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MODIFIED RESPONSE SPECTRUM ANALYSIS PROCEDURE FOR ONE-WAY TORSIONALLY COUPLED STRUCTURES

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Abstract

Nowadays, numerous tall buildings are being constructed as limited urban land areas become used up and the shapes of modern tall buildings are often irregular as the layout are governed by many constraints and architectural demands. The tall buildings using shear walls as the lateral force resisting system having un-symmetrical floor plans such that center of rigidity is eccentric from center of mass are the focus of this study. Many researchers have shown that shear forces in shear walls computed by response spectrum analysis (RSA) procedure as specified in ASCE 7-10 [1] are much smaller than the more realistic shear forces computed by nonlinear response history analysis (NLRHA). Khy et al. [2] have proposed a modified response spectrum analysis (MRSA) procedure to obtain more accurate shear demands for design of shear strength in shear wall of tall buildings and the proposed method provides satisfactory results when implemented with regular-shaped buildings of 15, 20, 31, and 39 stories. In this study, the MRSA procedure is tested with 16-story buildings with torsional irregularity. Floor plan of the building is symmetric about x-axis but not symmetric about y-axis. The mode of vibration for translation in y direction is coupled with torsional (twisting) motion about vertical axis. Three levels of torsional vibration properties are considered: 1) torsionally flexible, 2) torsionally stiff, and 3) torsionally-similarly-stiff systems. The classification of these systems is based on Chopra and Goel [3] but the participation mass ratio is considered rather than vibration period. The buildings are assumed to be located in Bangkok, Thailand, and they are subjected to earthquake ground motions according to the Thai seismic design standard [4]. The buildings were first analyzed and designed according to convention RSA procedure, and then analyzed by NLRHA to obtain the more realistic seismic demands and to evaluate accuracy of RSA shear forces in shear walls and columns. It was found that RSA procedure slightly underestimates story drift ratios, but significantly underestimates design shear forces when compared with NLRHA results. Linear RSA is recommended to computed story drift ratios for design. Vibration modes higher than the first-two modes can be conservatively assumed to be elastic. Previously modified RSA based on higher-mode elastic ($\mathrm{MRSA_{HE}}$) method for regular buildings, can be extended to one-way torsionally coupled buildings by considering the first-two modes as inelastic and other higher modes as elastic. This proposed MRSA procedure can provide satisfactory estimates of shear force demands in all torsionally irregular systems. The method to compute strain using internal forces from elastic analysis to estimate inelastic strains proposed by Khy et al. [2] can provide results close to NLRHA when it is applied to tall buildings with torsional irregularity.

Keywords: torsional irregularity; modified response spectrum analysis; nonlinear response history analysis

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, design engineer has several choices either to follow prescriptive code-based approach, i.e., equivalent lateral force (ELF) and response spectrum analysis (RSA) procedure, or performance-based design (PBD) approach [5, 6], which requires nonlinear response history analysis (NLRHA). PBD is an alternative approach for design of code-exceeding tall buildings; however, it is rarely used in current design practice because of its complexity, such as nonlinear dynamic structural analysis, nonlinear structural model, selection and scaling of appropriate ground motions, and significant computational efforts. As allowed in ASCE 7-16 [7], the RSA procedure is widely used in current practice to compute design demands of structures. However, there are restrictive limitations on height, type and irregularity of structural system that can be used in ASCE 7-16. For example, in building frame system, the special RC shear wall is limited to 48.8 m according to ASCE 7-16. However, some design engineers use code-based RSA procedure to compute design demands of tall RC shear wall building with height taller than 48.8 m, which does not comply with the scope of the prescriptive code. This can lead to unsafe design of tall buildings because RSA procedure has been found to underestimate shear demands in structural walls when compared to results from NLRHA [2, 8-10] and RSA procedure in ASCE 7-16 does not provide information on location of yielding in structural walls where ductile detailing should be implemented to ensure ductile behavior.

Recently, a modified response spectrum analysis (MRSA) procedure using a simplified inelastic first-mode and elastic higher mode to estimate shear force in structural walls, together with a method based on equal displacement concept using internal forces from elastic analysis to estimate inelastic deformation location in RC walls and columns has been proposed [2]. However, this MRSA procedure was developed using regular tall buildings with RC shear walls where there is no significant coupling between torsional and translational motion. In this study, translational modes in each principal direction can be identified based on the large mass participating ratio in the direction of consideration, and generally the first-translational mode response experiences inelasticity, while other higher modes can conservatively be assumed to remain elastic. Applicability of the MRSA procedure to unsymmetrical plan buildings having strong coupling between torsional and translational modes is yet to be investigated.

The objective of this study is to extend MRSA procedure to estimate seismic demands in torsionally irregular buildings. Three types of torsionally irregular systems: (1) torsionally-flexible (TF) system, (2) torsionally-stiff (TS) system, and (3) torsionally-similarly-stiff (TSS) system, previously defined by Chopra and Goel [3], are used to represent different characteristics of torsional response. According to Chopra and Goel [3], torsionally-flexible (TF) system is the system whose period of torsion-dominant mode is much longer than that of translation-dominant mode; torsionally-stiff (TS) system is the system whose period of torsion-dominant mode is much shorter than that of translation-dominant mode; torsionally-similarly-stiff (TSS) system is the system whose period of the first two modes are close where translational and torsional modes are strongly coupled. In this study, coupling is defined in term of modal mass participation ratios (PMR) where translational mass in x-direction is denoted by PMRx, translational mass in y-direction PMRy, and rotational inertial about z-axis PMRz. A mode is considered as a “coupled” mode between translation and torsion when its PMRs are large in both translational and torsional directions. Strong coupling happens when the values of PMRs for translational and torsional directions are nearly equal for that mode. According to this consideration, TSS system in this study is thus defined in term of similar PMRs in torsional and translational directions, which is different from definition of TSS system by Chopra and Goel [3].

