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Integrated methods for smart design and CNC manufacture of reticulated structures with bolt-ball joint

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Abstract
The reticulated structure with bolt-ball joints has excellent mechanical properties and the advantage of less material consumption, and has been widely used in China since 1950. In recent years, the authors have cooperated to study on the integrated methods for smart design and CNC manufacture of reticulated structures. A smart design software for reticulated structures have been developed. The software can carry out parameterized smart design for reticulated structure engineering projects. Based on parameter changes, hundreds and thousands of reticulated structure analysis models can be automatically established for comparison and optimization. By the smart design methods, the material usage of reticulated structures can be saved up to 10% compared with conventional design methods, and design efficiency can be improved by more than 50%. An automatic nesting software for members of reticulated structures has also been developed, and the utilization rate of pipe raw materials has reached more than 99%. A precise design method for bolt-ball joints has been built. It can save more than 30% of the material used in bolt-ball joints compared with the conventional design method in China. The first set of CNC production line for members and bolt-ball joints of reticulated structures has been built recently in China. It can realize the whole process of CNC manufacture for members from cutting, welding, painting and drying, for bolt-ball joints from reference hole, polishing, milling, drilling, chamfering and tapping. The smart design software of reticulated structures is integrated with CNC machining equipment to realize the data sharing of design and manufacture. This paper introduces in detail the latest integrated technology of bolt-ball joint reticulated structure in China.

Keywords: reticulated structure, bolt-ball joint, smart design, CNC, integrated design and manufacture

1. Introduction
The spatial reticulated structure, with its advantages of beautiful appearance and reasonable stress, is widely used in public buildings such as airports, exhibition halls, and sports venues[1]. The commonly used nodes in spatial grid structures can generally be divided into three categories: weld-ball joints, bolt-ball joints, and steel plate joints[2]. The bolt-ball joints grid structure has the advantages of factory production, easy quality assurance, short installation and construction cycles, and is therefore increasingly widely used[3]. At present, the design and processing of bolt-ball joint grids are usually separated. After completing the structural design, the members and bolt-balls are processed according to the construction drawings. This process is prone to errors and wastes time. It is necessary to conduct research on the integration of design and CNC manufacturing of reticulated structures with bolt-ball joint.

Representative works in structural parameter optimization currently include: Jenkins applying genetic algorithms to shape optimization of roof structures[4]; For the optimization of discrete variable truss, SUN Huanchun et al.[5] proposed a two-level algorithm applied to the shape optimization of discrete section variable space truss, which step-by-step optimized the position of nodes and the cross-section of members. Yeh I.C[6] utilized a hybrid technique to optimize some planar and spatial structures, and genetic algorithms were effective but computationally cumbersome. Bennage and Dhingra[7] proposed a design method that integrates topology factors within a structural optimization framework. At present, most design software can generate construction drawings to guide construction, but further deepening design is needed, and it is not possible to directly generate the data required to control the CNC machine tool production line.

This article conducts research on the smart methods for design and CNC manufacture of reticulated structures with bolt-ball joint. Based on parameter changes, hundreds and thousands of reticulated structure analysis models can be automatically established for comparison and optimization. By the smart design methods, the material usage of reticulated structures can be saved up to 10% compared with conventional design methods, and design efficiency can be improved by more than 50%. An automatic nesting software for members of reticulated structures has also been developed, and the utilization rate of pipe raw materials has reached more than 99%. A precise design method for bolt-ball joints has been built. It can save more than 30% of the material used in bolt-ball joints compared with the conventional design method in China. The integrated technology of this design and CNC manufacture has been successfully applied in the automated production line of reticulated structure with bolt-ball joint in China。

2. Smart design methods for reticulated structures

The smart design method for grid structures includes four parts: (1) Parameterized modeling method, which extracts the characteristic parameters of the grid structure to achieve parameterized modeling; (2) Integrate traditional design experience and determine parameters that have a significant impact on the performance of grid structures as optimizable parameters; (3) Conduct batch model design analysis; (4) Choose appropriate optimization algorithms to quickly determine the optimal parameters.

