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Experimental and numerical investigation into the load resistance and hysteretic response of rhombic grid hyperboloid-latticed shells

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ABSTRACT

The rhombic grid hyperboloid-latticed shells (RGHLSs) in the China Comic and Animation Museum (CCAM) are located on the ground floor, and they sustain enormous vertical and horizontal loads induced from upper building structures on top of them. Each RGHLS consists of numerous bidirectional inclined major and secondary columns that intertwine with one another to form a rhombic grid with X-shaped joints. Without both horizontal circumferential members and horizontal lateral braces in the radial direction of the RGHLS, as well as the existence of significant difference of compressive stiffness between major and secondary columns, the RGHLS would ultimately fail in a complicated form of in-plane and out-of-plane multi-column interaction instability in addition to its overall twist deformation under relatively low vertical loads. Currently, no design method for estimating its design strength and safety is available. Therefore, the load-carrying capacity of the RGHLS must be examined experimentally. This paper selects the RGHLS denoted by Y4 in the structure of the CCAM as the prototype, and presents an experimental investigation of its reduced scale (1:1/4) test model. A loading protocol consisting of six loading phases has been devised in order to predict the static vertical and horizontal load resistance, and horizontal hysteretic response of the RGHLS by keeping the amplitudes of the vertical load constantly as 1.0, 1.4 and 1.6 times the vertical design load of the reduced-scale test model, respectively. The experimental results obtained indicate that the test model remains elastic under 1.8 times its design loads, which is commonly adopted as static structural strength limit in practical design in China. In addition, horizontal cyclic load test indicated that the reduced-scale test model demonstrated sufficiently large horizontal load-carrying capacity as well as exhibited stable and ample hysteretic curves even under 1.6 times vertical load actions without any obvious stiffness reductions. This study comprehensively introduces the experimental test schemes and deeply analyzes the experimental results, thus forming an important basis for designing the load-carrying capacity of such RGHLSs. Ultimately, according to the experimental loading protocol, numerical simulations and analyses of the test model have been conducted by adopting ANSYS 12.1. The interaction strength design curve of the test model under a combination of vertical and horizontal loads is also proposed by carrying out additional numerical simulations of the model. The FE and experimental results have been compared, and they correspond well to one another, indicating that the results of the reduced-scale test model are accurate enough and reliable.

1. Introduction

The CCAM [1] is located in Hangzhou, China. The overall building of the CCAM is 44.5 m in its height, and its maximum plane dimension is 165 m× 55 m. The overall architectural rendering of the CCAM is illustrated in Fig. 1(a), and its structural composition is illustrated in Fig. 1(b).

The CCAM consists of six RGHLSs with different diameters on the ground floor. One of the smaller RGHLSs with an elliptical plan denoted by Y4, as illustrated in Fig. 1, is focused in this study. Its dimension at the bottom is 9 m× 8 m, and its top elevation is 10.4 m. A 3D model of the RGHLS (Y4) is illustrated in Fig. 2.

The RGHLS is designed not only to sustain mainly the vertical load N resulted from the dead and live load of the overall building structure, but also to sustain horizontal load H induced from seismic or wind actions. The RGHLS consists of bidirectional inclined major and secondary columns that intertwine with one another to form the hyperboloid-latticed shell. Due to the architectural requirement, circumferential members were removed from early structural design, thus leading to the hyperboloid-latticed shell with a rhombic grid. The major

