Parametric modeling program of single-layer spherical reticulated shell structure and prediction program of global stability ultimate bearing capacity

H Qi¹, X R Wang², Z Y Huang¹, X Y Dai³ and J Z Zhuang³*

¹Beijing No.3 Construction Engineering Co., Ltd, Beijing 100044, China
²Beijing Mechanized Construction Group Co., Ltd, Beijing 100055, China
³China Agricultural University, Dept. of Civil Engineering, Beijing 100083, China

Email: zhuangjz@cau.edu.cn

Abstract. In this paper, the "battery" program was compiled based on the parametric tool Rhino+Grasshopper and the parameterized modeling function of K-type single-layer spherical reticulated shell structure was realized. At the same time, based on BP neural network algorithm and considering the complex mapping relationship in nonlinear analysis, a neural network model and program was established to predict the ultimate bearing capacity of K8 single-layer spherical reticulated shell structure. The results show that the program can realize the modeling process efficiently and the reliability of the neural network to predict the ultimate bearing capacity of single-layer reticulated shells is verified, which provides an effective tool for improving the parametric modeling and structural optimization of single-layer reticulated shell structure.

1. Introduction

Parametric design is a new design tool based on geometric designs. With the development of computer technology and the aid of computer, parametric design has gradually become the main way of architectural design. As an architectural design method, the essence of parametric design is to turn all elements of architectural design into variables of a certain function according to certain corresponding rules. By changing the function or algorithm, people can easily modify the design scheme and achieve the desired design effect. Parametric design can greatly improve the speed of model generation and modification and increase work efficiency. It has high application value in architectural design [1-3].

In the increasingly complex architectural modeling, reticulated shell structure is widely used in architectural design for its rich and beautiful architectural shape. However, due to the large number of lattice shells and complex structure, traditional manual modeling requires a lot of time. As a part of parametric design, parametric modeling has strong tunability and good adaptability to complex architecture. It can simplify the modeling process to a certain extent by using parametric modeling method and generating models with program scripts. Rhino+Grasshopper operating platform is the most commonly used parametric tool in the field of architectural design [4].

Artificial Neural Network is an algorithmic mathematical model to simulate the actual human neural network. It is connected by a large number of neurons with adjustable connection weights. It has a strong ability of information storage, processing and self-learning, and has been widely used in the field of system modeling. Structural optimization is a complex process involving strategies and mathematical algorithms. The design parameters introduced in the
form of variables, constraints and optimization functions play a very important role. Using BP neural network to study the ultimate bearing capacity of single-layer spherical reticulated shell structure is of great significance to improve the parametric modeling and structural optimization of reticulated shells [5-7].

Gao Ming et al. [4] combined the positive quadrangle mesh frame example and the modeling process of a stadium project tent structure and gave the basic application idea of parametric modeling in the modeling of spatial grid structure. Based on Rhinoceros software and Grasshopper plug-in, Wu Jiahe [8] studied the realization process of parametric modeling design of double-layer reticulated shell structure according to the characteristics of double-layer reticulated shell structure. Xu Zhen et al. [9] proposed a two-point adjustment modeling method for the structure of the fork-barrel reticulated shell based on the parametric fork-barrel surface and Grasshopper software. According to the characteristics of ribbed ring grid structure, Zheng Yang [10] introduced the parametric modeling process of radial bar, annular bar and other bars. In terms of the research of reticulated shell structure with neural network, Abhijit Mukherjee et al. [11] studied the applicability of artificial neural networks in modeling the initial design process and the network can predict a good initial design for a given set of input parameter. Osama Moselhi et al. [12] described the basic neural network architecture and discussed its potential applications in construction engineering and management. A neural network application program for optimal marker estimation was developed. He Yongjun et al. [13] used BP neural network to classify and distinguish the failure modes of reticular shells under strong earthquakes. Chen Shiying et al. [14] used BP artificial neural network's ability to simulate complex nonlinear mapping relationship to establish the mapping relationship between reticular shell span, vector span ratio and reticular shell type with the least amount of steel and realized the selection optimization of reticular shell structure through section optimization.

