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Experimental and numerical studies of instability mechanism and load resistance of rhombic grid hyperboloid-latticed shells under vertical load

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ABSTRACT

This paper presents the instability mechanism of an innovative Rhombic Grid Hyperboloid-Latticed Shell (RGHLS) under vertical load through experimental and numerical investigations. The RGHLS is only composed of bidirectional inclined primary and secondary columns without any circumferential members or lateral braces in its radial direction along its height. Therefore it would likely fail by out-of-plane multi-column interaction instability and the corresponding load-carrying capacity should be predicted. The experimental investigation of a reduced-scale test model of RGHLS was firstly performed to study its vertical load-carrying capacity and the multi-column interaction instability. A special spatial beam-string device for vertical multi-point loading of the test model has been initially designed and fabricated to precisely distribute the concentrated load to the top of the columns according to proportional distribution of loads required by designers. The experimental results revealed that the inclined columns indeed exhibited strong mutual restraining actions, and the ratio of the actual ultimate load-carrying capacity of the test model to its design load was 3.37, indicating a reasonable safety margin. In addition, FE numerical results of the test model corresponded well with the experimental results. Ultimately, additional FE numerical analyses have been conducted on the test model. Accordingly the effects of the ratio of stiffness between the secondary and primary columns, overall initial geometric imperfection, in-plane stiffness of top ring beam, and dimensions of portal columns on the load-carrying capacity and failure mode of RGHLS have been investigated extensively. As a result, the ratio of stiffness between the secondary and primary columns has been particularly recommended within a range of 0.46–0.70, so as to eliminate premature failure of X-joints prior to the instability of columns in the prototype of RGHLS.

1. Introduction

The China Comic and Animation Museum (CCAM) is located in Hangzhou, China. Its largest plane dimension is 165 m × 55 m. There are 6 floors above ground, and the overall height of the CCAM is 44.5 m. As illustrated in Figs. 1 and 2, there are steel frame structures on the first floor and above, and there are 6 hyperboloid-latticed shells with different diameters on the ground floor as vertical sub-structures to bear the structures above. This paper selects the RGHLS denoted by Y2 in the structure of the CCAM as the research subject. As illustrated in Fig. 3, the RGHLS (Y2) is formed by rotating two sets of vertical straight columns on the cylindrical surface by 60 degrees in clockwise and anti-clockwise directions separately. As a result, the RGHLS possesses larger diameters at the top and bottom, while a smaller one at its mid-height. The RGHLS (Y2) is 9.93 m in its overall height with 37 m and 35 m in its top and bottom diameters, respectively.

The RGHLS is a type of diagird structures that has been developed in recent years. It is favored by architects due to its concise and transparent design as well as its artistic building forms, and it has been widely adopted in high-rise building and TV tower structures. When the diagird structure is adopted in high-rise buildings with a core inside, it bears mainly horizontal loads induced from wind or earthquake and possesses excellent lateral stability because the slab connects the diagrid structures and the core. Hence, most civil engineering researchers have focused on investigations of the lateral stiffness and resistance [1,2], shear lag effect [3], aseismic performance [4,5], and progressive collapse resistance [6,7] of diagird structures.

In the structural design of the CCAM, the RGHLS (Y2) was designed to release horizontal loads by installing isolation rubber bearings on the top of the top ring beam, and it would be prone to fail by out-of-plane multi-column interaction instability only under vertical load because of the rhombic grids and a lack of circumferential members (except the

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(a) Front elevation (b) Bird's eye view

Fig. 1. Architectural rendering of the China Comic and Animation Museum.

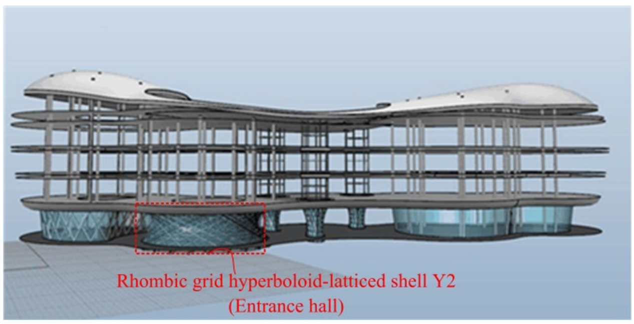

Fig. 2. Structural system of the China Comic and Animation Museum.

