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Seismic performance evaluation of single-layer reticulated dome and its fragility analysis

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ABSTRACT

In order to have a better understanding of the failure mechanism of a single-layer reticulated dome under seismic load, parametric analyses through increment dynamic analysis (IDA) are conducted on the dome. The results of the analyses indicate that the limit load of the structure significantly increases together with the plastic development with the decreasing rise–span ratio, roof mass and initial defects prior to the failure to collapse. The plastic development reduces and the structural ductility gets worse as the cross-section area of a structural member decreases. The failure of a single-layer reticulated dome under a strong seismic load is due to the failure in dynamic strength resulting from the excessive damage of material. A structural damage model which can estimate different degrees of damage of the dome is defined. Then, the fragility curves of the different values of the structural damage model with the corresponding different degrees of damage under seismic records are obtained through IDA analysis which can be used for seismic performance evaluation and risk assessment for its loss or fatality acceptability. A theoretical guidance is thus provided for the engineering application of this kind of structure.

1. Introduction

As more and more large-span space structures are used in such public facilities as exhibition halls, stadiums and railway stations in recent years, reticulated domes have attracted much attention from the civil engineering community because of their reasonable bearing mechanism, light deadweight, high stiffness and lively novel forms. Their obvious geometric nonlinear effect is believed to be particularly important to the instability. Much work has been done on this particular aspect in resent years. For example, [1,2] investigated the bucking collapse of a steel reticulated dome through nonlinear elastic–plastic hinge analysis and found that the collapse load of the structure was reduced by the geometric imperfection of nodal coordinates and the semi-rigidity of the connections. The collapse load of the structure was estimated using the axial strength of each member. [3] investigated the buckling characteristics of a single layer of two-way grid shell under gravity loads by evaluating its nonlinear behavior and the ultimate strength of the structure. [4,5] investigated the stability of a single-layer dome with initial curvature of members using random imperfection mode and modified consistent imperfection mode methods and found that the structural buckling mode and the development of plasticity would be changed with the initial curvatures of members.

The seismic performance of a reticulated dome is not only directly related to the safety of a building, but also has a huge impact on the socio-economic development and the security of people. It is therefore of great significance to study the seismic performance of a large-span space structure under different seismic loads. [6] observed the local and global dynamic instabilities by conducting the shaking table tests of two shallow reticulated domes under seismic loads. The law of defining the structural dynamic instability was proposed by the sudden changes in the responses curves. [7] studied the influence of form parameters and support styles on the cylindrical reticulated megastructure with single-layer substructure. [8] investigated the dynamic collapse mechanism of a single-layer reticulated dome under seismic loads using computing program ABAQUS and distinguished the failure pattern by the structural responses at the failure state. [9] studied the influence of a substructure on the failure behavior of a single-layer reticulated dome under severe earthquake. Results showed that the failure characteristics and failure load of the structure under severe earthquake were greatly influenced by the substructure.

In order to use probability statistics method to study and forecast the seismic performance with different damage degrees, the performance levels of concrete structures were specified in [10–12]. Many structural fragility analyses had been made under different seismic loads. For example, [13] divided the destruction into seven grades with different damage degrees. [14] presented a framework for seismic risk evaluation, which included site risk analysis, seismic vulnerability analysis and seismic damage analysis. [15] used two analysis approaches

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together with a hazard combination technique to evaluate the seismic risk in the Vancouver metropolitan region in Canada. [16] used stochastic ground motion models for characterization of seismic hazards. [17] utilized the response surface modeling (RSM) technique for rapid estimation of the seismic damage to track-on steel-plate-girder (TOSPG) bridges. However, the fragility analyses done on reticulated domes are still at the exploratory stage.

Therefore, the seismic performance of a single-layer reticulated dome is evaluated using a structural damage model with different damage degrees defined under seismic records.

2. Numerical calculation model and analysis method

2.1. Numerical calculation model

As shown in Fig. 1, the model used for the evaluation is a Kiewit single-layer reticulated dome supported by three directionally fixed hinges. It has the initial defects with size of L/300 (L is the span of the dome) and the first-order mode of structure vibration. Each member in the structure is divided into 3 segments, using a PIPE cross-section with 8 integration points. 1P means at least one integration point into the plastic and 8P means the whole cross-section into the plastic. The cross-section of each member satisfies the requirements for a conventional design. The Rayleigh damping with a ratio of 0.02 and the Q235B steel refers to China Code (GB700-88) with a yield strength of 235 N/mm^2, carbon content between 0.12 and 0.20 percentage is used as the material of the member adopted in the calculation process. The user-defined material sub-routine UMAT incorporating ABAQUS is used to simulate the influence of accumulated damage and the rupture of material. Material damage factor D in the sub-routine is defined in the form of formula (1), and the corresponding elastic modulus and yield strength of the steel are defined in the form of formulae (2) and (3), respectively. Thus, the constitutive model with the accumulated damage of material taken into account can be used for the analysis of a large span space structure under strong seismic loads. This constitutive model is derived by [18] from the hysteretic performance experiments of multi circular steel pipes.