2.1. Smart design method for standard reticulated structures

The complete process of the standard model optimization method is illustrated in Figure 1. Initially, it is essential to extract the modeling parameters of the standard model, primarily comprising geometric parameters of the structure. The geometric parameters of grid structures encompass grid length, the number of grids on each side, thickness, position, and height of the slope. Similarly, the geometric parameters of cylindrical reticulated shells encompass grid length, rise height, number of grids on each side, thickness, etc. The geometric parameters of spherical reticulated shells include grid length, rise height, number of rib-divided sectors, coupling position, thickness, etc. Subsequently, it is also necessary to extract the control parameters and methods for structural load and boundary conditions. This ensures that by inputting or modifying similar control parameters, a standard structural model encompassing loads and boundaries can be automatically established.

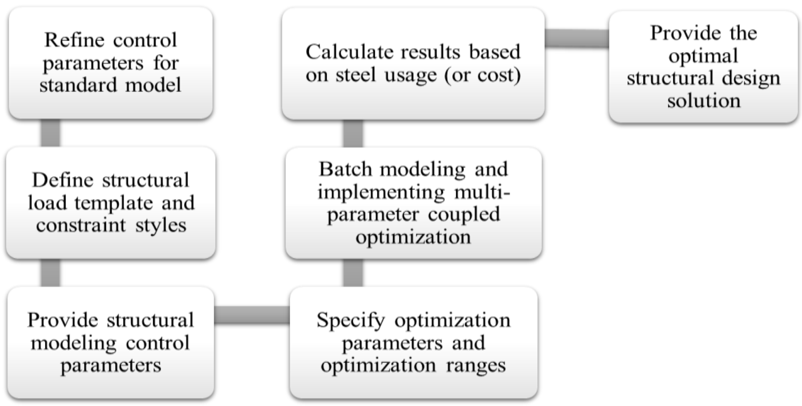

Figure 1: Flowchart of the standard model optimization method

After completing the modeling process, structural optimization methods typically involve single-parameter optimization and multi-parameter coupling optimization. Initially, the impact of a single parameter on structural performance is analyzed, and the importance of each parameter is ranked accordingly. Subsequently, the coupling effects of various parameters are compared and contrasted, leading to the determination of an optimization scheme. It is important to note that different structural forms have distinct optimal control parameters and parameter values, resulting in varying steel consumption for the generated structures. Following the optimization of each parameter individually, multi-parameter coupling optimization is conducted to derive the final optimal model. Taking a 90 m × 60 m square pyramid grid structure as an example, this paper explores the effects of grid size, thickness, and slope height on the amount of steel used in the structure:

