Optimization of Spherical Reticulated Shells in Design-build Contract Mode

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ABSTRACT

The structural optimization of spherical reticulated shells is not only a problem of reducing of the steel consumption in the design-build contract mode. There are several objective functions in the question. We should also consider reduction in transport costs and storage charges of components, construction difficulty and construction period. The number of member types is used as a substitute for the secondary indicators by correlation analysis. The objective function is the number of member types and the steel consumption in the end. We carry out the bi-objective optimization by iterative experimental design. The operation process of the method is explained by a case study of 60-meter-span Kewitte single-layer spherical reticulated shell. The example shows this method reduces computational workload, and the convergence rate is fast.1

INTRODUCTION

Design-build contract mode (DB) is a project contract mode which is provided by contractor to provide design and construction services, which is responsible for the whole project cost, time limit and quality. This model reduces the owner's responsibilities, obligations and risks.

Many scholars have done a lot of work on the optimization of spherical reticulated shells. Wang and Tang considered the displacement, stress, rod stability and the stability of the whole structure, the section optimization design of the Kewitte spherical reticulated shell [1]. Zhang, Dong and Huang, taking the displacement and stress as constraints, considering the influence of geometric non-linearity of the structure, the reticulated shell is optimized by taking the lightest weight of the member as the objective function [2]. Mou, Liang, and Sui proposed an improved genetic algorithm to optimize the cross-section of a single-layer reticulated shell [3]. At present, the optimal design of spherical reticulated shell is mostly the optimal design of member section, taking the lightest weight as the objective function, without

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considering the project duration, construction equipment conditions, the quality of construction personnel, construction difficulty, management fees and other factors, which do not conform to the actual situation of the DB model.

Optimization of spherical reticulated shell under DB mode by using uniform iterative design method. Through the correlation analysis of factors, the number of member type instead of the duration of the project, the construction equipment condition, the quality of the construction personnel, the construction difficulty and the management fee. Under the condition of satisfying the displacement, stress and stability, the optimal design of spherical reticulated shell under DB mode is carried out with the least amount of steel and the minimum number of cross section of the shell.

ITERATIVE UNIFORM DESIGN METHOD

The iterative uniform design method is based on the uniform experimental design method to increase the iterative step design method. The uniform design method is applied to the parameter analysis and approximate optimization of the prestressed concrete single-layer shallow reticulated shells, obtained the ideal combination of the optimal level by Xiao, Cao and Ma[4]. The uniform experimental design method has the characteristics of uniform distribution of test points, but due to a limited number of test points, uniform design cannot achieve convex planning, often the first uniform design results cannot meet the design requirements in the practical applications[5]. Based on uniform design, increase the iterative steps, can speed up the convergence of the results and realize the convex set programming.

Through the uniform test design and regression analysis, the functional relationship between the target and the variables can be obtained and can solve the first optimal combination under certain constraint conditions through the mathematical software. Based on the first optimal combination, set the new level to determine the uniform design table for testing, then regression analysis considering the previous test data, make the planning more convex programming. The second optimal combination will be closer to the global optimal combination than the first optimal combination. Assume that the second optimal combination is the global optimal combination, and the first and second optimal combinations are compared. If it is less than a given allowable error $\varepsilon$, that the optimal combination of the second is the real global optimal combination; If the error is larger than a given allowable error $\varepsilon$, that second is not the real optimal combination of global optimal combination, need to continue the iterative uniform design until the error between n, n+1 optimal combinations is less than $\varepsilon$, it can stop the iteration. Since the optimal variable may be a discrete variable, $\varepsilon$ will appear jump phenomenon in the iterative process. In this case, if the error between the combinations is smaller than $\varepsilon$ that the true global optimal solution in between, can still stop by iteration, the optimal value of objective function minimum is a global optimal solution, and the corresponding combination is the global optimal combination.

OPTIMIZATION ANALYSIS OF SPHERICAL RETICULATED SHELL

In general, reducing component types can reduce transportation and management costs. At the same time, the less the section type of the bar, the easier the processing
and installation, the lower the transportation cost and management fee. In addition, it is also beneficial to shorten the construction period. Here to simplify, With the type of section of the member of the approximate replacement of the project duration, the construction of the equipment conditions, the quality of construction personnel, construction difficulty, management fees and other indicators. The minimum amount of total steel (including the amount of steel used for the bar and the amount of steel used for joints) and the minimum number of section types of the bars are closer to the actual target. Due to the different dimensions of each target, the ratio of each target value to the original design value is regarded as a new sub objective. Finally, the weight function of all sub objectives is used as the goal of the optimization model.

