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Global shape optimization of free-form cable-stiffened latticed shell based on local optimal solutions

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ABSTRACT

In the present work, local optimal solutions in shape optimization of cable-stiffened latticed shells are discussed and a modified optimization method is presented. Firstly, a shape optimization method is used to minimize the strain energy of different kinds of cable-stiffened shells. It can be confirmed that local optimal solutions exist in this shape optimization problem. Secondly, in order to get smooth solutions, this paper puts forward a modified optimization method, in which total length of members or smoothness parameter is employed as a correction term in the optimization equation. In this approach, the modified equation can be solved by weight sum method. The results indicate that smooth optimal solutions can be obtained by solving this equation. Finally, a variable weight method is proposed to achieve the global optimal shape from any initial shape in one-step optimization. In this approach, the weight changes along with the iteration process. The results illustrate that this method is efficient and the global optimal shape is achieved successfully.

1. Introduction

Cable-stiffened single-layer latticed shell is a new type of long-span space structures, which comprises ordinary single-layer latticed shell and the cable-stiffened system. The stability of the single-layer latticed shell can be improved significantly. It has been applied to several engineering projects [1–3], and some research achievements can be found regarding the cable-stiffened single-layer latticed shells [4–7]. As the surface shape has a great influence on the structure behaviours, it is very important to find a shape with the best structure behaviours in given architectural appearance and constraint conditions.

Many effective methods have been proposed for free-form shape optimization. Ohmori et al. [8] have found bending free forms for both axisymmetric shells and spatial structures, and the bending moment is used as optimization objective. Bletzinger et al. [9] presented numerical methods which combined free-form shells optimization and physical experiments for structural optimization. Chen et al. [10] presented a method to find a lattice space frame with maximum nonlinear buckling load and generalized reduced gradient (GRG) method was used. This method was supposed to find the local optima near the initial design parameter point. Fujita et al. [11,12] proposed an approach for shape optimization of Bezier surface shell. Strain energy was used to represent the mechanical performance and sequential quadratic programming (SQP) was used as the optimization algorithm. Toğan et al. [13] proposed a new adaptive penalty scheme and adaptive mutation and crossover to increase the probability of catching the global solution and enhance the performance of GAs. Feng et al. [14] proposed a shape optimization method that can be applied to the optimization for one kind of cable-stiffened single-layer latticed shell, in which quadrangular meshes are diagonally stiffened by cables. Richardson et al. [15] proposed a two-phase approach to the preliminary structural design of grid shell. In this approach form-finding technique and genetic algorithm optimization are employed. Cui et al. [16] proposed a node shift sensitivity method to optimize single-layer grid shells, and in this method nodes can move freely in 3D space. A morphogenesis method for the topology and shape optimization of framed structures subject to spatial constraints is proposed by Cui [17]. Shimoda et al. [18,19] proposed parameter-free shape optimization methods for shell and frame structures, and the shape gradient function and the optimality conditions are derived.

Some research has been done on multi-objective problems for shape optimization with different non-mechanical properties and mechanical properties. The roundness of surface and uniform member lengths are considered as the second optimization objective respectively by Ohsaki et al. [20,21]. Ohmori et al. [22] proposed a scheme of computational morphogenesis for the shell structures constructed with completely arbitrary curved surface, and the multi-objective genetic algorithm was utilized for obtaining the Pareto solutions. Winslow et al. [23] proposed a design tool for synthesis of optimal grid shell structures. A multi-objective genetic algorithm was used to vary rod directions over the

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surface in response to two or more load cases. Feng et al. [24] proposed a multi-objective optimization method which combines section optimization with shape optimization. This method can be applied to the optimization for one kind of cable-stiffened single-layer latticed shell, in which quadrangular meshes are diagonally stiffened by cables. Ikeya et al. [25] presented an optimization method for designing both the shape and thickness of shell structures.

Generally, there are some different local optimal shapes in the solutions of shape optimization problem. Some of the local optimal shapes are non-smooth solutions that cannot be applied in practical engineering, and therefore these solutions should be avoided by some techniques. In the literatures mentioned above, geometric modeling techniques are widely employed in optimization method to avoid the non-smooth solutions, however, it should be noted that these techniques lead to more restrictions for the nodal coordinates. Thus, the optimization method to avoid non-smooth solutions with less restrictions is proposed in this current work.

In this paper, a study on local optimal solutions and a modified optimization method in shape optimization is taken, meanwhile two kinds of cable-stiffened latticed shells are considered. The minimization of strain energy is employed as the optimization objective and the interior-point method [26] is adopted to solve the constrained optimization problem. Firstly, an optimization equation is established and a numerical example is carried out. The results illustrate that both smooth and non-smooth solutions are obtained. All the solutions satisfy the Karush-Kuhn-Tucker (KKT) conditions, which proves that local optimal solutions exist. Secondly, in order to obtain smooth solutions in feasible region, a modified optimization method is presented. In this approach, the total length of members or the smoothness parameter is added into the optimization equation as a correction term, respectively. This modified equation can be solved by the weight sum method [27]. Finally, a variable weight method based on the modified optimization method is proposed, and the results indicate that the global optimal shape can be achieved from any initial shape by this method.

