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Explicit modeling of damping of a single-layer latticed dome with an isolation system subjected to earthquake ground motions

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ABSTRACT

The non-uniformly distributed material damping in single-layer latticed domes subjected to earthquake ground motions has been ignored in engineering practice, and the structural damping of bearings and joints has been modeled at a structural level in previous studies. In this paper, an explicit method for modeling the material damping and structural damping using a finite element method is proposed. The proposed method includes important characteristics for modeling single-layer latticed domes. The steel material damping is directly taken into account using Ramberg–Osgood material model (power-law) with hysteretic damping; the structural damping at bearings is modeled based on the bearing type. The ball joints of domes tend to be simplified as nodes in the finite element method without considering the actual geometric shapes and sizes of the balls for convenience. In this paper, the energy dissipation at joints and modeling methods for damping are proposed and discussed in terms of the joint type in domes. To illustrate the proposed method for computation, a typical single-layer latticed dome with base isolation bearings subjected to six near-fault earthquake ground motions is selected as an example. The dynamic demands of this single-layer latticed dome are analyzed using the simulation technology proposed in this paper. The effects of key parameters of the dome on the damping forces, which are of interest to many practitioners, are presented and discussed. Compared with the previous modeling methods for damping, the proposed method can model the damping effects of domes with a higher fidelity, which eliminates the unrealistically high forces generated with conventional modeling methods.

1. Introduction

To reasonably evaluate the seismic dynamic performance of a structure, the sources of energy dissipation of the structure must be carefully considered, and a thorough understanding of the damping properties of these sources is needed. However, these damping properties are not only very complex, but also obscure [1].

In structures, damping appears in several forms, which may be broadly categorized as external and internal [2]. External sources mainly come from active control systems such as the dampers used to reduce the vibration of a structure and boundary effects such as the loss of energy at the bearings through either friction or transmission into the supporting structure. The other form of external damping is aero-acoustic effects caused by moving through a fluid such as air. Internal sources include the internal friction of materials and the friction at the joints in a structure [3]. These frictions include [2]: macro-slip, micro-slip, structure and metal defects, and visco-elastic characteristics, which cause different force–deformation (or stress–strain) relationships in a structure (or material) during loading and unloading, even within the elastic range. The area enclosed by the force–deformation (or stress–strain) curve (hysteresis loop) serves as an indication of the amount of energy dissipated. In fact, all damping is ultimately caused by frictional effects, which may take place at different scales [4]. As stated by Charney [5], a better solution is to utilize a simple friction or hysteretic model to simulate these effects, such as the Bouc–Wen model. However, although the energy dissipation mechanisms of some sources are known and their damping properties can be determined by experiments, these sources have often not been considered in the previous dynamic analyses because of the absence of an acceptable mathematical model to estimate damping forces [6]. To accurately estimate the damping forces in

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a structure, some non-viscous damping models were also developed by Adhikari [7], Woodhouse [8] and Val and Segal [9]. Thus, it is recommended that the sensitivity of the calculated parameters of a structure to the damping model formulations be investigated [10].

For steel domes, a typical reported viscous damping ratio is about 1–2% [11]. Because the damping ratio is small and it is difficult to be exactly quantified due to the estimation of structural damping depending on a wide range of factors, the damping ratio usually was not accurately considered in previous dynamic analyses. In respect to damping model, a simple damping model such as linear viscous damping can be assumed without much concern. The use of a viscous damping model tends to represent the damping effect at a global scale [12], and the current viscous damping models are used based on the assumption of a small amplitude (also called "zero amplitude") [13]. Therefore, Rayleigh damping is widely used within the elastic range of a structure. Rayleigh damping models used in inelastic seismic analyses have also been presented [14–17]. In these studies, Rayleigh damping model was modified to eliminate the unrealistically high damping force. However, Rayleigh damping still lacks physical evidence, and there is no guarantee that the actual damping forces are properly modeled. As shown in Petrini et al. [18], the initial-stiffness proportional damping is inappropriate for an inelastic dynamic analysis, and tangent-stiffness viscous damping appears to be more appropriate. Jehel et al. [19] considers that it is easier to control the viscous damping ratio by the use of Rayleigh damping based on the tangent stiffness in inelastic dynamic analyses. Some researchers have suggested eliminating the stiffness proportional damping term and only specifying a value for the mass proportional damping term [10]. At present, there is no clear consensus on how to resolve this issue. Nevertheless, the reliability of the results predicted by a nonlinear dynamic analysis is strongly dependent on the selected damping model. Extensive research indicates [7,20,21] that the structural damping observed in practice is a strong function of the displacement and a weak function of the frequency. Therefore, a damping model based on the displacement should be the most accurate. However, the damping model with this characteristic is almost never used for spatial structures in a dynamic analysis during earthquake engineering because of its complex dynamic equations. In dynamic equations, it should be noted that only the non-modeled energy dissipation needs to be considered in the damping term. Otherwise, the damping sources should be explicitly simulated [10].

