controlled. Figure 3 shows the design and construction process.
4.2.2. Case 2: Condé Nast Cafeteria

From the analysis, we found that the architectural program stage and conceptual design stage in this design case are completely categorized as traditional design, which simply deals with lots of sketches and handcrafted models (Figure 4a, 4b), instead of digital process. Not until the design form is finalized is CAD/CAM media greatly utilized to aid CAM physical model making in the stage of design development (Figure 4c, 4d, 4e). In the stage of detailed design, besides the detailed drawings (Figure 4f) of the frame and skin units, mock-up of the detailed grappling have to be directly output from the CAM equipment (Figure 4g). In the stage of digital fabrication process in which more precise CAD models are required in order to fabricate the accurate curved glass panel units. The tested 1:1 glass panel mock-ups are manufactured by the pin-mold, and then to be assembled on the site (Figure 4h, 4i). From the above analysis of each process, Gehry’s design process in this interior design project can be induced (Figure 5).

Figure 3. Design and construction process of Guggenheim Museum in Bilbao

Figure 4. Process images of Condé Nast Cafeteria
4.2.3. Case 3: “Wave” BMW Pavilion

From the analysis, it can be seen that Franken continues to adopt CAD/CAM media as assistance right from the stage of conceptual design to construction process. He called this design process “digital continuity”. In the stage of architectural program, he intensively communicates design strategies with clients (Figure 6a). Then, in the stage of conceptual design, utilize the digital operation process run with parametric design to produce design forms (Figure 6b). Finally, decide “master form” (Figure 6c) in the stage of design development. The forms are not only proceeded with spatial simulation, but physical models are also output with CAM equipments to examine the design and test fabrication procedures and methods (Figure 6d). Franken also produce 1:1 mockups of each detailed part for the tests in the stage of detailed design (Figure 6e). After analyze the form, Franken uses frame units to proceed with digital fabrication, and “pre-fabricate” them in the factory to understand the construction procedures (Figure 6, 6g). Then the prefabricated units are transported to the site and rapidly assembled together (Figure 6h). From the whole process, “master forms” can also simultaneously offer the data about 3D and 2D drawings which are needed during the construction process. We can induce Franken’s design and construction process in this project in Figure 7.
4.2.4. Case 4: “Dynaform” BMW Pavilion

In the stage of architectural program, Franken communicates with clients about design strategies and set up ideas and situations. Then, he operates the parametric dynamic design process to generate the design forms (Figure 8a) during conceptual design stage. From the evolution of dynamic forms, decide “master form” in the end (Figure 8b). Franken also decides to separate the frame and skin from the form in the stage of design development and proceeds with spatial simulation. Also, he uses the data of 3D model to output directly the CAM physical models to examine the design (Figure 8c). In the stage of detailed design, he used CAD/CAM media when producing 1:1 mockups for the tests (Figure 8d). Moreover, the structure devices in this project are all very unique. The contractors must draw large quantities of 2D/3D shop drawings (Figure 8e). In the final stage of digital fabrication, the design form is digitally produced with frame and skin units after the structure and surface analysis process (Figure 8f, 8g). Then, units mockups are in mass production and pre-fabrication is conducted to test the construction procedure, solving the construction problems and to control the construction time as well. After all the problems are solved, they are transported to the site for assembly (Figure 8i). Figure 9 illustrates the design and construction process of “Dynaform” project.
4.3. DISCUSSION

Based on the processes (Figure 1) for domestic projects integrated by Lee (2005) and the four processes (Figures 3, 5, 7, 9) extracted from four international freeform design projects by Gehry and Franken, the steps of these processes from the stages of design to construction, including architectural program, conceptual design, design development, detailed design, and digital fabrication, will be compared and analyzed.

