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Application of Freeform Surface to the Parametric Design of Plate Sheet Structure

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This paper constructs a small-scale, lightweight structure with complex freeform surfaces via parametric design. First, the method of freeform surface modelling and parametric design were introduced, and combined into the parametric design aided freeform surface modelling. Then, the parametric design and software for complex surface structure were determined. On this basis, the small-scale structure was conceptualized and the model was improved in the design phase. The PP sheet was selected as the final simulation material and the model was established according to the specified method. The stress deformation of the structure was simulated to correct the stress defects in the design, while the airflow impact was simulated to verify the rationality of the structural form. The results show that the parametric design helps apply complex freeform surface to small and light structure and assist the generation of the designed form. The research findings shed new light on the application of parametric design in the field of structure.

1. Introduction

Freeform surface modelling has been extensively applied in structure. This is attributable to its ability to visually express objects with complex shapes, especially those which cannot be represented accurately by analytical functions. The effect of freeform surface modelling has been further enhanced by the development of computer technology. Unsurprisingly, much attention has been paid to the application of freeform surface modelling.

The design of freedom surface is closely intertwined with the method of parametric design. This method can categorize complex structure objects into different categories according to their respective features. With the development of the computer-aided design (CAD), there has been a rapid growth in the demand for parametric design in the structure field. Thus, the application scope of parametric design is shifting from industrial product design to structural design.

In light of the above, this paper combines freeform surface modelling and parametric design into a novel method for modelling of complex surface structure. The Polypropylene plate (PP) sheet was selected as the final simulation material and the model was established according to the specified method.

2. Methodology

2.1 Freeform surface modelling

Freedom surface modelling is a powerful tool to describe complex surfaces and a key subject in geometric CAD. The core of freedom surface modelling lies in computer presentation, that is, determining most proper mathematical methods for computer processing. This method can effectively fulfil the requirements for surface presentation and geometric design, and facilitate the transfer of geometric and surface information of products (Zhou, 2012).

The popular surface presentation methods include spline surface, subdivision surface, implicit surface and net surface. Each presentation approach has its strengths and weaknesses, and differs from others in the scope of application. After 30 years of development, freedom surface modelling now encompasses two types of surface presentation methods, namely, parametric design of rational B-spline surface and presentation of implicit algebraic surface, and a framework of such three strategies as interpolation, fitting and approximation.

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For simplicity, the spline surface can be expressed as the tensor product of some spline fundamental functions. The n-th tensor power of a spline surface f is a segmented polynomial surface, and a continuous surface will form after Cn-1 segments are connected. The spline surface can be expressed as:

$$f(u, v)=\sum_{i-0}^{m}\sum_{j=0}^{m} c_{ij} N_i^n(u) N_j^n(v) \tag{1}$$

where $N_i^n(\cdot)$ is the B-spline fundamental function; C_{ij} is the controlling grid of the surface.

The Spline curve is a smooth curve passing through a series of given points, whereas B- spline, a special presentation form of spline curve, can be further promoted as nonuniform rational B-spline (NURBS). The NURBS is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces. It offers great flexibility and precision for handling both analytic and modelled shapes. NURBS are commonly used in CAD, manufacturing (CAM), and engineering (CAE). This model has become the research focus of surface modelling due to its convenience and accuracy (Chen, 2009).

2.2 Parametric design

Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response. Parametric design is a paradigm in design where the relationship between elements is used to manipulate and inform the design of complex geometries and structures.

As mentioned before, parametric design can categorize complex structure objects into different categories according to their respective features. Thus, it is an ideal tool for form innovation in structural design, which requires in-depth theoretical and practical research in bionics (Gao, 2002), physics, geometry, mechanics and other disciplines (Shen, 1998). The idea of parametric design helps to achieve the functional and aesthetic requirements for freeform surface, a shape-resistant spatial structure (Pearce, 1998).

2.3 Parametric design aided freeform surface modelling

A structure with complex forms can be regarded as a nonlinear dynamic system, whose performance is affected by the correlation between different parameters. This system can be described by a dynamic and open parametric relational model. Once the model is established, the complex forms can be solved by computation (Oosterhuis, 2008). In other words, parametric design is an efficient and objective way of structural design based on the principles of parametric system and advanced computer technology. During the design, the parametric relationship is established between the leading factors and the structural components.

There are two kinds of parametric design techniques: parametric primitives and parametric engine modification. The former corresponds to design inputs and the bottom components in the bottom-top system, while the latter refers to the controlling drive of the relational models among the parameters. The parametric design focuses on the internal relational model of the possible problems, laying the basis for the solution to actual problems.

3. Generation and analysis of complex form

3.1 Procedure of parametric design for complex surface structure

The first step of parametric design is to determine the core design logic. Unlike the traditional design, the parametric design of complex surface structure views the structure as a self-organized complex system. The form is automatically generated under the constraints instead of being designed instinctively.