The ratio of total steel to initial design is the smallest.

\[
F_1 = \min \left[ \sum_i A_i \rho_i + \sum G_i / G^* \right]
\]

(1)

The ratio of the number of bar sections to the initial design is the smallest.

\[
F_2 = \min \left[ N / N^* \right]
\]

(2)

The total objective function is:

\[
F = \min [\alpha F_1 + \beta F_2]
\]

(3)

Ai is the cross-sectional area of the i-th bar, li is the length of the i-th bar, \( \rho_i \) is the density of the i-th bar, Gi is the weight of the i-th sphere node, \( G^* \) is the sum of the steel weight of the bar in the initial design and the steel weight of the ball joint. N is the number of bar section type, \( N^* \) is the initial design of the bar section type number .\( \alpha \) and \( \beta \) are the weight of each sub-goal, according to the intention of different projects and owners to determine.

CASE STUDY

| \( h/m \) | \( a^0 \) | \( b^0 \) | \( G/m^3 \) | \( F_{\text{max}}/m^3 \) | \( N \) | \( f_{\text{vs}} \) | \|\| |
|---|---|---|---|---|---|---|
| 10(1) | 8(3) | 5(1) | 30.773 | 56.9 | 7 | 1.046 | 45 |
| 10(1) | 6(1) | 5(1) | 36.669 | 56.3 | 8 | 6.004 | 18 |
| 14(3) | 7(2) | 6(2) | 30.835 | 34.6 | 9 | 6.479 | 21 |
| 14(3) | 10(5) | 5(1) | 36.919 | 41.2 | 9 | 4.512 | 30 |
| 12(2) | 7(2) | 7(3) | 30.421 | 40.6 | 9 | 3.315 | 35 |
| 16(4) | 9(4) | 6(2) | 34.250 | 25.7 | 9 | 6.376 | 27 |
| 18(5) | 8(3) | 5(1) | 42.763 | 20.3 | 10 | 15.496 | 24 |
| 16(4) | 7(2) | 8(4) | 32.005 | 21.7 | 9 | 4.969 | 28 |
| 12(2) | 9(4) | 6(2) | 33.957 | 43.7 | 7 | 3.325 | 27 |
| 18(5) | 10(5) | 9(5) | 39.187 | 16 | 6 | 3.255 | 50 |
| 16(4) | 8(3) | 8(4) | 32.087 | 23.8 | 7 | 4.046 | 32 |
| 10(1) | 10(5) | 7(3) | 33.093 | 66.2 | 8 | 1.276 | 40 |
| 12(2) | 9(4) | 8(4) | 34.554 | 38.4 | 8 | 1.973 | 36 |
| 18(5) | 6(1) | 7(3) | 30.898 | 26.8 | 9 | 7.806 | 24 |
| 14(3) | 6(1) | 9(5) | 31.617 | 25.3 | 8 | 3.361 | 30 |
A 60-meter-span Kewitte single-layer spherical reticulated shell is used as an example analysis. Select the reticulated shell height \( h \), the number of circumferential grid \( a \), the number of radial grid \( b \) for the analysis of variables. Dead load standard value is 1.0kN/m\(^2\), live load standard value is 0.5kN/m\(^2\), basic wind pressure is 0.5kN/m\(^2\). The running time of the uniform design table U15 (53) is 3 times of the design level, its CD2 deviation is 0.013149. Test plan and results are shown in Table 1. The data were regressed using Origin software, the approximate function relationships were given.