2. Methodology

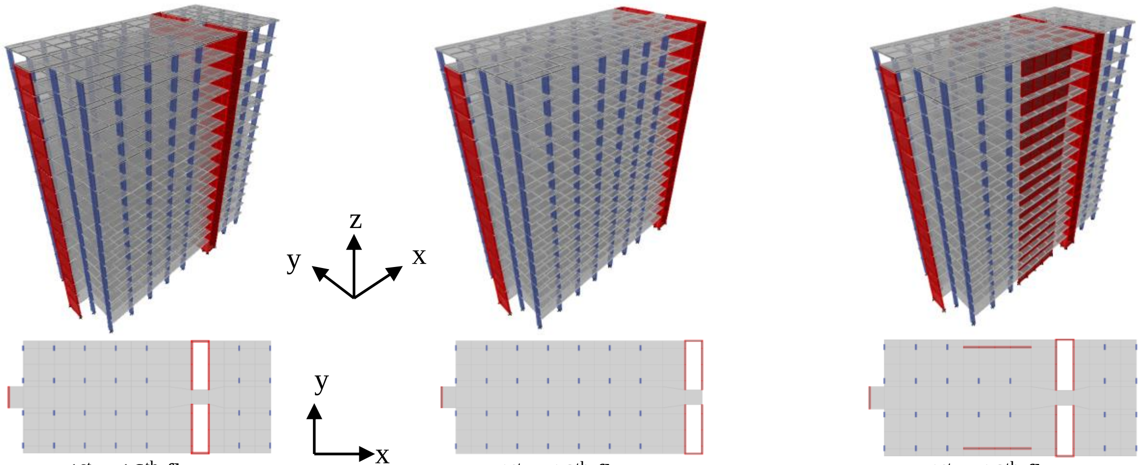
The procedure adopted in this study is outlined as follows:

1) Prepare structural systems with three types of torsional irregularities: torsionally-flexible (TF), torsionally-stiff (TS), and torsionally-similarly-stiff (TSS) systems.

2) Analyze the structures by RSA procedure [1] and design the structures according to ACI 318M-14 [11], such that the design strengths are approximately equal to the demands from factored load combinations including gravity load, wind load, and earthquake load. This step was facilitated and accomplished by using ETABS [12].
3) Analyze the structures by NLRHA using PERFORM-3D [13] to evaluate the accuracy of the RSA procedure used in the design. RSA results used for evaluation were computed again in PERFORM-3D to avoid discrepancy from different software.
4) Compute the force response reduction factor of each mode by using modal pushover analysis (MPA).
5) Develop a modified response spectrum analysis (MRSA) procedure to compute the design shear forces in shear walls and columns in one-way torsionally coupled structures.
6) Evaluate the accuracy of RSA and MRSA procedures by comparing the computed demands with results from NLRHA in step 3.

3. Description of buildings

An existing 16-story RC building as shown in Fig. 1a was used as an example building. This building is symmetric about x-axis but asymmetric about y-axis. Response of this building to earthquake excitation in y-direction has coupling between translation and torsion while the response due to excitation in x-direction is uncoupled and not presented. This building is thus defined as a one-way torsionally coupled structure. Only responses due to earthquakes in y-direction are investigated in this paper. Basic characteristics of this building are summarized in Table 1. The lateral force resisting system of this building is special-ductile RC shear wall corresponding to seismic design parameters: R=6, C_d=5, and Ω_0=2.5. R is response modification factor; C_d is deflection amplification factor; and Ω_0 is over-strength factor. The modal properties of this building were computed from elastic model with effective cracked cross-sectional properties. The first-four torsionally coupled modes in y-direction are identified (Table 2) based on large PMRy and PMRz. Torsion-dominant mode is defined as when its PMRz is larger than PMRy. Translation-dominant mode is defined as when its PMRy is larger than PMRz. The building in Fig. 1a is characterized as torsionally-flexible (TF) system because torsion dominates in the first mode and its period is significantly longer than modal period of translation-dominant mode ($T_{tor.}/T_{tran.}$=2.48).



1st – 16th floor
(a) TF system

1st – 16th floor
(b) TS system

1st – 16th floor
(c) TSS system

Fig. 1 – Typical floor plans and three dimensional models of the example 16-story buildings: (a) TF system; (b) TS system; and (c) TSS system.

The TF system in Fig. 1a was modified to create two other systems: torsionally-stiff (TS) system in Fig. 1b and torsionally-similarly stiff (TSS) system in Fig. 1c. TS system was created by moving the c-shaped walls to the right end of the floor plan. In TS system, torsion response dominates the second mode and its period is significantly shorter than the translation-dominant mode (T_{tor}/T_{tran}=0.21) as shown in Table 3. TSS system was created by symmetrically adding two walls in the x-direction with length adjusted so that modal participating mass ratio in y-direction equals to modal participating rotational inertia ratio about z-axis in the first two modes as shown in Table 4. In this TSS case, torsion- or translation-dominant mode cannot be separately identified.

Table 1 – Basic characteristics of the example 16-story building.

Number of story	16
Total height (m)	49.2
Typical story height (m)	3
Aspect ratio in x-direction (height/length)	1.21
Aspect ratio in y-direction (height/width)	2.44
Typical span length x-direction (m)	5.1
Typical span length y-direction (m)	5.4
Floor area (m^2)	824
Wall thickness (m)	0.25
Column size (m x m)	0.3 x 0.9
RC flat slab thickness (m)	0.18

Table 2 – The first-four torsionally coupled modes in y-direction of TF system.

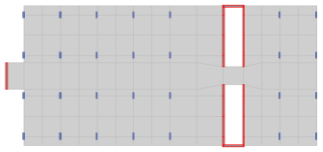
Mode	*T* (sec)	PMRx	PMRy	PMRz	
1st torsion	3.08	0%	26%	42%	
1st translation	1.24	0%	41%	25%	
2nd torsion	0.67	0%	7%	11%	
2nd translation	0.25	0%	13%	6%	

Table 3 – The first-four torsionally coupled modes in y-direction of TS system.

