DEVELOPMENT OF A GROUND MOTION SCALING METHOD CONSIDERING MULTI-MODE EFFECTS

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ABSTRACT :

Non-linear dynamic time-history analyses conducted as part of a performance-based seismic design approach often require that the ground motion records are scaled to a specified level of seismic intensity. Recent research has demonstrated that certain ground motion scaling methods can introduce a large scatter in the estimated seismic demands. The resulting demand estimates may be biased, leading to designs with significant uncertainty and unknown margins of safety. This paper proposed a novel ground motion scaling method considering multi-mode effects for seismic evaluation of high-rise buildings. It is shown that the scaling method that work well in reducing the scatter in estimated peak seismic demands for a wide range of structural characteristics.

KEYWORDS: Multi-mode effects, performance-based seismic design, non-linear dynamic analysis, RSA, scaling of ground motions

1. INTRODUCTION

The amount of tall buildings located in seismic regions is rapidly increased in recent years. The seismic responses of tall buildings are much influenced by higher modes. The seismic demands of higher modes may be more critical than those of the first vibration mode for some specific responses. Although the elastic design response spectrum is enough for the elastic response spectrum analysis (RSA), the sets of scaled ground motion records, which are consistent with the design response spectrum, are still required for nonlinear response-history analysis (NLRHA). Ground motion records should be selected from actual earthquakes considering magnitude, distance, site condition, and other parameters that affect the characteristics of ground motions. Historical ground motion records can be scaled by either matching the peak ground acceleration or some specific spectral responses. According to the latest building codes (ICBO 2006), no less than seven two-component sets of ground motion time history should be used for each assessment of seismic performance. Thus, there should be 14 sets of ground motion time history available for the service- and collapse-prevention-level assessments by using response-history analyses (RHA).
The advantage of historical ground motion scaling is that individual ground motion record retains its original characteristics including peaks and valleys of the response spectrum. However, to avoid the response being dominated by the peaks and valleys of any single one ground motion, it is recommended that there are no less than seven ground motion records to be used for NLRHA (ICBO, 2006).

2. SCALING OF HISTORICAL GROUND MOTIONS

In order to gain insights into the nonlinear responses of the multi-story buildings under the excitation of historical ground accelerations, extensive NLRHA have been conducted. The techniques of ground motion scaling methods (Shome and Cornell 1998, Kurama and Farrow 2003) have also been studied in the research. Two of the most common ground motion scaling methods, for a building having T_1 as the fundamental vibration period in the considered direction, are described as follows:

1. Code method: the ground motion scaling procedure prescribed in IBC (ICBO, 2006). Given a suite of ground motion records, a scale factor is applied to each record to either increase or decrease its intensity. Each scale factor is determined such that the corresponding spectral accelerations between the period range from $0.2T_1$ to $1.5T_1$ satisfy that the average of response spectrum from the scaled motion does not

fall below the target design response spectrum.

2. $Sa(T_1)$ method (Shome and Cornell, 1998): each ground motion is scaled so that its spectral acceleration value, $Sa(T_1)$, at the linear-elastic fundamental period of the structure being analyzed, matches the target design response spectrum.

The accuracy of any ground motion scaling procedure such as MMS in reducing the scatter in estimated peak seismic demands for buildings must be evaluated for a wide range of systems and ground motions, with the goal of establishing its range of applications and limitations. Therefore one of the key tasks in this study is to comprehensively evaluate the MMS procedure and compare its results with those obtained from other commonly used methods. Seismic demands computed from the smoothed design spectrum and the scaled spectrum obtained from the natural earthquake accelerations using three methods for the SAC buildings (Gupta and Krawinkler, 1999) will be presented first. The selected SAC buildings represent three building heights, 3-story, 9-story and 20-story in Los Angeles.

