Accuracy of RSA Design Demands for Multi-Tower Buildings

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Abstract. Response spectrum analysis (RSA) procedure commonly used in design practice has been found to underestimate design forces in tall buildings. This study aims to check the accuracy of the RSA procedure when applied to multi-tower buildings sharing a common podium. Two hypothetical multi-tower buildings, the first consists of two towers with the same height (building SH), and the second consists of two towers with the different height (building DH), were designed for Chiang Mai site of Thailand using the conventional RSA procedure, and then the nonlinear response history analysis (NLRHA) is carried out. Results from NLRHA, which is the most accurate method, were used as reference values to evaluate the accuracy of RSA procedure. The results show that seismic shear demand from nonlinear analysis is about 3 times larger than the demand obtained from the RSA procedure. This could lead to shear failure in the shear walls designed by RSA procedure. Since the elastic method is preferred in practice, a modified response spectrum analysis (MRSA) procedure previously proposed for computing shear demand in regular tall buildings, was tried to apply to irregular tall buildings in this study. It is found that MRSA provides good estimates of shear force in vertical elements. MRSA can significantly enhance the design of tall buildings by avoiding brittle shear failure.

1. Introduction

Reinforced concrete (RC) shear walls are commonly used as lateral force-resisting system in tall buildings. To design such structures to resist earthquake, several methods would be used such as: equivalent lateral force (ELF), response spectrum analysis (RSA) procedure, and performance-based design (PBD) approach, which requires nonlinear response history analysis (NLRHA). As allowed in ASCE 7-16 [1] the RSA procedure is widely used in current practice to compute design demands of structures. However, there are limitations on height, type and irregularity of structural system that can be used in ASCE 7-16. Structural irregularities are one of the major causes of damage amplification under seismic action as it can increase in seismic demands of a structural system. There are several special considerations in ASCE 7-16, when dealing with irregular tall buildings. For example, for seismic design category (SDC) E, structural system with extreme torsional irregularity, weak story or extreme soft story irregularity is not permitted. Therefore, the dynamic response of irregular structures is an issue that is explicitly warned against in design guidelines. However, design engineers do not pay much attention to those limitations, and they use RSA procedure in the code to compute the design demands of a tall building with RC shear walls with a height taller than 48.8m, which is not compliant.
to the scope of the prescriptive code. This can lead to the unsafe design of tall building because RSA procedure has been found to underestimate the actual demands computed from NLRHA procedure. The issue of underestimation of design demands obtained from the RSA procedure has been noticed by many researchers. There are many reasons for the inaccuracy of the RSA procedure, which are:

1. Shear forces can still increase after flexural yielding occurs [2], while building codes assume that shear forces are limited by flexural yielding and they would reduce by the same manner.
2. The use of a single force response reduction factor ($R$) to reduce the total combined response is one of the primary reasons. Several researchers have demonstrated that higher modes are not significantly affected by inelasticity as much as the first mode [3-6].
3. Flexural overstrength inherent in design is the reason for excessive force demand needed to cause flexural yielding [2, 7]. There are many sources of flexural overstrength such as expected material strength which is greater than the material strength used in the design, reduction factor used in the design, and minimum reinforcement requirement.

Many subsequent studies have proposed different approaches to overcome the issue of underestimation of shear demand obtained from the RSA procedure. Khy et al. [8] conduct a study on RC shear wall tall buildings ranging between 15 to 39 story, subjected to earthquake excitations in Bangkok are first designed using the RSA procedure, and then NLRHA is carried out. It was found that the RSA procedure underestimates shear demand when compared to NLRHA results. Khy et al. [8] proposed a modified response spectrum analysis (MRSA) to compute shear forces in tall buildings, and it was found that MRSA provides good estimates of shear forces in RC shear wall tall buildings. Therefore, MRSA method is tried to apply to irregular tall buildings in this study.

