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Research on stability of single-layer inverted catenary cylindrical reticulated shells

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ABSTRACT

The structural configuration and method of analysis of the single-layer inverted catenary cylindrical reticulated shell are introduced in this paper, and the elastic as well as elastic–plastic stability of this kind of reticulated shell is then investigated. The stability of the structures with different types of grid patterns is compared, and the reasonable grid pattern is hence recommended. The structural buckling mode and ultimate load-carrying capacity are studied in detail by parametric analysis. Influence of various factors on structural ultimate load is investigated, and the fitting formula of ultimate load is thus presented. Comparison analysis between the inverted catenary and circular cylindrical reticulated shells is also carried out. The work will provide guidance in theory for practical applications of this kind of structure.

1. Introduction

A growing interest in long span space reticulated structures has been witnessed worldwide over the past half century. The search for new structural forms to accommodate large unobstructed areas is always the main objective of architects and engineers. A large amount of theoretical and experimental research programs was carried out by many universities and research institutions in various countries. As a result, a great deal of useful information has been disseminated and fruitful results have been put into practice.

The space reticulated structures can be formed either in a flat or a curved surface [1]. A cylindrical shell is a typical developable curved surface, having a zero curvature in the direction of generatrix. Cylindrical reticulated shells are the simplest type of reticulated shells. They represent the mechanical properties of reticulated shell and can be shortened or lengthened conveniently according to different demands. Therefore, the cylindrical reticulated shells are extensively employed although their horizontal thrust to supports cannot be avoided. The inherent curvature in a reticulated shell will give the structure greater stiffness, so reticulated shells can be built in single layer grids [2]. However, since the single layer latticed shells are easily liable to buckling [3–5], the span should not be too large. Research on stability of single-layer reticulated shells, including the circular cylindrical reticulated shells, has been conducted over the past 30 years and fruitful results have been obtained [3–12]. The circular cylindrical reticulated shells, in which the circular segment is taken as the directrix, have also been investigated since the 1990s in China [13–14], and the simplified calculating formula of ultimate load-carrying capacity of the single-layer circular cylindrical reticulated shell has been obtained and adopted by the *Technical specification for latticed shells* (*JGJ61-2003*) of China [15]. However, little research was focused on the cylindrical reticulated shells formed by other types of directrix.

The pure tensile or compressive geometries are generally regarded as the optimum shapes of shell structures. As a pure compressive geometry, the inverted catenary arch is certainly an optimum structural shape. A new type of cylindrical reticulated shell, inverted catenary cylindrical reticulated shell, can be formed when the inverted catenary arch is selected as the directrix of the developable reticulated shell. This paper is focused on research of the single-layer inverted catenary cylindrical reticulated shell. The structural configuration and method of analysis of this kind of reticulated shell are first introduced, and the structural elastic as well as elastic–plastic stability is then comprehensively and systematically investigated, and the fitting formula of structural ultimate load is also presented.

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2. Structural configuration and method of analysis of the single-layer inverted catenary cylindrical reticulated shell

2.1. Structural configuration

A catenary, a curve of pure tension, is formed when a cable is suspended at each end and allowed to hang freely. Also, its geometric equation can be derived and expressed as follows.

$$z(x) = C\left[\cosh\left(\frac{S}{2C}\right) - \cosh\left(\frac{x}{C} - \frac{S}{2C}\right)\right] \tag{1}$$

$$H = C\left[\cosh\left(\frac{S}{2C}\right) - 1\right] \tag{2}$$

in which, C is constant, S and H are the span and midpoint sag of the cable, respectively, as shown in Fig. 1.

The pure compression geometry can be formed by inverting the form of the hanging model, and the single-layer inverted catenary cylindrical reticulated shell is then obtained when the inverted catenary is taken as the directrix. Like the circular cylindrical reticulated shell, three different types of grid patterns of the single-layer inverted catenary cylindrical reticulated shell are considered in this paper. Namely, the orthogonal grid with single bracing of Pratt truss, orthogonal grid with single bracing of Warren truss and the three-way grid, as shown in Fig. 2, which are simply called Type-I, -II, and -III grid patterns, respectively. All the structures consist of circular steel tube members. As shown in Fig. 2(b), S, L, and H denote the structural span, length, and the rise, respectively. The structural rise–span ratio f and length–span ratio $LtoS$ can then be expressed as $f = H/S$ and $\mathrm{LtoS} = L/S$, respectively.

