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Sufficiency of the spectral shape in predicting peak and cumulative structural earthquake responses

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Abstract. In recent years, selection of strong ground motion records by means of intensity measures representing the spectral shape of the earthquake excitation has been studied by many researchers. These studies indicate the adequacy of this record selection approach in reduction of the scattering of seismic responses. In present study, this method has been studied more in depth to reveal the sufficiency of the spectral shape in predicting structural seismic responses such as the plastic deformation and the dissipated hysteresis energy which are associated with cumulative properties of the selected records. For this purpose, after selecting the records based on the spectral shape, the correlation of some seismic responses and strong ground motion duration of earthquake records are explored. Findings indicate strong correlation of some structural responses with the significant duration of the records. This fact implies that the spectral shape could not reflect all characteristics of the strong ground motion and emphasizes the importance of additional criteria along with the spectral shape in the record selection.

Keywords: intensity measure; spectral shape; sufficiency; significant duration

1. Introduction

In recent decades, improvement of computational power and development of engineering software have made the nonlinear response-history analysis more relevant and possible. In such analyses, input excitation is the ground acceleration during earthquakes well known as the earthquake records which should reflect the expected seismic motion at the site. Existing methods for record selection in response history analysis are mainly based on engineering judgment, but nowadays it is considered as a research priority (NIST 2011, Kostinakis and Athanatopoulou 2015).

The most straightforward method in record selection is the selection by magnitude (M) and distance (R) bins; however recent studies shows the scattering of seismic responses in this approach (Iervolino and Cornell 2005). Site soil condition may be applied as complementary measure in this method; however, considering the soil condition along with the magnitude and distance bins may result in limited number of appropriate records (Bommer and Scott 2000).

Strong ground motion duration can also be used as a complementary measure in earthquake record selection. Some researchers have reported this parameter as a secondary response predictor as it affects different response parameters in different manners (Hancock and Bommer 2006). Peak response parameters weakly correlate with the duration while cumulative demands such as absorbed hysteresis energy do more strongly. However, some studies point out that the record selection should be based on both the spectral shape and duration of ground motion (Chandramohan *et al.* 2016a, b).

Records selection based on intensity measure (IM), introduced in performance based earthquake engineering, is an efficient approach to reduce the number of required analyses (Vacareanu *et al.* 2014). An IM is a strong ground motion parameter that significantly correlates with seismic responses. Selection of the IM should be based on the efficiency and sufficiency of this ground motion parameter in prediction of structural seismic responses (Luco and Cornell 2007, Zhong *et al.* 2016).

Efficiency of the IM means that after selecting the records based on this IM and structural analysis, structural responses have small dispersion. On the other hand, a sufficient IM can predict the conditional distribution of demand parameter for the given value of IM independent of other features of the earthquake record (such as the magnitude, source-to-site distance and significant duration).

Spectral acceleration at the period of vibration in first mode of the structure ($S_a(T_1)$) is a prevalent IM as it is related to the structural response quantities and also to other features of the earthquake record. Also, hazard curve for this IM is readily determined in probabilistic seismic hazard analysis. These facts made this IM an accepted quantity used for earthquake record selection. However, demand parameters in multi-degree-of-freedom inelastic structures obtained by the response history analysis under some records with equal values of $S_a(T_1)$ may significantly be scattered (Katsanos *et al.* 2010). Also, it is demonstrated in some studies that $S_a(T_1)$ is not essentially efficient or sufficient in prediction of response quantities in tall buildings or structures sited in near field regions (Alavi and Krawinkler 2000). To overcome this limitation, some

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researchers tried to modify this IM or propose a new one with better performance (Tothong and Luco 2007, Pejovic *et al.* 2017, Baker and Cornell 2006).

To enhance efficiency and sufficiency of IM, Baker and Cornell (2006) proposed a vector valued IM consisting of $S_a(T_1)$ and ε; ε is the normalized residual and is defined as the difference of spectral values in response spectrum of the record and the corresponding median value divided by the standard deviation of the spectral parameter. The median value and standard deviation of the spectral parameter are determined by means of empirical ground motion prediction equations. The ε parameter is an indicator of spectral shape such that records with positive ε value at a given period (i.e., the records whose spectral response at this period is greater than the median value obtained by the ground motion prediction equation) have spectral peak at this period and on the other hand, those with negative ε values have spectral valley at this period. This point is the core basis of efficiency of the ε parameter in prediction of seismic responses of multi-degree-of-freedom inelastic building structures. In fact, given the spectral response at the first mode of such structure, it is required to have more information about the spectral values at other periods and the ε parameter meets this requirement implicitly.