In this paper, the parameterization tool Rhino + Grasshopper will be used to model the single-layer spherical reticulated shell structure. At the same time, the BP neural network algorithm will be used to study the ultimate bearing capacity of single-layer reticulated shell structure considering the complex mapping relationship in nonlinear analysis, and the prediction model of ultimate bearing capacity of K8 single-layer spherical reticulated shell structure will be also obtained, which is extended to Kn type reticulated shell structure. It will provide a new research direction for the parametric modeling and structural optimization of single-layer reticulated shell structure.

2. Introduction to Rhino and Grasshopper
Rhino (full name of Rhinoceros) is the first 3D modeling software that introduced NURBS modeling technology into Windows system officially launched by Robert Mcneel & Assoc company in August 1998. It has powerful modeling function, good compatibility with Windows and low hardware configuration requirements. It is welcomed by the majority of 3D product users. Rhino has a great role in promoting the development of 3D software industry. In the field of architecture, Rhino is widely used by virtue of its powerful surface modeling ability and has many professional plug-ins to assist architectural design, such as RhinoBIM, VisualARQ, Grasshopper, etc.

Rhino has opened script editing function for users. The script language is called Rhinoscript, which is convenient for users to explore and pursue higher body creativity. However, script writing needs certain programming skills, which is difficult for non-computer industry personnel. Robert Mcneel & Assoc developed the "grasshopper" visual node programming plug-in to solve this problem. Users can complete most of the modeling functions through simple plug-in interface and visual operation, which effectively reduces the user's time in learning script writing.

Grasshopper uses simple node type visual data operation and organizes algorithm and geometric operation by node and line. It can display the effect of parameter change dynamically and real-time and can complete the data generated by each process. Grasshopper is developed by high-level language. It is easy to operate, but also has great openness. It provides C# and VB programming calculator under. Net framework, so that users can develop their own Grasshopper calculator, save and use it permanently [15].
As shown in Figure 1, there are two main types of nodes in Grasshopper: parameters and arithmetic units. Parameters are used to store information and arithmetic units are used to process information. A, B and C on the left side of the picture are the parameter input parts and the right side is the arithmetic unit. The program compiled in Grasshopper starts from the parameters and generates the operation results after the processing of each arithmetic unit. Figure 2 is the Grasshopper program for calculating the addition of three values. Parameters are the basic data of control program generated results, which can be geometric type, numerical type, Boolean value or string type. The arithmetic unit is the core part of the program. Different calculators can achieve different program functions through different combinations. It is this modular assembly method that greatly reduces the programming requirements. Users can write programs without writing code, at the same time, it also greatly improves the efficiency of user programming [16].

Figure 1. Node to node data connection in Grasshopper

Figure 2. Grasshopper program

3. Parametric modeling of reticulated shells
Based on the parametric modeling software Rhino + Grasshopper, the parametric modeling of single-layer spherical reticulated shell is carried out. First of all, select the surface in Rhino, import it into Grasshopper, parameterize the surface data, input it into the corresponding arithmetic unit, then extract the discrete nodes, connect and generate mesh. The grid is divided into two parts: the upper and lower chord nodes of the truss are found according to the corresponding arithmetic unit. The grid structure can be obtained by connecting the upper and lower chord nodes in a certain way and then the spherical reticulated shell is generated by rotating the generatrix or sweeping along the circular curve. The modeling program diagram is shown in Figure 3.
As shown in Figure 4, the diameter, rise, radial section number and rib number of the reticulated shell can be adjusted by adjusting the slider on the left side and the real-time image can be reflected. Figure 5 and Figure 6 are the structural drawings of reticulated shells with different parameters.

Figure 3. Program interface.

Figure 4. Parameter input interface.

Figure 5. Reticulated shell structure drawing.

Figure 6. Reticulated shell structure drawing.
4. BP neural network algorithm

BP neural network is a multilayer feedforward network trained by error back propagation. Its algorithm is called BP algorithm. Its basic idea is gradient descent method. Gradient search technology is used to minimize the error mean square error between the actual output value and the expected output value of the network.

