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NONLINEAR RESPONSE TIME HISTORY ANALYSIS OF WALL-FRAMES USING MODAL-BASED GROUND MOTION SELECTED MOTIONS

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Abstract

This paper presents the nonlinear response time history analysis (NLRHA) of reinforced concrete wall-frame structures using input ground motions (IGMs) selected by the modal-based ground motion selection (MGMS) procedure. The MGMS procedure was proposed to take the effect of the frequency contents combination in the time domain on the seismic response of structures into account and the applicability and accuracy of the MGMS procedure have been verified through the NLRHA of frame structures. In the MGMS, three equivalent single-degree-of-freedom (ESDOF) systems are firstly developed from the modal pushover analysis of the first three modes of the building structure. Then, NLRHA of the three ESDOFs using twenty seed IGMs that are selected using the spectrum-matching-based ground motion selection procedure are carried out. Comparing the time history results of top displacements of the three ESDOFs, the MGMS procedure selects seven IGMs that induce the highest level of multimode interaction for the NLRHA of the full structure model. A case study involving two reinforced concrete wall-frame structures with different combinations of wall and frame is conducted to verify the applicability of the MGMS on selecting proper IGMs for the NLRHA of wall-frame structures. From the results of case study, it is found that the seismic demands of wall-frame structures computed using the MGMS-IGMs have much less deviation, indicating that the MGMS procedure can effectively select IGMs for the NLRHA of wall-frame structures.

Keywords: nonlinear response time history analysis; wall-frame; modal-based ground motion selection

1. Introduction

Wall-frame structures are widely used in the mid- and high-rise residential and commercial buildings that accommodate a great number of people. It is of crucial significance for engineers and researchers to keep the safety of the wall-frame structures under the attack of earthquakes to reduce the loss of life and property.

With the development of computer and modelling technics, the nonlinear response time history analysis (NLRHA) is widely adopted in the seismic design of buildings, owing to its capability of accurately calculating the seismic response of building structures. Meanwhile, one of the most crucial factors that affect the accuracy and reasonability of the NLRHA is the selection of input ground motions (IGMs), since the earthquake events have extreme uncertainty and contingency [1]. Currently, most of the seismic design codes recommend to select and modify the IGMs to match the design spectrum [2-5] or uniform hazard spectrum (UHS) of the site of interest, as the response spectrum is one of the most popular and significant representations of the seismic hazard. Plenty of research efforts have been paid on the selecting and modifying IGMs to match the design spectrum and UHS [6-8]. At the same time, Baker [9] and Lin et al. [10] have developed the conditional mean spectrum (CMS) and the conditional spectrum (CS), respectively, as the target response spectrum based on probabilistic seismic hazard analysis, being convinced that significant overestimation of the seismic demands will be induced by amplifying the IGMs to match response spectra with a design spectrum or UHS. To consider the nonlinear behaviour of structures in the IGMs selection, Kalkan et al. [11] and Reyes et al. [12] developed a modal-pushover-based ground motion scaling procedure to select and scale IGMs to ensure the structure to have a certain level of peak modal response.

However, the response spectrum and the peak modal responses only reveal the effect of frequency contents of ground motions in the frequency domain, since they just show the peak response values of different vibration modes of a multi-degree-of-freedom (MDOF) system under the action of the earthquake. Consequently, no matter what kinds target spectrum or target responses are used in the IGMs selection, the effect of the combination of frequency contents in the time domain on the seismic response of the structures cannot be considered. Nevertheless, previously recorded ground motions show various frequency contents and frequency contents combination in the time domain and it is found in [13] that both frequency contents and the combination of frequency contents in the time domain of IGMs have a significant impact on seismic response of building structures. Ignoring the frequency contents combination in the time domain in the IGM selection can lead to a considerable reduction of the accuracy and reliability of the computed seismic responses, even if the spectra are well matched.

Recently, a modal-based ground motion selection (MGMS) procedure is proposed by Liu et al. [14] to consider the effect of the combination of frequency contents in the time domain on seismic response of structures in the IGMs selection. In the MGMS procedure, the effect the combination of frequency contents in the time domain is represented by the level of multi-mode interactions, and the MGMS procedure selects IGMs those induce the most significant multi-mode interactions for the NLRHA of structures. The capability of the MGMS procedure on selecting more proper IGMs for the NLRHA of structures has been proved through a comprehensive case study on frame structures. But, since the wall-frame structure consists of a rigid frame system and a shear wall system and there are significant interactions between the frame and the wall, the structural behaviour of the wall-frame structure is completely different from that of the frame structure, when the structures are subjected to lateral load. As a result, although the MGMS procedure can reduce the variations induced by the selection IGMs for the NLRHA of frame structures, the applicability of the MGMS procedure in selecting more appropriate IGMs for the NLRHA of wall-frame structures is not guaranteed.

In this paper, the NLRHA of wall-frame structures using IGMs selected by the MGMS procedure is presented to investigate the capability of the MGMS procedure in selecting more suitable IGMs for the NLRHA of wall-frame structures and reducing variations caused by the selection of IGMs. A case study on two reinforced concrete wall-frame structures with different combinations of wall and frame under different levels of IGMs is conducted. It is found that the seismic demands of wall-frame structures computed using the MGMS-IGMs have much less deviation, indicating that the MGMS procedure can effectively select IGMs for the NLRHA of wall-frame structures.