3. MULTI-MODE GROUND MOTION SCALING PROCEDURE

The principal idea of MMS is to minimize the first few modal participating difference between the spectral accelerations or displacements of a scaled ground motion and that of the smoothed target design response spectrum. For discussion purposes, the SRSS rule is used to illustrate the computation of the scaling factor proposed in the MMS method. Thus, given the acceleration response spectra, the base shears (V_d and V_{EQ}) and roof displacements ($u_{roof,d}$ and $u_{roof,EQ}$) can be expressed as:

$$V_D = \sqrt{\sum_{n=1}^{N}\left(\Gamma_i L_i S_{ai,des}\right)^2}\ ,\quad V_{EQ} = \sqrt{\sum_{n=1}^{N}\left(\Gamma_i L_i S_{ai,EQ}\right)^2} \tag{3.1}$$

and

$$u_{roof,d} = \sqrt{\sum_{n=1}^{N}\left(\Gamma_i S_{ai,des}/\omega_i^2\right)^2}\ ,\quad u_{roof,EQ} = \sqrt{\sum_{n=1}^{N}\left(\Gamma_i S_{ai,EQ}/\omega_i^2\right)^2} \tag{3.2}$$

where V_d (or $u_{roof,d}$) and V_{EQ} (or $u_{roof,EQ}$) are calculated from the smoothed design spectrum and the spectrum obtained from the natural earthquake accelerations respectively. On the other hand, Γ_i and L_i are the modal participation factor and modal excitation factor of the i^{th} mode respectively. Finally $S_{ai,des}$ and $S_{ai,EQ}$ are the spectral accelerations in the smoothed design spectrum and the spectrum obtained from the natural earthquake accelerations respectively.

3.1. Computation of the scaling factors from the MMS method

The least square error fitting method can be used to reduce the modal participating difference between the spectral accelerations or displacements of a scaled ground motion of the first few modes and that of the smoothed design response spectra. The square error of the smoothed spectral set and the original un-scaled spectral set of accelerations can be expressed as:

$$(error)^2 = \sum_{i=1}^{N} W_i\left[S_{ai,des} - SF\cdot S_{ai,EQ}\right]^2,\ \ (i = 1 \sim N) \tag{3.3}$$

where SF is the scaling factor whereas W_i is the i^{th} modal weighting factor. The minimum error can then be achieved when the partial derivative of $error^2$ with respect to the scaling factor SF becomes zero:

$$\frac{\partial\left(error^2\right)}{\partial(SF)} = 0 \tag{3.4}$$

Thus, SF can be expressed as:

$$SF = \sum_{i=1}^{N} W_i \cdot S_{ai,des} \cdot S_{ai,EQ} \Big/ \sum_{i=1}^{N} W_i \cdot \left(S_{ai,EQ}\right)^2 , \quad (i = 1 \sim N) \qquad (3.5)$$

Since the elastic peak base shear, V_i is expressed in terms of $\Gamma_i L_i S_{ai}$ (see Eq. 3.1), it is proposed that the weighting factors, W_i for each mode be expressed as shown in Eq. (3.6) for the computation of scaling factors. For the interest of computing base shear:

$$W_i = \Gamma_i^2 L_i^2 \Big/ \sum_{i=1}^{N} \Gamma_i^2 L_i^2 , \; (i = 1 \sim N) \qquad (3.6a)$$

whereas for computation of roof the displacement:

$$W_i = \left(\Gamma_i / \omega_i^2\right)^2 \Big/ \sum \left(\Gamma_i / \omega_i^2\right)^2 , \; (i = 1 \sim N) \qquad (3.6b)$$

Thus, weighting factor given in Eq. (3.6a) can be applied in Eq. (3.5) for the computation of scaling factors when base shear is considered as the key design parameter. Eq. (3.6b) has been found satisfactory in reducing the scatter of peak roof displacement estimates but not for other response parameters in the seismic performance evaluation of a 34-story steel building (Weng et al., 2008). Thus in this paper, only the weighting factors given in Eq. (3.6a) proposed for computing the scaling factor are applied. The effectiveness of applying Eqs. (3.6a) and (3.5) in computing the seismic demand for the SAC buildings in Los Angeles is present in this paper. The effects of the number of modes included not studied previously are also illustrated for the performance evaluation of the 34-story steel building. When the RSA method is applied, it has been suggested that the number of modes be determined to include at least 90% of the total building effective mass (ICBO, 2006).

