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Seismic response and failure mechanism of single-layer latticed domes with steel columns and braces as substructures

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ABSTRACT

Seismic response and failure mechanism of single-layer latticed domes with steel columns and braces as substructures are studied using incremental dynamic analysis in the paper. The member models considering cyclic buckling and low cycle fatigue of steel are used in the analyses. The results show that the seismic responses will be greatly influenced by the material low cycle fatigue under strong earthquakes in different ways for the domes with different parameters. Two typical failure modes are found for the structures: one is the failure of domes and the other is the failure of both the dome and the substructure. Influence of rise-span ratio of domes, brace sections and column sections in substructures on the ultimate PGA and yielding PGA are studied, and the optimized values of the parameters are suggested for structural designing.

1. Introduction

As a common form of spatial structures, single-layer latticed dome has been used world widely including earthquake prone areas. The seismic response analysis of single-layer latticed dome under small earthquakes could be performed with little difficulty, but single-layer latticed dome tends to deform large and reach plasticity under severe earthquakes, so the geometrical and material nonlinearity, cyclic behaviour of members, and even fracture should be considered during the analysis under severe earthquakes [1–3].

Most of the single-layer latticed domes are built upon substructures such as columns, but the seismic response research under severe earthquakes originates from the domes without substructures. Kato et al. [4] investigated the dynamic response characteristics of single layer latticed domes subjected to horizontal earthquake motions, and the statically equivalent seismic forces and the approximate collapse accelerations as a function of the safety factor for domes under self weight were expressed in the paper. The complicated failure mechanism of single-layer latticed domes was illustrated with time history analysis and two failure modes-dynamic instability and dynamic strength failure-were discussed systematically [5], then the criterion for distinguishing the two failure modes according to the fuzzy synthetic evaluation theory was proposed [6]. Besides the theoretical and numerical studies above, some shaking table tests were also performed to study the collapse and failure pattern of singe-layer reticulated domes under severe earthquakes [7,8] and verify the numerical method for the dynamic analysis of single-layer latticed domes [9].

The literatures above are restricted to single-layer latticed domes without substructures, but the interaction between the dome and the substructure in dynamic responses is complicated and can not be neglected [2]. The seismic responses of single-layer latticed domes can be much reduced by means of yielding of substructures [10]. Yu et al. [11] investigated the influence of elastic concrete columns upon failure characteristics of single-layer latticed domes under seismic loads and the reasons which caused the influence were discussed. The results show that the stiffness of substructure has great effect on the failure behaviors of domes. Sun et al. [12] investigated the dynamic stability behaviour of single-layer latticed domes with V shape columns under seismic loads, and the results show that the stiffness of the substructure can play a very important role in the dynamic stability behaviour of the dome. The effect of BRBs in the substructures on the seismic resistance of single-layer reticulated domes was examined by Kato et al. [13] and Zhi et al. [14]. The failure mechanism of reticulated domes with reinforced concrete columns as substructures under severe earthquakes was studied with the nonlinear dynamic response analysis by Yu et al. [15], in which three different failure modes and the discrimination criterion were illustrated, and it has been found that reinforced concrete substructure has significant impact on the failure behaviors and the critical load of reticulated domes under seismic loads.

As an effective and economic structural component, ordinary steel

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pipe braces or W-section braces have been widely used to provide lateral stiffness for structures. Despite several studies on the domes with BRBs in substructures above, the seismic behaviour including failure mechanism of single-layer latticed domes with ordinary braces in substructures have not been studied. In this paper, typical single-layer latticed domes with steel columns and braces as substructures are modeled, and the structural failure mechanism together with the influence of rise-span ratio *R* of domes, brace sections and column sections in substructures on the seismic responses are investigated by incremental dynamic analyses (IDA).

2. FEA model and method

The computational framework Open System for Earthquake Engineering Simulation (OpenSees) [16] is used to create the numerical models and do the analyses, where all the structural members are modeled by fiber-based nonlinear beam-column elements.

2.1. Models of single-layer latticed domes with substructures

Single-layer latticed domes of Kiewit 8 system with columns and braces as substructures are created as shown in Fig. 1, and the main model parameter values are given in Table 1. All the structural members including ring beams, columns and braces are assumed steel circular pipe and rigidly connected, the sections of which are determined according to Chinese code for design of steel structures GB50017 [17], and the sections of dome members are shown in Appendix Fig. A1. All the column bottoms are rigidly fixed. The yield stress is 345 MPa and the Young's modulus $E = 2.06 \times 10^5$ MPa, Super dead load of 1 kN/m^2 on the dome is converted to nodal masses.

The nine FEA models shown in Table 1 are denoted with the symbol Dn$_1$-n$_2$, where n$_1$ represents reciprocal of the rise-span ratio *R* and n$_2$ represents the brace slenderness ratio.