2. Modal-based ground motion selection procedure

The basic idea of the MGMS procedure is to select IGMs that can induce most significant multi-mode responses of structures simultaneously from seed IGMs that are selected by conventional spectrum matching procedure for the NLRHA of the structure. The number of seed IGMs is twenty since it was found by Ansal [15] that when more than twenty IGMs are adopted for site-response analysis, there are negligible changes in the mean response spectrum with additional inputs and a consistent mean response spectrum can be generated. On the other hand, the number of IGMs selected by the MGMS is seven, as most of the codes of practice required to use at least seven IGMs for the NLRHA of structures.

To select seven IGMs that can induce most significant multi-mode responses of structures simultaneously from seed IGMs, the MGMS procedure firstly convert the building structure model as three equivalent single-degree-of-freedom (ESDOF) systems that have modal properties similar to that of the first three modes of the structure. The procedures of equalizing the structures to ESDOFs are:

1. Apply three sets of lateral force with a distribution of $m\phi_n$, where n = 1,2,3, m is the storey mass and ϕ_n is the mode shape of nth mode, to the structure separately. Then generate three base shear-roof displacement ($V_{bn}-u_{rn}$) curves. Idealise ($V_{bn}-u_{rn}$) curves as bilinear curves.

2. Convert the bilinear ($V_{bn}-u_{rn}$) curves to the pushover (F_{sn}/L_n-D_n) curves of the ESDOFs using the following equations,

$$\frac{F_{sn}}{L_n}=\frac{V_{bn}}{M_n^*} \quad \text{and} \quad D_n=\frac{u_{rn}}{\Gamma_n\phi_{rn}} \tag{1}$$

Where

$$\Gamma_n=\frac{L_n}{M_n},\ L_n=\phi_n^T\mathbf{mi},\ M_n=\phi_n^T\mathbf{m}\phi_n \tag{2}$$

3. Compute the natural period of ESDOFs by

$$T_n^*=2\pi\sqrt{\frac{L_nD_{ny}}{F_{sny}}} \tag{3}$$

Where

$$D_{ny}=\frac{u_{rny}}{\Gamma_n\phi_{rn}} \tag{4}$$

4. Model the three ESDOFs with the base shear-top displacement relations of the ESDOF the same as the (F_{sn}/L_n-D_n) and the natural period of ESDOFs being T_n^* .

After modelling the ESDOFs of the structure, NLRHA of the ESDOFs with the twenty seed IGMs will be conducted to calculate the displacement time history $u_{jn}(t)$ and the maximum top displacement $\hat{u}_{jn}$ of the *n*th ESDOF under the excitation of the *j*th motion, where $j\in(1,20)$. The indicator of the level of the multi-mode interaction of *j*th IGM at time t_k, β_{jk}^{max} is defined as the peak value of the factor β_{jk} that establishes the following inequalities simultaneously:

$$\left(\left|u_{j1}(t_k)\right|\geq\left|\Gamma_1\right|\beta_{jk}\hat{u}_{j1}\right) \tag{5a}$$

$$\left(\left|u_{j2}(t_k)\right| \geq \beta_{jk}\hat{u}_{j2}\right) \tag{5b}$$

$$\left(\left|u_{j3}(t_k)\right| \geq \beta_{jk}\hat{u}_{j3}\right) \tag{5c}$$

where $t_k \in T_{j0}$, T_{j0} is the duration of the IGM j, $k \in \left(1, N_j\right)$, N_j is the recorded points number in IGM j , $u_{jn}(t_k)$ is the top displacement of the *n*th ESDOF at time t_k, $\hat{u}_{jn} = \max\limits_{t_k \in T_0}\left|u_{jn}(t_k)\right|$ is the maximum absolute displacement of *n*th ESDOF and $\beta_{jk} \in [0, 1/\left|\Gamma_1\right|]$. β_{jk}^{max} gives the degree multi-mode interaction induced by the combination of the IGM's frequency contents at time t_k. Generally, the larger the value of β_{jk}^{max} is, the more significant the multi-mode interaction is. When β_{jk}^{max} is zero, at least one of the first three modes does not contribute to structural response at time t_k.

After obtaining β_{jk}^{max} for all $t_k \in T_{j0}$, the level of the multi-mode interaction indicator of motion j, β_j for ground motion *j* can be calculated as

$$\beta_j = \max(\beta_{\mathrm{jk}}^{\max}) \text{ for } t_k \in T_{j0} \tag{6}$$

From the definition, β_j shows the maximum level of multimode interaction induced by motion j. When β_j equals to 1/|Γ$_1$|, the ground motion *j* can induce the fundamental mode reaches the peak response and the other two modes have responses close to a peak value simultaneously in at least one time point in the duration of ground motion j. On the other hand, if β_j equals to zero, the structural response induced by ground motion *j* is a combination of modal responses of at most two modes for all the time points in the duration of ground motion j. But these two cases are extremely rare for the natural earthquake records since the modes are not vibrating separately or in phase. Thus, β_j is most likely less than 1/|Γ$_1$| but larger than 0.