The basic BP algorithm includes two processes: forward propagation of signal and back propagation of error. In forward propagation, the input signal is introduced from the input layer, which acts on the output node after processing in the hidden layer. After nonlinear transformation, the output signal is generated. If the actual output does not match the expected output, it will turn into the error back-propagation process. The error backpropagation is that the output error is transmitted back to the input layer step by step through the hidden layer and the error is allocated to all the units in each layer. The error signals obtained from each layer are used as the basis for adjusting the weights of each unit. By adjusting the connection strength between the input node and the hidden layer node, the connection strength between the hidden layer node and the output node and the threshold value, the error decreases along the gradient direction. After repeated learning and training, the network parameters corresponding to the minimum error are determined and the training stops. At this time, the trained neural network can deal with the input information of similar samples and process the non-linear transformation information with the minimum output error.

BP neural network is shown in Figure 7.

5. Neural network model prediction of K8 single-layer spherical reticulated shell

5.1. Neural network training

Kewitt type reticulated shell, referred to as K-type reticulated shell, is a single-layer spherical reticulated shell which is widely used at present. BP neural network is used to train the prediction model of ultimate bearing capacity of K8 single-layer spherical reticulated shell under self-weight, which is the most widely used in K-type reticulated shells. On this basis, a neural network model suitable for Kn type reticulated shells is proposed.

On the basis of a large number of nonlinear studies, academician Shen Shizhao [17] proposed a more practical regression formula for the stability analysis of reticulated shells. The results are still different from those obtained by finite element analysis. Based on the data of reference [17], BP neural network is used to study the ultimate bearing capacity of single-layer spherical reticulated shell and the prediction model of ultimate bearing capacity of K8 single-layer spherical reticulated shell is obtained. In some learning samples for training, the input parameters are the span, rise-span ratio, diameter of radial beam and circumferential beam, wall thickness of radial beam and circumferential beam, diameter of inclined bar, wall thickness of inclined bar and frequency. The span of latticed shell is 40m, 50m, 60m and 70m.

5.2. Network parameters

When BP neural network is used to predict the ultimate bearing capacity, the parameters of the network with and without frequency influence are basically the same except that the input layer
neurons are set as 6 and 7. The number of training samples is 48, the number of test samples is 16, the number of hidden layers is 2, the number of neurons in hidden layer is 32 and 16, the number of neurons in output layer is 1, the learning rate is 0.01, the number of iterations is 500 and the number of samples is 16.

5.3. Result analysis
The network results of some samples are compared with those obtained by using finite element method and regression formula. The results are shown in Table 1. The whole process of $Q_{cr}$ is the exact solution of ultimate bearing capacity obtained by finite element analysis software and $Q_{cr}$ is the approximate solution calculated by using the regression formula recommended in reference [17].

Table 1. Ultimate bearing capacity results of K8 single-layer spherical reticulated shell structure (partial).

| Span (m) | Section | Rise span ratio | Whole process of $Q_{cr}$ | Neural network without frequency | Error | Neural network considering frequency | Error | $Q_{cr}$ (regression formula) | Error |
|---------|---------|-----------------|---------------------------|-------------------------------|-------|--------------------------------------|-------|-----------------------------|-------|
| 40      | 1       | 0.200           | 13.65                     | 14.439                        | 5.78% | 15.487                               | 13.46%| 13.05                       | 4.40% |
| 40      | 2       | 0.200           | 17.39                     | 17.389                        | 0.01% | 17.388                               | 0.01% | 17.56                       | 0.98% |
| 40      | 3       | 0.167           | 16.84                     | 17.517                        | 4.02% | 17.002                               | 0.96% | 16                           | 4.99% |
| 50      | 1       | 0.125           | 5.34                      | 5.333                         | 0.13% | 5.449                                | 2.03% | 5.63                         | 5.43% |
| 50      | 2       | 0.125           | 6.83                      | 7.553                         | 10.58%| 6.942                                | 1.63% | 6.95                         | 1.76% |
| 60      | 1       | 0.143           | 6.29                      | 6.278                         | 0.19% | 6.722                                | 6.87% | 6.57                         | 4.45% |
| 60      | 2       | 0.143           | 7.71                      | 7.691                         | 0.24% | 7.598                                | 1.46% | 7.67                         | 0.52% |
| 70      | 1       | 0.200           | 10.44                     | 10.407                        | 0.32% | 9.785                                | 6.27% | 9.46                         | 9.39% |
| 70      | 2       | 0.200           | 13.62                     | 13.737                        | 0.86% | 13.801                               | 1.33% | 12.93                       | 5.07% |

