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Dynamic damage criterion and damage mode for single layer lattice shell

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ABSTRACT

When member buckling and joint fractures are considered in the numerical analyses of single layer lattice shells, the relationship curve between peak ground acceleration of the earthquake and the maximum nodal displacement, and the time–history curve of maximum nodal displacement, are erratic and unpredictable. Therefore, with such considerations, the current approach to determine dynamic damage of single layer lattice shells by comparing peak ground acceleration of the earthquake with critical ground acceleration derived from incremental dynamic analysis is inappropriate. An improved structure dynamic damage criterion is proposed for single layer lattice shells in this paper, which reviews the balance status of structure dynamic resistance against the earthquake action, and the structure damage time can be predicted by the occurrence of non-convergent solution to the structural nonlinear dynamic equilibrium equations in the iterative process from the mathematical point of view. Numerical examples are presented to illustrate the simplicity and practicality of the proposed criterion. This criterion serves clear physical meaning and is of considerable potential applicability in analyzing single layer lattice shell structures. Results of parametric analyses of single layer lattice shells under severe earthquake actions indicate that the structure dynamic damage is not determined by material strength failure. For single layer spherical lattice shell, it is determined by structural instability resulted from member buckling; and for single layer cylindrical lattice shell, it is determined by the combined effect of structural instability and the change of structural topology that resulted from member buckling and joint fractures respectively.

1. Introduction

Single layer lattice structures are extensively used for landmark buildings in China, and majority of those buildings are located in earthquake-hit areas, which carry high risk of building damage in the event of earthquake. In addition, these landmark buildings are usually used as the centers of social, economical and cultural activities, therefore are densely occupied and involve high cost in construction and maintenance. Any collapse of such building in the event of earthquake will cause devastating property damage and loss of life, and subsequently impose heavy burden on the society. Comprehensive understanding of dynamic responses and in-depth study of dynamic damage modes are the theoretical basis in building up seismic-resistant design methodology for single layer lattice shell structures. It is a critical subject in the research field of spatial structures for its significance in both theory development and engineering applications. In the research of dynamic damage mechanism of single layer lattice shells subject to sever earthquakes, priority should be given to the establishment of dynamic damage criteria. However, in the current study, member buckling and joint fractures are neglected in the dynamic damage analyses. With the employment of incremental dynamic analysis method [1], the structure seismic behaviors are reviewed by conducting a series of complete structure time–history analyses with various inputs of earthquake ground accelerations. In such analyses, Critical Ground Acceleration (CGA) is determined based on the performance of key structural features, such as Maximum Nodal Displacement (MND), in response to a variety of Peak Ground Accelerations (PGA). And structure damage is predicted if the PGA of earthquake was higher than the CGA, otherwise the structure is safe [2–10]. However, this criterion does not specify the relationship between the PGA and the CGA, and has limited application only to certain types of single layer lattice shells. Hence, further study is carried out to determine the CGA by examining the structural performance in response to the earthquake ground motion of various peak accelerations; in the meanwhile member bucking and potential joint fractures are taken into account in the numerical model to perform a more realistic simulation. Although there are some studies relating to structure stability and member buckling, there is no systemic analysis on the relationship between member buckling and structure dynamic damage [11–13].

In this paper, an analysis model that accounts both member buckling [14] and joint fractures [15] is presented, the structure performance in response to ground motion of various peak accelerations is summarized,

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and finally an improved structure dynamic damage criterion for single layer lattice shell subject to severe earthquakes is proposed. Using this damage criterion as basis, taking into account of member buckling and joint fractures, complete parametric analyses are carried out to determine the dynamic damage modes for different types of single layer lattice shells.

2. Analysis model

2.1. Member buckling prediction

Steel circular hollow sections are widely used as members of single layer lattice shells. Through extensive experiments, the ISO summarize the instability equation of steel circular hollow section as follows [16]:

$$R(\sigma_c, \sigma_{b1}, \sigma_{b2}) = \frac{\sigma_c}{N_c} + \frac{1}{N_b}\sqrt{\left(\frac{\xi_{m1}\sigma_{b1}}{1\frac{\sigma_c}{N_{e1}}}\right)^2 + \left(\frac{\xi_{m2}\sigma_{b2}}{1\frac{\sigma_c}{N_{e2}}}\right)^2} \quad (1)$$

where $\sigma_c = N / \psi$ is the axial compressive stress; N and ψ are the axial force and the member cross section area respectively; σ_{b1} and σ_{b2} are the maximum flexural stresses about the two main axes respectively; $\sigma_{b1} = M_1 / W_e$ and $\sigma_{b2} = M_2 / W_e$, where W_e is an elastic section modulus, and M_1 and M_2 are the maximum bending moments about the two main axes respectively; ξ_{m1} and ξ_{m2} are reduction factors at the ends of the member, where $\xi_{m1} = \xi_{m2} = 0.85$; N_{e1} and N_{e2} are the Euler critical buckling stresses about the two axes, where $N_{e1} = N_{yc} / \lambda_1^2, N_{e2} = N_{yc} / \lambda_2^2, \lambda_1 = k_1 L_1 / \pi\rho\sqrt{N_{yc}/\chi}, \lambda_2 = k_2 L_2 / \pi\rho\sqrt{N_{yc}/\chi}$; L_1 and L_2 are the unsupported lengths of the member about the two axes; k_1 and k_2 are the effective length factors for L_1 and L_2; ρ is the radius of the section; χ is Young's modulus; N_c and N_b are the characteristic axial compression force and the characteristic bending force respectively, and they are given by

