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Extending modal pushover-based scaling procedure for nonlinear response history analysis of multi-story unsymmetric-plan buildings

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ABSTRACT

The modal-pushover-based-scaling (MPS) procedure has been developed for appositely selecting and scaling earthquake records for nonlinear response history analyses (RHAs) of multi-story symmetric-plan and single-story unsymmetric-plan buildings. This procedure is extended here to unsymmetric-plan buildings with significant torsional response under bi-directional earthquake excitations. The accuracy of the procedure is evaluated by using three-dimensional computer models of nine unsymmetric-plan buildings with 5, 10 and 15 stories. These models were subjected to nonlinear RHAs considering sets of seven far-field records selected and scaled according to the extended modal-pushover-based-scaling (EMPS) procedure. Structural responses were compared against benchmark values, defined as the median values of the engineering demand parameters (EDPs) due to a larger set of unscaled far-field records. Also examined here is the ASCE/SEI 7-10 scaling procedure for comparison purposes. This study clearly shows that the EMPS procedure provides much superior results in terms of accuracy (true estimates of expected median EDPs) and efficiency (reduced record-to-record variability of EDPs) than the ASCE/SEI 7-10 scaling procedure for far-field ground motions. Thus, the EMPS is deemed to be an appropriate procedure for nonlinear RHAs of multi-story unsymmetric-plan buildings.

1. Introduction

Performance-based procedures for evaluating existing buildings and proposed designs of new buildings in the U.S. require response history analyses (RHAs) for an ensemble of earthquake records in order to determine engineering demand parameters (EDPs) for validation of targeted performance criteria. Earthquake records selected for RHAs often need to be scaled to a seismic hazard level considered. Fraught with several challenging issues, selection and scaling of ground motions necessary for nonlinear RHA remains the subject of much research in recent years.

Among the many procedures proposed to modify ground motion records, the most widely used approaches are amplitude scaling and spectrum matching [1]. The objective of amplitude scaling procedures is to determine scaling factors for a small number of records such that the scaled records provide an accurate estimate of structural responses, and, at the same time are efficient, i.e. reduce the record-to-record variability (dispersion) of responses. The term "accuracy" means that the scaled records should provide median (or mean) responses close to the "exact" responses considering large population of records compatible with the hazard conditions specified. The term "efficiency" means that ground motions after scaling to the design (target) spectrum should impose similar seismic demands to the structure. While large record-to-record variability in EDPs leads to uncertainties in design and diminishes the confidence level, small record-to-record variability (dispersion) indicates that scaled records represents well the target demand level. Thus, a reliable scaling method should not only produce accurate but also efficient estimates of EDPs.

In earlier approaches, ground motion records were scaled to match a target intensity measure such as peak ground acceleration, effective peak acceleration, arias intensity, or effective peak velocity [2,3]. These approaches are generally inaccurate and inefficient for structures responding in the nonlinear range [3,4]. Scaling of records to match the target spectrum at the fundamental vibration period of the structure provides improved results for elastic structures whose response is dominated by its first-"mode" of vibration [5]. However, if the contributions of higher modes are important or the structure deforms significantly into the inelastic range, this scaling method becomes less accurate and less efficient [3,6,7]. Modifications of this method considering the target spectrum

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ordinates at the first and second vibration periods have been proposed [8,9]; however, efficiency of these modified methods is compromised for near-fault records with a dominant velocity pulse [10]. To account for higher-mode contributions to response and lengthening of the apparent vibration period after the structure deforms into the inelastic range, the scaling factor for a ground motion record can be chosen to minimize the difference between its elastic response spectrum and the target spectrum over a period range [11–16]. Because the preceding methods do not consider explicitly the nonlinear behavior of the structure, they may not be appropriate for near-fault sites where the inelastic deformations can be significantly larger than the deformations of the corresponding linear system [7,17–19]. For such sites, scaling methods that are based on the inelastic deformation spectrum or consider the response of the first-"mode" inelastic single-degree-of-freedom (SDF) system are more appropriate [16,20,21]. These ideas were utilized by Kalkan and Chopra [22] to develop a modal-pushover-based-scaling (MPS) procedure for selecting and scaling earthquake ground motion records in a form convenient for evaluating existing structures and proposed designs of new structures. This procedure explicitly considers structural strength, determined from the first-"mode" pushover curve, and determines a scaling factor for each record to match a target value of the deformation of the first-"mode" inelastic SDF system. The MPS procedure has been proven to be accurate and efficient for low-, medium-, and high-rise buildings with symmetric plan [22–24] and ordinary standard bridges [25,26] subjected to one component of ground motion.