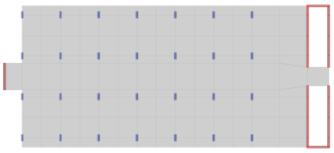
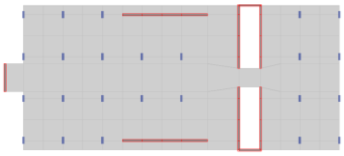
Mode	*T* (sec)	PMRx	PMRy	PMRz	
1st translation	3.66	0%	46%	20%	
1st torsion	0.78	0%	12%	51%	
2nd translation	0.75	0%	21%	1%	
2nd torsion	0.15	0%	6%	14%	

Table 4 – The first-four torsionally coupled modes in y-direction of TSS system.

Mode	*T* (sec)	PMRx	PMRy	PMRz	
1	2.45	0%	33.5%	33.6%	
2	1.20	0%	33.2%	33.3%	
3	0.51	0%	9.4%	9.7%	
4	0.24	0%	9.4%	10.1%	

All systems were designed using factored load combinations according to Thai seismic design standard [4]. The design live loads of 2.5 kN/m^2 and super-imposed dead loads of 2.75 kN/m^2 were used at each floor. The design wind pressure was used according to Bangkok Building Control Law [14]. The elastic spectral acceleration representing the earthquake load for downtown Bangkok is presented in Section 4. Seismic demands were computed by RSA procedure.

4. Earthquake ground motions

The studied building is assumed to be located on a soft-soil site in downtown Bangkok (zone 5). The design spectral acceleration (Fig. 2), which is 2/3 of the maximum considered earthquake (MCE) level having 2% probability of exceedance in 50 years, was taken from Thailand seismic design standard [4]. This spectrum is considered as the uniform hazard spectrum (UHS). For the studied 16-story buildings, damping ratio of 2.5% was used as recommended by PEER [6]. While UHS spectrum in Fig. 2 is used in RSA procedure, NLRHA needs to use earthquake ground motions that are consistent with the same seismicity to be able to fairly evaluate accuracy of RSA procedure [15]. A set of six ground motions were selected based on probabilistic seismic hazard analysis and hazard de-aggregation. They were selected from large magnitude and long distance earthquakes and simulated to propagate through layers of soft soil underlying Bangkok [16, 17]; their spectra are also shown in Fig. 2. In this study, the ground motions were modified by SeismoMatch [18] to have spectral shapes closely matched the UHS. Individual spectra of these UHS matching ground motions together with the mean spectrum are compared to the target spectrum (UHS) in Fig. 3.

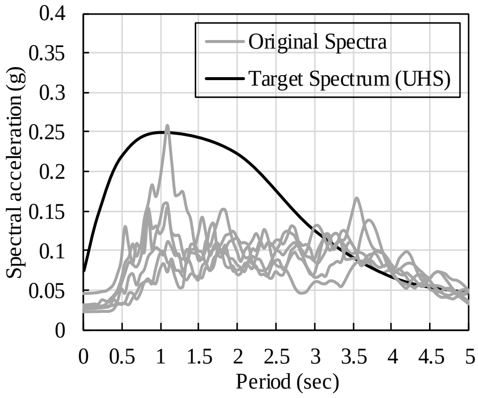


Fig. 2 – Original spectra of CMS ground motions conditioned at 3 sec and target spectrum for 2.5% damping ratio in Bangkok zone 5.

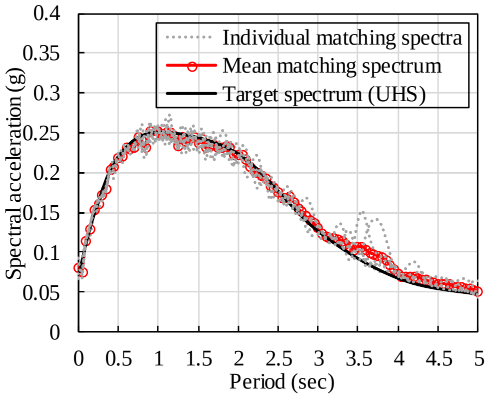


Fig. 3 – Individual matching spectra, mean matching spectrum, and target spectrum for 2.5% damping ratio in Bangkok zone 5.

5. Analytical models

All results presented were calculated using PERFORM 3D [13]. The linear structural model used for the RSA considers cracked cross sections of RC structural members according to ACI 318M-14 [11].

For nonlinear structural model, the RC walls were modeled using nonlinear fiber elements over the entire height of the walls because flexural yielding may occur at any location due to higher-mode effects in tall buildings. The out-of-plane behavior of the wall was assumed to be elastic with small effective stiffness. The material stress-stain relationship for concrete proposed by Mander et al. [19] was adopted and a bilinear inelastic model proposed by Menegotto and Pinto [20] was used for steel. The expected material strength was assumed to be 1.25 times the nominal strength for both concrete and steel [21]. RC columns were modeled by linear elastic elements with nonlinear plastic zones at both ends modeled by fiber elements. The conventional RC beams and coupling beams were modeled with a middle elastic portion and rotational plastic hinge elements at both ends using modeling parameters from ASCE 41-13 [22]. Joints between members were considered to be rigid connections. Slabs were modeled by elastic shell elements and all nodes in each floor were constrained to behave as an in-plane rigid floor diaphragm. Damping matrix for NLRHA was formulated by modal viscous damping model recommended by Chopra and McKenna [23].