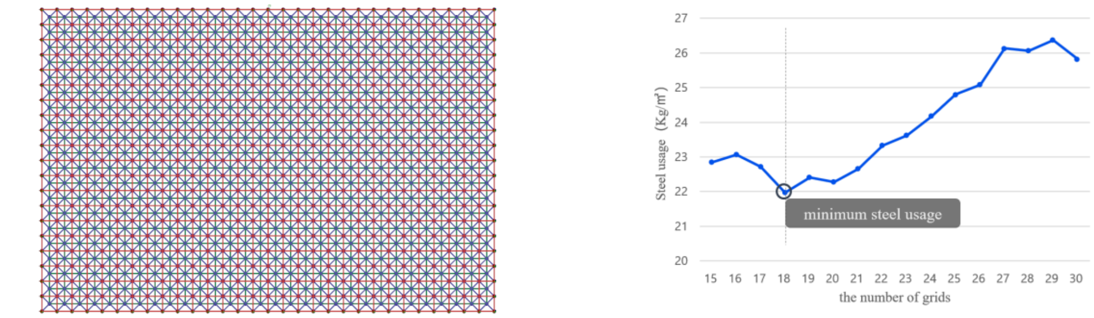

Figure 2: The effect of grid size on steel usage

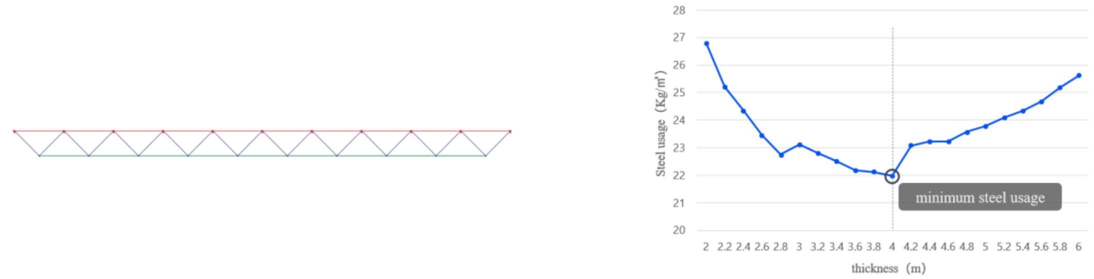

Figure 3: The effect of thickness on steel usage

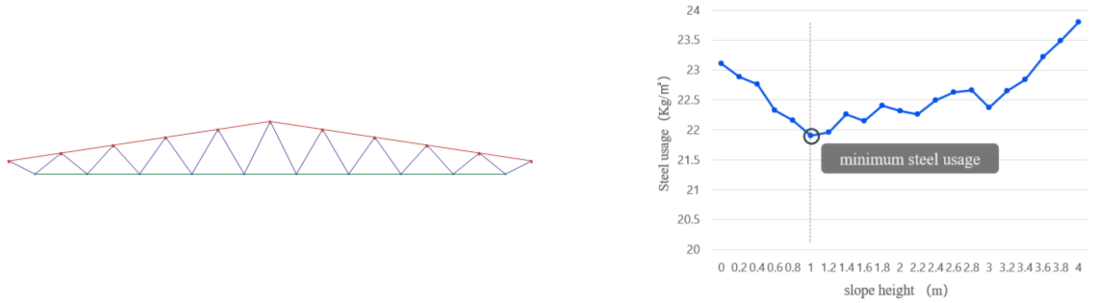

Figure 4: The effect of slope height on steel usage

2.1.1. Single-parameter optimization of thickness

Taking the 90 m × 60 m square pyramid grid as an example, large-scale model comparisons can effectively find the optimal thickness. The minimum and maximum thickness ranges from 2 m to 6 m. The minimum and maximum thickness ranges from 2 m to 6 m, and thickness optimization was carried out with thickness change steps of 0.01 m, 0.05 m, 0.1 m, 0.2 m, 0.5 m, and 2 m, respectively. The number of models compared was 401, 81, 41, 21, 9, and 3, and the corresponding minimum steel consumption is shown in Figure 5:

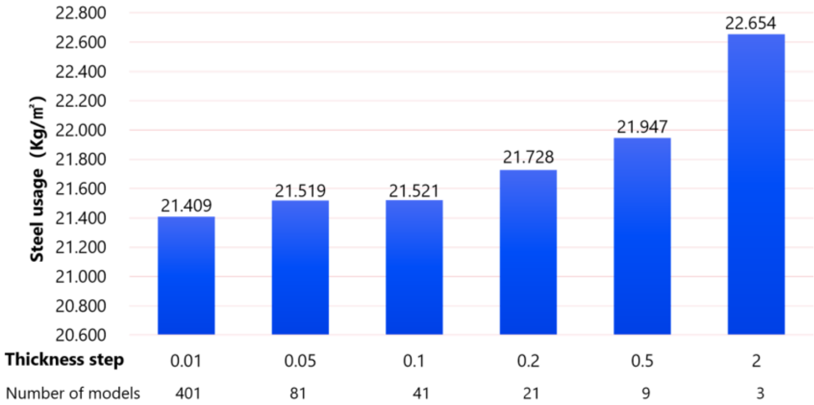

Figure 5: The minimum steel usage corresponding to different thickness increments

If 9 trials are performed manually, the optimal steel usage is 21.947 kg/m^2, total steel usage 118.5 t. Smart design 401 trails, the best total steel usage is 115.6 t, can save 2.9 t steel.