After defining the level of the multi-mode interaction indicator of motion, the MGMS procedure selects seven IGMs with the largest β_j that fulfils the relations (5) and (6) from the seed IGMs, to select seven motions that induce the most significant multimode interaction for the NLRHA of the structure. On the other hand, computing the β_j for each motion is time-consuming and not necessary. Instead, the MGMS procedure adopted a trial-and-error algorithm to select IGMs with the largest β_j. In the algorithm, the value of β_j is set to be the same for all the twenty IGMs. The initial value of β_j is set as 1/|Γ$_1$|, where very few motions can establish the inequalities in Equation (5). Then, the values of β_j are decreased repeatedly until there are seven IGMs establish the inequalities in Equation (5). As a result of the selection algorithm, the seven selected motions have higher values of β_j and lead to higher multi-mode interaction and responses than the rest of the seed IGMs. The seven selected IGMs are then used as the inputs for NLRHA on the full structure model. The mean seismic demands computed from NLRHA with the full model can be used to conduct seismic analysis and design of the structure. The procedure of the IGMs selection procedure of the MGMS is shown in Fig. 1.

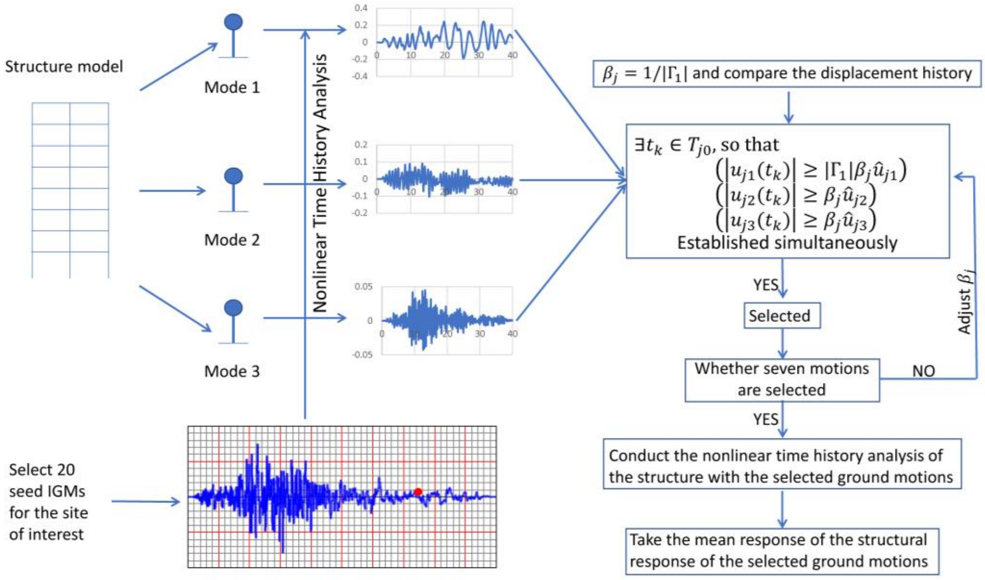


Fig. 1 – Flowchart of modal-based motion selection procedure.

3. Case study

3.1 Ground Motions

In the case study, two design spectra of ASCE-10 [5] was selected and the target response spectrum and design parameters for the target response spectra were summarised in Table 1. For each target spectrum, a set of twenty ground motion records from the strong ground motion database of the Pacific Earthquake Engineering Research (PEER) Centre (http://peer.berkeley.edu/) were selected and scaled by minimising MSE method, where the computed weighted mean squared error of record is minimised, and suite average with regards to target spectrum. Details of the selected records are given elsewhere [16]. The pseudo-acceleration spectra of the target ASCE spectrum and the selected ground motions are shown in Fig. 2.

3.2 Prototype of Wall-frame Structures

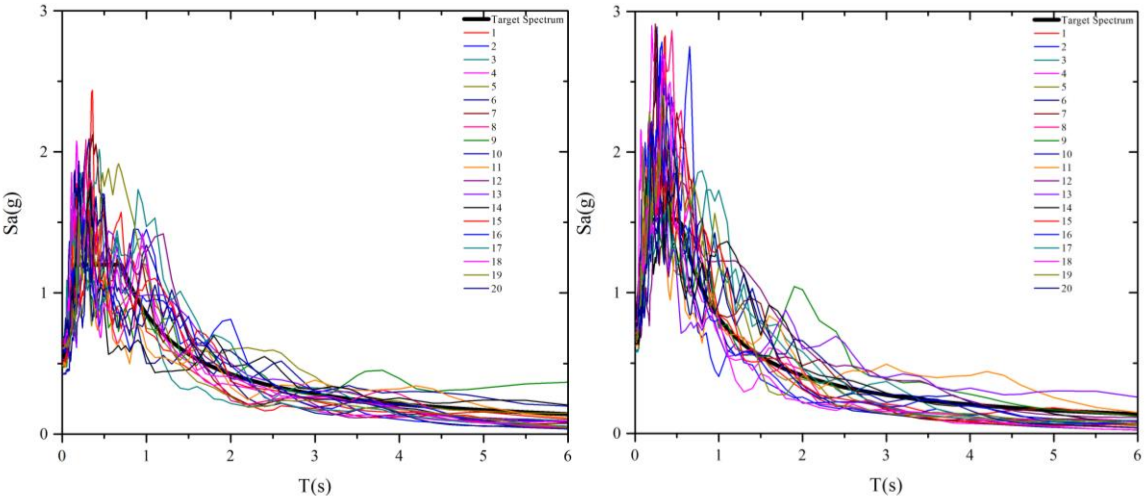
Two reinforced concrete (RC) wall-frame structures from [16] were used in the case study. The structures are 25-storey tube-in-tube reinforced concrete wall-frame structures with the storey height of 3.5 m. The floor plan is shown in Fig. 4. The three-dimensional system was modelled by a two-dimensional model with half of the structure since the structure is symmetric in the plan. The two-dimensional model of the structure is presented in Fig. 4(b). Dimensions of the RC shear wall and frame is presented in Table 2. The dimension of the shear wall is 350 mm × 6000 mm, while the frame sections vary to represent different combinations of wall and frame. Materials used for the concrete and steel are C40 with the cylinder compressive strength of 26.8 MPa and HRB 500 steel with the yield strength of 500 MPa, respectively. Reinforcement ratios of the wall structure are tabulated and the design loads used can be found elsewhere [17].

