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Modeling and structural behavior of cable-stiffened single-layer latticed domes of hexagonal meshes

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ABSTRACT

As an effective structural system, the cable-stiffened single-layer latticed shell of quadrangular meshes have been extensively studied and used in many projects. This paper proposes the cable-stiffened single-layer latticed shell of hexagonal meshes. In order to reveal its working mechanism and evaluate its structural mechanical behavior, a geometrical modeling method for single-layer latticed dome of hexagonal meshes is presented firstly, then two planar hexagonal structures with and without cables are comparably analyzed, where the structural in-plane stiffness are compared and the influences of cable section and cable pretension on in-plane stiffness are studied, and the structural working mechanism of cable-stiffened hexagonal structure is presented. Last, three pairs of domes of hexagonal meshes with and without cables are numerically created and comparably analyzed, where the following structural behaviors are compared: (1) member strength and stability; (2) stiffness; (3) static stability. The results indicate that all the structural behaviors of single-layer latticed domes of hexagonal meshes are significantly improved by the introduction of the prestressed cables.

1. Introduction

As a main type of spatial structures, single-layer latticed shells have been widely used. Among all the polygonal meshes, triangular mesh is the best in terms of stability and stiffness, so most of the single-layer latticed shells are meshed with triangles.

The single-layer latticed shell of quadrangular meshes without any stiffening measures is seldom used in engineering practice due to its weak stability and stiffness. However, as a structural strengthened system for single-layer latticed shell of quadrangular meshes, the cable-stiffened single-layer latticed shells of quadrangular meshes have been extensively studied and applied in several projects. The prestressed cables or rods are introduced as the diagonal braces into the quadrangular meshes to enhance stability and stiffness of the shell. Schlüterhof Roof in German historical museum [1] shown in Fig. 1 is a typical project of this kind of structures.

There are many researches about the theoretical analysis, designing method and construction process of this kind of structures. Schlaich [2,3] analyzed the mechanical principles and presented some typical engineering applications. Schober studied the form-finding of hippo house at the Berlin zoo [4]. Wu analyzed the introducing process of cable prestress [5]. Umezawa analyzed the buckling load increase of the Kumagaya dome after the prestressed rods were set [6]. Douthe illustrated the working mechanisms of grid shells with a test model made of paper tubes [7]. Zhang studied the strength and buckling of cable-stiffened cylindrical lattice shells [8]. Liu has done static and dynamic analyses on the double-curved flat grid shell [9]. Feng used the translational surfaces technique on the shape optimization of free-form cable-braced grid shells [10]. Moreover, many researches can be found regarding the stability of cable-braced grid shells [11–20].

Due to the same reason – weak stability and stiffness – the single-layer latticed shells of hexagonal meshes are seldomly constructed. However, from the architectural viewpoint, compared with single-layer latticed dome of triangular meshes, the members are relatively sparsely distributed in single-layer latticed shell of hexagonal meshes, and lightness and transparency effect can be obtained together with glass or membrane roof covering materials. Similar to cable-stiffened single-layer latticed shell of quadrangular meshes, in order to enhance the structural mechanical behavior of single-layer latticed shell of hexagonal meshes, the cable-stiffened single-layer latticed dome of hexagonal meshes is proposed in the paper, and the structural composition of the whole structure and unit are shown in Fig. 2, where the prestressed cables or rods are introduced as the diagonal braces into the hexagonal meshes. In order to study its structural mechanical behavior, a geometrical modeling method for single-layer latticed dome of hexagonal meshes is presented in the paper firstly, then the mechanical behaviors of single unit and whole structure are studied.

2. Geometrical modeling of single-layer latticed dome of hexagonal meshes

It is obvious that the key of geometrical modeling of cable-stiffened single-layer latticed dome of hexagonal meshes lies in the model of the

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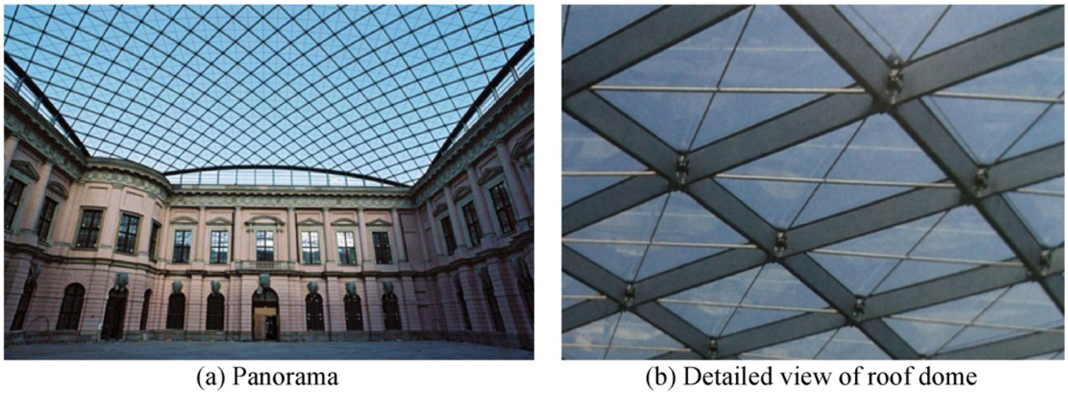