After determining the basic logic, the algorithm between the designed qualifications and presentation outputs were established, and relevant digital software was used to generate a 3D computer model that can be adjusted flexibly.

The setting range of parameters covers the information about the major contradictions to be solved by the design, such as function, structure and so on. Once the 3D model is established, the results will be presented graphically. In this way, it is possible to design the details of complex surface structure.

3.2 Software for parametric design aided freeform surface modelling

The Rhino software was adopted for modelling. Rhino is a professional advanced 3D modelling software, which supports NURBS modelling in structure, machinery and other industrial fields. Rhino modelling is based on NURBS curve surface. The NURBS curve consists of such structural components as curve zero, curve end, curve span, curve frame, curve controlling points and curve editing points. Among them, curve controlling points and curve editing points are essential to the curvature and shape of the curve. The NURBS curve parameters are either uniform or nonuniform. Different parameter combinations lead to different curve properties (Lan et al., 2016).

The finite-element analysis (FEA) was carried out on Karamba, a Grasshopper-based tool for parametric structure engineering. The software has been widely applied to structural analysis and optimization, as it can accurately depict the truss, frame and shell body of a structure. The basic workflow of Karamba is as follows: First, configure support, load and other conditions, create models in Rhino and Grasshopper via model transformation, and construct a finite-element model. Then, the model outputs the parameters calculated by algorithms. Finally, the results of the model are visualized.

During the planning phase of form design, Autodesk Flow Design was introduced for airflow analysis. It is a virtual wind-tunnel software applicable to product design, engineering and structure. The software simulates the surroundings of the object, making it possible to verify the preliminary design plan.

4. Experiment and results

4.1 Conceptualization of small-scale structure

The experiment aims to build a small-scale, lightweight structure with freeform shape standing 2m tall in the range of 2m×4m. In the planning phase, the main task is to determine the preliminaries according to the requirements. Specifically, top cover and walls are necessary, because they are critical to shape-resistant structure; sound, light and ventilation are also needed. Hence, it is necessary to design a two-layer spherical shell with round openings across internal and external walls, which allow light to come in and rainwater to discharge (Figure 1). On this basis, the branch form was determined as a narrow, long stick, for the land use is limited in the range of 2m×4m. To meet the free-standing requirement, a suspended face was generated by physical engine. However, the shape is not desirable enough, as evidenced by the repeated shearing at the openings (Figure 2). A 1:20 cardboard model was developed by laser cutting (Figure 3).

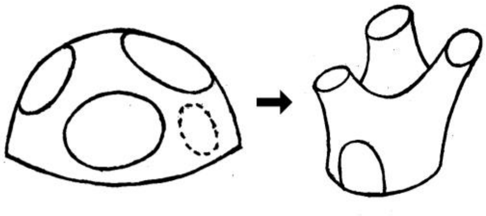


Figure 1: Conceptualized structure

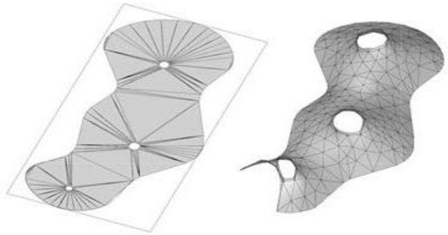


Figure 2: Simulation model

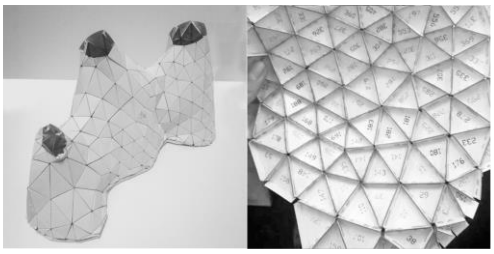


Figure 3: 1:20 cardboard model

4.2 Model improvement in the design phase

In the design phase, the techniques were finalized for each option for experiment. Meanwhile, the operability of model was verified by adjusting the parameters. Then, a series of optional plans were generated and sorted out. According to previous design, the 1:20 cardboard model faces the following problems. First, the top opening cannot function well because it is too close to the entrance; the structure is flat on the side face and the façade is so small that no one can enter the structure. To solve the problems, three tower-shaped spaces were altered into two (Figure 4). Second, the opening is too large, and the components affect the shape of freeform surface. Thus, the suspended face was given up, and the opening was manually adjusted to be more variable (Figure 5). The form of freeform surface composed of the following simple triangular faces was obtained by Rhino modelling.