The modal properties, including the first three natural periods and the corresponding modal mass participation factor of the wall-frame systems, were summarised in Table 3. Linear elastic pushover analysis was conducted, where the building was subjected to the force with first mode distributions; the friction of the elastic seismic base shear can be seen in Table 3. On the other hand, discretised plastic hinges located at the ends of frame members were used to model the nonlinear behaviour of frame structures. The properties of plastic hinges and modelling parameters were calculated using FEMA 365 [18]. In the analysis, only the flexural inelasticity of the shear wall was modelled, and the shear deformation of the wall was assumed to be elastic.

Table 1 – Design parameters of ASCE design spectra.

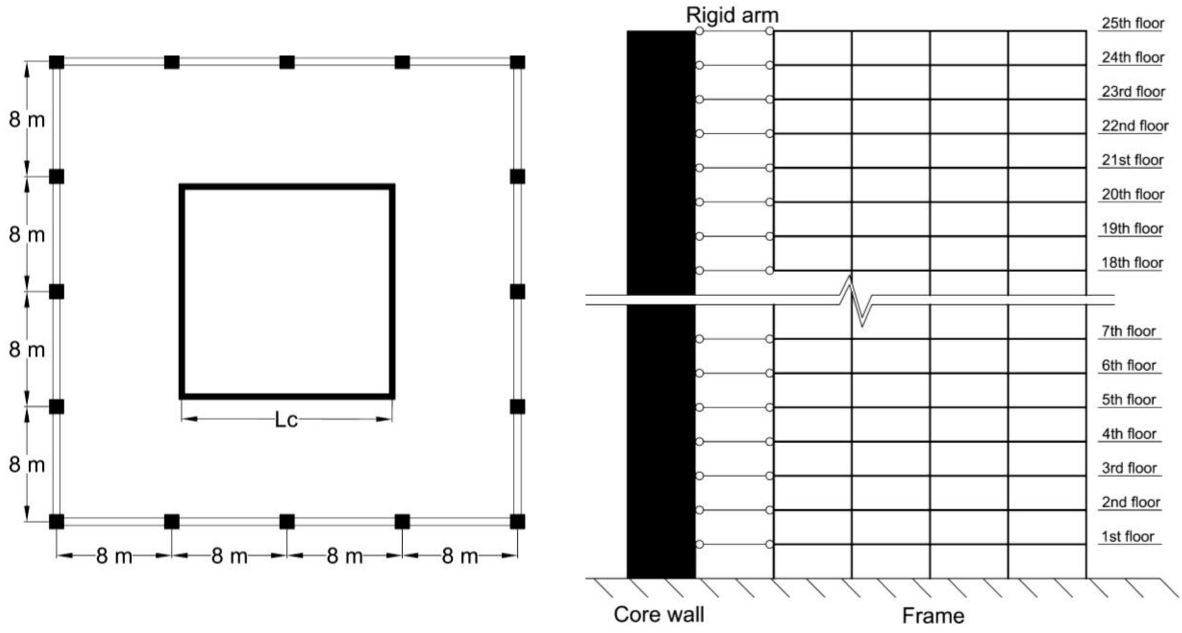
Design spectrum	**S_{ds} (g)**	**S_{d1} (g)**	**T_L (s)**
Target ASCE spectrum 1	1.200	0.850	10
Target ASCE spectrum 2	1.521	0.819	12

Note: S_{ds} and S_{d1} are design spectral accelerations for T = 0.2s and T = 1s, respectively. T_L is the long-period transition period.



(c) (d)

Fig. 2 – Acceleration spectra of selected and scaled motions and design spectrum



(a) (b)

Fig. 3 – Example wall-frame structure; (a) Floor plan; (b) 2-D wall-frame model

Table 2 – Dimensions of main structural elements of wall-frame structures.

Wall-frame structure		**WF 1**	**WF 2**
Wall	Length (L_c: mm)	5000	5000
	Thickness (b: mm)	350	350
Column (b×h: mm)		1000×1000	1200×1200
Beam (b×h: mm)		400×900	500×1000

The Wilson-θ time integration method, which is unconditionally stable for $\theta > 1.37$, in the nonlinear version of SAP2000 [19] was used to perform the NLRHA on the two wall-frame structures under the selected IGMs. The value of θ was defined as 1.4 to ensure numerical integration is stable and convergent. A damping ratio of 5% is assigned to the first and third modes to generate the damping matrix. The P-Δ effects are also included in NLRHA.