Baker and Cornell (2006) in assessing the role of the ε parameter in the record selection procedure, proposed a novel approach for determination of the target spectrum. This target spectrum which considers the magnitude, distance and ε values that result in the given value of the $S_a(T_1)$, is called the conditional mean spectrum (CMS). In present study, the CMS has been used in the record selection procedure. Before detailed description of this method, its pros and cons have been reviewed in previous works.

Baker and Cornell (2006) in studying the efficiency of the CMS and the common practice for record selection in prediction of the peak inter-story drift responses have detected that the spectral shape have close relation with structural responses and the *M*, *R* and epsilon parameters are indirect indicators of the spectral shape. Hence, any recorded strong ground motion can be used in the response history analysis without any limitation on its *M*, *R* and epsilon values, but the spectral shape of the motion should be compatible with that of the CMS. In this way, the number of qualified strong ground motion records increases in the response history analysis.

It is demonstrated that for probabilistic analysis and design of structures, the CMS is more reliable than the uniform hazard spectrum (UHS) in some cases (Baker and Cornell 2006); this is due to the fact that the UHS is the envelope of spectral responses of all possible rupture scenarios in the site and it is not associated with a certain earthquake scenario. Consequently, seismic analysis of structures based on the UHS may result in conservative responses while this deficiency does not matter in CMS.

Even though previous researches have demonstrated the significant correlation of the spectral shape and structural responses and the ability of the CMS to account for the spectral shape in the record selection procedure, there may be some features of earthquake records that may have major effects on the structural demands while these features cannot be captured by the spectral shape (Bradley 2010). In the present paper, this fact has been assessed in detail. Speaking precisely, the sufficiency of the spectral shape in the record selection procedure has been studied quantitatively. In this way, probabilistic seismic hazard analysis is applied for an assumed site to determine the CMS. Then four structural models of reinforced concrete frames with various numbers of stories have been selected from the previous studies. These structural models have inelastic response characteristics with the strength and stiffness deterioration applied in the concentrated plasticity elements (plastic hinges) in beam-to-column joints. In the next step, a forty-record-set of earthquake records have been selected for each structure within a comprehensive database of records. The selection procedure is formulated as an optimization process so that the mean spectrum of the selected records has the closest match with the CMS.

After the response history analysis of the nonlinear structural models, correlation of the structural responses with the duration of the strong ground motion records have been investigated by statistical tools. Finally, sufficiency of the spectral shape in prediction of peak and cumulative structural responses has been revealed.

2. Conditional Mean Spectrum (CMS)

To determine the CMS, the value of $S_a(T_1)$ should be calculated by the probabilistic seismic hazard analysis in the given hazard level. Next, by means of the seismic hazard deaggregation, the dominant magnitude, distance and epsilon bin ($\bar{M}$, $\bar{R}$ and $\bar{\varepsilon}(T_1)$) is determined. Given the $\bar{\varepsilon}(T_1)$, one can calculate the empirical conditional distribution of the spectral acceleration at all other periods using the empirical correlation coefficient of the spectral responses. Hence, the mean and standard deviation of spectral acceleration can be calculated by the below equation

$$\mu_{\ln S_a(T_2)|\ln S_a(T_1)=\ln S_a^*(T_1)} = \mu_{\ln S_a(T_2)}(\bar{M},\bar{R}) + \sigma_{\ln S_a(T_2)}(\bar{M})\,\rho_{\ln S_a(T_1),\ln S_a(T_2)}\,\bar{\varepsilon}(T_1) \quad (1)$$

$$\sigma_{ln\,S_a(T_2)|ln\,S_a(T_1)=ln\,S_a^*(T_1)} = \sigma_{ln\,S_a(T_2)}(\bar{M})\sqrt{1-\rho^2_{ln\,S_a(T_1),ln\,S_a(T_2)}} \quad (2)$$

In the above equation, as mentioned earlier, $\bar{M},\bar{R}$ and $\bar{\varepsilon}(T_1)$ are obtained by the seismic hazard deaggregation conditional on $S_a(T_1) = S_a^*(T_1)$. The $\mu_{\ln S_a(T_2)}(\bar{M},\bar{R})$ and $\sigma_{\ln S_a(T_2)}(\bar{M})$ respectively represent the mean and standard deviation of $\ln S_a(T_2)$ which are obtained by empirical ground motion prediction equations. The $\rho_{ln\,S_a(T_1),ln\,S_a(T_2)}$ represents the correlation coefficient of spectral acceleration in periods T_1 and T_2. This coefficient can be determined by empirical relations such as one proposed by Baker and Jayaram (2008) as

$$\begin{array}{lll} \text{if } & T_2 < 0.109 & \rho_{ln\,S_a(T_1),ln\,S_a(T_2)} = C_2 \\ \text{else if } & T_1 > 0.109 & \rho_{ln\,S_a(T_1),ln\,S_a(T_2)} = C_1 \\ \text{else if } & T_2 < 0.2 & \rho_{ln\,S_a(T_1),ln\,S_a(T_2)} = \min(C_2, C_4) \\ \text{else} & & \rho_{ln\,S_a(T_1),ln\,S_a(T_2)} = C_4 \end{array} \quad (3)$$