Two versions of MRSA were proposed, the first is based on higher-mode elastic approach denoted as “MRSA$_{HE}$”, and the second is based on a higher-mode inelastic approach denoted as “MRSA$_{HI}$”. The shear demand of MRSA$_{HE}$ and MRSA$_{HI}$ is computed from equation (1) and (2) respectively.

\[
V_{HE} = I \times \sqrt{\left( \frac{SF \times \Omega_0}{R} \right)^2 V_{ie}^2 + V_{2e}^2 + V_{3e}^2 + ...} 
\]

\[
V_{HI} = I \times \sqrt{\left( \frac{V_{ie}}{R_i} \right)^2 + \left( \frac{V_{2e}}{R_2} \right)^2 + \left( \frac{V_{3e}}{R_3} \right)^2 + ...} 
\]

where $SF$ is the scale factor, $\Omega_0$ is the overstrength factor, $I$ is the importance factor, $V_{ie}$ is the shear of the $i^{th}$ mode.

1.1. Objective
The objective of this study is to check the accuracy of conventional RSA and previously proposed MRSA method when applied to irregular tall buildings and to suggest a practical way that can be used for such structure.

2. Methodology
The procedure to conduct this study is outlined as the followings:

1. Create the linear mathematical model using ETABS software [9].
2. Compute the design demands that results from all factored load combinations including gravity load, wind load, and seismic forces from RSA procedure.
3. Design the structural system according to ACI 318M-14 [10].
4. Create the nonlinear mathematical model using PERFORM-3D software [11], and analyze the structure by NLRHA.
5. Compute the force response reduction factor ($R_i$) for the selected modes using pushover analysis.
6. Compute the demand forces from both MRSA$_{HE}$ and MRSA$_{HI}$ methods [8].
7. Evaluate the accuracy of RSA and MRSA methods by comparing them with the results of NLRHA.
3. Description of studied buildings and earthquake ground motions

Two irregular RC shear wall tall buildings are designed for Chiang Mai site in Thailand. Both buildings consist of two towers sharing a common podium. One of the buildings consists of two towers with the same height, and it is denoted as building “SH”. The other building consists of two towers with different heights, and it is denoted as building “DH”. Building SH and DH are shown in Figure 1 and 2 respectively.

The lateral force resisting system was considered to be special RC shear wall whose design factors according to ASCE 7-16 [1] are shown in Table 1, where $R$ is the response modification factor, $C_d$ is the deflection amplification factor, $\Omega_0$ is the overstrength factor, and $I$ is the important factor. Design wind pressure is taken from Bangkok Building Control Act (2001) [12] with the values shown in Table 2.

| Table 1. Design factors according to ASCE 7-16 [1]. | Table 2. Wind load pressure according to Bangkok Building Control Law Act [12]. |
|---|---|
| Factors | Values | Building height ($H$) | Design Wind Pressure ($kN/m^2$) |
| $R$ | 6 | $H \leq 10$ m | 0.5 |
| $C_d$ | 5 | $10 < H \leq 20$ m | 0.8 |
| $\Omega_0$ | 2.5 | $20 < H \leq 40$ m | 1.2 |
| $I$ | 1.25 | $40 < H \leq 80$ m | 1.6 |
| Risk category | III | $H > 80$ m | 2 |
| Site class | D | |
| SDC | D | |

The in-plane flexural stiffness used in the linear and nonlinear model is shown in Table 3. The out-of-plane behavior of walls and slabs was assumed to remain elastic in both linear and nonlinear model with small effective stiffness of $0.25E_cI_g$. 

![Figure 1. Three-dimensional model of building SH.](image1)

![Figure 2. Three-dimensional model of building DH.](image2)

![Figure 3. Podium floor plans (1st to 9th floor).](image3)

![Figure 4. Tower floor plans (10th to top floor).](image4)
For the nonlinear model, a nonlinear fiber element was used for RC walls and columns, while moment-rotation hinges were assigned for coupling beams. The nonlinear fiber behavior is controlled by the nonlinear stress-strain relation of concrete and steel material properties. The stress-strain relation of concrete proposed by Mander et al. [13] was adopted. The expected strength was used in the model, as the actual strength is usually greater than the nominal strength specified by the designer. The expected material strength of concrete and steel were taken as 1.25 times the nominal strength.