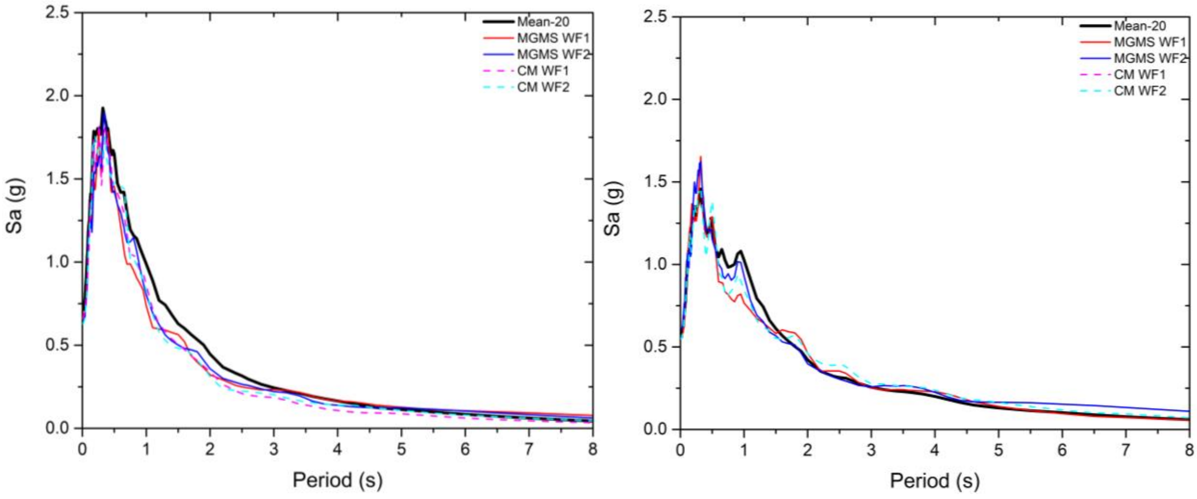
Table 3 – Modal property of wall-frame structures and friction of base shear taken by frame and wall.

Wall-frame structure	**Mode**	**Natural period (s)**	**Modal mass participation ratio**	**Percent of seismic base shear taken by frame (%)**	**Percent of seismic base shear taken by wall (%)**
WF 1	1	2.96	0.750	33	67
	2	0.9	0.110		
	3	0.46	0.043		
WF 2	1	2.31	0.750	46	54
	2	0.72	0.110		
	3	0.38	0.041		

3.3 Input ground motions for NLRHA

To compare the seismic responses of the structures under the excitation of IGMs selected with and without the MGMS procedure, a closest spectra matching (CM) ground motion selection procedure was adopted to select IGMs from all the ground motion sets for NLRHA of the structures. In the CM procedure, seven ground motions with response spectra matching the best with the mean response spectra of the motion set over the period range between $0.2T_l$ and $2T_l$, where T_l is the fundamental period of the structure, are selected for each motion set. Closest spectra matching of an IGM means that the response spectrum of the IGM has the smallest value of the sum of squared error over the period from $0.2T_l$ and $2T_l$ with respect to the mean spectrum of the set. For the MGMS method, the selection of motions follows the steps given in the previous section.

The closest spectrum matching procedure ensures the selected IGMs have the most similar frequency contents to the mean response spectrum of IGMs of the whole motion set. The MGMS selected IGMs not only have similar frequency contents to the mean response spectrum of the motion set but also can induce the greatest level of multi-mode interaction. It should be noted that the MGMS method and CM procedure are structure-dependent and hence the MGMS-selected and CM-selected IGMs for the frame WF1 and WF2 are different. The average acceleration spectra of all ground motions of the motion set (denoted as Mean-20), motions from the CM procedure (denoted as CM WF1 and CM WF2 for WF1 and WF2 respectively) and the MGMS-selected motions (denoted as MGMS WF1 and MGMS WF2) are presented in Figs. 4(a)-(b) respectively. Despite the use of different selection procedures, the mean response spectra of all the groups of IGMs, so that all the motion groups have a similar range of frequency contents.



(a) (b)

Fig. 4 – Mean spectra of each group of IGMs for NLRHA. (a) motion Set 1; (b) motion Set 2

