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Ground-motion scaling for seismic performance assessment of high-rise moment-resisting frame building

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ABSTRACT

Next generation performance-based earthquake engineering involves the use of a probability framework, which incorporates the inherent uncertainty and variability in seismic hazard, structural and non-structural responses, damage states and economic and casualty losses. One key issue in seismic performance assessment is the scaling of ground motions for nonlinear response-history analysis. In this paper, the impact of ground-motion scaling procedures, including 1) geometric-mean scaling of pairs of ground motions, 2) spectrum-matching of ground-motions, 3) first-mode-based scaling to a target spectral acceleration and 4) maximum-minimum orientation scaling, on the distributions of floor acceleration, story drift and floor spectral acceleration of a sample high-rise building is investigated using a series of nonlinear response-history analyses of a 34-story moment-resisting frame building. The advantages and disadvantages of each ground-motion scaling method are discussed for seismic performance assessment of a 34-story building.

1. Introduction

The structural and non-structural damages observed during the 1989 Loma Prieta and 1994 Northridge earthquakes motivated expert practitioners and researchers to develop the first-generation tools for Performance-Based Earthquake Engineering (PBEE), such as those documented in FEMA 273 and 274 [1] and FEMA 356 [2]. The deterministic assessment procedures in those documents provided relations between structural response indices (such as story drifts and inelastic member deformations) and performance levels (such as immediate occupancy, life safety and collapse prevention) and shifted the focus of assessment from forces to displacements and deformations. FEMA 350 [3], which was drafted as part of the SAC Steel Project, extended the first generation tools through the use of probabilistic assessment procedures.

In contrast to the first-generation tools for PBEE, where performance assessments are performed using a deterministic approach, the ATC-58 project in the United States develops next-generation tools and guidelines for performance-based seismic design and assessment using a probability framework, which can incorporate the inherent uncertainty and variability in seismic hazard, structural and non-structural responses, damage states and repair costs in the assessment process [4].

A significant amount of research work has been carried out for ground motion selection and scaling. Shome et al. [5] suggested that the scaling of ground-motion records to the 5%-damped target spectral acceleration for a given event (magnitude (M) and distance (R) pair) at the fundamental frequency of a structure is efficient to estimate the nonlinear response of the structure for the event. Baker and Cornell [6] considered Intensity Measure (IM) consisting of two parameters, spectral acceleration and epsilon (ε), at a given period to predict the response of a structure when selecting ground motions as ε was found to be an good indicator of spectral shape. Baker and Cornell [7] proposed a spectrum, namely, conditional mean spectrum – considering ε (CMS-ε), that accounts for the correlation in spectral accelerations at different periods and computes the spectral accelerations for a given M-R pair conditional to a given target spectral acceleration at the fundamental period of a structure (T_1). PEER report *2009/01* [8] suggested selection of ground motions based on record properties (use the CMS for spectral shape, the proper inelastic spectral displacement target) to precise and accurate prediction of peak inter-story drift ratio response. Haselton et al. [9] proposed an alternative simplified method which allows the analyst to use a general ground motion set, selected without regard to ε, to calculate an unadjusted building collapse capacity by using nonlinear dynamic analysis, and then to correct this capacity using an adjustment factor to include the impact of the expected $\varepsilon(T_1)$ for the building site and collapse hazard intensity, $S_{a,col}(T_1)$. This eliminates the necessity of considering $\varepsilon(T_1)$ in selection of

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the ground motion records. Jayaram et al. [10] indicated conventional dynamic structural analysis often involves scaling input ground motions to a target mean response spectrum. The variance in the target spectral acceleration is usually ignored, which can bias the structural response estimates. They proposed a computationally efficient and theoretically consistent algorithm to select and scale ground motions that match target spectral accelerations in both mean and variance.

Weng et al. [11] proposed a multimode ground motion scaling (MMS) ground-motion scaling method which includes contributions from the dominating modes and uses the square root of the sum of the squares (SRSS) or complete quadratic combination (CQC) rule in the estimate of seismic demands. They conducted a series of nonlinear response-history analyses for sample low-, medium- and high-rise buildings and concluded that the MMS method is effective in reducing the dispersion in peak seismic demands.

Kalkan and Chopra [12] have developed a modal-pushover-based scaling (MPS) method to scale ground motions for use in nonlinear response history analysis of buildings and bridges. The step by step method is useful for first mode dominant structures as well as for structures susceptible to higher mode effect. The MPS procedure has been evaluated (from the prospective of seismic design and not performance assessment) for low- and mid-rise buildings (four-, six- and thirteen story buildings) in the paper.

Katsanos et al. [13] reviewed various methodologies developed for selecting appropriate records that can be used for dynamic analysis of structural systems in the context of performance-based design and observed that there are many ways to achieve record selection. They concluded that it is still difficult to limit the bounds of the ensuing structural response dispersion uniformly. NIST [14] provided recommendations related to selecting and scaling ground motions for design and performance assessment of low and medium-rise buildings, and discussed best practices for applying the current rules in building codes and standards.

