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Effect of support flexibility on seismic responses of a reticulated dome under spatially correlated and coherent excitations

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ABSTRACT

Reticulated domes with substructure system are affected by multiple-support seismic excitations that are spatially correlated and coherent. The influence of the coherency on the seismic responses of such a structure has been investigated but the effect of the spatial correlation and coherency on the responses for the system with different flexibility of the substructure has not been studied. A parametric investigation is carried out to address this issue for a single-layer reticulated dome. For the analysis, sets of records for multiple-support are simulated and used for time history analysis. The statistics of the responses of the dome with substructures of varying degree of flexibility are extracted from analysis, and compared with those obtained under uniform excitations. The results show the importance of considering spatially correlated and coherent excitations, especially as the stiffness of the substructure system increases. They also show that a flexible substructure system for the dome acts as a "base isolation" system for the dome under spatially correlated and coherent multiple-support excitations, and reduces the potential yielding and damage of the structure under large earthquakes. As the stiffness of the substructure system increases the consideration of uniform excitations instead of spatially correlated and coherent excitations can underestimate the seismic load effect by more than 25% for structural members in the reticulated dome and by more than 100% for the columns.

1. Introduction

Seismic excitations are spatially correlated and coherent. The spatial coherency depends on the frequency and the inter-station (inter-support) distance. The coherency is a complex number, and its absolute value represents the stochastic variations in the ground motions [1]. The spatial correlation is used to deal with the correlation of the ground motion measures and the magnitude of the Fourier amplitude spectrum. The assessment of spatial coherency was carried out based on the historical records from dense arrays by Bycroft [2], Abrahamson et al. [3], Harichandran and VanMarcke [4], and Hao et al. [5]. Their results showed that the coherency decreases with increasing frequency and distance between the two recording stations (i.e., inter-station distance), and is negligible for the inter-station distance greater than about 5 km. The spatial correlation of the ground motion measures such as the peak ground acceleration (PGA) and spectral accelerations (SAs) was assessed by Boore et al. [6], Wang and Takada [7], Goda and Hong [8], Hong et al. [9], Jayaram and Baker [10], Goda and Atkinson [11], and Sokolov et al. [12]. The spatial correlation of Arias intensity was presented by Foulser–Piggott and Stafford [13]. More recently, the spatial correlation of the (integral) of Fourier amplitude spectra (FAS) was presented by Liu and Hong [14]. They indicated that the spatial correlation model for the FAS is similar to that for the SA, and that the consideration of coherency alone does not result in the simulated records having spatial correlation of the PGA and of SAs that matches the one observed from historical records.

The coherency is considered for estimating the seismic responses of structures or structural systems with multiple supports in several studies as pointed out in Ref. [15]. The simulated records that match the target coherency are used for the structural analysis because historical records with recording stations that exactly matching the specific inter-support distances for an engineering project are unavailable. In particular, simulated records are used for reticulated structures [16,17]. The numerical results presented in Ref. [16] indicate that the horizontal multi-support excitations have a large amplification effect on the seismic responses of the trussed arch. This amplification depends on the structural span and should not be ignored in the seismic design. The double layer reticulated shells under multiple-support excitations and under uniform excitations was investigated in Ref. [17]. They concluded that the stresses in members near the supports under multiple-support excitations are greater than those under

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uniform excitations; and that these members deserve special consideration in seismic design. Note that the simulated records used in these studies cannot reproduce the observed spatial correlation of SA or FAS, and are not directly related to scenario seismic events that are often characterized by the combination of the earthquake magnitude and site to seismic source distance [18,19]. The potential effect of the spatial correlation on the seismic responses of the reticulated structures is ignored. This is expected since procedures for simulating records with both target spatial correlation and target spatial coherency are only discussed and presented until recently [14,20].

In addition to the above, the substructure flexibility for a dome could influence the overall response of the structural system. In fact, Yu et al. [21] investigated this influence considering the system under a single (but scaled) actual record with one vertical and two horizontal components. It was observed that the manner in which the domes fails depends on the substructure flexibility. For stiff substructure, extensive plastic deformation before collapse is expected; for flexible substructure, plastic deformation before collapse is distributed mainly on the outer members of the reticulated dome. Moreover, their results indicate that the maximum (scaled) earthquake excitation that the structure can sustain depends on the substructure flexibility. However, it is unclear if these observations are applicable for other ground motion records and for multiple-support excitations.