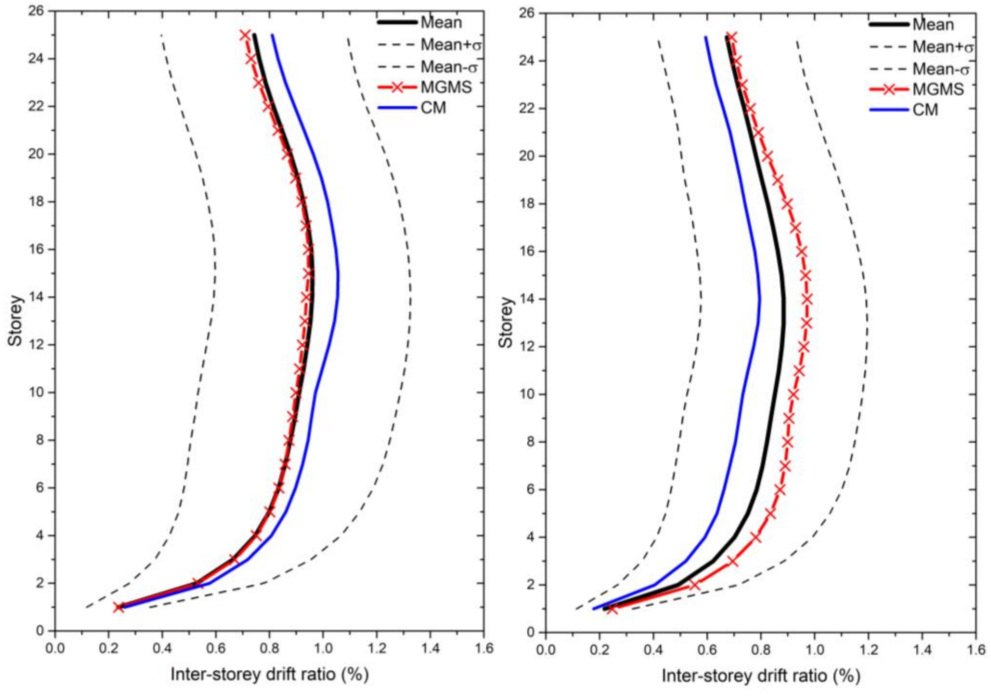
4. Results and discussions

Figs. 5 to 6 plot the mean inter-storey drift ratio (IDR) and hinge plastic rotation (HPR) of the two wall-frame structures WF1 and WF2 under excitations of all the seed IGMs of the motion set (denoted as Mean), the group of motions with closest spectra matching (denoted as CM) and the MGMS-selected IGMs (denoted as MGMS) respectively. Since the whole set of seed IGMs covers a wider range of frequency contents combination in the time domain and the mean demands of NLRHA using the whole set of seed IGMs are more accurate and reasonable, the mean demands of NLRHA using the whole set of seed IGMs are used as the reference for the comparison.

From Fig. 5(a), it is seen that the IDRs of WF1 excited by the MGMS-IGMs are very close to the mean IDRs calculated using all IGM of motion set 1, while IDRs computed with MGMS-IGMs are more conservative along the height of the structure for motion set 2. When WF1 was subjected to IGMs from CM procedure, the IDRs for all the storeys are over- and underestimated for motion set 1 and set 2 respectively. When comparing the IDRs of WF2 under motion set 1, NLRHA using the MGMS-IGMs slightly underestimated the IDRs along the height of the structure, while the usage of the CM-IGMs causes a conservative prediction of IDRs at the lower part of the structure. For the case that WF2 was subjected to IGMs from set 2, it is clear that the IDRs of MGMS-selected IGMs match the mean IDRs of the whole set excellently, but the CM-IGMs resulted in a significant underestimation of the IDRs.

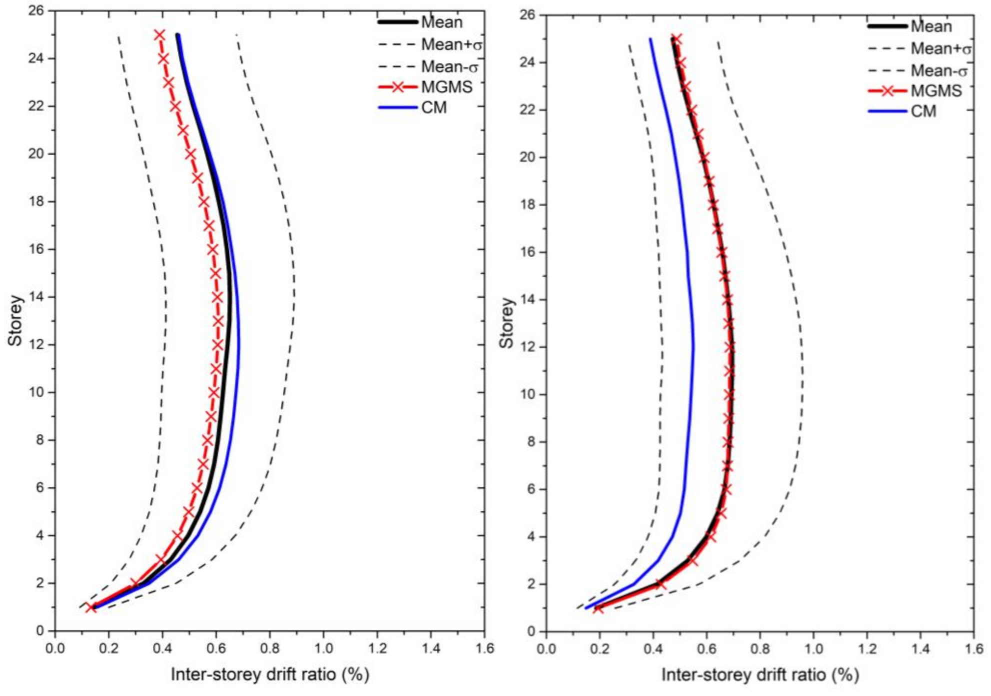
It can be seen from Fig. 6 that the HPR computed using IGMs from the MGMS approximate the mean HPR of the whole motion set excellently when WF1 was subjected to IGMs of motion set 1 and WF2 was subjected to IGMs of motion set 2, while conservative estimations of the HPR are observed when WF1 was excited by motions of motion set 2 and WF2 was excited by motions of motion set 1. It is also noted that for both wall-frame structures, CM-selected IGMs over- and under-estimated the HPR for motion set 1 and set 2 respectively.