Scaling two horizontal components for use in three-dimensional (3D) analysis of buildings has received less attention. Researchers have proposed that both components of a record be scaled by the same factor, selected to match their geometric mean spectrum to the target spectrum over a period range [12,27]. For far-fault sites, the ASCE/SEI 7-10 standard [28] requires that the ground motion records be scaled so that the average value of the square-root-of-sum-of-squares (SRSS) spectra for all horizontal-component pairs does not fall below the target spectrum. Beyer and Bommer [27] present a comprehensive summary of various aspects that should be included in the process of selecting and scaling two components of ground motions. They conclude that selecting and scaling records according to their "goodness-of-fit" with the target spectrum leads to efficient estimates of median responses. Recently, Reyes and Chopra [29] extended the MPS procedure for one component of ground motion (mentioned above) to two horizontal components. In summary, most existing scaling procedures may not be appropriate for the following cases: (1) near-fault sites where the inelastic deformation can be significantly larger than the deformation of the corresponding linear system [3,4,7]; (2) tall buildings where the higher mode responses are significant [24]; (3) unsymmetric-plan buildings where various coupled lateral torsional vibration modes may provide comparable contributions to response. Clearly, there is a need to develop procedures for selection and scaling of ground motions to be used in nonlinear RHA of unsymmetric-plan buildings, ranging from low-rise to high-rise buildings subjected to multi-component ground motions.

Lastly, Reyes and Quintero [30] proposed a new version of the MPS procedure for single-story unsymmetric-plan buildings. In order to generalize the findings from single-story systems to multi-story systems, it is essential to perform further validation and verifications of the MPS procedure using realistic multi-degree-of-freedom (MDF) systems. This paper extends this procedure to multi-story unsymmetric-plan buildings. In addition, the developed procedure is compared against the ASCE/SEI 7-10 scaling procedure for far-field ground motions. Based on results from nine multi-story unsymmetric-plan buildings with various plan shapes and heights, it is shown that the EMPS procedure provides much superior results in terms of accuracy and efficiency than the ASCE/SEI 7-10 scaling procedure. This manuscript is the first study evaluating the ASCE7-10 and EMPS ground motion scaling procedure for irregular plan multi-story realistic structural systems. The ASCE7-10 procedure has been the common practice in U.S. for design verification of important structures, which often have irregular plans; thus, our study fills an important gap by showing the limitations of this ground motion scaling procedure and by examining its accuracy and efficiency considering various different types of plan irregular buildings.

2. Extended MPS procedure (EMPS)

3D analysis of buildings requires the use of the two horizontal components of the ground motion records. In current versions of the MPS procedure, the two components are scaled independently in order to increase the accuracy, efficiency and effectiveness of the method [29,30]. However, these investigations have been limited to the analysis of multi-story symmetric-plan and single-story un-symmetric plan buildings. In this investigation, the scale factors are estimated using roof displacements at the center of mass (C.M.) instead of deformation of the first-"mode" inelastic SDF system [30]. Scaling factor (*SF*) for each ground motion is obtained independently for each horizontal direction by solving the following nonlinear equation:

$$u_r - \hat{u}_r = 0 \tag{1}$$

where u_r is the peak roof displacement calculated by implementing the uncoupled modal response history analysis (UMRHA) [31, chapter 20], and $\hat{u}_r$ is the target roof displacement. In practical implementation, the target roof displacement may be estimated from the response spectrum by combining inelastic "modal" displacements, just as for linear systems. This application of modal combination rules to nonlinear systems obviously lacks a rigorous theoretical basis, but seems reasonable if the modes are weakly coupled [31, chapter 20].

The EMPS procedure is implemented here in three phases: (1) target roof displacement and pushover analyses, (2) scaling phase, and (3) selection phase. The step-by-step procedure is presented below in a general form, valid for 3D analysis of multi-story buildings.

2.1. Target roof displacement and pushover analyses

(1) For a given site, define the target spectra $\widehat{A}_x$ and $\widehat{A}_y$, in this study, taken as the median of the 5% damped pseudo-acceleration response spectra of two components of the records. For a selected earthquake scenario, it is commonly assumed that response spectra and EDPs are log-normally distributed [32]. For this reason, it is more appropriate to represent the "mean" structural response by the median; a conclusion that is widely accepted. Because the geometric mean and median of a random variable having a log-normal distribution are the same, we decided to employ the term "median" instead of geometric mean, as is commonly done.
The use of the median spectrum as the target spectrum is not a constraint of the proposed EMPS procedure; any other target spectrum (e.g., 84th percentile target spectrum) can be utilized.

(2) Compute the natural frequencies ω_n (periods T_n) and modes ϕ_n of the first few modes of linear-elastic vibration of the building. For each ground motion component direction (x or y), identify the first, second and third modes as the three modes with the largest effective modal mass.