Huang et al. [15] studied four scaling methods, namely, 1) geometric mean scaling of pairs of ground motions, 2) spectrum matching of ground motions, 3) first-mode-period scaling to a target spectral acceleration and 4) scaling of ground motions per the distribution of spectral demands to see the impact of alternate ground-motion scaling procedures on the distribution of displacement responses in single-degree-of-freedom (SDOF) structural systems.

The selection and scaling of ground motions for the analysis for high-rise buildings are more challenging than that for shorter buildings. High-rise buildings have longer natural period. The difference in period between the first and higher modes is greater and the higher-mode effect is more significant for high-rise buildings. One should consider a wide period range when scaling ground motions for the analysis of high-rise buildings because the loss contributed from short- and long-period spectral demands may both be significant. Scaling methods based solely on the spectral demand at the first-mode period may not be appropriate. Spectrally-matched ground motions to a uniform hazard spectrum (UHS) for a very wide period range may produce overly conservative results since 1) the short- and long-period spectral demands may be governed by different events and 2) the impact of the correlation in spectral demands at different periods is not included in the development of a UHS.

The main objective of this paper is to study the impact of ground-motion scaling procedures on the distributions of structural responses of high-rise buildings. A series of nonlinear response-history analysis are performed for a 34-story moment-resisting frame building subjected to ground motions scaled using different methods, namely, 1) geometric-mean scaling of pairs of ground motions, 2) spectrum-matching of ground-motions, 3) first-mode-based scaling to a target spectral acceleration, 4) maximum-minimum orientation scaling methods and 5) spectrum-matching method to study the contribution of higher modes. The impact of ground-motion scaling on seismic performance of high-rise building is discussed. We focus not only on the median values of the structural responses (e.g., peak floor acceleration, peak story drift and average floor spectral acceleration) but also on their dispersions.

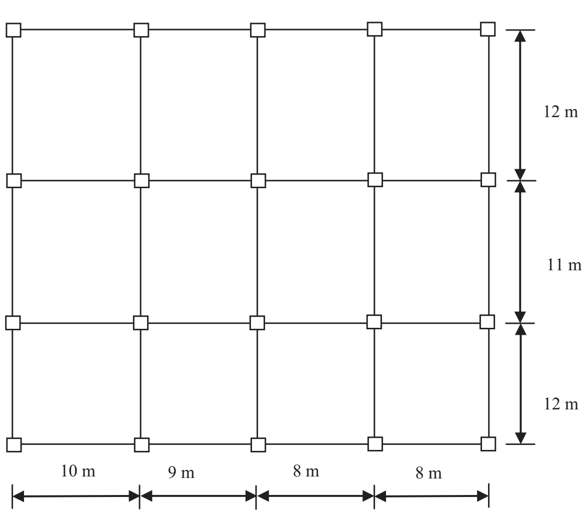

Fig. 1. 2D Plan view of the building.

2. Building description and numerical modeling

Fig. 1 presents the plan of the sample 34-story building for this study. The building has four (three) bays in the X (Y) direction and a typical story height of 3.5 m. The building consists of moment resisting frames with steel-concrete composite columns and steel beams. Each column consists of concrete core with a compressive strength of 55 MPa and steel box-section outside the concrete core as main reinforcement. The steel section is bonded to the inside concrete core and the relatively low-strength out-side concrete (with a compressive strength of 20.5 MPa) through shear lugs. Corner reinforcement and steel stirrups are provided near the periphery of the column section.

The sample building is located on a rock site in northern Taiwan and designed according to the design spectrum of Fig. 2. In this study, the building was modeled using SAP2000 [16]. The periods of the first three modes of the numerical model for the sample building in the X (Y) direction are 4.58, 1.63 and 0.94 (4.90, 1.76 and 1.02) seconds, respectively. The period of the first torsional mode is 3.5 s. Plastic hinges were assigned to the numerical model for the sample building. Moment hinges per Table 5–6 of FEMA 356 (Steel Beams - Flexure) were assigned at the ends of the beams. P-M2-M3 hinges in SAP2000 were assigned at the ends of the columns to consider the interaction of axial force and bi-axial bending moments. The pushover curves of the building in the X and Y directions are presented in Fig. 3.

A series of nonlinear response-history analyses were performed in SAP2000 for the numerical model described above using direct integration method with P-Delta effect included. Mass-and-stiffness proportional damping was used in the analysis with 5% damping ratio assigned at periods of 4.90 and 1.76 s based on the periods of the first and third modes of the sample building.

3. Seed ground motions

Thirty pairs of seed ground motions were selected from PEER NGA ground motion database with moment magnitude between 6.7 and 7.6, closest site-to-source distance between 3 and 13 km and Site Classes of B and C per ASCE-7 site classification [17] [1]. Table 1 presents a list of the thirty pairs of seed ground-motion records used in this study. Each

[1] The site of the sample building is about 10-km away from the Xin-Cheng fault in Taiwan, which governs the seismic hazard of the site.