From the comparison of the inter-storey drift ratio and hinge plastic rotation results, it is clear that the NLRHA with MGMS-selected IGMs can ensure a more accurate yet less biased estimation of the seismic demands, even compared with NLRHA using IGMs with closest spectra matching. This shows the capability of the MGMS procedure in selecting more proper IGMs for the NLRHA of wall-frame structures. With a slight increase in the computation effort, the MGMS procedure can effectively and practically supplement the standard spectrum-matching method to choose proper IGMs for NLRHA of wall-frame structures.



Set 1 Set 2

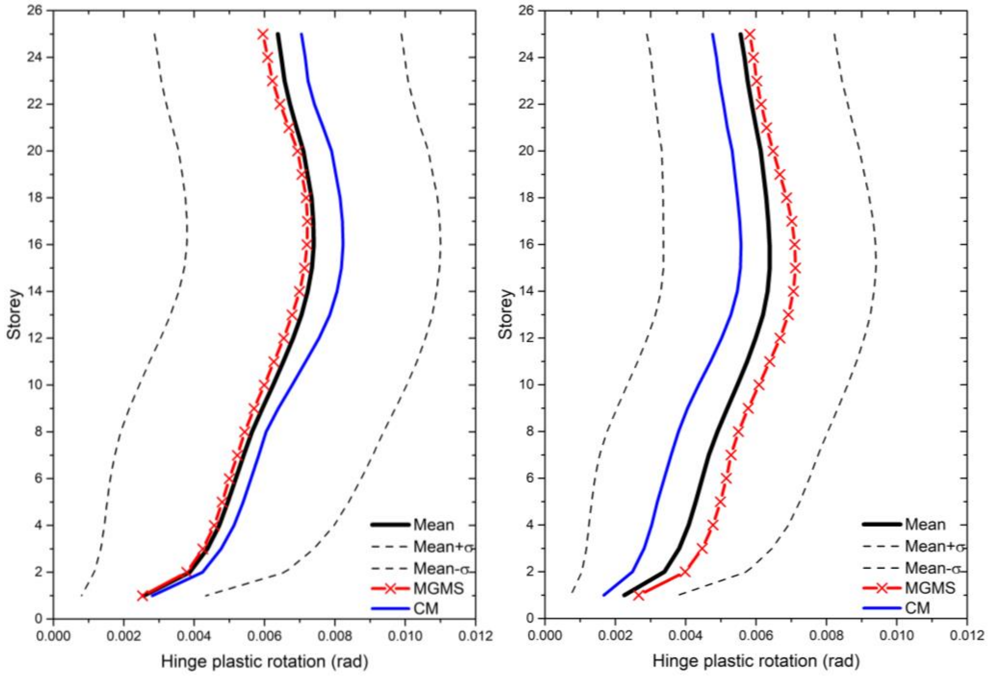
(a)



Set 1 Set 2

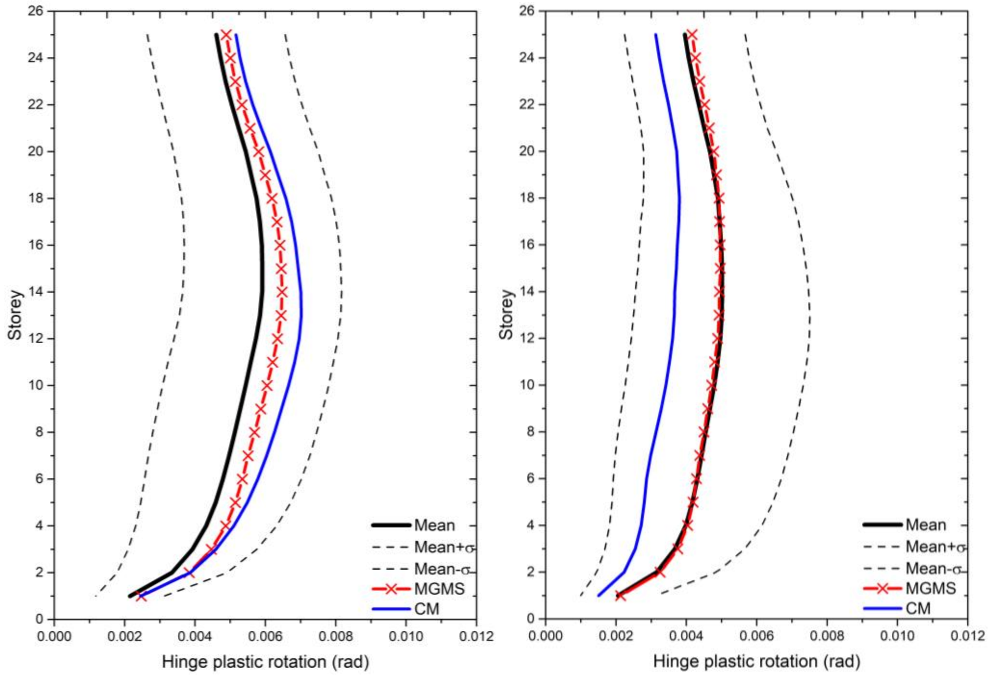
(b)

Fig. 5 – Inter-storey drift ratio of the wall-frame structures. (a) WF 1; (b) WF 2



Set 1 Set 2

(a)



Set 1 Set 2

(b)