2.1.2. Single-parameter optimization of slope height

The minimum and maximum range of slope height is 4m-4m, and thickness optimization is carried out with slope height variation steps of 0.01 m, 0.05 m, 0.1 m, 0.2 m, 0.5 m, and 2 m, respectively. The number of models compared is 401, 81, 41, 21, 9, and 3, and the corresponding minimum steel consumption is shown in Figure 6:

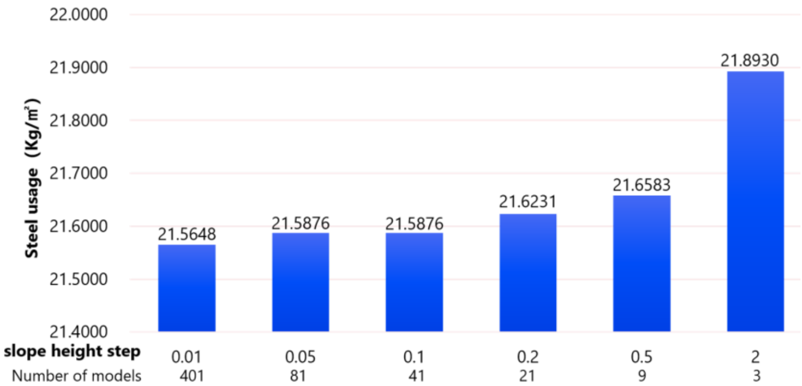

Figure 6: The minimum steel usage corresponding to different slope height increments

If 9 trials are performed manually, the optimal steel usage is 21.658 kg/m^2, total steel usage 117.0 t. Smart design 401 trails, the best total steel usage is 116.4 t, can save 504.9 kg steel. 精度

2.1.3. Multi-parameter optimization

A multi parameter coupled optimization was carried out on the 90 m × 60 m square pyramid grid, including grid size, thickness, and slope height. The optimization intervals of each parameter are shown in Table 1.

Table 1: Interval of each optimization parameter

Optimize parameter	Minimum value (m)	Maximum value (m)
Grid size	3	6
Thickness	2	6
Slope height	0	3

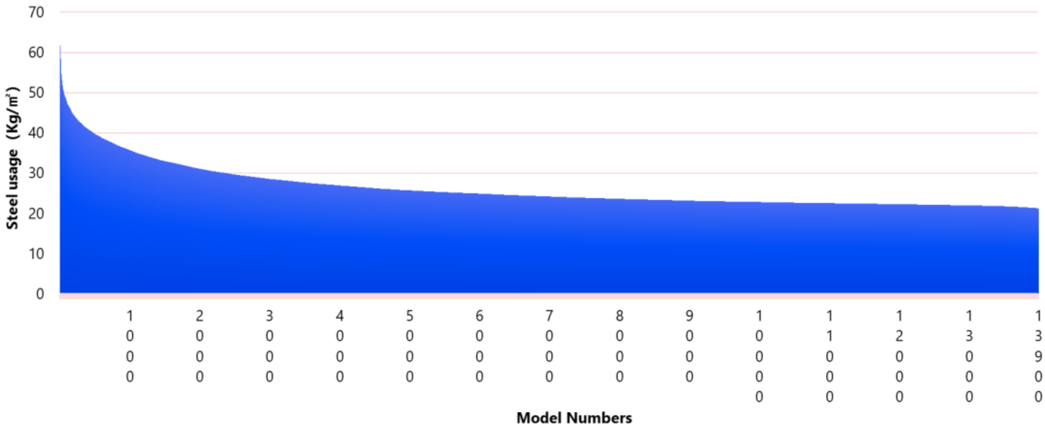

Figure 7: The minimum steel usage corresponding to different model numbers

According to different parameter combinations, a total of 13900 models were generated. Figure 7 shows the relationship between the minimum steel consumption of the structure and the number of models. It can be seen that: The finer the parameter intervals, the more calculation models, and the more the steel usage can be saved.