4. COMPARISONS OF THE MMS METHODS VERSUS CURRENT GROUND MOTION SCALING METHODS

4.1. Description of the example structures

The proposed procedure is investigated using three steel moment frame (MF) model buildings under various ground motion scenarios. The example buildings are the three 'post-Northridge' designs of 3-, 9-, and 20-story model buildings for the city of Los Angeles (developed in the SAC Steel Project (Gupta and Krawinkler, 1999)). It is referred to as the SAC buildings in this paper. These structures meet the seismic code requirements as per UBC-94 (ICBO, 1994) and represent typical low-, medium-, and high-rise buildings designed for Los Angeles at that time. Details regarding frame dimensions, material properties, and loads can be found in the reference (Gupta and Krawinkler, 1999). For each building, a 3-dimensional model of the building is constructed. For the discussion purposes, the responses of the North-South frames of each building are presented in this paper. Figure 1 shows the basic layout of these frames. Each structure model was constructed using the centerline dimensions and the PISA3D program for nonlinear response history analyses (Tsai and Lin, 2003). The bilinear elastic-perfect-plastic beam-column element without strain hardening has been used for modeling all beams and columns. Effects of gravity loads and the P-Delta effects are considered. Damping ratios of 5% are assumed for the first two modes. For the purpose of illustrating the effectiveness of the MMS method, only two modes (constitute more than 90% of the total building effective mass) were incorporated into the computation of the scaling factors. Table 1 shows the first two fundamental periods, modal participation factors Γ_i, modal excitation factors L_i and each weight factor for the first two modes in the North-South direction of the three SAC buildings.

Table 1. Modal properties and weighting factors of Los Angeles-SAC Buildings

Modal Characteristics	**Los Angeles**		
	3-story	**9-story**	**20-story**
T_1	1.07	2.33	4.00
T_2	0.31	0.88	1.38

Γ_1	1.27	1.37	1.35
Γ_2	-0.34	-0.54	-0.55
L_1	1990	5338	6576
L_2	-1387	-1899	-2100
W_1	0.97	0.98	0.98
W_2	0.03	0.02	0.02

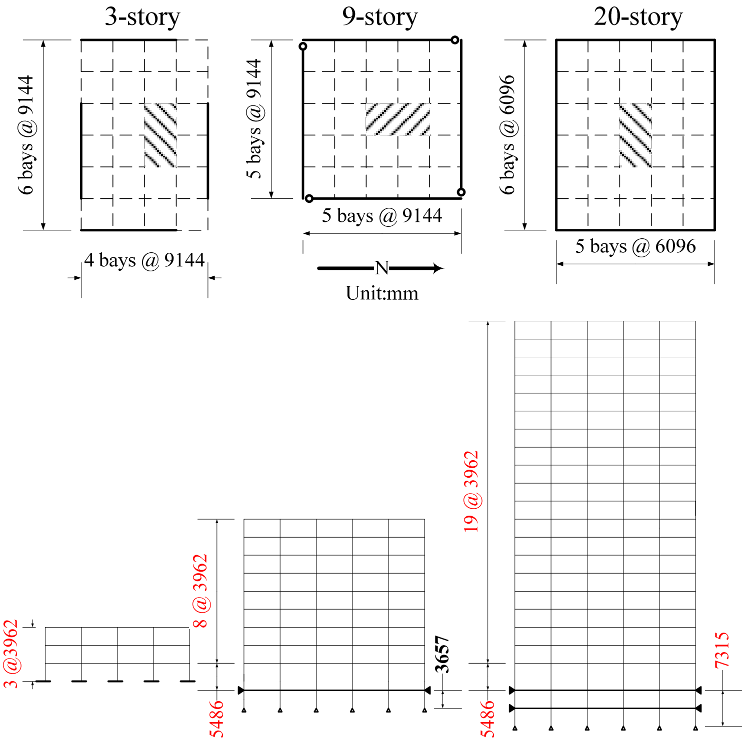
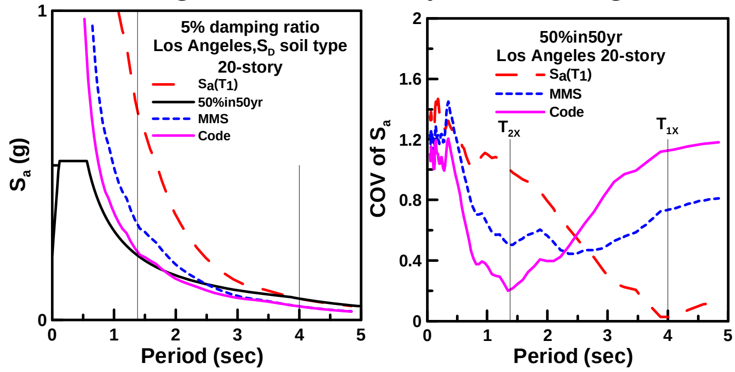