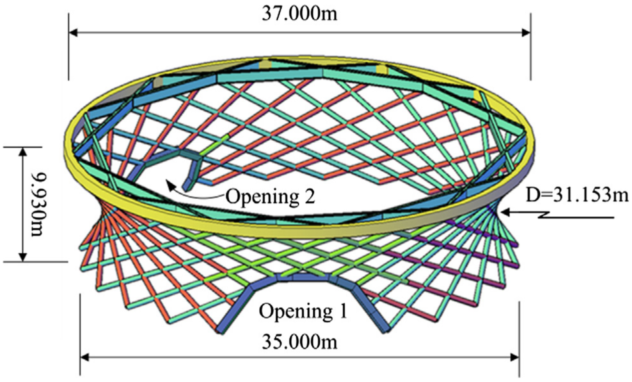

Fig. 3. Schematic structural illustration of the RGHLS (Y2).

top ring beam) and lateral braces in the radial direction along the height of the RGHLS (Y2). Moreover, in order to satisfy the architectural functional requirements, two different sized openings (opening 1 and opening 2, Fig. 3) have been set up in the RGHLS (Y2). This would further reduce the instability load of such structure, thus the out-of-plane multi-column interaction instability is a major concern for structural design of the RGHLS (Y2). Furthermore, different sizes of circle hollow sections of the primary and secondary columns were adopted in their design because the ratio of stiffness between them is a factor that may cause premature failure of the X-joints.

Structural system similar to diagrid structures was initially applied in aeronautical and aerospace technologies. As illustrated in Fig. 4 [8–10], the structures that are formed by interweaving the inclined columns are named as grid structures. They were typically utilized as the structural elements of airplane frames, payload fairings of launch vehicles and load-bearing structures of satellites [11,12]. They are made out of composite materials, and a skin that is also made out of composite materials is adhered to the surface of the grids.

Instability is still a main concern and research focus for grid structures. The earliest relatively mature linear analysis method of elastic grid structures was presented by Reddy et al. [13] in 1985. They classified the buckling modes of grid structures subjected to axial compression as grid crippling, skin buckling and global buckling, respectively, where the former two buckling modes are known as local buckling. In addition, a smeared analysis method where a grid structure is represented by an equivalent continuous homogeneous elastic cylindrical shell was proposed. Obviously the smeared method is computationally efficient to execute and accurate for calculating global buckling but deficient for local buckling. In the same year, Wang and Hsu [14] proposed a discrete method, where the skin and grids were modeled separately with compatibility maintained at their interfaces. It is able to capture both global and local behavior as well as ensuring high accuracy. However, it is too time consuming and therefore not widely utilized. Afterwards, Jaunky et al. [15] found that the traditional smeared method may overestimate the buckling load of grid strictures in a certain range of geometric parameters because the traditional smeared method dose not account for local skin-grids interaction effects. Hence, an improved smeared method was developed. Wang and Abdalla [16] adopted the Bloch wave theory in the smeared method, which overcomes the deficiency of traditional smeared method for local buckling. With the rapid development of heavy-lift launch vehicles, the scale of grid structures becomes much larger. Wang et al. [17] presented a numerical-based smeared stiffener method (NSSM) by combing the numerical implementation of asymptotic homogenization (NIAH) method with Rayleigh-Ritz method, whose computational time could remain stable with the substantial increase of model scale.

Besides, instead of considering linear buckling in traditional smeared method, Gotsulyak and Siyanov [18] investigated the nonlinear stability of grid structures, and Shi et al. [19] presented the initial buckling and post-buckling response of axial loaded grid structures with reinforced cutouts. It is found that the grid structures are weakly sensitive to imperfection and grid reinforcements near the cutout area are more effective than the skin reinforcements. Wu et al. [20], Wodesenbet et al. [21] and Beerhorst and Hühne [22] developed optimization procedures for grids structures separately, which were efficient for the preliminary design of grid structures.

In terms of experimental investigations, Kim [8] conducted experimental investigations on stability of isogrid stiffened cylinders subjected to axial load, and pointed out that rib buckling is the critical failure mode of such structures. Ren et al. [9] and Kidane et al. [10] conducted experimental investigations on kagome grid stiffened composite cylinders, and found out that the local skin buckling of such structures would induce global buckling mode.

The aforementioned stability theories and experimental investigations on the grid structures were extremely intensive and comprehensive. However, the research was limited to cylindrical-shaped grid structures as they were adopted in aeronautical and aerospace fields, and cross sections of bidirectional grids were designed same. The current available research on the stability of hyperboloid latticed shells includes the theoretical and experimental investigation on the waist portion and the bottom open-space region of the Guangzhou New TV Tower by Guo et al. [23–27], focusing on their out-of-plane multi-column instability mechanism and strength design method. The findings revealed the multi-column instability mechanism of the primary columns, and the effect of diagonal bracings and circumferential members on the load-carrying capacity of the primary multi-column. As compared to the triangular grids in the Guangzhou New TV Tower, there are no circumferential members in the RGHLS (Y2) of the CCAM.