In this paper, the damping mechanisms of a single-layer latticed dome are analyzed and discussed. A dynamic analytical procedure for modeling damping is proposed in OpenSEES. This procedure includes important features that were not considered in the previous dynamic analyses. The damping forces of particular interest to many practitioners are given and discussed.

2. Steel material damping

2.1. Ramberg–Osgood (R–O) steel material model

The R–O stress–strain relationship is a power law relation between the stress and strain. The following R–O equation is the usual representation of the non-linear behavior of a steel material [22].

$$\varepsilon = \frac{\sigma}{E} + p\left(\frac{\sigma}{\sigma_p}\right)^{\alpha} \tag{1}$$

where ε is the strain, σ is the stress, E is the initial elastic modulus, p is the given level of plastic strain (typically 0.2%), σ_p is the proof stress corresponding to the plastic strain p, and α is a parameter pertaining to the transition between the elastic and plastic stages of the stress–strain curve, which is also called the hardening exponent. α usually has a value of about 5 or greater. Based on numerous experiments and calculations, the hardening ratio $\alpha = 8$ is widely used for a common steel material. It has also become a standard practice to determine the value of α using the 0.01% and 0.2% proof stresses [23],

$$\alpha = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})} \tag{2}$$

The stress–strain relationship described in Eq. (1) does not obey Hooke's law, even within the elastic range, and the strain is the sum of the elastic and plastic components. As a result, the nonlinear material energy dissipation within the elastic range and the material damping can be captured by hysteretic loops. The stress–strain curves based on the R–O equation with different hardening ratios α are illustrated in Fig. 1. It can be noted in Fig. 1 that the material strength increases with an increase in the hardening ratio in the elastic phase, while in the plastic phase it decreases with an increase in the hardening ratio.

2.2. Cyclic stress–strain behavior of material and steel material damping within elastic range

The stress–strain hysteresis curve of the steel material for $\alpha = 8$ is shown in Fig. 2. Here, the elastic modulus and yield strength of the steel material are 200 GPa and 207 MPa, respectively. In Fig. 2, it can be observed that the steel material exhibits a relationship between the stress and strain that is not elastic, even at a stress well below the yield point. Thus, the stress–strain relationships during loading and unloading are different and lead to the hysteresis loops due to the internal friction of the steel material. These hysteresis loops represent the energy dissipation of the steel material, and its energy dissipation capacity can be described by means of the equivalent damping ratios under the different material stresses,

$$\xi = D/(4\pi W) \tag{3}$$

where D determines the amount of energy dissipated per unit volume of the material during one cycle of oscillation, W represents the maximum elastic strain energy, and ξ is the material damping ratio. For example, the maximum stress is equal to about 175 MPa, and the damping ratio of the steel material is about 0.08, as illustrated in Fig. 3. The viscous damping ratios under different stress levels are evaluated and shown in Fig. 4. These results indicate that the steel material damping ratio depends on the stress and on the

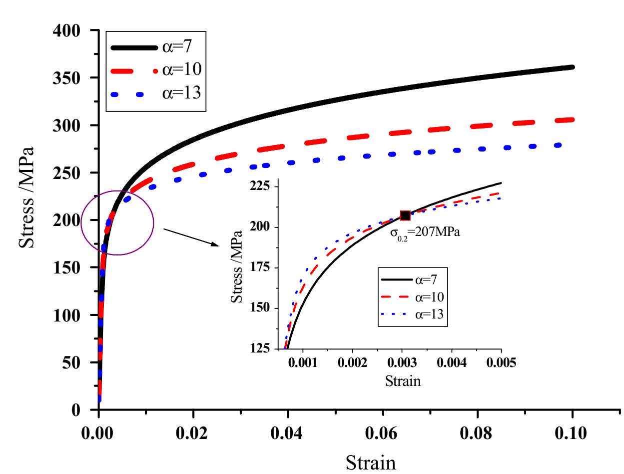

Fig. 1. Stress–strain curves based on R–O model with different hardening ratios α.