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Influence of number of records and scaling on the statistics of seismic demand for lattice structure

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ABSTRACT

Seismic design codes prescribe general guidelines to select a small number of ground motion records to be used to calculate the seismic demand for design. In particular, Chinese design codes recommend criteria for selecting three record components and for selecting seven record components to be used for seismic analysis and design. The statistical origin of the criteria as well as the preferred intensity measure for the record scaling are unknown; their adequacy for lattice domes has not been investigated and elaborated. This study evaluates the statistics of seismic responses of the single-layer reticulated dome due to limited number of record components, and investigates the effect of using the PGA and SA based scaling on the statistics of the responses. The time history analysis is carried out using 166 selected record components. Statistics of the maximum of seismic load effects on structural members, support reaction and base shear are obtained based on the analysis results by considering all records, and randomly sampled 3 and 7 records according to code criteria. The results are used to make recommendations on the preferred intensity for scaling the records and the number of record components (three or seven) to be used to analyze and design such domes under seismic load.

1. Introduction

Seismic responses of structural systems can be estimated using the time history analysis for selected ground motion records. The responses of interest may include the maximum displacement, drift ratio, base shear, stress, and ductility demand. Since the seismic ground motion is stochastic and varies from record-to-record, the peak structural responses under seismic excitations are uncertain. To reduce the computing time and to facilitate engineering practice, the seismic design codes [1–4] prescribe general guidelines to select a small number of ground motion records used to calculate the seismic responses for structural design and checking. Loosely speaking, the codes require that the selected records after scaling should “match the design spectrum”, and the average or envelop of structural responses for the selected and scaled records are to be used for the structural analysis and for judging the adequacy of the designed structures. There are difficulties in record selection because of the record-to-record variability, and the combinations of magnitude and site-to-source distance contributing to seismic hazard [5,6], which can be identified through deaggregation analysis [7,8].

The commentary to NBCC [3] recommends that typically seven or more records (i.e., record components) that are compatible with the response spectrum should be used. The ASCE/SEI-7-10 [4] stipulates that at least three appropriate ground motions shall be used in the analysis, and that the historical records should be selected from records of events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake. Two criteria for scaling and selecting the number of records for space frame structures are recommended by the Chinese code applicable to space frame structures [1,2]. The first one indicates that if three records are used, the envelop of the maximum response from the time history analysis results, and the response obtained by the modal combination analysis with the design spectrum needs to be considered. The second criterion requires that if seven or more than seven records are considered, the average of the time history analysis results for all the selected records is to be used. In both cases, the records are to be scaled to target peak ground acceleration (PGA) value prescribed by the code. The target value depends on the structural category and site condition.

In all cases, it appears that the imposed minimum number of records is based on engineering experience rather than comprehensive statistical analysis [9], and the influence of small sample size (i.e., small number of records) on the statistics of responses of multi-degree-of-freedom (MDOF) system has not been investigated, especially considering the criteria stipulated in [2] with

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additional restrictions to be elaborated in the following sections. The consideration of the MDOF system is important for structures with closely spaced vibration periods such as the light weight single-layer reticulated domes [10–12]. This structural type is often built for sports stadiums, gymnasiums, and auditoriums. However, the rationale for imposing a minimum number of records to be used for seismic design and checking, including that stipulated in [2] for lattice shell structures, could not be found in the literature. Moreover, the scaling of the records based on the PGA could be questionable because the uncertainties or dispersions associated with the estimated seismic demands depend highly on the variable adopted as the intensity measure for the scaling [13]. In fact, Fan et al. [14] showed that the use of the spectral acceleration (SA) value at the fundamental vibration period as the intensity measure (or scaling) provides a largely reduced dispersion in the maximum displacement of the lattice dome as compared to that by using the PGA as intensity measure. This is consistent with the observation that the most appropriate intensity measure in terms of sufficiency and efficiency seems to be the SA for buildings [13]. It must be emphasized that the reduction of the dispersion of the maximum displacement of the lattice dome observed in [14] may not be applicable to seismic load effects such as structural member forces, support reactions and base shear which are important for design and sizing structural members. This is because these seismic load effects could be affected by multiple modes or modes with "localized" effects.

The main objectives of this study are to evaluate the statistics of seismic responses of the single-layer reticulated dome due to limited number of records (i.e., small sample size effect), to investigate the effect of the PGA based and SA based scaling on the statistics of the seismic responses if a small number of records is used, and to discuss their implication on the Chinese design code for space frame structures, including lattice domes [2].