### Table 3. Effective stiffness of structural members in linear and nonlinear model.

| Elements     | Linear model | Nonlinear model |
|--------------|--------------|-----------------|
| Shear wall   | 0.35         | Fiber           |
| Slab         | 1.0 $E_cI_g$ | 1.0 $E_cA_g$    |
| Column       | 0.7 $E_cI_g$ | 1.0 $E_cA_g$    |
| Beam         | 0.35         | 1.0 $E_cA_g$    |

where $E_c$ is the modulus of elasticity of concrete; $I_g$ is the gross moment of inertia of cross section; $A_g$ is the gross cross-sectional area.

Chiang Mai site located on stiff soil (site class D), where the target spectrum (UHS) was developed using the procedure described in ASCE 7-16, for a response spectral parameter of $S_S = 0.963g$, and $S_I = 0.248g$. The damping factor formula in ASCE 41-13 [14] was used to obtain the design spectrum curve that corresponds to 2.5% damping. The spectral matching ground accelerations were obtained using ten ground motions that have similar seismic mechanism of the studied site [15]. The individual matching spectra, the mean value of matching spectra, and the target spectrum (UHS) for 2.5% damping ratio in Chiang Mai are shown in figure 5.

### Figure 5. Individual matching spectra, mean matching spectrum, and target spectrum for 2.5% damping ratio in Chiang Mai.

4. **Response spectrum analysis procedure**

The concept of RSA procedure described in building codes is to reduce the elastic demand by response modification factor ($R$) and to amplify the displacements by deflection amplification factor ($C_d$), as shown in equations (3) to (5). The scaling factor ($SF$) is computed according to ASCE 7-16, which is the ratio of 85% of base shear from static analysis and base shear from the dynamic analysis.

$$V_{RSA} = \frac{SF \times I}{R} \sqrt{V_1^2 + V_2^2 + V_3^2}$$  

$$M_{RSA} = \frac{SF \times I}{R} \sqrt{M_1^2 + M_2^2 + M_3^2}$$  

$$\delta_{RSA} = 1 + \frac{C_d}{R} \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2}$$

where $V_{RSA}$ and $M_{RSA}$ are the design elastic demand of shear and moment, respectively; $\delta_{RSA}$ is the total amplified displacement or drift.
5. Comparison of RSA and NLRHA results

In this section, a comparison between linear RSA and NLRHA is presented. Three analytical models are used in this section which are: RSA (shown in section 4), LRSA (without $R$ and $C_d$), and NLRHA. The results of NLRHA are presented as the mean value of the peak results obtained from all the ground motions. Normalized results are presented, where floor displacement is normalized by total building height $H$, inter-story drift is normalized by story height $h$, story shear is normalized by the effective seismic weight $W$, and the overturning moment is normalized by $WH$, as shown in figure 6. Note that the title of each figure shows the building name and earthquake direction.

![Comparison of RSA and NLRHA results](image)

**Figure 6.** RSA and NLRHA results of (a) Floor displacement (b) Inter-story drift ratio (c) Story shear (d) Story overturning moment, for Chiang Mai buildings, due to earthquake in both directions.

It is found that the RSA procedure underestimates the force demands when compared to the actual demands obtained from NLRHA for both buildings, while it provides good estimates of floor
displacements and drifts ratios for both buildings. RSA results represent seismic demands that engineers currently use in design and it is not adequate to avoid brittle shear failure, as shown in Figure 6 (c).