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Nomenclature

B	dimensions of the portal columns used in the FE model, mm
B_0	current dimensions of the portal columns in the reduced-scale test model, mm
C	kinematic parameter, dimensionless
D	dead load, kN
E	Young's modulus of each steel member, GPa
EX	x-direction seismic actions, kN
$f_{y,p}$	yield strength of steel members in the prototype, MPa
$f_{y,m}$	yield strength of steel members in the reduced-scale test model, MPa
$f_{u,m}$	ultimate strength of steel members in the reduced-scale test model, MPa
H	horizontal load, kN
H_m	horizontal load-carrying capacity of the reduced-scale test model, kN
H_p	horizontal load-carrying capacity of the prototype, kN
$H_{p,d}$	design value of the horizontal load of the prototype, kN
H_d	design value of the horizontal load of the reduced-scale test model, kN
H_u	horizontal ultimate load-carrying capacity of the RGHLS subjected to the horizontal load alone, kN
h	height of each story, mm
L	live load, kN
M	moment applied at bottom of the RGHLS that is induced from the horizontal load H at its top, kNm
N	vertical load, kN
N_m	vertical load-carrying capacity of the reduced-scale test model, kN
N_p	vertical load-carrying capacity of the prototype, kN
$N_{u,r}$	vertical load-carrying capacity of the FE model adopting different dimensions of the portal columns in the reduced-scale test model, kN
$N_{u,1.0}$	vertical load-carrying capacity of the reduced-scale test model alone, kN
$N_{p,d}$	design value of the vertical load of the prototype, kN
N_d	design value of the vertical load of the test model, kN
n	number of kinematic hardening model to be superimposed, dimensionless
r	variation factor of the dimensions of the portal columns in the reduced-scale test model, dimensionless
s	reduction factor between the prototype and the reduced-scale test model, dimensionless
T	temperature effect, kN
U_z	vertical displacement at the top of the test model, mm
W	wind load, kN
α	back stress, MPa
γ	kinematic parameter, dimensionless
ν	Poisson's ratio, dimensionless
Δu_e	structural story drift, mm
$[\theta_e]$	story drift angle, dimensionless
Δ	horizontal displacement at the top of the model, mm
ε_y	initial yield strain of steel members, dimensionless
$\bar{\varepsilon}_{pl}$	equivalent plastic strain, dimensionless

(a) Architectural rendering of CCAM

(b) Structural system of CCAM

Fig. 1. The architectural rendering and structural system of the CCAM.

columns are designed as straight inclined members in the major direction without any stops from the bottom to the top of the RGHLS, and they sustain the major percentage of the vertical loads. The secondary columns have to be segmented in a helical direction in order to form the hyperboloid-latticed shell, and they are welded to the major columns through full penetration butt welds. It is well known that the secondary columns sustain much less vertical load than the major columns. Therefore, the vertical compressive stiffness of the major columns is significantly higher than that of the secondary columns in the RGHLS. As a result, overall twist deformation about a vertical center line of the RGHLS would occur when it buckles globally under the vertical loads. Furthermore, in addition to the direct vertical load, the RGHLS sustains a combined in-plane and out-of-plane bending moment actions on its surface at the waist portion, making the RGHLS prone to fail by multi-column interaction instability. The multi-column interaction instability failure mechanism is very complex and there is very little research being conducted on the failure mechanism as well as the design method for estimating overall load-carrying capacity of the RGHLS. Detailed design method and calculations for its load-carrying capacity have not been established so far.

Strength design methods of continuous cylindrical shells have been established fairly comprehensively by previous researchers. Tsien [2] and Donnell [3] derived the load-carrying capacity of the continuous cylindrical shells under axial compression by using equilibrium method. Schmidt [4] investigated the load-carrying capacity of continuous cylindrical shells under uniform axial compression through numerical analysis based on stability theory of cylindrical continuous shells, and corresponding calculation method was provided. In the book "Theory of elastic stability" written by Timoshenko [5], the elastic buckling loads of the cylindrical shells under uniform axial compression, uniform lateral external compression, and a combination of both have been derived, respectively. In addition, in the book "The stability design guide of steel structure" written by Chen [6], the design methods for predicting the buckling strength of the cylindrical shells under axial compression, external uniform compression, shear force, and a combined axial and radial compression have been given, respectively. Recently, Rathinam and Prabu [7] conducted a sensitivity analysis of initial geometric imperfection on the critical buckling load of a thin cylindrical shell. FE method was adopted to investigate the influence of a centrally located dent on the critical buckling load of the cylindrical