Figure 1 Floor plans (showing layouts of moment resisting frames in unbroken lines) and elevations of SAC buildings; 3-, 9-, and 20-story from left to right



(a) (b)

Figure 2 (a) The mean elastic 5%-damped spectral acceleration; (b) the corresponding COV spectrum after the 50%in50yr LA ground motion set scaled by three scaling methods for the 20-story LA SAC building

4.2. SAC Ground Motions

In the SAC project, two sets of 20 ground motion records representing probabilities of exceedance of 50% and 2% in 50 years, denoted as 50%in50yr and 2%in50yr respectively, have been assembled for Los Angeles City. These two sets of ground motions were adopted in evaluating the MMS procedure for different earthquake hazard levels. In order to match the seismic demand of the smoothed 5% damped elastic acceleration response spectra for Los Angeles, two sets of corresponding synthetic ground accelerations were constructed incorporating the phase angles (Chai et al., 2002) in the two sets of 20 natural ground motions stated above for the 50%in50yr and 2%in50yr hazard levels, respectively. In order to evaluate the scatter of the peak seismic demands computed from both the RSA and RHA methods, a coefficient of variance (COV) factor is defined as

$$COV = \sqrt{\sum_{i=1}^{n}\left(X_i - \hat{X}\right)^2 /(n-1)} \Big/ \hat{X} \tag{4.1}$$

where n is the number of earthquake records, X_i is the peak response value determined from the RSA or RHA procedure associated with the i^{th} scaled natural earthquake acceleration record. The $\hat{X}$ is the mean value of the peak responses calculated by the RSA procedure (using the smoothed design spectrum) or the RHA procedure (using the aforementioned synthetic earthquakes compatible with the smoothed design spectrum). The COV parameter provides comparison for all the earthquakes considered for each SAC building.

Figure 2a shows the smoothed 5% damped elastic acceleration response spectrum for the LA 50%in50yr earthquake. In the same figure, three other response spectra, constructed from the averaged responses of the 50/50 set of LA ground motions scaled according to three different methods, are also compared. Figure 2b shows the COVs of the response spectra, with respect to the LA smoothed 50%in50yr response spectrum, computed from the ground motions using three scaling methods. It can be found in Figures 2a that the average of the twenty spectra computed using MMS method is closer to the smoothed design spectrum in the overall range from periods of T_1 to T_2, particularly near the first mode period T_1. Further studies described later will allow us to compare the effectiveness of the MMS with that of the Code or $S_a(T_1)$ method in reducing the scatter of the peak seismic demands computed from both the RSA and RHA procedures.