The present study is focused on the assessment of the effect of support flexibility on seismic responses of a reticulated dome under spatial correlated and coherent excitations. Sets of the multiple-support excitations used for the analysis are simulated using the procedure developed in [14]. The procedure takes into account target spatial correlation and coherency that are developed based on actual ground motion records, and considers that the FAS can be adequately defined using the stochastic point-source method [22–24]. The simulated spatially correlated and coherent records are used in linear/nonlinear inelastic time history analysis of the reticulated dome with substructure of varying degree of flexibility. Statistics of the maximum responses for the structure with five different substructure systems under spatially correlated and coherent excitations and under uniform excitations are used to investigate the influence of substructure flexibility on the responses. The simulation of the records for a scenario event, the analysis procedure and results, and the conclusions are detailed in the following sections.

2. Structural modeling and seismic excitations

2.1. Structural modeling

There are many types of single-layer reticulated domes that are light and with sufficient stiffness [16,17,21,25]. The domes that are often built for sports stadiums, gymnasiums, and auditoriums could be supported by substructure or columns that are subjected to spatially correlated and coherent ground motions. An example of such a structural system, a single-layer Kiewitt 8 spherical reticulated dome with typical and configurations, is illustrated in Fig. 1. This type of dome under seismic excitations was considered in [21,25]. The structure shown in the figure is considered in the present study.

The diameter of the considered dome is 90 m and the height to diameter ratio is considered to be equal to 1/5 which is within the commonly considered range of 1/3–1/7 [26]. The dimensions and material properties of the structural members of the dome are listed in Table 1. Also shown in the table is the permanent load calculated according to the code [26].

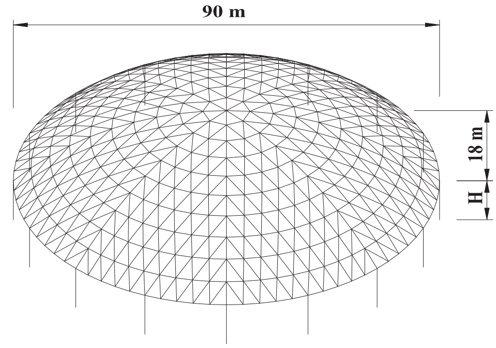

Fig. 1. A single-layer reticulated dome (with diameter of 90 m and height from the top of the column to the top of the dome equal to 18 m).

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

Member	Size
Radial member	$\phi 245\times 8\ mm^2$
Ring member	$\phi 245\times 8\ mm^2$
Oblique member	$\phi 219\times 8\ mm^2$
Ring beam	$\phi 1000\times 30\ mm^2$
Column	$\phi 1000\times 30\ mm^2$
Permanent load	$120\ kg/m^2$
Elasticity modulus	$2.06\times 10^5\ N/mm^2$
Density	$7850\ kg/m^3$
Poisson's ratio	0.3

Table 2
Substructure models with varying columns stiffness.

Substructure model (SM)	Column length (m)	Pipe wall thickness of the columns (mm)	Fundamental vibration frequency
SM-1	12	30	1.2195
SM-2	10	30	1.4691
SM-3	10	40	1.5651
SM-4	8	40	1.7884
SM-5	8	50	1.8263

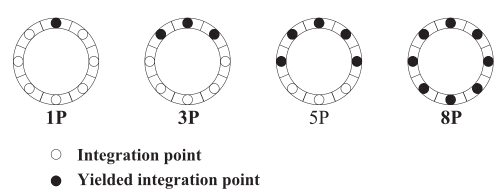

Fig. 2. Illustration of cross-section of structural element and potential yielding at integration points for the PIPE20 element (*i*P represents the number of yielding integration points).

To investigate the effect of the substructure flexibility on the structural responses under spatially correlated and coherent excitations, five substructure systems, named SM-1 to SM-5 shown in Table 2, are considered. These substructures are designed by varying the column length and the pipe wall thickness of the columns.

The overall structure is modeled using ANSYS® Multiphysics 10.0 [27] with 305 joints and 816 members. Each structural member of the reticulated dome is represented by three PIPE20 elements. This element is a uniaxial element with tension–compression, bending, and torsion capabilities, and has 6° of freedom at each node. The cross-section of the element with 8 integration points is shown in Fig. 2. The degree of plastic deformation of the pipe member could be classified based on the