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学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Influence of Modeling Choices on Nonlinear-Dynamic Behavior of a Single-Layer Reticulated Dome
(単層ラチスドームの非線形動的挙動に解析モデルが及ぼす影響 )

Nonlinear time history response analysis is a reliable approach for examining the large deformation of steel structures, particularly for the next generation structural design. The impact of modeling choices on the nonlinear response of steel structures has garnered significant attention in earthquake-prone regions. While the inertia force commonly retain the initial condition, the modeling of restoring and damping forces play a critical role in capturing nonlinear-behavior of steel structures. Fiber elements are frequently used to represent the nonlinearity of restoring forces because they can trace the propagation of plasticity along the length of structural members. However, the sensitivity of computational results of highly nonlinear-behavior, such as global buckling, local buckling and curvature distribution—depends heavily on the discretization schemes and element formulations. Observation of damping ratios by vibration tests have provided strong evidence that these ratios remain relatively constant across relevant vibrations modes. However, since the vibration frequencies of inelastic system differ from those of elastic system, the use of damping models based on initial stiffness can result in unintended spurious damping forces. This study examines the influence of modeling choices on the dynamic response of a reticulated dome and a braced frame, analyzed by nonlinear time history response analysis using the platform OpenSees.

A reticulated dome with a span of 40.0 m and a rise of 13.3 m supported entirely by pinned connections, was selected as a representative model of spatial structures for seismic risk estimation. The dome was designed to remain stable under dead load and sustain insignificant and moderate damage states when subjected to Taft ground motions, with peak accelerations scaled to 0.45g and 0.7g based on a previous seismic risk study. Round hollow structural sections (HSS) were used for the individual members of the reticulated dome. Fiber elements based on force- and displacement-based formulations were validated against physical test results of round HSS members with slenderness ratios ranging from 40 to 74, which were commonly used in the dome. The validation considered models with 2, 4, 8, 10 and 30 segments. The displacement-based fiber element with 8 segments demonstrated high-fidelity in predicting the global response of the dome members in the reticulated dome with high-fidelity, accounting for plastic curvature induced by global buckling within the contraction range of -0.5% to 0.5%.

The force- and displacement-based fiber elements with 2, 4, 8 and 10 segments were utilized to investigate the impact of the member discretization on the dynamic response of the inelastic dome. The displacement-based fiber element with 8 segments demonstrated the highest accuracy in capturing both the global system and component-level behavior of the dome. The inherent damping of the reticulated dome was examined using three models: the initial-stiffness-proportional Rayleigh model, the tangent-stiffness-proportional Rayleigh model, and the modal-damping model. For the study of the damping models, the Taft ground motion and a suite of 28 pairs of ground motions selected by Table A-6C in FEMA P695, scaled to 1.3 times the design spectrum specified in Japanese Standard Law with a 10% probability of exceedance in 50 years, was employed. For all ground motion cases, at least 95% of the individual members exhibited contraction and elongation within $\pm$ 0.5%. This result affirmed the reliability of the computational outcomes, as they aligned with the validated behavior of the members. A representative damping ratio for the dome was calculated using the modal-damping model incorporating a step-by-step update based on elastic-plastic behavior. The representative damping ratios in all three directions for the initial-stiffness-proportional damping were 1.26 times the target damping ratio, while those for tangent-stiffness-proportional Rayleigh damping and modal-damping model were closely matched the target value. Among the damping models, the tangent-stiffness-proportional Rayleigh model produced the largest 84th percentile displacement, whereas the initial-stiffness-proportional Rayleigh model yielded the smallest. When the tangent-stiffness-proportional Rayleigh model was used, it produced the most severe damage evaluations compared to the initial-stiffness-proportional Rayleigh model and the modal damping model. The initial-stiffness-proportional Rayleigh model has a potential to yield less unconservative evaluation of damage states for spatial structures compared to the other two models. The modal-damping model is recommended for the seismic risk analysis to mitigate the effects of the spurious damping forces and ensure more accurate assessment for the reticulated domes.

Subsequently, a steel concentrically braced frame (CBFs) was analyzed, focusing on the strength deterioration of steel braces induced by global and local buckling. Suzuki and Lignos proposed a constitutive model, termed the SL Model, to capture local-buckling-induced degradation of steel HSS column. The SL Model was integrated into fiber elements to reproduce the hysteretic behavior of steel braces with round-HSS. The coefficient for the SL Model was calibrated through regression analysis on stub column data. The dataset includes results from 8 stub column tests under monotonic compressive loading, with diameter-to-thickness ratios ranging from 19 to 57, representing a wide range of deformation capacities at local buckling. The SL model with the calibrated coefficients traced the deterioration behavior of the stub columns in the datasets. The calibrated SL Model was validated using round-HSS braces with slenderness ratios ranging from 15.8 to 103 and width-to-thickness ratios ranging from 14.3 to 63, and was compared against the Giuffré-Menegotto-Pinto Model for isotropic strain hardening. The Giuffré-Menegotto-Pinto Model tended to overestimate the post-buckling responses of steel braces with slenderness or diameter-to-thickness ratios below 40. In contrast, the calibrated SL Model accurately evaluated the cyclic loading performance of steel braces, including post-buckling responses, across the full range of slenderness and diameter-to-thickness ratios. The calibrated SL Model was implemented in an 8-story chevron braced frame. In this frame, the lateral loads were primarily resisted by chevron braces, while the beams were designed as simply supported and proportioned to remain elastic under tension forces and brace compression, in accordance with the US Provisions.