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# A theoretical strut model for severe seismic analysis of single-layer reticulated domes

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ABSTRACT

This paper focuses on proposing an efficient theoretical strut model to predict the post-buckling behaviors of members of single-layer reticulated domes under severe earthquake. The model was established based on finite element (FE) method and it can well reflect the performance of individual member during the complete loading period by using one element, especially the inelastic post-buckling behaviors. By using the model, the failure behavior of single-layer reticulated domes under severe earthquake can be well captured. With the help of this model, the interaction between individual member buckling and structural global instability can be accounted, and then the influence on plastic internal forces redistribution due to the degradation of bearing capacity of members under large displacement can be well depicted. The model is suitable for severe seismic analysis as it involves a wider range of strain than the existing phenomenological models. At last, the efficient model is verified by several experiments and good agreement is found between the simulated and experimental results.


## 1. Introduction

In 1961, the brittle failure of the Bucharest dome in Romania, and in 1978, the sudden collapse of the Hartford Coliseum roof had dramatically drawn much attention on the collapse behavior and failure mechanism of the long span spatial structures. As a typical type of spatial structures, the single-layer reticulated domes, of which stability is crucial to the safety and serviceability, have a relatively high strength-to-weight ratio and can cover large space without intermediate supports [1,2]. Consequently, the static stability of this kind of structures have been well investigated, such as the geometrical deviation of structure, slenderness ratio of members, form of loading, etc. [3–6]. With the increasing use for landmark buildings in high intensity regions, the dynamic stability of the single-layer reticulated domes have gradually drawn much attention and been investigated [7–10].

The aforementioned studies mainly concentrate on the global stability of the single-layer reticulated domes. However, such structures are highly redundant, and the failure of an individual member does not necessarily lead to an overall structural collapse but merely causes a redistribution of forces among members in the neighboring regions. The buckling member may be capable of sustaining reduced load according to its own post-buckling characteristics [1,9], especially when the structures are subjected to severe earthquake. Fan, et al. have investigated the influence of the interaction between individual member buckling and global instability of the structure on the static failure mechanism of the single-layer reticulated domes by introducing initial member imperfections [1,11,12]. However, the influence on the failure mechanism under dynamic phase, especially when the structures subjected to severe earthquake, has not been systematically explored, not yet available provisions for engineering application.

To investigate the influence of the member-global buckling interaction on the dynamic failure mechanism, one direct solution is using shell element based on FE method. Kumar [13] and Lotfollahi [14] developed such kind of shell FE models, which are validated by experiments conducted by Fell [15] and Black [16], to investigate the post-buckling characteristics of steel braces. However, it is extremely hard to model and analyze the single-layer reticulated domes using shell elements due to the unacceptable computational efforts. Another possible solution is using beam element. Liew [17] proposed a plastic hinge model based on the interaction of buckling of members with instability of structures. The member initial imperfections could be accounted without physically altering the member geometry. However, the transitions from the elastic state to the full plastic state at the plastic hinge were assumed to take place suddenly. Such instantaneous transitions were not observed in reality. Furthermore, this model is not practical to be used to simulate the dynamic stability of structures due to the lack of unloading curves. Qi [18] introduced a phenomenological model, Marshall Model [19], to consider this interaction. Although the model occupied less modeling efforts, its application limitations cannot be ignored. It only fits for the hollow circular section member and it is not suitable to simulate the cyclic behaviors of the members accurately because the model

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is relatively rough which only contains several approximate straight line segments defined by empirical parameters. Moreover, the applicable range of strain is too narrow to simulate the collapse of the single-layer reticulated domes under severe earthquake. Other FE models using beam elements which are mainly used for braces in frames, can provide helpful suggestions for the dynamic analysis of the single-layer reticulated domes. Lee [20–22] and Uriz [23] proposed a general FE discretization scheme for beam analysis to simulate and investigate the inelastic buckling behavior of steel members. Dicleli [24,25] presented a physical theory model that can be used to simulate the complex cyclic inelastic behavior of steel braces incorporating theoretical formulations and some semi-empirical techniques. Ikeda [26] presented a refined phenomenological model combining analytical formulations with results developed on the basis of experiments. Although those models can accurately capture the behavior of members, the modeling and post-processing efficiency always decreased when they are used to model reticulated domes which have much more members than frames.

An ideal solution is to propose a theoretical model which can well capture the inelastic post-buckling behaviors of members of single-layer reticulated domes and effectively account for the degradation of bearing capacity due to the large displacement after the member buckling. It is preferred that the model is based on a physical analogy that one beam element is used to represent a single member in a spatial structure, which does not need to model the imperfection of members. The main purpose of the theoretical model is to use as few elements as possible to model each member of structures and to obtain a realistic representation of material and geometric nonlinear effects and the effects of imperfections. This concept was originally proposed by Papadrakakis [27] and was further extended by Maheeb [28] for members with various types of cross-section for planar bracing systems. Liew [17] extends the concept to three dimensional systems. Nevertheless, the model in reference [17] should be improved as mentioned above. Consequently, this paper proposes an efficient theoretical strut model which is established based on FE method. It can well reflect the performance of individual member during the complete loading period by using one element, especially the inelastic post-buckling behaviors. With the help of this model, the interaction between individual member buckling and structural global instability can be accounted, and then the influence on plastic internal forces redistribution due to the degradation of bearing capacity of members under large displacement can be well depicted. The model is suitable for severe seismic analysis as it involves a wider range of strain than the existing phenomenological models. At last, the model is verified by several experiments and good agreement is found between the simulated and experimental results.