Fig. 1. German historical museum.

corresponding single-layer latticed dome, because the cables are easy to be created if only the dome is modeled. A geometrical modeling method for single-layer latticed dome of hexagonal meshes is proposed, and the dome created by this method has the following characteristics:

1) The nodes of the dome are in a smooth surface nearly identical to a sphere.
2) Each hexagon is in a plane, which is necessary for the installation of glass or other roof materials.
3) All members except those at the dome margin are in equal length, which facilitates the manufacture and lead to a neat architectural effect.

2.1. Geometrical modeling process

According to the method, the modeling process is illustrated as follows together with Fig. 3, where each sub-figure corresponds to each step below, and in each sub-figure, the solid lines denote the members created before the step, while the dash lines denote the members being created in the step:

1) The central hexagon: a regular hexagon with side length of l is created, whose central point is point O, from which six axes (OA, OB, etc.) originate and pass through the midpoint of each side line. The dome has the same geometry in every two adjacent axes.
2) The plane and partial members of second hoop hexagons: six planes passing through six side lines of the central hexagon are created respectively, and all the six planes have the same angle θ with respect to the central hexagonal plane. As the key parameter which determines the overall shape of the dome, θ can be calculated according to the span, rise and member length of the desired dome by iteration method. The six dash lines (1–4, 2–3, etc.) starting from the six vertices are the intersections of every two adjacent planes, and the lengths of all the six lines are taken as l, thus forming the partial members of the second hoop hexagons.
3) The other members of the second hoop hexagons: in each plane of the six hexagons of the second hoop, mirror the partial members (4–1, 1–2, 2–3, etc.) with the lines passing through the outer endpoints of the adjacent dash lines as the mirror lines (3–4, etc.), the other lines (4–6, 6–5, 5–3, etc.) of the second hoop hexagons can be obtained.
4) The hexagons of the third hoop between the adjacent axes: between axis OA and axis OB, as the side lines of one hexagon in third hoop, line 6–4 and line 4–7 will determine a plane denoted as $P1$, and another plane passing through point 6 and parallel to line 1–4 is denoted as $P2$, then line 6–8 of l in length is created by intersection of plane $P1$ and plane $P2$. Line 7–9 can be obtained by the same method. In the plane $P1$, mirror line 6–4 and line 4–7 with the line passing through the midpoints of line 6–8 and line 7–9 as the mirror line, line 8–10 and line 10–9 can be gained, thus completing the hexagon. The other corresponding hexagons between the other adjacent axes can be created by the same method.
5) The hexagons of the third hoop on the axes: It can be verified that line 12–11, line 11–6 and line 6–8 are in a common plane, where mirror line 12–11, line 11–6 and line 6–8 with the line 8–12 as the mirror line, line 12–13, line 13–14 and line 14–8 can be gained, thus the hexagon on axis OA is completed. The other five corresponding hexagons on the other five axes can be created by the same method.
6) The hexagons of the fourth hoop between the adjacent axes: between axis OA and axis OB, two hexagons will be created in the

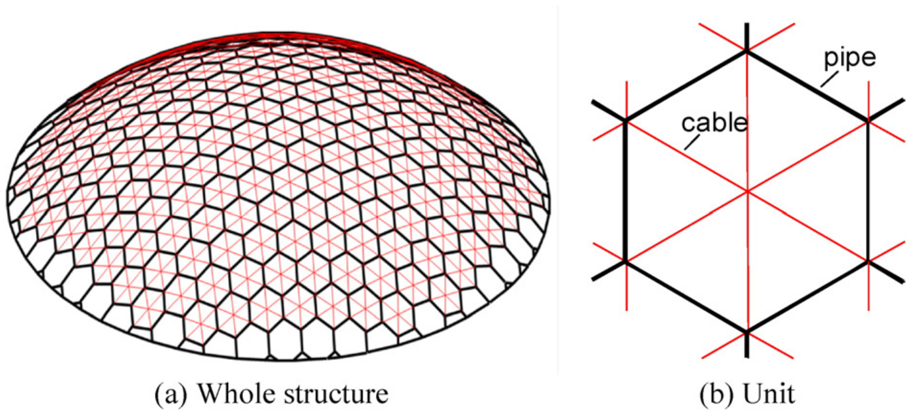

Fig. 2. Cable-stiffened single-layer latticed dome of hexagonal meshes.