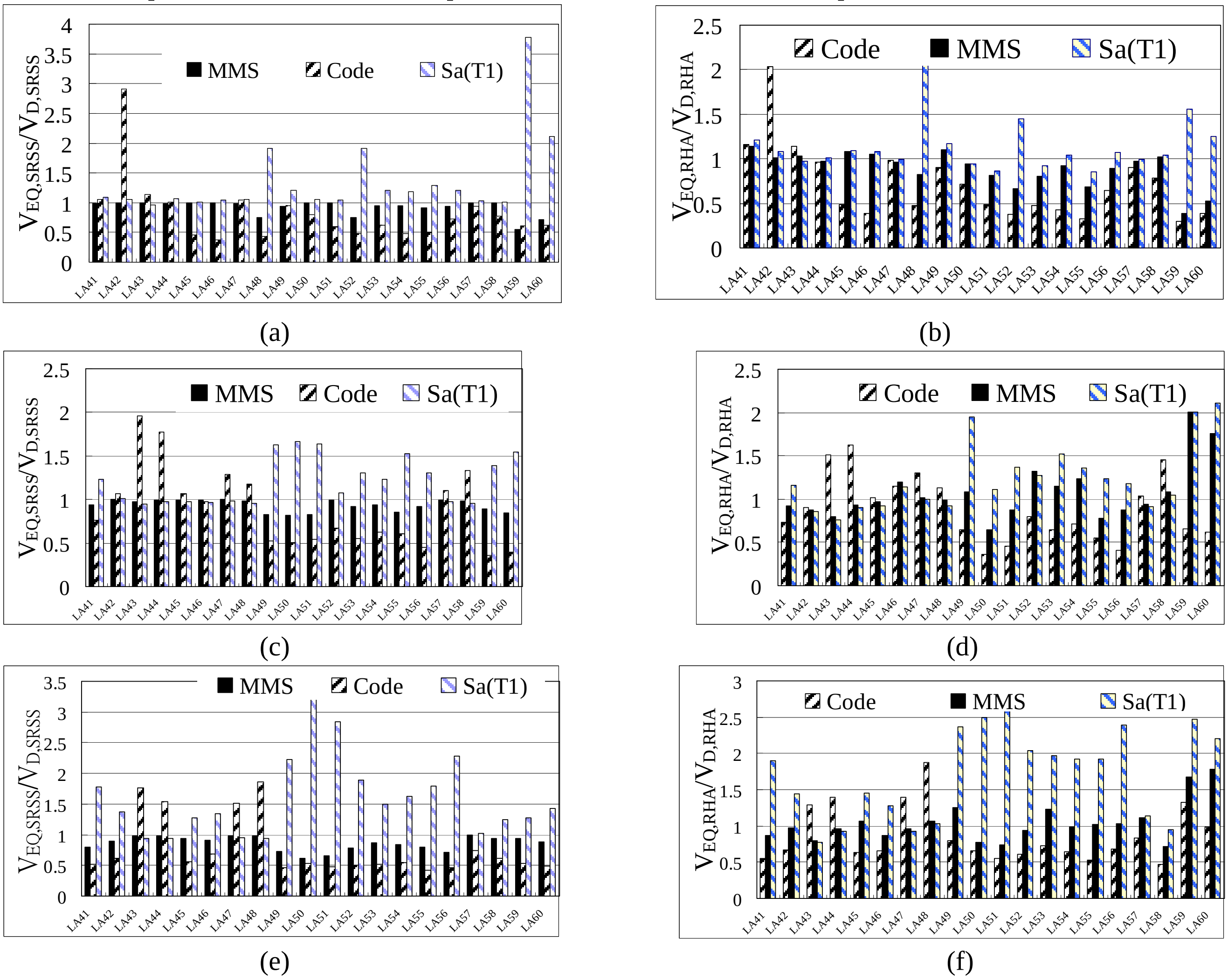


Figure 4. The base shear ratio $V_{EQ,SRSS}/V_{D,SRSS}$ or $V_{EQ,RHA}/V_{D,RHA}$ for all 20 earthquakes considered under the 50%in50yr earthquake level scaled by three scaling methods in the (a, b) 3-story, (c, d) 9-story, (e, f) 20-story LA SAC buildings