6. Response spectrum analysis procedure

The RSA procedure in ASCE 7-10 was adopted. For force demands, it requires that the RSA base shear is at least 85% of the base shear computed from the equivalent lateral force (ELF) procedure by using a scaling factor (*SF*). For story drifts, ASCE 7-10 employs a deflection amplification factor (C_d) to multiply the results which were already divided by *R* factor. The design bending moment, shear force, floor displacement, and story drift in the RSA procedure are then computed from the following equations:

$$M = \frac{SF \times I_e}{R}\sqrt{{M_{1e}}^2 + {M_{2e}}^2 + {M_{3e}}^2 + \cdots} \tag{1}$$

$$V = \frac{SF \times I_e}{R}\sqrt{{V_{1e}}^2 + {V_{2e}}^2 + {V_{3e}}^2 + \cdots} \tag{2}$$

$$\delta = \frac{C_d}{R}\sqrt{{\delta_{1e}}^2 + {\delta_{2e}}^2 + {\delta_{3e}}^2 + \cdots} \tag{3}$$

$$\Delta = \frac{C_d}{R}\sqrt{{\Delta_{1e}}^2 + {\Delta_{2e}}^2 + {\Delta_{3e}}^2 + \cdots} \tag{4}$$

where M_{ie}, V_{ie}, δ_{ie}, and Δ_{ie} are the elastic bending moment, shear force, floor displacement, and story drift of mode *i*, respectively; I_e is the importance factor; and *SF* is the scaling factor required to make the RSA base shear at least 85% of the ELF base shear.

7. Modified response spectrum analysis procedure

The modified response spectrum analysis (MRSA) method was previously developed to address under-estimation of shear demands in structural walls and it has been tested with regular tall buildings with RC shear walls by Khy et al. [2]. In development of this method it was found that behavior of modal response to earthquake experience inelasticity only in the first modes, while the higher-mode responses remain essentially linear elastic.

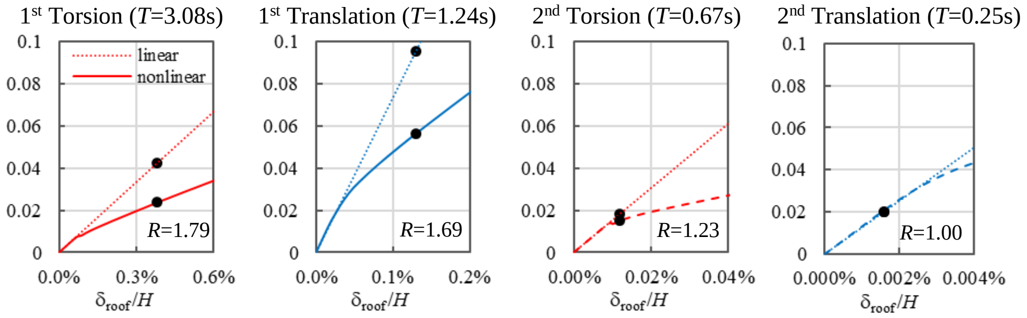
For torsionally irregular buildings, the first two modes have coupling between translation and torsion. Figure 4 shows the modal pushover curves for the first four modes of each of the three systems (TF, TS and TSS). Black dots indicate modal target roof displacement assuming that inelastic displacement is equal to elastic displacement by the equal displacement rule. These results demonstrate that, for the one-way torsionally coupled structures, the first two modes deform into inelastic range, while the third and fourth modes experience little yielding. This observation leads to the proposed modified response spectrum analysis such that the shear force demand for design of structural walls is calculated from elastic responses divided by response modification factor *R* for the first two modes where there is coupling between translation and torsion. The higher-mode shear forces are assumed to be elastic values. This method is called modified response spectrum analysis assuming higher modes elastic (MRSA_{HE}).

The overstrength in flexural capacity can lead to higher shear force in the system and the overstrength factor is applied in the first two modes together with scaling factor *SF*. However, the values in those two modes need not be larger than elastic values, or $(SF \times \Omega_0)/R$ needs not be larger than 1. For one-way torsionally coupled buildings, shear forces in MRSA_{HE} method are computed from

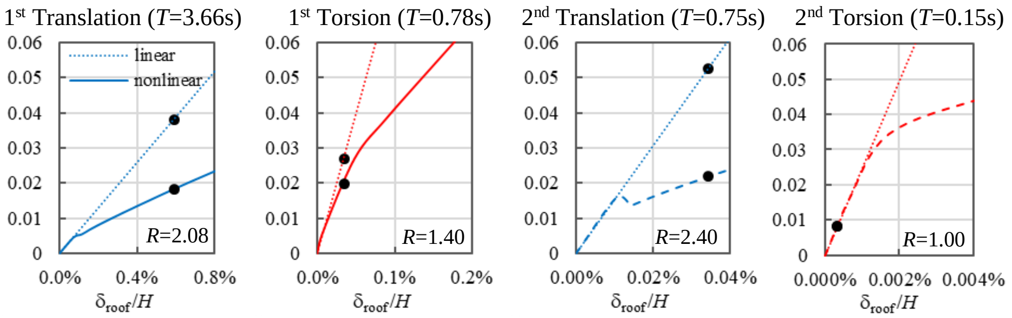
$$V_{\mathrm{MRSA_{HE}}} = I\sqrt{\left(\frac{SF \times \Omega_0}{R}\right)^2 \left(V_{1e}^2 + V_{2e}^2\right) + V_{3e}^2 + V_{4e}^2 \cdots} \tag{5}$$

where $\dfrac{SF \times \Omega_0}{R} \le 1$; V_{ie} is the elastic shear force contributed by mode i.

(a) TF system



(b) TS system



(c) TSS system

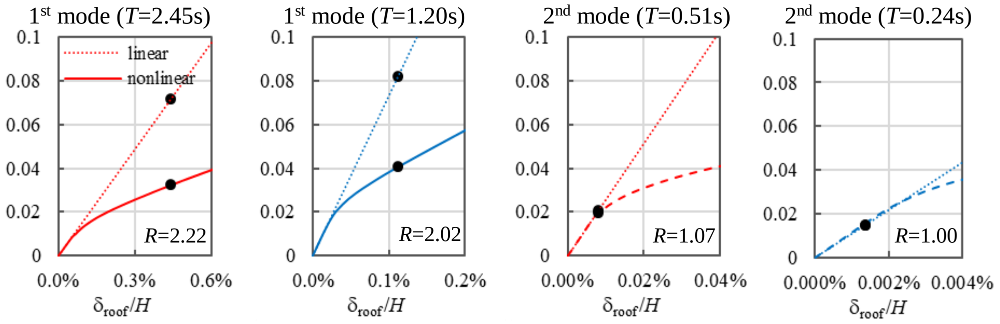


Fig. 4 – Linear and nonlinear pushover curves along with the target roof displacements of the first four modes: (a) TF system; (b) TS system; and (c) TSS system.