2.2. Smart design method with variables

The aforementioned smart structural design methods are all based on specific grid shape parameters. Structural models generated through parametric design based on specific patterns can only be optimized using these grid shape parameters. To address the smart design of arbitrary existing spatial structures, this paper proposes a smart design approach based on user-defined variables at nodes. This method assigns the optimization parameters of spatial structures to individual nodes. By setting parameters such as the direction of each node's movement path, the length multiplier and optimization range of the movement path, and the iteration step size, we can couple or decouple these node optimization parameters to generate a batch of structural models. From these models, the optimal one is selected, enabling the parametric intelligent design of arbitrary structures.

Taking a reticulated shell structure as an example, the structural span is 192 m, the length is 60 m, and the height is 50 m. Structural optimization parameters include number of grids in span direction, number of grids in length direction and thickness, The optimization intervals of each parameter are shown in Table 2.

Table 2: Interval of each optimization parameter

Optimize parameter	Minimum value	Maximum value
Number of grids in span direction	20	50
Number of grids in length direction	6	20
Thickness (m)	3	9

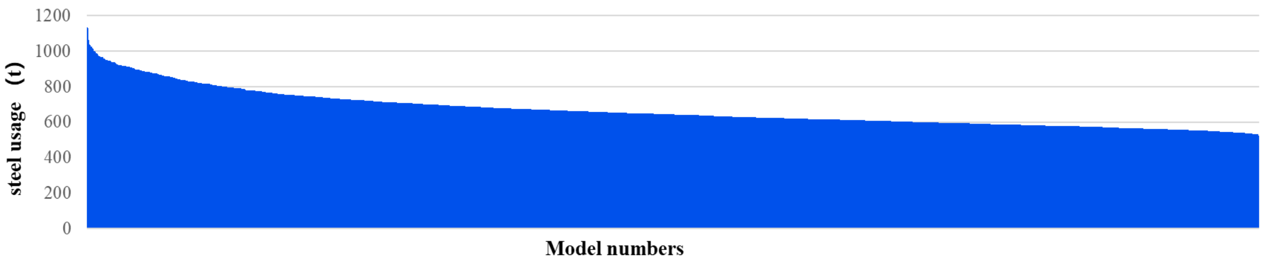

Figure 8: The minimum steel usage corresponding to model numbers

Following the standard grid structure optimization method described above, a total of 1664 models were established for comparative analysis. The optimized results are shown in Figure 8，the difference between the maximum and minimum amount of steel used is 607.6 t. Figures 9 shows the relationship between steel usage and various optimization parameters. The final selected optimization parameters are: 28 grid divisions in the span direction, 8 grid divisions in the length direction, and a thickness of 6.5 m. At this time, the amout of steel used is 526.0 t.