4.3. Comparison of elastic seismic demand estimates by MMS, $S_a(T_1)$ and Code Methods

In order to illustrate the compatibility of the 20 synthetic earthquakes with respect to the smoothed design spectrum, arithmetic mean of the peak story shear forces obtained from the RHA using the twenty 50%in50yr-level synthetic ground motions. In order to evaluate how well the MMS method works, the effects of three ground motion scaling methods on the variance in elastic seismic demands estimates are examined. First, it is assumed that all the structural responses of the three SAC buildings remain elastic under the 50%in50yr earthquakes. Then, two base shear ratios $V_{EQ,SRSS}/V_{D,SRSS}$ and $V_{EQ,RHA}/V_{D,RHA}$ are calculated for each of the three buildings using each of the 20 (50%in50yr) ground motions. The estimated peak shears $V_{D,SRSS}$ and $V_{EQ,SRSS}$ were calculated from the SRSS rule using the smoothed design spectrum and the spectrum obtained from the scaled natural earthquake accelerations, respectively. Likewise, the peak responses obtained from the RHA procedures, using each synthetic earthquake matching the smoothed design spectrum and the scaled natural earthquake accelerations are defined as $V_{D,RHS}$ and $V_{EQ,RHA}$, respectively.

Figure 4 provides the stated base shear ratios for the three buildings for the 20 (50%in50yr) earthquakes using the proposed MMS and the other two scaling methods. When the base shear ratio $V_{EQ,SRSS}/V_{D,SRSS}$ (or $V_{EQ,RHA}/V_{D,RHA}$) is closer to 1.0, it implies that the estimate of the peak seismic shear demand is closer to that computed from the smoothed response spectrum. It is evident in Fig. 4 that the MMS method provides an overall better agreement between the V_{EQ} and V_D than those obtained from using other two scaling methods.

4.4. Comparison of nonlinear seismic demand estimates by MMS, $S_a(T_1)$ and Code Methods

Nonlinear response history analyses were conducted by applying the 2%in50yr set of LA ground motions scaled according to the MMS, $S_a(T_1)$ and Code methods in the subsequent analysis. Arithmetic mean of the peak response values obtained from NLRHA using the twenty 2%in50yr-level synthetic ground motions were first computed, the COVs of the specific peak responses computed for the twenty scaled natural ground motions can be evaluated. The COVs are presented for two key responses along the height of the each SAC building in LA as follows:

4.4.1 Variability of peak story shear

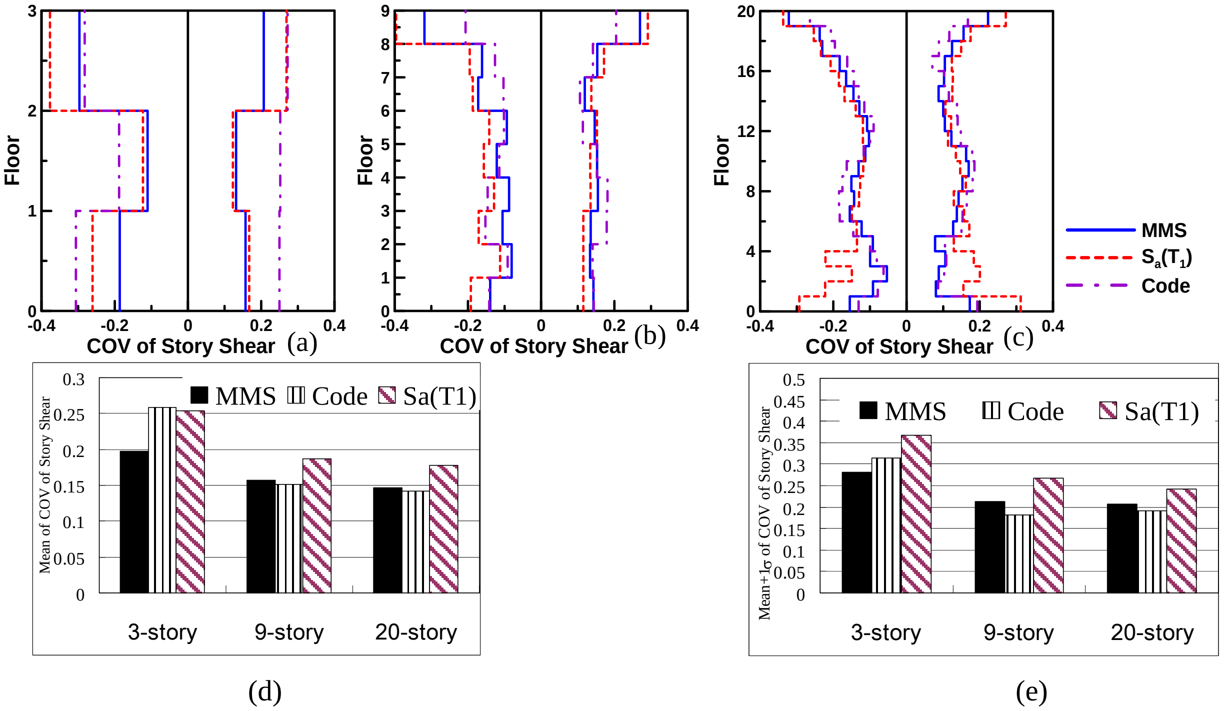
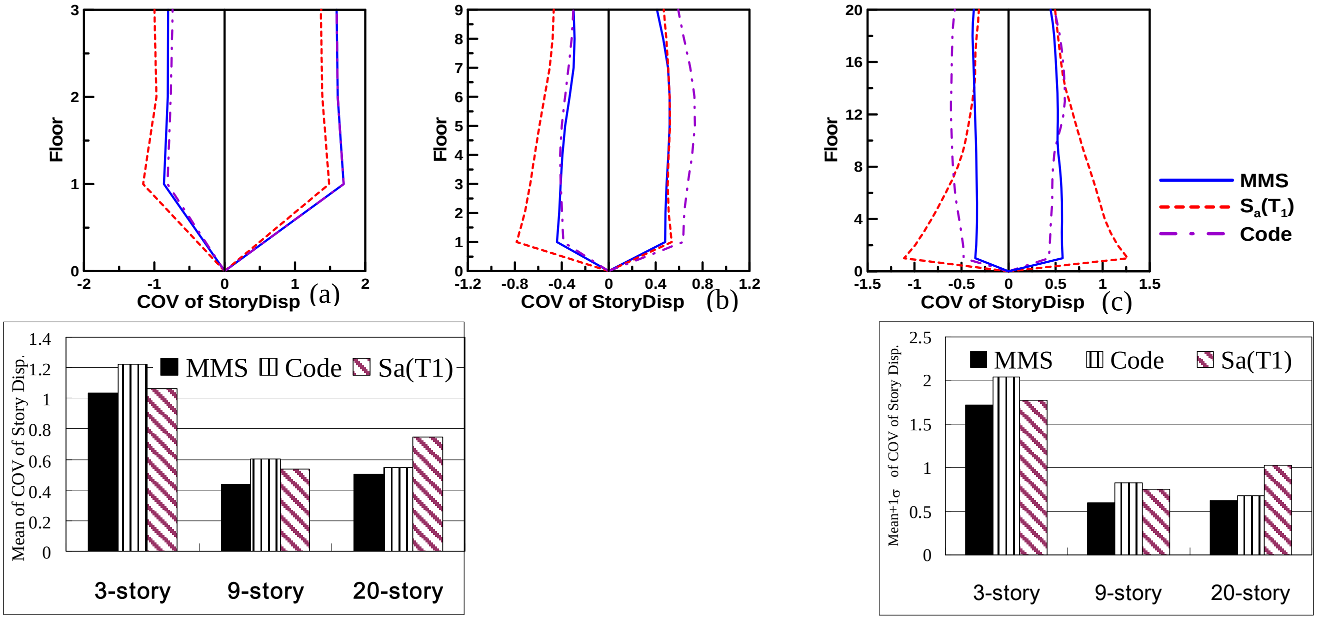