Fig. 6 – Hinge plastic rotation of the wall-frame structures. (a) WF 1; (b) WF 2

5. Conclusions

This paper presents the nonlinear response time history analysis (NLRHA) of wall-frame structures using input ground motions (IGMs) selected by the modal-based ground motion selection (MGMS) procedure. To consider the effect of frequency contents combination in the time domain of IGMs on the seismic response of structures, the MGMS procedure selects seven IGMs that can induce most significant multi-mode interaction from twenty seed IGMs that are selected by the spectrum matching procedure with the site-specific target spectrum. In the MGMS procedure, NLRHA of three equivalent single-degree-of-freedom (ESDOF) systems that are developed based on the modal property of the first three modes of the structure is firstly conducted using all the seed IGMs. The level of multi-mode interaction is revealed by comparing the top displacement time histories. To investigate the capability of the MGMS in selecting proper IGMs for the NLRHA of wall-frame structures, a case study of two 25-storey reinforces concrete wall-frame structures with different wall and frame combinations was conducted. From the comparison of seismic demands computed by the NLRHA using all the seed IGMs, MGMS-selected IGMs and IGMs selected based on closest spectrum matching (CM) selection procedure, the following conclusions can be drawn.

1. The MGMS procedure can select proper IGMs for the NLRHA of wall-frame structures since the seismic demands of NLRHA using MGMS-selected IGMs match the of NLRHA using the wholes set of seed motions well.

2. Despite that the closes spectra matching (CM) selection procedure select IGMs whose response spectra matches the mean spectra of the whole set of seed IGMs best, the NLRHA with MGMS-selected IGMs can ensure a more accurate yet less biased estimation of the seismic demands, compared with NLRHA using motions with CM procedure. This shows the crucial significance of considering the effect of frequency contents combination in the time domain of ground motions on the seismic response of structures.

3. Since the MGMS procedure is capable of selecting proper IGMs for NLRHA of wall-frame structures effectively with a slight impact on the computational time, the MGMS procedure can be considered as a practical and necessary supplement to the standard spectrum-matching procedure used by most of the seismic design codes of practice.

6. Acknowledgements

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7. References

[1] Wang G (2011): A ground motion selection and modification method capturing response spectrum characteristics and variability of scenario earthquakes. *Soil Dynamics and Earthquake Engineering*, **31**(4):611-625.

[2] National Standard of the People's Republic of China (2010): *Code for Seismic Design of Buildings (GB 50011-2010)*. China Architecture & Building Press, Beijing.

[3] CEN (2004): *Eurocode 8: design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings (EN 1998–1:2004)*. European Committee for Standardization, Brussels.

[4] ASCE/SEI 7-16 (2016): *Minimum Design Loads for Buildings and Other Structures*. Reston, VA.

[5] ASCE/SEI 7-10 (2010): *Minimum Design Loads for Buildings and Other Structures*. Reston, VA.

[6] Haselton CB, Whittaker AS, Hortacsu A, Baker JW, Bray J, Grant DN (2012): Selecting and scaling earthquake ground motions for performing response-history analyses. *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[7] Buratti N, Stafford PJ, Bommer JJ (2011): Earthquake accelerogram selection and scaling procedures for estimating the distribution of drift response. *Journal of Structural Engineering*, **137**(3):345-357.

[8] Smerzini C, Galasso C, Iervolino I, Paolucci R (2014): Ground motion record selection based on broadband spectral compatibility. *Earthquake Spectra*, **30**(4):1427-48.

[9] Baker JW (2010): Conditional mean spectrum: Tool for ground-motion selection. *Journal of Structural Engineering*, **137**(3):322-31.

[10] Lin T, Haselton CB, Baker JW (2013): Conditional spectrum-based ground motion selection. Part I: hazard consistency for risk-based assessments. *Earthquake engineering & structural dynamics*, **42**(12):1847-65.

[11] Kalkan E, Chopra AK. Modal-pushover-based ground-motion scaling procedure. J*ournal of Structural Engineering* 2010;**137**(3):298-310.

[12] Reyes JC, Quintero OA. Modal pushover-based scaling of earthquake records for nonlinear analysis of single-story unsymmetric-plan buildings. *Earthquake Engineering & Structural Dynamics*, **43**(7):1005-21.

[13] Takewaki I. *Critical Excitation Methods in Earthquake Engineering*. 2nd ed. Oxford, United Kingdom: Butterworth-Heinemann; 2013.

[14] Liu Y, Kuang JS, Yuen TYP (2020): Modal‐based ground motion selection procedure for nonlinear response time history analysis of high-rise buildings. *Earthquake Engineering & Structural Dynamics*, **43**:95-110.

[15] Ansal A, Tönük G, Kurtuluş A (2018): Implications of site specific response analysis. *Recent Advances in Earthquake Engineering in Europe:51-68: 16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

[16] Liu Y, Kuang JS, (2017): Spectrum-based pushover analysis for estimating seismic demand of tall buildings. *Bulletin of Earthquake Engineering*,**15**:4193–214.

[17] Liu Y, Kuang JS, Huang QX (2018): Modified spectrum-based pushover analysis for estimating seismic demand of dual wall-frame systems. *Engineering Structures*, **165**:302-314.

[18] ASCE. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356)*. Building Seismic Safety Council, Federal Emergency Management Agency, Washington, D.C.

[19] CSI SV. 15. *Integrated finite element analysis and design of structures basic analysis reference manual*. Berkeley, California (USA): Computers and Structures Inc.