\[
G = 231.58392 + 22.31929h - 37.43227a - 80.4315bh - 1.75736h^2 + 4.7069a^2 + 10.40767b^2 + 0.07652ha + 0.01594hb + 0.15233ab + 0.04417h^3 - 0.1999a^3 - 0.44999b^3
\]  \hfill (4)

\[
N = 7.43741 + 2.16551h + 3.81802a - 8.55788b - 0.02689h^2 - 1.26605a^2 + 2.05912b^2 + 0.11704ha - 0.28688hb + 0.06742ab - 0.0004263h^3 + 0.07225a^3 - 0.11452b^3
\]  \hfill (5)

\[
W_{\text{max}} = -29.49558 - 53.85421h + 103.59154a + 49.9563b + 3.4569h^2 - 13.09809a^2 - 7.32658b^2 - 0.56272ha - 0.08884hb + 0.05373ab - 0.07057h^3 + 0.58544a^3 + 0.34239b^3
\]  \hfill (6)

\[
\lambda = 0.04143 + 6.93736h + 7.18106a - 17.94972b - 0.37519h^2 - 0.8284a^2 + 2.05912b^2 - 0.07167ha - 0.18994hb + 0.23052ab + 0.01032h^3 + 0.02444a^3 - 0.07669b^3
\]  \hfill (7)

The sub-target weight is \( \alpha = 1, \beta = 1 \), then the approximate objective function is:

\[
F = \alpha F_1 + \beta F_2 = \frac{G + 15\%G}{G^*} + \frac{N}{N^*}
\]

\[
= 8.214368425 + 0.95264214h - 0.769939723a - 3.516801352b - 0.059051071h^2 + 0.009487288a^2 + 0.560816569b^2 + 0.015445585ha - 0.031367038hb + 0.012350742ab + 0.001361743h^3 + 0.001650569a^3 - 0.027080024b^3
\]  \hfill (8)

The optimal level combination problem is reduced to the following mathematical condition extremum problem:
Minimize \[ F(h,a,b) \]
\[
\begin{align*}
L/7 \leq h \leq L/2; 4 \leq a \leq 16; 4 \leq b \leq 16
\end{align*}
\]
\[
\begin{align*}
s.t., N \geq 1 & \quad W_{\text{max}} \leq L/400; \lambda \geq 4.2
\end{align*}
\]

The constraint conditions \( W_{\text{max}} \) and \( \lambda \) according to the Technical specification for space frame structures (JGJ 7-2010) determined, \( L \) is the span of reticulated shell. Using Matlab software to solve the extreme value problem get the first uniform test approximate optimal solution, \( h=18.7427, a=7, b=9, F=1.47978 \). The allowable error \( \varepsilon \) is 1%.

The first iteration uniform test design scheme is shown in Table 4, and four sets of test results are given, combined with the first uniform design data of a total of 19 sets of data, Fitting the new regression equation, solving the approximate optimal solution for \( h=22.3932, a=6, b=10, F=1.5309 \). Compared with the optimal solution of the first uniform test, the error is 3.45%, and the iteration is continued. Second iteration uniform test design scheme see Table 5, combined with the first two uniform test of a total of 23 sets of data, fitting out the new equation, the approximate optimal solution is \( h=19.4804, a=8, b=11, F=1.55732 \). Compared with the first iteration uniform test optimal solution, the error is 1.73%, continue iteration. Third iteration uniform test design scheme see Table 6, combined with the first three uniform test of a total of 27 sets of data, fitting out the new equation, the approximate optimal solution is \( h=17.9463, a=8, b=12, F=1.54345 \). Comparing the results of third iterations and the results of the second iteration, the error is 0.89%, that the iterative convergence, take the results of the third iteration is the optimal combination of \( h=17.9463, a=8, b=12, F=1.54345 \). It can be seen that the iterative uniform experimental design method reduces the design and test times of the test points, accelerates the convergence speed of the results, and gives the ideal design scheme efficiently and quickly.

CONCLUSIONS

The optimization of spherical reticulated shells under DB contract mode is not only a problem of reducing the amount of steel consumption, we should also consider the project duration, construction equipment conditions, the quality of construction personnel, construction difficulty, management fees and other factors. We put forward a more realistic model that the number of member section type is substituted for the project duration, the construction equipment condition, the quality of the construction personnel, the construction difficulty and the management fee, use the amount of steel bar and the minimum section type minimum number as the target of iterative uniform test design method. In this method, the multi-dimension multi-objective optimization problem is transformed into a non-dimensional single objective optimization problem, and the ratio of each target value to the initial design is taken as a sub objective. Finally, according to the sub objective weight to get the goal.

The optimum design of a 60-meter-span Kewitte single-layer spherical reticulated shell is used as an example to illustrate the operation of the method. This method reduces the computational workload, and the convergence rate is fast.
REFERENCES