2. Cable-stiffened latticed shell

This section introduces a basic latticed shell model and two kinds of cable-stiffened systems. The cable-stiffened latticed shells employed in the following sections are based on the latticed shell and cable-stiffened systems.

2.1. Structural parameters

In the present study, a two-way single-layer latticed shell with rectangle plan is adopted, as shown in Fig. 1. In the O-XYZ coordinate system in Fig. 1, the span of the shell equals 58.54 m, and it is divided into ten parts from −29.27 m to 29.27 m along the x-axis and the y-axis equally. The z-coordinates of points are obtained by different interpolation approaches.

A steel pipe with radius of 300 mm and thickness of 10 mm is employed as the post and the member of the two-way latticed shell. It is modeled as beam element with Young's modulus and Poisson's ratio of 206,000 MPa and 0.3, respectively. The length of the post equals 1 m. The pretensioned cable is modeled as truss element with area, Young's modulus and Poisson's ratio of 261.41 mm^2, 160,000 MPa and 0.3, respectively. It can take compressive force in the present study. A uniform load of 20 kN is applied on each point of the latticed shell, and it is pin-supported on the boundary. The z-coordinates of the boundary are set to 0 m.

In order to keep the rise-span ratio less than 1/10 approximately, the maximum and the minimum z-coordinates of points are limited to 6 m and −6 m, respectively. The feasible region can be written as:

$$\begin{cases} \mathbf{Z}_{\min} = -6 \text{ (m)} \\ \mathbf{Z}_{\max} = 6 \text{ (m)} \end{cases} \tag{1}$$

2.2. Cable-stiffened systems

Two kinds of cable-stiffened systems are employed in this paper, the schematic diagrams are shown in Figs. 2 and 3. In the cable-stiffened system 1 as shown in Fig. 2, diagonal pre-tensioned cables are used in the two-way latticed shell. The in-plane shear rigidity of the shell is improved by this cable-stiffened system [7].

In the system 2 as shown in Fig. 3, one end of a post is attached to each point and the other end is connected to the points at diagonal corners by pre-tensioned cables. The out-of-plane bending rigidity of the shell is improved by this system [7].

Usually, four points connected to one post are not in the same plane. As the schematic diagram is shown in Fig. 3, the normal vector of the plane I formed by points a, b and c is $\boldsymbol{n_1}$, and the plane II formed by points a, c and d is $\boldsymbol{n_2}$. Taken the average of $\boldsymbol{n_1}$ and $\boldsymbol{n_2}$ as the direction vector $\boldsymbol{n_p}$ of the post, the coordinates of the post point $p(x_p,y_p,z_p)$ can be calculated by its direction vector $\boldsymbol{n_p}$, its length l and the coordinates of point i (x_i,y_i,z_i).

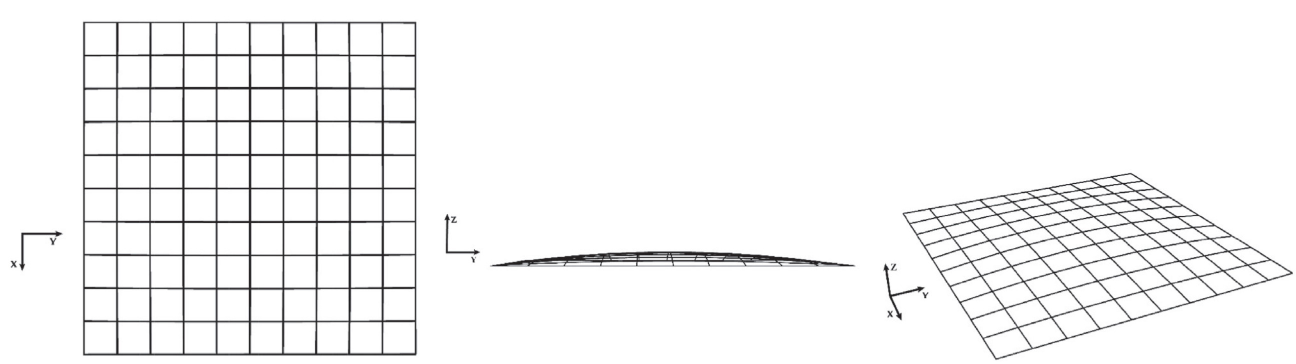
$$\mathbf{n_1} = \overrightarrow{ac} \times \overrightarrow{ab} \qquad \mathbf{n_2} = \overrightarrow{ad} \times \overrightarrow{ac} \qquad \mathbf{n_p} = \frac{\mathbf{n_1} + \mathbf{n_2}}{|\mathbf{n_1} + \mathbf{n_2}|} \tag{2}$$

$$(x_p,y_p,z_p) = (x_i,y_i,z_i) + l\cdot\mathbf{n_p} \tag{3}$$

3. Optimization method and local optimal solutions

3.1. Optimization equation

The minimization of strain energy is employed as the optimization objective and the z-coordinates of the points are employed as



(a) Vertical view (b) Front view (c) Overall configuration

Fig. 1. The two-way latticed shell.