In MRSA procedure, bending moment is computed and designed for in the same manner as in the conventional RSA procedure, yielding may occur at any location along the height of RC walls or columns. Strains in RC walls or columns need to be determined to identify locations of yielding of vertical reinforcement or possible crushing of concrete. Based on equal displacement concept, Khy et al. [2] proposed a method using internal forces from elastic analysis to estimate inelastic strains and they were found to be close to results from NLRHA. This method is adopted in this study where the maximum tensile and compressive strains in RC walls or columns are computed from

$$\varepsilon_t = \frac{P}{E_c A_g} + \frac{M}{E_c I_{eff}}(c + \frac{c_{\text{long}}}{3}) \tag{6}$$

$$\varepsilon_c = \frac{P}{E_c A_g} - \frac{M}{E_c I_{eff}}(c - \frac{c_{\text{long}}}{3}) \tag{7}$$

where ε_t and ε_c are the maximum tensile and compressive strains, respectively; M and P are the elastic bending moment and vertical axial force computed from linear RSA combined with factored gravity load, respectively; c is the distance from the elastic neutral axis to the location where strain is being computed; c_{long} is defined as the longer distance measured from the elastic neutral axis to either edge of the wall ; A_g is the gross cross section of the wall or column; E_c is the Young's modulus of concrete; I_{eff} is the effective moment of inertia of cross section of the wall or column, which can be taken from Table 6.6.3.1.1(b) of ACI 318M-14 [11].

$$0.35 I_g \le I_{eff} = \left(0.80 + 25\frac{A_{st}}{A_g}\right)\left(1 - \frac{M_u}{P_u h} - 0.5\frac{P_u}{P_0}\right) I_g \le 0.875 I_g \tag{8}$$

where I_g is the gross moment of inertia; A_{st} is the area of vertical reinforcement in the wall or column; M_u and P_u are the design bending moment and axial force of the wall or column that produces the least value of I_{eff} ; h is the depth of the column or the length of the wall; and P_0 is the nominal axial strength at zero eccentricity.

8. Results

8.1 Accuracy of RSA procedure

All analyses were conducted with earthquake ground motions applied in y-direction. Results shown for NLRHA are the mean values of peak responses to six UHS spectral matching ground motions. RSA, linear RSA without using C_d and R factors (LRSA), and linear response history analysis (LRHA) were conducted using elastic models with cracked cross-sectional properties. The stiffness of these elastic models are smaller than initial stiffness of nonlinear models used in NLRHA which are based on gross cross-sectional properties. LRHA is also presented and compared to LRSA to demonstrate error due to modal combination rule used in RSA. The difference between LRHA and NLRHA also indicate effect of nonlinearity if yielding occurs. All results presented were computed from PERFORM-3D [13] software.

Story drifts at center of mass of each floor level computed from RSA, LRSA, LRHA and NLRHA are compared in Fig. 5. Story drifts at stiff and flexible sides are presented in Fig. 6. It shows that LRHA provides similar results to LRSA for TF and TSS systems, and LRHA gives slightly larger drifts than LRSA for TS system; hence, the error due to modal combination rule used in RSA is minor. RSA procedure slightly underestimates story drifts when compared to NLRHA while LRSA estimates well story drift at the center of mass. LRSA and LRHA slightly underestimate story drifts at the stiff side but slightly overestimate story drifts at the flexible side when compared to NLRHA results (Fig. 6). Normally, story drifts at the flexible side are more interesting to investigate as they are the largest in each floor. Note that effects of accidental torsion are included in all of the results presented in this study although accidental torsion was considered during design stage (step 2 in Section 2).

It is important to note that RSA significantly underestimates story shear force demands when compared to NLRHA (Fig. 7).

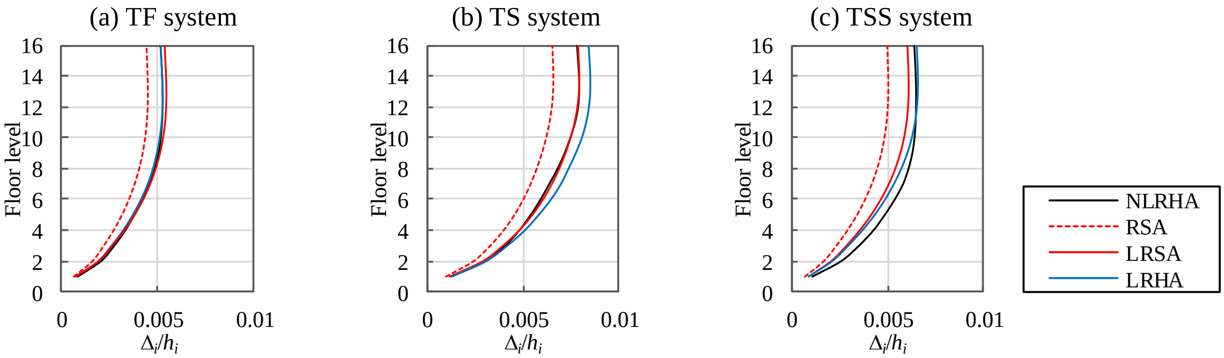


Fig. 5 – Story drift at center of mass computed from RSA, LRSA, LRHA and NLRHA: (a) TF system; (b) TS system; (c) TSS system due to earthquake load in y-direction.