$$\mathrm{D} = (0.9732)\frac{\varepsilon_m^p}{\varepsilon_u^p} + 0.0268\sum_{i=1}^{N}\frac{\varepsilon_i^p}{\varepsilon_u^p} \tag{1}$$

$$E_{\mathrm{D}} = (1-0.404\,\mathrm{D})E \tag{2}$$

$$\sigma_{\mathrm{D}} = (1-0.063\,\mathrm{D})\sigma_S. \tag{3}$$

2.2. Analysis method

Time–history analysis method is commonly used nowadays for the calculation of the seismic performance of a structure under seismic loads, because the records of ground motions can be directly inputted into the structure to reflect the response of a structure under the seismic load to overcome the shortcomings of response spectrum method and pushover analysis method. Incremental dynamic analysis (IDA) can be used for the nonlinear response analysis of a structure under different seismic loads, based on the nonlinear dynamic time–history method. This method can give the reliability level of the corresponding structure and describe its performance from the view point of probability statistics, thereby becoming the most promising analytical method for the seismic performance evaluation of structures.

The performance of a structure is evaluated by analyzing the relationship between the intensity measure (IM) of a seismic load and the damage measure (DM) of a structure. As different IM and DM represent different performances of a structure and the corresponding discreteness of the curve, for the purpose of IDA analysis in this paper, PGA is used as the parameters of IM.

3. Parameters analysis for a single-layer reticulated dome

A total of 50 ground motions with class II of soil type are selected for the study in this paper and the records of ground motions are downloaded from the websites of U.S. Pacific Earthquake Engineering Research Center. With a single-layer reticulated dome with a span of 40 m used as the object, a large-scale parametric analysis is carried out with all the parameters shown in Table. 1.

3.1. Effect of rise–span ratio

As a single-layer reticulated dome under stress is sensitive to the change in shape, the rise–span ratio is a key factor having its influence on the shape of the structure. The rise–span ratio has also an important effect on the mechanical properties of a structure under a seismic load.

As shown in Fig. 2, for a single-layer reticulated dome with a roof mass of 60 kg/m^2, the limit failure load of the structure is significantly enhanced with the decreasing rise–span ratio, because the structure with a smaller rise–span ratio is flatter and so, the effect of the seismic horizontal component is relatively reduced. For the vertical seismic action, the structure has a higher seismic tolerance capacity because of the mechanical characteristics of a single-layer reticulated dome. The maximum node displacement of a reticulated dome at the moment of failure increases with the decreasing rise–span ratio, because the vertical vibration is the main vibration pattern, which brings the membrane force of the structure into full play so that the anti-seismic performance is better for the same deformation. The structural responses at the time of failure indicate that the failure of the structure is a failure in dynamic strength. The ratio of 1P and 8P members at the moment of failure increases with the decreasing rise–span ratio, which means a wider scope and a deeper extent of plastic development in the structure.

3.2. Effect of roof mass

As shown in Fig. 3, for a single-layer reticulated dome with a rise–span ratio of 1/3, the limit failure load of the structure significantly reduces with the increasing roof mass and causes a more severe structural damage, because the structure with a bigger roof mass is subjected to a greater seismic force under the same seismic intensity. The maximum

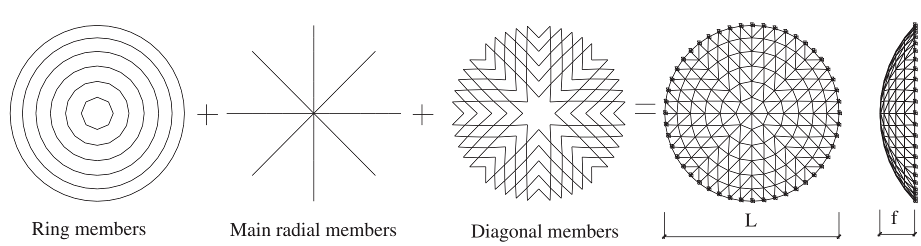

Fig. 1. Numerical model.