2. Considered dome and ground motion records

2.1. Reticulated dome and seismic design requirements

The reticulated dome that is considered in this study and shown in Fig. 1 has been investigated by others [10–12]. The dome has a diameter of 60 m and the height to diameter ratio of 1/5 which is within the range of 1/3–1/7 often recommended for practical construction [2]. The dome is pinned at each node at the ground level (i.e., each of the nodes in the outer ring). The geometric and material properties of the structural members are shown in Table 1. The dome is modeled using ANSYS® Multiphysics 10.0 [15] with 289 joints and 800 members. Each structural member of the reticulated dome is represented by three PIPE20 elements, each with 8 integration points. This element is a uniaxial element with tension–compression, bending, and torsion capabilities, and has six degrees of freedom at each node; for the details of the cross section see [12]. Joints are assumed to be rigidly connected and only the axial force, shear force and bending moment for the members are considered. Although the element can cope with plastic, creep and swelling effects, only the linear elastic response is investigated. The mass of the structure is considered to concentrate at the joints and is modeled using the MASS21 element in ANSYS, which is a point element having up to six degrees of freedom.

A well-known fact is that the natural vibration frequencies of the dome are closely spaced. The first three vibration modes are illustrated in Fig. 2a–c. The results indicate that the natural vibration frequencies for the first, third and fifth modes are 2.1928, 2.4675 and 2.4928 Hz, respectively. The first mode is a horizontal vibration mode; the third mode is a vertical vibration mode; and the fifth mode is more complex. The shapes of the second and fourth modes can be obtained by rotating 90° (clockwise) the shapes of the first and third modes around the Z axis. Also, a few selected higher vibration modes (i.e., 16th, 33rd and 90th vibration mode shapes) are shown in Fig. 2d–f to illustrate the mode shapes that have localized effects. For completeness, the distribution of the natural vibration frequencies for the first 225 modes range from 2.1928 to 5.8819 Hz is presented in Fig. 2g.

For the considered structure located at a site with site classification II, according to the code [2] recommendations, the target PGA value for the scaling equal to 35 cm/s^2 needs to be considered (which is for "frequent earthquake"), and the design spectrum shown in Fig. 3 is to be used. The SA equals 98.12 cm/s^2 at the fundamental vibration period T_n that equals 0.456 (s) (i.e., $=1/2.1928$). This value will be used in this study as the target SA value when the SA based scaling scheme is adopted.

2.2. Selected historical ground motion records

Given the ground motion records and the structure model, time history analysis can be carried out and the maximum displacement, deformation, strain, stress and forces of the elements can be identified from the time histories of the responses.

Table 1
Geometric and material properties of the structural members of the dome.

Member	Size
Radial member	ϕ146 × 5.5 mm
Ring member	ϕ146 × 5.5 mm
Oblique member	ϕ133 × 4 mm
Permanent load	180 kg/m^2
Elasticity modulus	2.06 × 10^5 N/mm^2
Density	7850 kg/m^3
Poisson's ratio	0.3

Note: The permanent load is calculated based on JGJ7 [2].

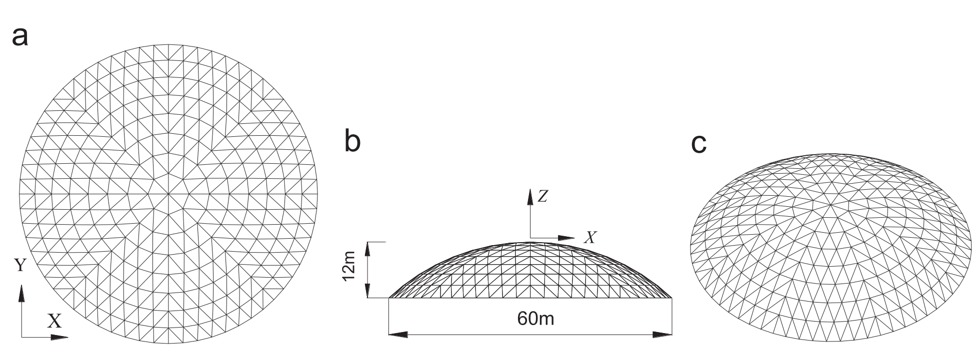

Fig. 1. Plan, elevation and 3D views of the considered single-layer reticulated dome. (a) Plan view, (b) elevation view, (c) 3D view.