Figure 5 The COV distributions of peak story shear in (a) 3-story, (b) 9-story, (c) 20-story, and (d) the mean and (e) the mean plus one standard deviation of absolute COV distributions of the peak story shear in the three LA SAC buildings after the 2%in50yr ground motion set scaled by three scaling methods

Figures 5a to 5c show the COVs of the peak story shear profiles along the building height in the N-S direction using the three scaling methods, for the 3, 9 and 12-story buildings, respectively. The results suggest that the MMS method is somewhat better, in reducing the variation of the peak story shear demand estimates in the three SAC buildings, than the other two scaling methods. The $S_a(T_1)$ and Code methods could induce rather significant scatter of the peak story shear demand estimate. In addition, the $S_a(T_1)$ method significantly increases the variations of the peak story shear demand estimates from the ground floor up to the 5^{th} floor compared to other two scaling methods adopted for analyzing the 20-story LA SAC building. Figures 5d and 5e show that the mean, and the mean plus one standard deviation of the absolute peak story shear COV distributions in the three SAC buildings subjected to the stated ground motion set scaled by three scaling methods. Again, the MMS method appears to provide an effective mean in reducing the scatter of the peak story shear along the full buildings height compared to the other two scaling methods.

4.4.2 Variability of peak floor displacement

Figures 6a to 6c show the COVs of the peak lateral floor displacements from using the three scaling methods in the N-S direction, for the three SAC LA buildings. The differences in COVs from using three scaling methods are not so pronounced in the 3 and 9-story building. However, the COVs computed for the $Sa(T_1)$, and Code methods vary noticeably along the 20-story building height, but its magnitude and variation are significantly reduced when the MMS method is used. In addition, the $S_a(T_1)$ method significantly increases the variation of the peak floor displacement demand estimate from the ground floor to the 6^{th} floor compared to other two scaling methods applied in the 20-story SAC building in LA. Figures 6d and 6e show that the mean and the mean plus one standard deviation of absolute COV distributions of the peak floor displacement in the three LA SAC buildings. It can be observed that the MMS method fares better in reducing the scatter of the peak floor displacement along the full building heights than the other two scaling methods. The effectiveness of the MMS method in reducing the scatter of the peak floor displacement along the building height is hence demonstrated.



(d) (e)

Figure 6 The COV distributions of peak floor displacement in (a) 3-story, (b) 9-story, (c) 20-story, and (d) the mean and (e) the (mean + 1σ) of absolute COV distributions of the peak floor displacement in the three LA SAC buildings after the 2%in50yr ground motions set scaled by three scaling methods

5. CONCLUSIONS

Based on these analyses, conclusions were drawn as follows:

- Among the three scaling methods considered in this study, including the MMS, the Code and the $S_a(T_1)$ methods, it appears that the MMS method results in more consistent seismic demands with those obtained using the smoothed design response spectra. This improved consistency is particularly significant for high-rise buildings.

- The $S_a(T_1)$ method often failed to reduce the scatter of the estimated peak story shear, overturning moment and peak inter-story drifts of all the investigated buildings (Figures 5(a), 5(c), 6(a) and 6(c)).
- Compared to the other two scaling methods, the MMS method can effectively reduce the scatter of the spectral acceleration differences with respect to the smoothed design response spectrum.
- The MMS method can provide a better agreement between the V_{EQ} and V_D. In other words, it can better match the peak base forces induced from applying a series of scaled historical ground motion records to those computed using RSA procedures on a smoothed design spectrum.
- Except the scaling factors obtained using the MMS method, those determined from the $S_a(T_1)$ and Code methods are often larger than the upper limit prescribed in the building codes (Malhotra, 2003). Furthermore, it appears that $S_a(T_1)$ and Code methods often lead to an overestimation of the seismic force responses of the investigated buildings. The more vibration modes are incorporated by the MMS method, the smaller scaling factors satisfied with the stated upper limit are yielded.
- The MMS method can be conveniently applied for elastic RSA or NLRHA of low-to-high rise buildings. It appears particularly effective in reducing the scatter of the seismic demand estimates on the peak story shear, overturning moment and peak inter-story drift for tall buildings.

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