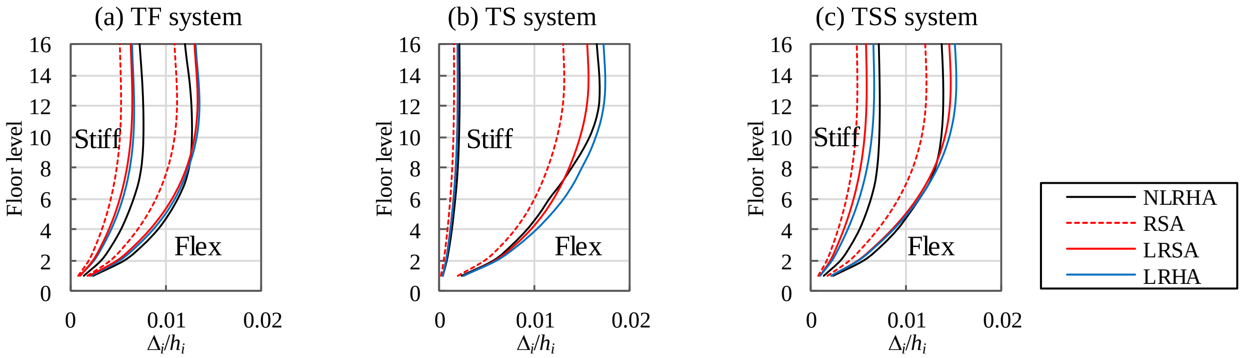


Fig. 6 – Story drifts at stiff and flexible sides computed from RSA, LRSA, LRHA and NLRHA: (a) TF system; (b) TS system; (c) TSS system due to earthquake load in y-direction.

8.2 Accuracy of MRSA procedure

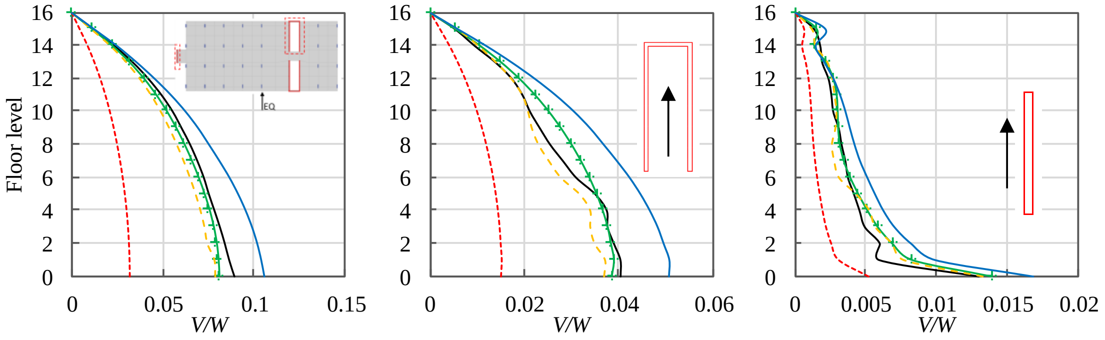
To evaluate the accuracy of the MRSA$_{HE}$ method, the computed results were compared with the benchmark results obtained from NLRHA. The MMPA method proposed by Chopra et al. [24] was also included in the comparison because the MRSA$_{HE}$ and MMPA use similar higher-mode-elastic assumption. However, it should be noted that MRSA$_{HE}$ uses elastic model with cracked sectional properties, while MMPA require inelastic model to compute inelastic response of the first-two modes for MMPA. The first-six modes of the building in the direction of seismic excitation were used for MRSA$_{HE}$ and MMPA methods. The over-strength factor of $\Omega_0 = 2.5$ according to ASCE 7-10 were used in MRSA$_{HE}$ method.

Shear forces in a story and RC walls of the TF, TS, and TSS systems computed from RSA, MRSA$_{HE}$, MMPA, LRHA and NLRHA procedures are compared in Fig. 7. It is found that MRSA$_{HE}$, and MMPA significantly improve the underestimation of RSA procedure for all cases. Although, MRSA$_{HE}$ computes inelastic shear forces of the first-two modes in an approximate way, MRSA$_{HE}$ generally estimates well NLRHA results for all cases. Its accuracy could be as good as MMPA method. Accuracy of MMPA significantly depends on pushover analysis and the assumed elastic target displacement. For TS system, although pushover analysis shows that large inelasticity occurs in the third mode where relatively large elastic target displacement is used compared to that of TF and TSS systems, MMPA considering this mode as elastic estimates reasonably well shear forces from NLRHA as shown in Fig. 7b.

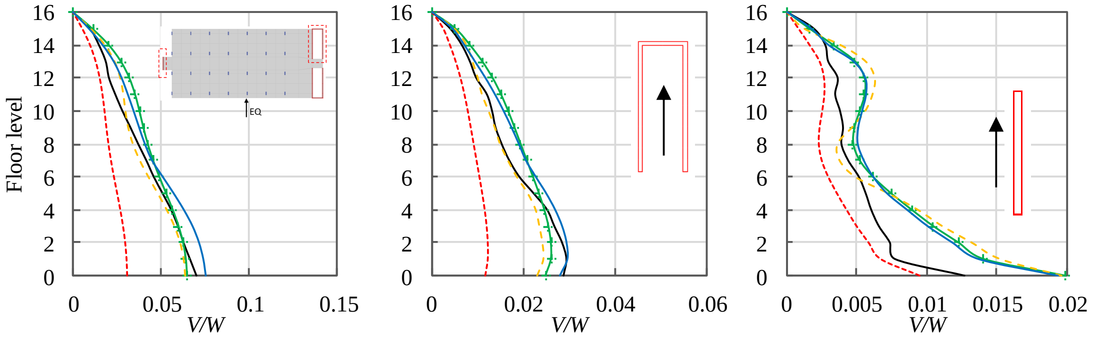
8.3 Computation of strains

Variation of strain along the height of RC walls computed from MRSA and NLRHA procedures are compared in Fig. 8 (where tensile strains are indicated as positive). Strain in columns is not presented because columns mainly act as gravity load resisting members and there is no yielding occur in column in this study. It is found that the predicted strains in MRSA method can well estimate the inelastic strains in the walls when compared to results from NLRHA. Yielding of vertical reinforcement is occurred at the first floor of RC wall at the flexible side for all TF, TS, and TSS systems. Compressive strains in RC walls are less than 0.2% for all cases in this study.