It can be seen from the analysis of the data in Table 1 that the network loss considering frequency is smaller than that without considering frequency, which indicates that the network loss can be reduced by considering frequency. The maximum error of network error is 10.58%, the minimum is 0.01%, the standard deviation of error is 2.58%, and the average value is 1.63%, which shows that the network can better predict the ultimate bearing capacity of reticulated shell structure. The error standard deviation and mean value of the network results with and without frequency are less than the error results of the regression formula in reference [17], which shows that the neural network fitting is better than the regression formula in reference [17]. It is very feasible to use neural network to predict the ultimate bearing capacity of K8 single-layer spherical reticulated shell structure.

6. Conclusion
- Using Rhino + Grasshopper parametric tool to compile "battery" program can efficiently carry out parametric modeling of single-layer reticulated shell structure, with fast modeling speed and real-time preview of parameter adjustment effect.
- Based on the principle of BP neural network, a neural network program considering the complex parameter relationship in the nonlinear analysis of reticulated shells is compiled.
- The feasibility and accuracy of the neural network program to predict the ultimate bearing capacity of K8 single-layer spherical reticulated shell is verified by an example of K8 reticulated shell.

References
[1] Wang M L 2016 Application of Parametric Design in the Structural Design of Complex Surface Architecture (Beijing: Beijing University of Civil Engineering and Architecture)
[2] Zhu M and Wang C L 2012 Applying of Rhinoceros Software and Grasshopper Plug-in for Quick Structural Modeling of Double-layer Reticulated Shells Build. Struct. S2 424-7
[3] Wang X D 2014 Parametric Design and Architecture Based on Rhinoceros Information and Computers: Theoretical edition (05) 162-3
[4] Gao M, Yan D Q, Zhang J L, et al 2013 Application of Parametric Modeling in Design of Space Frame Structures Build. Struct. 43(17) 149-151

[5] Kamarthi V S, Sanvido E V and Kumara T R S 1992 Neuroform- neural Network System for Vertical Formwork Selection J. Comput. Civil Eng. 06(02) 178-199.

[6] Hajela P and Berke L 1991 Neurobiological Computational Models in Structural Analysis and Design Comput. Struct. 41(4) 657-67.

[7] Grande E, Imbimbo M and Tomei V 2018 Structural Optimization of Grid Shells: Design Parameters and Combined Strategies J. Archit. Eng. 24 (1) 04017027.1-04017027.9.

[8] Wu H H 2018 Parametric Design Modeling of Double-layer Reticulated Shell Structure Based on Grasshopper Plug-in Journal of Yancheng Institute of Technology (Natural Science edition) 31(02) 40-7

[9] Xu Z and Zhang S L 2018 Parameterize Modeling of Cross-tube Reticulate Shell Based on Grasshopper House (34) 190+25

[10] Zheng Y 2015 Application of Parametric Modeling in Grid Structure of Rib-ring Type Jiangxi Science 33(02) 224-226+274

[11] Mukherjee A, Deshpande J M 1995 Modeling Initial Design Process using Artificial Neural Networks J. Comput. Civil Eng. 9(03) 194-200.

[12] Moselhi O, Hegazy T and Fazio P 1991 Neural Networks as Tools in Construction J. Constr. Eng. M. 117(04) 606-25.

[13] He Y J and Zhang F S 2018 Classification and Discrimination of Earthquake Failure Modes for Reticulated Shells Based on Neural Network J. Railway Sci. Eng. 15(02) 458-65

[14] Chen S Y, Guo Y X and Lu X Y 2010 Lectotype Optimization of Single-Layer Steel Reticulated Dome Prog. Build. Steel Struct. 12(04) 46-50

[15] Zeng X D, Wang D C and Chen H 2011 Parametric Modeling Based on Rhinoceros & Grasshopper (Hubei: Huazhong University of Science & Technology Press)

[16] Yin P F 2018 Research on Modeling Metod of Free-form Space Grid Structure and Program Development Based on Rhino Software (Hubei: Wuhan university)

[17] Shen S Z and Chen X 1999 Stability of reticulated shell structure (Beijing: Science and Technology Press)