The static stability capacity tends to be the control factor in the structural designing of single-layer latticed domes, so the ultimate load factors P_S of static stability under the combination of dead load of 1 kN/m^2 and live load of 0.5 kN/m^2 are depicted in Fig. 2, from which it can be seen that all the coefficients exceed 2, the minimum allowable value specified in the Chinese technical specification for space frame structures JGJ7-2010 [18], and the static stability capacities are hardly influenced by the brace sections.

2.2. Analytical method considering material low cycle fatigue and member cyclic buckling

In the low-cycle fatigue analysis of metallic material, Coffin-Manson theory [19,20] is widely used, in which the relation between the strain amplitude ε_i experienced in each cycle and the constant amplitude cycle numbers to failure N_f can be expressed as the following equation:

$$\varepsilon_i = \varepsilon_0 (N_f)^m \tag{1}$$

Table 1
Model parameters of domes.

Parameter	Value
Span (*L*)	80 m
Column height (H)	10 m
Rise-span ratio ($R = f/L$)	1/3, 1/5, 1/7
Ring beam section	∅400 × 24 mm
Column section	∅325 × 18 mm
Brace slenderness ratio and section	100(∅299 × 12 mm),124(∅245 × 14 mm), 140(∅219 × 14 mm)

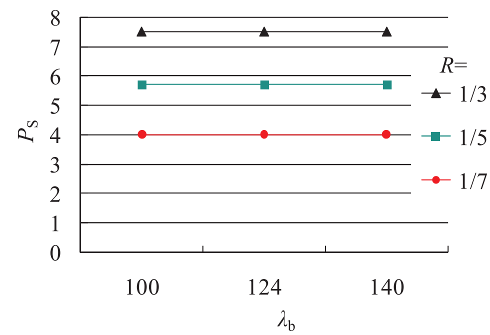

Fig. 2. Ultimate load factors P_S of static stability.

where ε_0 denotes the strain amplitude at which one whole cycle of an undamaged material will cause failure. *m* is a sensitivity parameter between the total strain amplitude and the cycle numbers to failure. The equivalent damage for one cycle with the strain amplitude of ε_i during cycling would be:

$$DI_i = \frac{1}{N_{fi}} = \frac{1}{10^{m^{-1}\log(\varepsilon_i/\varepsilon_0)}} \tag{2}$$

The total damage can be calculated by summing the damage of all cycles:

$$DI = \sum DI_i \tag{3}$$

Wrapping around a uniaxial material, a low cycle fatigue model suitable for fiber-based nonlinear beam-column element is developed based on the theory above in OpenSees by Uriz [21], where *DI* in each section fiber can be real-time recorded, and the normal stress of the fiber will be zero when *DI* of the fiber reaches one, thus simulating the failure of section fibers. The two parameters ε_0 and *m* need to be calibrated by the hysteretic tests data for the fatigue model to be used.

Studies [22–24] show that member buckling and postbuckling behaviour plays a great role in seismic response of single-layer reticulated domes under severe earthquake. In order to simulate the cyclic behaviour and low cycle fatigue of steel members subjected to cyclic loading under earthquakes, a modeling method incorporating the low cycle

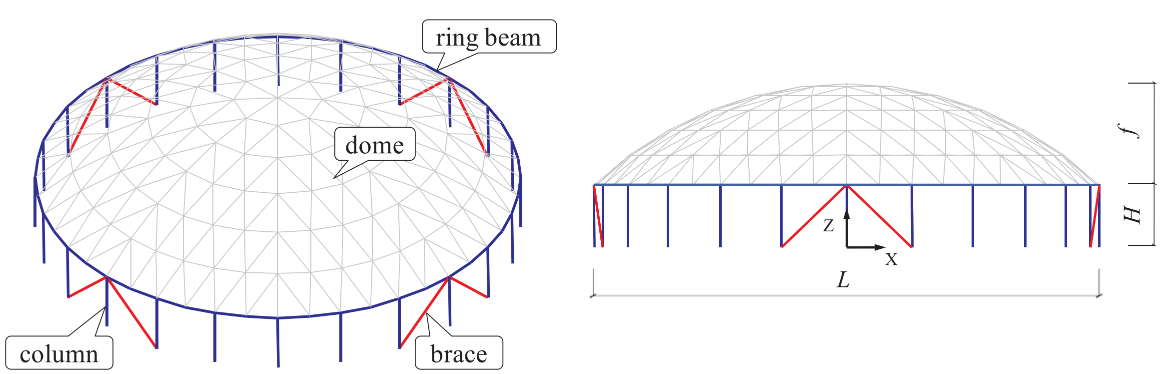

Fig. 1. Single-layer latticed dome with columns and braces.