(a) TF system



(b) TS system



(c) TSS system

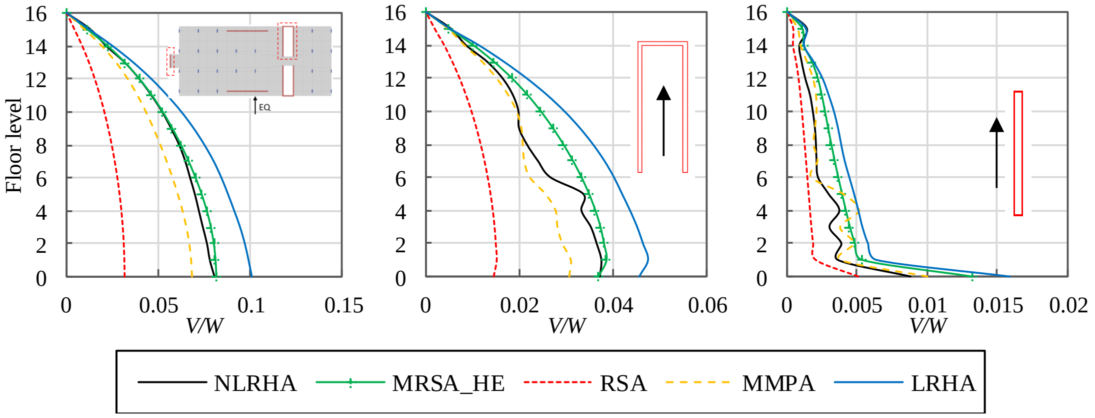


Fig. 7 – Shear forces in a story and RC walls of: (a) TF system; (b)TS system; and (c) TSS system computed from RSA, LRHA, MRSA$_{HE}$, MMPA, and NLRHA due to earthquake in y-direction.

9. Conclusions

MRSA procedure is extended to buildings with translation-torsion coupled in one direction by using a 16-story RC shear-wall building with asymmetric floor plan in one direction. This 16-story building is used to create three types of torsional irregularities: torsionally-flexible (TF), torsionally-stiff (TS), and torsionally-similarly stiff (TSS) systems in order to evaluate the accuracy of RSA and MRSA procedures. The main findings can be summarized as the followings:

1. LRSA provides good estimate of floor displacement and story drift ratios compared to NLRHA. RSA procedure slightly underestimates story drift ratios, but significantly underestimates design shear forces when compared to NLRHA results.
2. The first-two modes (first mode of torsion-dominant mode and translation-dominant mode) experience inelasticity, while other higher modes can be conservatively assumed to be elastic.
3. MRSA$_{\mathrm{HE}}$ using the first-two modes multiplied with $(SF\times\Omega_0)/R$ and elastic higher modes can estimate well shear forces computed from NLRHA for all cases.
4. Predicted strains from MRSA procedure using elastic analysis are in good agreement with NLRHA results.