4.3.1. Architectural Program

**Digital Mass**

From Figures 3 and 5, we can see that at this stage Gehry examines architectural configuration and space using sketches and handcrafted models. In fact, in addition to examining the space, Gehry already starts controlling the design budget from the area of the mass when producing the model of the mass. Indeed, if handcrafted models are replaced with models of the ‘digital mass’, more data regarding the design mass and digital information will be controlled, which helps with control of the budget. Digital data of the site need to be obtained and build the ‘digital site model’ to develop the design ‘digital mass’

4.3.2. Conceptual Design

**Form generation --> Final form**

For this stage, Figures 3 and 5 show that Gehry adopts traditional ways to manufacture large numbers of physical conceptual models and draws sketches to develop the design ideas. Franken, however, directly employs Maya parametric modeling software to generate the design form by the parameters (Figures 7, 9). From the early design shown in the domestic design projects (Figure 1), the form can be operated by editing the 3D curved-surface models, just like sculpture. These three ways represent operational methods of ‘Form Finding’ employed by many designers. However, to integrate a digital design process, parametric design modeling
and 3D curve model editing, are adopted in this study, firstly to use as the form development in one of the steps of ‘form generation’, and finally when the designers decide upon the ‘final form’

4.3.3. Design Development

3D Master Model

From the analysis of international projects, we learn that Gehry and Franken have already started to communicate with structural engineers or contractors in this process. Structural engineers will transfer the digital models made by architects into the analysis software to proceed with the Gaussian analysis regarding the surface, and the FEA structure analysis regarding the frame and use them to rationalise the frame and skin design. However, Figure 1 shows no such analysis step in domestic projects due to the small scale of the design project. Yet, these analyse, which are particularly more important to large architectural projects, can actually be used to rationalise the development of curved surfaces. Using them, standardized division can be performed in order to lower the budget. The ‘CATIA model’ in Figures 4 and 6, and the ‘master model’ in Figures 8 and 10, which are the digital models fabricated after the analysis, contain all the graphic information for the design and construction. Hence, in this study this model is called the ‘3D master model’. It can be developed from the initial ‘final form’, after rationalize and ‘smooth the surface’ form, designers start to divide the form into ‘frame and skin’, and then ‘analyze’ them.

CAM Physical Models

Gehry and Franken both produced many ‘CAM Physical Models’ in order to repeatedly examine the design with 3D digital models. From the processes of the projects in Figures 3 and 9, we can see that Gehry and Franken applied RP technology which can rapidly shape 3D models to fabricate these mass models. Also, in the process of interior design projects shown in Figures 5 and 7, the frame model was fabricated with laser cutter and CNC plasma. From these applications of model fabrications with different CAM technologies, we can deduce that:

a. ‘mass model’ -- information regarding 3D models is directly taken from RP output; such a fabrication process is fast.

b. ‘frame model’ – the 3D model is decomposed into 2D drawings, and then CNC or laser cutting can proceed. After cutting, the units are assembled manually. This fabrication process helps test the way of assembly during the real construction.

These two kinds of ‘CAM physical model’ can allow designers to fabricate 3D digital models precisely into physical models and to repeatedly examine the design
4.3.4. Detailed design

Mock-up

From the process of the interior design project in Figures 5 and 7, we can see that Gehry and Franken had to produce many detailed designs due to the high precision demanded by the small scales of interior design projects. They both used CNC milling to fabricate several detailed joints of 1:1 mock-ups to test usability and precision. However, if there were budget concern, then such models could be RP output without being made through the factory.

2D Units

From the design processes, we learn that Gehry and Franken have used professional detailed configuration software such as Bocad, and PK stahl, to produce the shop drawings. However, in Taiwan, currently only AutoCAD software is constantly used. The data for '2D units' must be obtained from a '3D master model' so that the detailed construction drawings can be made.

4.3.5. Digital Fabrication

Frame and skin Units

For our examples of the processes of international and domestic projects, all have been fabricated with ‘frame and skin units’ at the stage of digital fabrication. And this data can be directly obtained from the ‘3D master model’.

Unit Manufacture

Whether it is an international or a domestic process, unit manufacture mainly works by dismantling the 3D model of frame and skin units into ‘unit construction plans’ before the ‘unit manufacture’ process. Three steps are shown in Figure 1, including output of drawings with marking points, framework outputs, and panel outputs, all of which are main steps in the fabrication of a ‘unit construction plan’. In this study, these three steps are called: ‘construction plan with marking points’, ‘frame construction plan’, and ‘skin construction plan’. As shown in Figure 1, after the ‘unit construction plan’ is made, the data can be forwarded to construction contractors and will be used with CAM technology to carry out ‘unit manufacture’, and then to do the ‘adjustments’.