## 2. FE models developed for helping theoretical derivation

A three-dimensional FE model was developed for the benefit of the theoretical derivation. The 3D beam element B31 was applied based on the general FE analysis platform ABAQUS and ABAQUS/Explicit module is used to avoid the divergence caused by the numerical singularity due to the buckling. The hourglass modes are suppressed by constraining the ratio of artificial strain energy to input energy to remain less than 5%. Both nonlinear characteristics of material and geometry are considered.

Fell [15] and Kumar [13] used axial displacement of the members to apply the tension or compression force in their studies. Both ends of the specimens are pinned and the loading histories are listed in the papers. Consequently, the ends of the members are determined to be pinned in the FE model and the loading histories are also the same with those in the experiments to reproduce the results obtained from the experiments to validate the FE model. The modeling details are presented as follows.

### 2.1. Material properties

In this paper, the mixed hardening constitutive model is used, the basic assumption are given as follows:

(1) The shear deformation due to bending and warping is small.

(2) Plane cross sections originally normal to the central axis of the beam is assumed to remain plane and undistorted under deformation but not necessarily perpendicular to the central axis of the deformed beam.

Members in long-span lattice shell structures are always circular tubes. According to reference [29], the initial yield criterion which involves mixed hardening constitutive model can be expressed as

$$\begin{aligned} F &= f(\sigma_{ij}, \alpha_{ij}) - h\left(\varepsilon_{ij}^{p}\right) \\ &= \frac{1}{3}\left[(\sigma_{11}-\alpha_{11})^2 + 3(\sigma_{12}-\alpha_{12})^2\right] - \frac{1}{3}\sigma_s^2(\varepsilon_p) \end{aligned} \tag{1}$$

where $\sigma_{11}$ is the axial stress of the three-dimensional beam element, $\sigma_{12}$ is the shear stress of the three-dimensional beam element due to the warping, $\sigma_s$ is the yield stress. $\alpha_{ij}$ is the back stress components. $\varepsilon_p$ notes the equivalent plastic strain. The mixed hardening constitutive model of the beam-column element can be expressed as

$$\mathrm{d}\sigma_{11} = E\left(\mathrm{d}\varepsilon_{11} - \mathrm{d}\lambda \cdot \frac{2}{3}\left(\sigma_{11}^{\mathrm{tr}} - \alpha_{11}^{\mathrm{old}}\right)\right) \tag{2}$$

$$\mathrm{d}\sigma_{12} = 2G\left[\mathrm{d}\varepsilon_{12} - \mathrm{d}\lambda \cdot 2\left(\sigma_{12}^{\mathrm{tr}} - \alpha_{12}^{\mathrm{old}}\right)\right] \tag{3}$$

where $E$ and $G$ are elastic module and shear module, respectively. $\sigma_{ij}$, $\varepsilon_{ij}$ and $\alpha_{ij}$ are the stress, strain and back stress component, respectively. $\sigma_{ij}^{\mathrm{tr}}$ is the trial stress components. $\alpha_{ij}^{\mathrm{old}}$ is the back stress components in the last increment. $\mathrm{d}\lambda$ is a scalar multiplier which can be expressed as

$$\mathrm{d}\lambda = \frac{\mathrm{d}a}{\mathrm{d}b + \mathrm{d}c + \mathrm{d}d} \tag{4}$$

$$\mathrm{d}a = \frac{2}{3}E\left(\sigma_{11}^{\mathrm{tr}} - \alpha_{11}^{\mathrm{old}}\right)\mathrm{d}\varepsilon_{11} + 4G\left(\sigma_{12}^{\mathrm{tr}} - \alpha_{12}^{\mathrm{old}}\right)\mathrm{d}\varepsilon_{12} \tag{5}$$

$$\mathrm{d}b = \frac{4}{9}E\left(\sigma_{11}^{\mathrm{tr}} - \alpha_{11}^{\mathrm{old}}\right)^2 + 8G\left(\sigma_{12}^{\mathrm{tr}} - \alpha_{12}^{\mathrm{old}}\right)^2 \tag{6}$$

$$\mathrm{d}c = c(1-M)\left[\frac{4}{9}\left(\sigma_{11}^{\mathrm{tr}} - \alpha_{11}^{\mathrm{old}}\right)^2 + 4\left(\sigma_{12}^{\mathrm{tr}} - \alpha_{12}^{\mathrm{old}}\right)^2\right] \tag{7}$$

$$\mathrm{d}d = cM\sigma_s\sqrt{\frac{4}{9}\left(\sigma_{11}^{\mathrm{tr}} - \alpha_{11}^{\mathrm{old}}\right)^2 + \frac{16}{3}\left(\sigma_{12}^{\mathrm{tr}} - \alpha_{12}^{\mathrm{old}}\right)^2} \tag{8}$$

where $M$ is the mixed hardening parameter which is equal to 1 and 0 when the hardening condition is isotropic hardening and kinematic hardening, respectively. $c$ can be expressed as

$$c = \frac{2}{3}E^{\mathrm{p}} \tag{9}$$

where $E^P$ is the plastic module.

### 2.2. Mesh refinement study

The required number of the elements per member should be determined according to the mesh refinement study. It was carried out through pseudo static analyses by comparing the critical bearing capacity obtained by different member partition schemes. A single strut model with 1‰ initial curvature discretized by beam elements is simulated in ABAQUS. The mixed hardening constitutive model in Section 2.1 is used to simulate the responses of members under uniaxial monotonic load without transverse loads. Both ends of the member are pinned. The