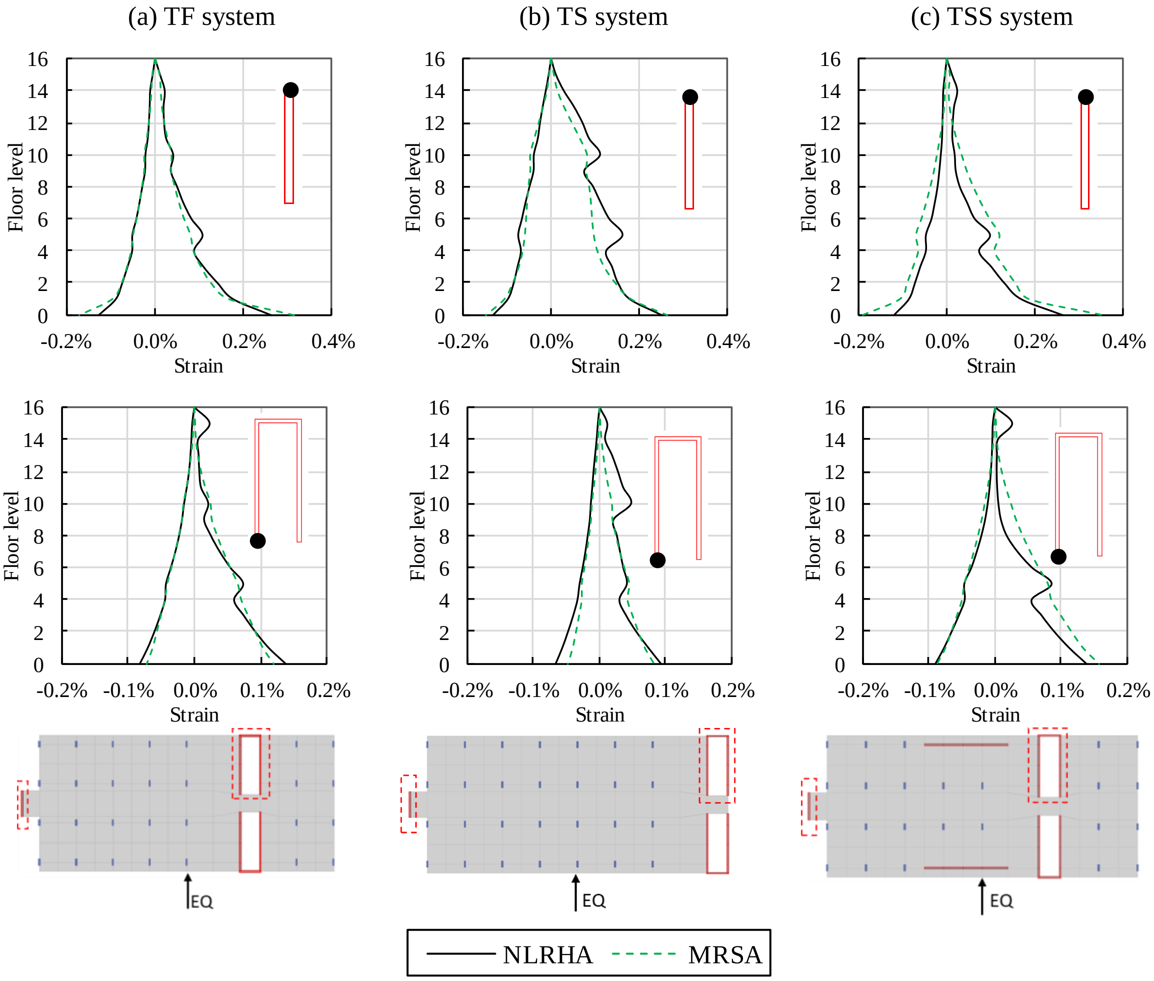


Fig. 8 – Strains in shear walls and c-shaped walls of TF, TS, and TSS systems computed from MRSA and NLRHA due to earthquake in y-direction. The black dot indicates the location of computed strain.

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11. References

[1] American Society of Civil Engineers (2010): *Minimum design loads for buildings and other structures*. ASCE/SEI 7-10. Reston, Virginia.

[2] Khy, K., C. Chintanapakdee, P. Warnitchai, and A.C. Wijeyewickrema (2019): Modified response spectrum analysis to compute shear force in tall RC shear wall buildings. *Engineering Structures*. **180**, 295-309.

[3] Chopra, A.K. and R.K. Goel (2004): A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. *Earthquake Engineering and Structural Dynamics*. **33**(8), 903-927.

[4] Department of Public Works and Town & Country Planning (2019): *Seismic Resistant Design of Buildings and Structures, DPT 1301/1302-61*. Bangkok, Thailand. (in Thai).

[5] Council on Tall Buildings and Urban Habitat (2008): *Recommendations for the Seismic Design of High-rise Buildings*. Illinois Institute of Technology. Chicago, IL.

[6] Pacific Earthquake Engineering Research Center (2017): *Tall Buildings Initiative, Guidelines for performance-based seismic design of tall buildings*. PEER-2017/06. Berkeley, California.

[7] American Society of Civil Engineers (2016): *Minimum design loads and associated criteria for buildings and other structures*. ASCE/SEI 7-16. Reston, Virginia.

[8] Najam, F.A. and P. Warnitchai (2018): A modified response spectrum analysis procedure to determine nonlinear seismic demands of high-rise buildings with shear walls. *The Structural Design of Tall and Special Buildings*. **27**(1), e1409.

[9] Khy, K. and C. Chintanapakdee (2017): Evaluation of seismic shear demands of RC core walls in Thailand determined by RSA Procedure. *Engineering Journal*. **21**(2), 151-172.

[10] Munir, A. and P. Warnitchai (2012): The cause of unproportionately large higher mode contributions in the inelastic seismic responses of high-rise core-wall buildings. *Earthquake Engineering and Structural Dynamics*. **41**(15), 2195-2214.

[11] American Concrete Institute (2014): *Building code requirements for structural concrete (ACI 318M-14) and commentary (ACI 318RM-14)*. Farmington Hills, USA.

[12] Computers and Structures, Inc. (2015): *ETABS, Integrated building design software, Version 15.2.2*. Berkeley, California.

[13] Computers and Structures, Inc. (2011): *PERFORM-3D, Nonlinear analysis and performance assessment of 3D structures, Version 5.0.1*. Berkeley, California.

[14] Bangkok Metropolitan Administration (2001): *Bangkok building control law, B.E. 2544*. http://203.155.220.230/bmainfo/law/law.php?t=031.

[15] Khy, K., C. Chintanapakdee, and A.C. Wijeyewickrema (2019): Application of Conditional Mean Spectrum in Nonlinear Response History Analysis of Tall Buildings on Soft Soil. *Engineering Journal*. **23**(1), 135-150.

[16] Poovarodom, N., A. Jirasakjamroonsri, T. Ornthammarath, and P. Warnitchai (2017): New design spectral acceleration of soft and deep deposits in Bangkok. *International Conference on Earthquake Engineering and Structural Dynamics*. Reykjavík, Iceland.

[17] Jirasakjamroonsri, A., N. Poovarodom, and P. Warnitchai (2018): Seismic site characteristics of shallow sediments in the Bangkok Metropolitan Region, and their inherent relations. *Bulletin of Engineering Geology and the Environment*. 1-17.

[18] SeismoSoft (2016): *SeismoMatch, A computer application capable of adjusting earthquake accelerograms to match a specific target response spectrum, Version 2016*. http://www.seismosoft.com.

[19] Mander, J.B., M.J. Priestley, and R. Park (1988): Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering, ASCE*. **114**(8), 1804-1826.

[20] Menegotto, M. and E. Pinto (1973): Method of analysis for cyclically loaded reinforced concrete plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending. *IABSE Symposium*. Lisbon, Portugal.

[21] Research and Consultancy Institute of Thammasat University): *Drafting of Thai building code project. Report Vol. 2: Building loads, submitted to Department of Public Works and Town & Country Planning*. Bangkok, Thailand; 2009. (in Thai).

[22] American Society of Civil Engineers (2013): *Seismic evaluation and retrofit of existing buildings*. ASCE/SEI 41-13. Reston, Virginia.

[23] Chopra, A.K. and F. McKenna (2016): Modeling viscous damping in nonlinear response history analysis of buildings for earthquake excitation. *Earthquake Engineering and Structural Dynamics*. **45**(2), 193-211.

[24] Chopra, A.K., R.K. Goel, and C. Chintanapakdee (2004): Evaluation of a modified MPA procedure assuming higher modes as elastic to estimate seismic demands. *Earthquake Spectra*. **20**(3), 757-778.