6. Inelasticity of modal responses

The modified response spectrum analysis based on higher-modes inelastic approach (MRSAHM) proposed by Khy et al. [8] needs to determine the force response reduction factor of each mode ($R_i$) using modal pushover analysis (MPA) [16]. In this study, the inelasticity of the first three translational modes in each direction are investigated using MPA. For estimating the ($R_i$) factor, MPA was conducted using linear and nonlinear structural models. The linear model used has the same initial stiffness as the nonlinear model. The lateral load distribution for conducting MPA was applied in proportion to the distribution of mass in the plane of each floor diaphragm, multiplied by mode shape in the direction under consideration ($m \phi_n$). The target roof displacement for the first translational mode in each direction was computed using the displacement coefficient method in ASCE 41-13 [14]. The target roof displacement for higher modes were assumed to be equal to the elastic response computed by modal analysis of the linear structural model considering a cracked cross-section of structural members. The base shear-roof displacement relation for the 1st translational mode in X-direction is shown in figure 7, where base shear is normalized by building weight ($W$), and roof displacement is normalized by building height ($H$). The force response reduction factor ($R_i$) is taken as the ratio of base shear of the linear to the nonlinear models at the target roof displacement. Summary of the force response reduction factors is shown in Table 4. The gravity loads of all dead loads plus 25% of live load were applied before pushover analysis. Note that the black dots in Figure 7 indicate the target roof displacement. It was found that the level of inelasticity of response in different modes was different, and the force response reduction factor ($R_i$) ranges between 1 to 2.3, which is about 2.5 to 6 times lower than the response modification factor ($R=6$) used in the design of these buildings.

![Figure 7](image)

**Figure 7.** Linear and nonlinear pushover curves along with the target roof displacements of the 1st translational modes in X-direction.

**Table 4.** Force response reduction factor ($R_i$) of the first-three translational modes.

| Building | SH | DH |
|----------|----|----|
| Direction | X | Y | X | Y |
| Mode 1 | 1.32 | 2.08 | 1.26 | 2.01 |
| Mode 2 | 1.22 | 2.37 | 1.16 | 2.28 |
| Mode 3 | 1.43 | 2.36 | 1.27 | 2.01 |
7. Modified response spectrum analysis

In this section, the modified response spectrum analysis (MRSA) proposed by Khy et al. [8] was conducted. Two versions of MRSA method were proposed to compute the shear forces in RC shear walls, where the first is based on higher-mode elastic approach denoted as “MRSA_{HE}”, and the second is based on a higher-mode inelastic approach denoted as “MRSA_{HI}”. The shear demand of MRSA_{HE} and MRSA_{HI} were computed from equations (1) and (2), respectively. Moreover, Khy et al. [8] suggested computing design bending moments using the RSA procedure as described in ASCE 7-16 (as shown in equation (4)). Both methods were applied using a linear model with effective stiffness corresponding to cracked cross-section properties of structural members. The total combined elastic shear demand was obtained by considering 30 modes of vibration using ETABS software. For MRSA_{HE}, the elastic first-mode shear multiplier is summarized in Table 5. Story shears for both buildings are shown in Figure 8.

Table 5. Elastic first-mode shear multiplier for MRSA_{HE}.

| Building | SH | DH |
|----------|----|----|
| Direction | X | Y | X | Y |
| $(SF \times \Omega_0/R)$ | 0.80 | 0.55 | 0.82 | 0.66 |

Figure 8. Story shear for both buildings due to earthquake in X- and Y-direction.

From Figure 8, it is found that MRSA can significantly enhance the underestimation of the RSA procedure in computing shear demands. Both versions of MRSA method provide fair results of shear demands due to seismic excitation in the X-direction. For earthquake in the Y-direction, MRSA_{HE} provides accurate results of story shear, while MRSA_{HI} underestimates the shear demands for SH building and provides accurate estimation for DH building.

8. Conclusions

The main findings of this study are summarized as follows:

1. RSA procedure underestimates force demands when compared to NLRHA results. The design (reduced) shear demand obtained from RSA procedure is not sufficient and it could lead to brittle shear failure in RC shear walls, if used in the design.
2. RSA procedure provides good estimate of floor displacements, inter-story drift ratios.
3. The inelastic behaviors of each mode were not identical, and higher modes were significantly affected by inelasticity as the first mode.
4. The MRSA_{HE} method provides good estimates of shear forces for both studied RC shear wall tall buildings. The MRSA_{HE} is preferred to be used in the design practice as it can be applied directly using a linear structural model.
5. The MRSA_{HI} provides acceptable results for both buildings, but it underestimates shear forces due to earthquake in Y-direction for SH building.
9. References

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