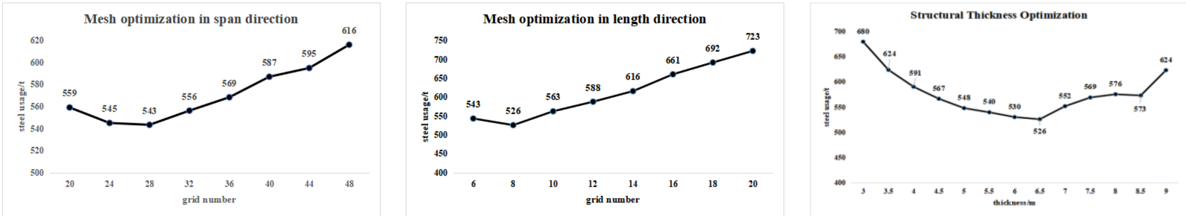

Figure 9: The relationship between steel usage and various optimization parameters

After the optimization of the standard model is completed, the variable thickness optimization of the shell structure is carried out through the smart design method with variables. Set a variable range of thickness increment for each bottom chord node along the length direction, with an optimization interval of -4 m to 4 m and a change step of 0.2 m. A total of 28 optimizable parameters were set, which can generate 3361 models. After optimization, the steel consumption of the model decreased to 483 t and 8.2%. Figure 10 shows the structural profile after standard model smart design is completed, and Figure 11 shows the profile after optimization using the smart design method with variables.

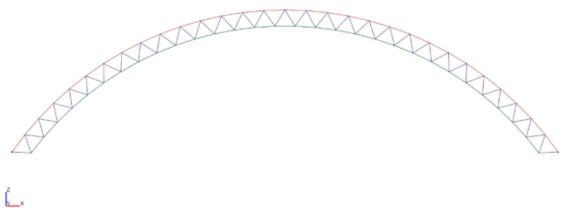

Figure 10: First step, standard model smart design

(chosen from 1664 models)

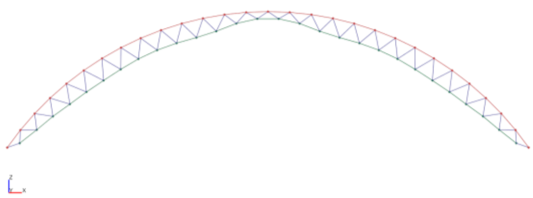

Figure 11: Second step, variables smart design

(chosen from 3361 models)

This approach demonstrates the effectiveness of custom variable-based smart design in achieving significant savings in material usage while maintaining structural integrity and performance. The flexibility and adaptability of the method enable it to be applied to a wide range of structural design challenges, offering a powerful tool for engineers and designers seeking to optimize their designs.

3. Integrated methods for smart design and CNC manufacture

3.1. Integrated method for design and manufacture of members

According to traditional design and manufacture methods, after the completion of reticulated structure with bolt-ball joint design, factory needs to generate manufacture data again according to the drawings to control the CNC machine tool processing, which wastes time and is prone to errors. The integrated method for design and CNC manufacture mentioned in this article refers to: after the design is completed, the program automatically optimizes member nesting, generates the required work orders for the automatic production line of the member, and directly guides the CNC machine tool production line to manufacture members.

The optimization of the nesting of members is extremely important in this process, and the utilization rate of raw materials should be maximized to reduce the total amount of waste. The limitations that need to be noted in the optimization process of nesting include: (1) Considering transportation cost, limiting the minimum and maximum lengths of raw materials; (2) Considering the convenience of factory procurement, limit the maximum allowable types of raw materials; (3) Consider the management cost of the factory warehouse and limit the minimum usage quantity for each material length. When optimizing the nesting of members, all members are first grouped according to their length, and each group of members is nesting using the best fit descending algorithm (BFD), the first fit descending algorithm (FFD), the worst fit descending algorithm (WFD), and the almost worst fit descending algorithm (AWFD). Based on the utilization rate of raw materials, the best nesting scheme for members under several algorithms is selected.

Taking a practical engineering section of P88.5×4 as the example, the total number of members is 659, and there are 70 types of cutting lengths. The minimum cutting length is 3173 mm, and the maximum cutting length is 4608 mm. The table of cutting lengths for members shown in Table 3 (the top 10 types). Table 4 shows the optimized nesting scheme (the top 10 types), and Table 5 shows the statistical table of raw materials after nesting optimization. A total of 8 lengths of raw materials were used, including one 3625 mm length of leftover material that can be reused in future projects. The optimized raw material utilization rate is 99.09%. If the available material length is removed, the raw material utilization rate can reach 99.70%.