Mock-up

From Figures 5 and 9, we can see that at the stage of digital fabrication Gehry and Franken produced ‘mock-ups’ at a scale of 1:1 in order to test the feasibility of new construction methods. In Figure 3 showing the Bilbao process, Gehry also produced such a ‘mock-up’ to do the wind test on the exterior titanium wall. In the process of producing large scale ‘mock-ups’, architects and contractors can control more easily the construction procedure and construction time. While doing the tests using this model, it
is always possible to go back to the step of ‘frame and skin units’ to make revisions if the model cannot meet the design requirements.

**Pre-fabrication**

From the analyzes of projects above it is seen that in the construction process of small interior design projects, units were ‘prefabricated’ in the factory (Figures 1, 5, 7) while this step cannot be applied to large structures due to their too large sizes. The process of ‘pre-fabrication’ is mainly to ‘mark’ according to the ‘construction plan with marking points’ in the factory first, then to ‘assemble’ the units for tests, then to ‘disassemble’ the units and to ‘reassemble’ them on site. This step mainly serves the purpose of researches into assembly procedures, precision of adjustment of unit joint, control of construction time, and can be a solution to construction problems. Whenever any unit fails to be assembled in this step, we can always go back to the step of ‘unit manufacture’ for readjustment. It mainly serves to ensure more precision when the units are eventually assembled on site.

**On-site Assembly**

In the process of the international projects, before the ‘on-site assembly’, 3D spatial locators connected to computer for the ‘marking’ are used so that the marking points can be precise. After the ‘marking’, ‘assembly’ proceeds. However, the process of domestic projects in Figure 1 shows that ‘adjustments’ need to be made after the ‘marking’ and the ‘assembly’. The main reason is that common, less precise laser locators are used in Taiwan for the ‘marking’, and also that the distortion or deformation incurring in the process of dismantlement and transportation after the process of pre-fabrication will also lead to inaccuracy. Hence, readjustment is needed for adjustment.

Integrating the analysis and comparison of each stage, a ‘preliminary framework for CAD/CAM design and construction process’ in freeform design can be outlined by the present study (Figure 10).
5. Conclusion

As Figure 10 shows, a preliminary framework for freeform design and construction processes using CAD/CAM media is presented in this research. The Figure reveals the digitised design and construction process of freeform space in contemporary architecture. The process and steps of the five stages are digitised and involve the utilization of different CAD/CAM media such as parametric 3D CAD software, laser cutting, rapid prototyping, CNC, and 3D laser scanning. In the early design stage, 3D CAD software first generates and then represents the freeform design forms. Following this the complicated freeform can be transformed into an accurate physical model with the aid of CAM machining, rapid prototyping, CNC, or laser cutting. The transformation from CAD digital models to CAM physical models will help designers to comprehend their designs. While the detailed design stage relies on 3D drafting or analysis software to create detailed drawings, physical mock-ups can be manufactured using RP and CNC machines. The construction process, which is referred to as the fabrication process in this study, is the most important of the processes. As designers need to decompose 3D freeform design into 2D units or elements for the manufacturing process, the unfolding and division processes become essential steps at this stage. The fabrication process using laser cutting or CNC in the factory begins after receiving the 2D digital file. The mock-up or pre-fabrication process is carried out in the factory for assembly procedure testing. The on-site construction and assembly processes are more efficient for having carried out this pre-fabrication process.

6. Significance, limitations and future study

The significance of this research is its exploration of an executable and general CAD/CAM design and construction process for freeform architecture which can be applied to the architectural design field and used in education. It can help students to understand deeply the process of using CAD/CAM media to realize freeform and complex geometry design. Fabrication process enables designers easily making their design from concept to physical. The lack of case studies is a definite drawback to this study but, it is hoped, a future study will present a more complete framework.

References


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