As we know, it is necessary to set supports on the two longitudinal edges of a cylindrical shell to supply horizontal thrust for the shell, whereas, the ends of the shell do not always need supports. For the inverted catenary cylindrical reticulated shell in this paper, the fixed-hinged supports are set on the two longitudinal edges as shown in Fig. 2, in which the black dots denote the supporting points. Moreover, three-dimensional (3D) trussed arches are set on both ends of the structure to keep the structural integrity.

Also, double layer grids are recommended for the cylindrical reticulated shells supported along longitudinal edges with a transverse span larger than 25 m. Hence, the structural span S of the analytical models of the inverted catenary cylindrical reticulated shell in this paper is constantly taken as 24 m.

As usual, the full-span uniformly distributed dead load g as well as the half-span uniformly distributed live load p are vertically applied on the structure as shown in Fig. 3, and different values of the ratio of live to dead load (p/g) are taken to consider the asymmetry of load distribution in analysis.

2.2. Calculation model and method of analysis

In this paper, the finite element method [16] is used to study the stability of the single-layer inverted catenary cylindrical reticulated shell, and the ANSYS Software [17] is employed to carry out the analyses. The beam element BEAM189 is selected to simulate the structural members since the effect of large deformation, large rotation, and large strain can be considered by it. Joints between elements are considered as rigid connection, and the uniform loads are transferred as equivalent nodal loads on the structures. Both the geometrical and material nonlinearities are considered in analysis. Also, an incremental–iterative method based on the Newton–Raphson method combined with constant arc length [18–21] is adopted to track the equilibrium path. The load related to the first buckling is defined as the structural ultimate load. The steel is regarded as ideal elasto-plastic material and the von Mises yield criterion is adopted in the analyses with consideration of the material nonlinearity. Additionally, 32 integration points in a cross section of the Beam189 element are considered for the circular steel tube members, and thus the whole process of plasticity spread of members can be fully understood by checking various integration points.

In order to control the analysis flow, an input file is programmed using the ANSYS Parametric Design Language (APDL) [22], which is a scripting language that enables the user to automate common tasks or even build the FE model in terms of parameters. A single-layer star-shaped reticulated shell consisting of 24 members, the classic numerical example discussed by Meek [23], is adopted to verify the accuracy and efficiency of the proposed implementation. As shown in Fig. 4(a), the 24-member reticulated shell with the supports assumed to be pinned and restrained against translational motion is subjected to concentrated load at the central node. The load–displacement curve by Meek [23] and that by present analysis are displayed in Fig. 4(b).

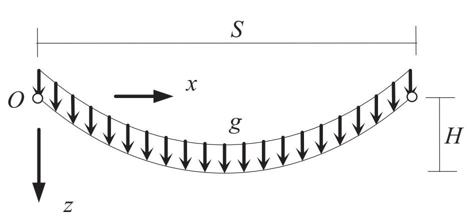

Fig. 1. The geometric shape of catenary.

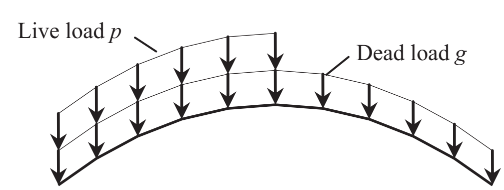

Fig. 3. Distribution of the live and dead loads.

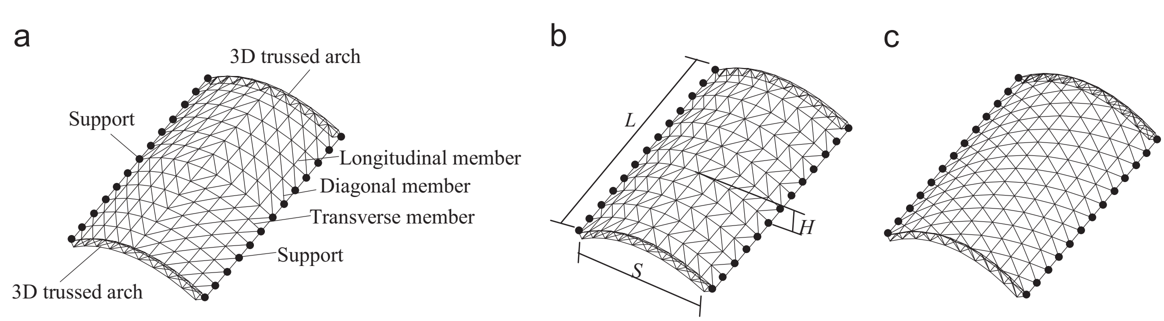

Fig. 2. Grid patterns of single-layer inverted catenary cylindrical reticulated shell. (a) Orthogonal grid with single bracing of Pratt truss (Type-I), (b) orthogonal grid with single bracing of Warren truss (Type-II), and (c) three-way grid (Type-III).