$$N_c = \begin{cases} \left(1.0 - 0.28\lambda^2\right) N_{yc} & \lambda \le 1.34 \\ \dfrac{0.89282978}{\lambda^2} N_{yc} & \lambda > 1.34 \end{cases} \quad (2)$$

$$N_b = \begin{cases} \dfrac{W_p}{W_e}\sigma_s & \dfrac{\sigma_s\phi}{\chi t} \le 0.0517 \\ \left(1.133386 - 2.58\dfrac{\sigma_s\phi}{\chi t}\right)\dfrac{W_p}{W_e}\sigma_s & 0.0517 < \dfrac{\sigma_s\phi}{\chi t} \le 0.1034 \\ \left(0.945198 - 0.76\dfrac{\sigma_s\phi}{\chi t}\right)\dfrac{W_p}{W_e}\sigma_s & 0.1034 < \dfrac{\sigma_s\phi}{\chi t} \le \dfrac{120\sigma_s}{\chi} \end{cases} \quad (3)$$

where N_{yc} is given by:

$$N_{yc} = \begin{cases} \sigma_s & \dfrac{5\sigma_s\phi}{3\chi t} \le 0.170 \\ \left(1.04654873 - 0.27381606\dfrac{5\sigma_s\phi}{3\chi t}\right)\sigma_s & 0.170 < \dfrac{5\sigma_s\phi}{3\chi t} \le 1.911 \\ \dfrac{0.6\chi t}{\phi} & \dfrac{5\sigma_s\phi}{3\chi t} > 1.911 \end{cases} \quad (4)$$

where σ_s is the yielding strength; t and ϕ are thickness and diameter of the member respectively; $\lambda = \max(\lambda_1, \lambda_2)$; and $W_p = [\phi^3 - (\phi - 2\,t)^3] / 6$.

Generally when $R(\sigma_c, \sigma_{b1}, \sigma_{b2}) \ge 1.0$, member buckling is predicted. However, if the member is imposed with heavy bending moment but relative small axial compression force, it is possible that $R(\sigma_c, \sigma_{b1}, \sigma_{b2}) \ge 1.0$, which indicates a pseudo-buckling prediction. Hence, strength equation should be further employed, which is given by

$$S(\sigma_c, \sigma_{b1}, \sigma_{b2}) = \frac{\sigma_c}{N_{yc}} + \frac{1}{N_b}\sqrt{\sigma_{b1}^2 + \sigma_{b2}^2}. \quad (5)$$

Therefore, buckling criterion for steel circular hollow section member is defined as follows:

$$\begin{cases} R(\sigma_c, \sigma_{b1}, \sigma_{b2}) \ge 1.0 \\ S(\sigma_c, \sigma_{b1}, \sigma_{b2}) \le 1.0 \end{cases}. \quad (6)$$

When $R(\sigma_c, \sigma_{b1}, \sigma_{b2}) = 1.0$ and $S(\sigma_c, \sigma_{b1}, \sigma_{b2}) \le 1.0$, the steel circular hollow section is under critical buckling status, and the critical axial compression force is given by:

$$N_{cr} = \sigma_c\psi. \quad (7)$$

2.2. Analysis model for pre-buckling member

3-node element with plastic hinge is employed to simulate the pre-buckling member. The incremental displacement at the end section of the member is comprised of the elastic part and the plastic part:

$$\Delta u = \Delta u^e + \Delta u^p \quad (8)$$

where Δu, Δu^e and Δu^p are overall incremental displacement, elastic incremental displacement and plastic incremental displacement of the end section.

The transversal elastic displacement of the member can be expressed by quartic polynomial interpolation functions, the rotational displacement is the derivative of the transversal displacement with respect to the length; the axial displacement can be expressed by quadratic polynomial interpolation function; and the torsional displacement can be expressed by linear interpolation function. Naming the two ends of the member with "i" and "j", the equilibrium equation for the end "i" is given as follows:

$$P_{mi} = \sum_{j=1}^{2}\sum_{n=1}^{6} K^e_{mi\,nj}\left(u_{nj} - u^p_{nj}\right) \quad (9)$$

where P_{mi} is the mth element of the force vector of the end "i"; $K^e_{mi\,nj}$ is the elastic tangent stiffness matrix; u_{nj} and $u_{nj}{}^P$ are the nth element of the overall displacement vector and the plastic displacement vector of the end "j". The plastic displacement is the accumulation of the incremental plastic displacement, and the incremental plastic displacement vector of the end "j" is given by:

$$\Delta u^p_j = \Delta\lambda_j \frac{\partial \Phi_j}{\partial S_j} \quad (10)$$

where $\Delta\lambda_j$ is the scaling factor; $S_j = P_j - \alpha_j$; P_j and α_j are vectors of the section force and the back stress; Φ_j is the yield surface function of the end "j", which is given by:

$$\Phi_j = \left(\frac{N_{xj} - \alpha_{Nxj}}{N_{xu}}\right)^2 + \left(\frac{T_{xj} - \alpha_{Txj}}{T_{xu}}\right)^2 + \left(\frac{M_{yj} - \alpha_{Myj}}{M_{yu}}\right)^2 + \left(\frac{M_{zj} - \alpha_{Mzj}}{M_{zu}}\right)^2 - 1 \quad (11)$$

where N_{xu}, T_{xu}, M_{yu} and M_{zu} represent the critical cross-sectional bearing capacities of the member, which are the axial force and three moments respectively; N_{xj} is the axial force of the cross section at the end j; M_{yj} and M_{zj} are the bending moments about the local y and z directions of