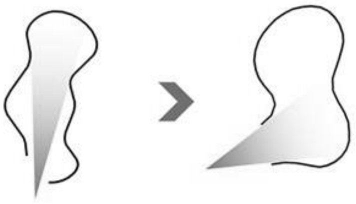


Figure 4: Shape optimization

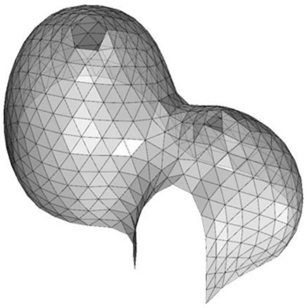


Figure 5: Rhino modelling

Then, the form plan was imported to Karamba for structural analysis and optimization. The modelling analysis shows that when the model bottom became the ground anchor, all the bars only bear the action of gravity. In the absence of external force, the deformation of the stressed place is positively correlated with the darkness of the colour (Figure 6). When the stress was set to 60N/m2 with timbre as the material, the structural deformation fell between 0cm and 0.0183cm (Figure 7). Next, airflow simulation was conducted on Autodesk Flow for the designed shape. It can be seen that the colour of the freeform surface was relatively stable with airflow passing through the structure internally. Hence, the structure is mechanically sound and comfortable. However, the weak places need to be strengthen with nodes or solidification (Figure 8).

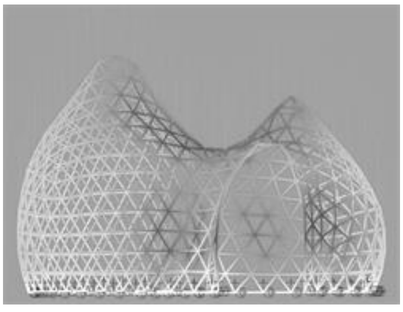
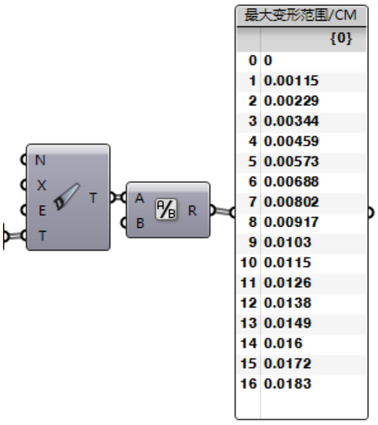


Figure 6: Overall stress condition



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最大变形范围/CM
     {0}
 0 0
 1 0.00115
 2 0.00229
 3 0.00344
 4 0.00459
 5 0.00573
 6 0.00688
 7 0.00802
 8 0.00917
 9 0.0103
10 0.0115
11 0.0126
12 0.0138
13 0.0149
14 0.016
15 0.0172
16 0.0183
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Figure 7: Structural deformation range

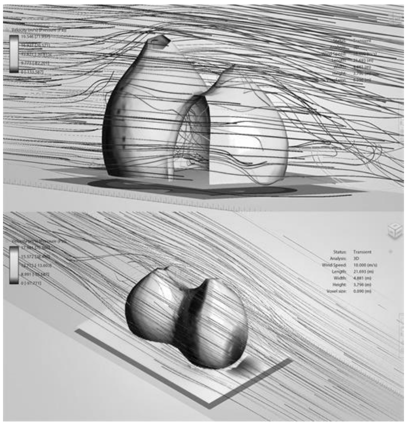

Figure 8: Airflow analysis

4.3 Structure process

4.3.1 Materials option and joint fixing techniques

Considering material options, the property parameters of timber are default in the parametric modelling software. Hence, materials lighter than timber were taken into account. Through careful deliberation, the PP sheet was selected as the final material. The PP sheet is an engineering plastic with high transparency, lightweight and strong shock resistance. It enjoys great popularity in the field of structure. Then, the material was segmented into triangular units on a laser cutting machine. The units were partitioned and numbered, and the joints were perforated. During installation, 5 units were connected into a single component through colligation (Figure 9).

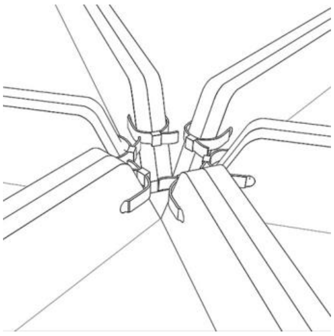

Figure 9: Connecting the units

4.3.2 Structure problems and countermeasures

The established freeform surface of PP plate was basically consistent with the design. The deformation was the same as the simulation results on Karamba, indicating that the parametric simulation is accurate (Figure 10). After structure, the small-scale structure remained stable in the absence of external force. People could enter the structure at ease. Sound, light and ventilation were available within the structure. In the meantime, some deformations occurred at the stressed joints, which can be eliminated by thickening these parts.

Figure 10: The constructed model

5. Conclusions

This paper constructs a small-scale, lightweight structure with complex freeform surfaces via parametric design. First, the method of freeform surface modelling and parametric design were introduced, and combined into the parametric design aided freeform surface modelling. Then, the parametric design and software for complex surface structure were determined. On this basis, the small-scale structure was conceptualized and the model was improved in the design phase. The PP sheet was selected as the final simulation material and the model was established according to the specified method. The stress deformation of the structure was simulated to correct the stress defects in the design, while the airflow impact was simulated to verify the rationality of the structural form. The results show that the parametric design helps apply complex freeform surface to small and light structure and assist the generation of the designed form. The research findings shed new light on the application of parametric design in the field of structure.

Acknowledgments

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