Table 3: Cutting lengths for members

Id	Bolt	Name	Steel grade	Section	Weld length (mm)	Cutting length (mm)	Number
1	2M24	1E	Q355B	P88.5×4	3303	3171	17
2	2M24	1EV	Q355B	P88.5×4	3690	3558	26
3	2M24	1EW	Q355B	P88.5×4	3695	3563	4
4	2M24	1EX	Q355B	P88.5×4	3700	3568	17
5	2M24	1EY	Q355B	P88.5×4	3705	3573	11
6	2M24	1EZ	Q355B	P88.5×4	3710	3578	28
7	2M24	1FQ	Q355B	P88.5×4	3710	3578	2
8	2M24	1FA	Q355B	P88.5×4	3715	3583	12
9	2M24	1FR	Q355B	P88.5×4	3715	3583	16
10	2M24	1FB	Q355B	P88.5×4	3720	3588	40

Table 4: Optimized nesting scheme

Id	Raw material length (m)	Used length (mm)	Remaining length (mm)	Number	Componets
1	7240	3588	3625	1	1FS
2	7240	7191	5	1	1FU/1FC
3	7240	7181	15	1	1FC/1FB
4	7240	7195	1	3	1FV/1FB
5	7240	7196	0	16	1FU/1FU
6	7240	7196	0	11	1FW/1FB
7	7240	7196	0	5	1FD/1FD
8	7240	7176	20	12	1FB/1FB
9	7240	7176	20	1	1FB/1FS
10	7240	7176	20	22	1FS/1FS

Table 5: Raw materials after nesting optimization

Steel grade	Section	Length (mm)	Number	Area (m^2)	Weight (kg)
Q355B	P88.5×4	7240	73	3251.16	4405.52
Q355B	P88.5×4	7260	74	3304.8	4478.21
Q355B	P88.5×4	7700	17	805.223	1091.13
Q355B	P88.5×4	7990	66	3243.9	4395.69
Q355B	P88.5×4	8020	7	345.342	467.96
Q355B	P88.5×4	8130	46	2300.51	3117.34
Q355B	P88.5×4	8180	30	1509.56	2045.55
Q355B	P88.5×4	8240	17	861.693	1167.65

After the optimization of nesting is completed, the required data for the CNC machine tool production line is generated according to the nesting scheme to guide the machining of members. Figure 12 shows the running CNC machine tool production line in China. The software can realize the whole process of CNC manufacture for members from cutting, welding, painting and drying.

Figure 12: Running CNC machine tool production line

3.2. Integrated method for design and manufacture of bolt-ball joints

In traditional design software, after the bolt-ball joints design is completed, bolt-ball construction drawings will be generated, and the factory will manufacture it according to the construction drawings. When using CNC machine for bolt-ball manufacture, it is necessary to use software to recognize bolt-ball drawings and generate machining data, which not only has low efficiency but also leads to recognition errors. This article proposes a precise design method suitable for CNC manufacture of bolt-balls, and directly generates CNC machining data in software.

Figure 13: Traditional designed bolt-ball

Figure 14: Precise designed bolt-ball

In traditional bolt ball design in China, equal cutting surfaces, are usually used on the same ball, which can lead to a larger diameter of the bolt-ball. The precise design method accurately determines the cutting surface required for each bolt hole based on the area of the pressure circle required for the sleeve. Figures 13 and 14 show the bolt balls processed using traditional design methods and precise design methods. It is obvious that traditional design method can lead to waste of some cutting surfaces, resulting in larger ball diameters.

To explore the effectiveness of the precise design method for bolt-balls, three design methods were used for bolt-ball joints design on three actual engineering cases of grid structures. Three design cases are: (1) Case 1: As shown in Figure 15, there is a square pyramid reticulated structure with a span of 60 m and a length of 90 m, with a total of 1251 nodes; (2) Case 2: As shown in Figure 16, the pyramid shaped spherical reticulated shell structure has a span of 60 m and a height of 20 m, with a total of 1631 nodes; (3) Case 3: As shown in Figure 17, a three-center cylindrical mesh reticulated shell structure is evacuated, with a span of 100 m and a length of 120 m, with a total of 2275 nodes.

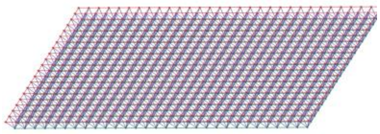

Figure 15: Case 1

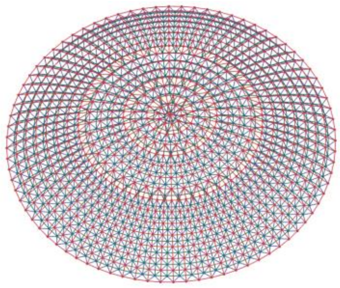

Figure 16: Case 2

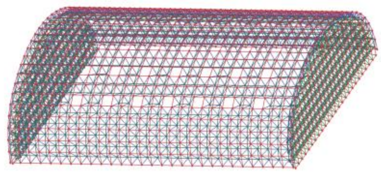

Figure 17: Case 3

Table 6: Comparison of design results

Structure	Design method	Steel usage for bolt-balls (t)	Difference (t)	change rate (%)
Case 1	Traditional design	25.62	/	/
Case 1	Precise design	15.70	-9.92	-38.7
Case 2	Traditional design	17.62	/	/
Case 2	Precise design	12.23	-5.40	-30.6
Case 3	Traditional design	41.16	/	/
Case 3	Precise design	24.54	-16.62	-40.4

Table 6 shows the comparison of design results. It can be found that compared to the traditional bolt ball node design method, the refined design method can save at least 30% of the steel used for bolt balls.

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%
(O0001(130-D1-1)) ;
(X-M) ;
M20 ;
M10 ;
M6 T1 ;
T50 ;
M08 ;
G54 G90 G0 A86.18 Y-0.00 X90.00 ;
G43 Z5.00 H1 ;
M3 S850 ;
G01 Z0.00 F200 ;
G91 G01 Z-4.00 F400 ;
X-90.00 ;
G0 Z4.00 ;
X90.00 ;
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Figure 19: CNC machine control code

Figure 20: CNC machine for bolt-ball

The software can directly generate CNC machine control codes based on the design results of bolt-ball joints, without the need to regenerate them into bolt-ball drawings. The generated code can control the entire process of reference hole, polishing, milling, drilling, chamfering and tapping on the machine. Taking into account the inherent errors of each CNC machine, such as the eccentricity of the rotation center, different precise machining control codes are ultimately generated for each CNC machines. Figure 18 is a schematic diagram of the generated CNC machine tool control code, and Figure 19 shows the CNC machine automatically manufacture bolt-balls.

4. Conclusion

This article studies the integrated methods for smart design and CNC manufacture for reticulated structures with bolt-ball joint:

(1) Proposed smart design methods for standard models and smart design methods with variables. After case comparison, it was found that compared to traditional design methods, smart design can generally save 10% of steel usage;

(2) A design and manufacture integration method suitable for members has been proposed, and a nesting optimization software has been developed, with a raw material utilization rate of up to 99.09%. A precise design method for bolt-ball joints suitable for CNC manufacture is proposed to address the shortcomings of traditional bolt-ball design methods in China, which can save at least 30% of the steel usage for bolt-balls;

(3) The first set of CNC production line for members and bolt-ball joints of reticulated structures has been built recently in China. It can realize the whole process of CNC manufacture for members from cutting, welding, painting and drying, for bolt-ball joints from reference hole, polishing, milling, drilling, chamfering and tapping.

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