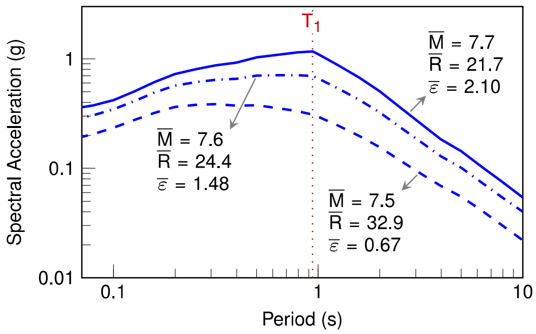

Fig. 1 The CMS for the studied site conditional on $S_a(T_1 = 0.939s)$ values of 2, 10 and 50% of exceedance probability in 50 years. Ground motion prediction equation of Campbell and Bozorgnia (2008) and the correlation model of the Baker and Jayaram (2008) are used in derivation of the CMS

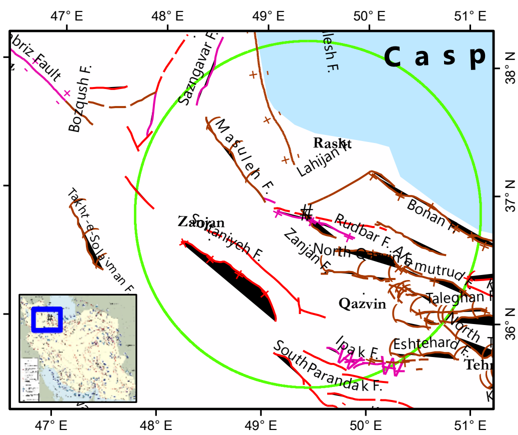

Fig. 2 Active faults circumferencing the studied site within a circular area with a radius of 150 km. The active faults are re-plotted from Hessami *et al.* (2003)

where

$$C_1 = 1 - cos\left(\frac{\pi}{2} - 0.366\ ln\left(\frac{T_{max}}{max(T_{min}, 0.109)}\right)\right)$$

$$C_2 = \begin{cases} 1 - 0.105\left(1 - \frac{1}{1+e^{100T_{max}-5}}\right)\left(\frac{T_{max}-T_{min}}{T_{max}-0.0099}\right) & \text{if } T_{max} < 0.2 \\ 0 & \text{otherwise} \end{cases}$$

$$C_3 = \begin{cases} C_2 & \text{if } T_{max} < 0.109 \\ C_1 & \text{otherwise} \end{cases}$$

$$C_4 = C_1 + 0.5\left(\sqrt{C_3} - C_3\right)\left(1 + \cos\left(\frac{\pi\, T_{min}}{0.109}\right)\right).$$

Fig. 1 shows the CMS for the studied site conditioned on $S_a(T_1 = 0.939s)$ values of 2, 10 and 50% of exceedance probability in 50 years. The mean magnitude, distance and ε values in each hazard level, derived by seismic hazard deaggregation, are also noted in this figure.

3. Probabilistic seismic hazard analysis

To study the record selection procedure, an arbitrary site has been chosen in northern Iran near the Rudbar city. This choice is due to the high seismic risk of this region and the past destructive earthquake having struck the area. As depicted in Fig. 2, some nearby active faults in this site are the Rudbar, Northern Qazavin and Talesh faults.

The first step in traditional probabilistic seismic hazard assessment is the recognition of active seismic sources in the studied region. These sources can be modeled as point, line or area sources. In present study, line sources being representative of active faults have been applied. To determine these sources, data obtained by various researches reflected in Hessami *et al*. (2003) has been used. Fig. 2 shows the active seismic sources in the studied area. In this figure, the region indicated by green circle with a radius of 150 km around the studied site, shows the considered range of active seismic sources for the seismic hazard analysis.

After delineation of seismic sources, next step in seismic hazard assessment is the collection of historical and instrumental earthquake events in the studied area. Events before the 1900 are considered as the historical part of the earthquake catalogue and events after 1900 are considered as instrumental one. Historical events are extracted from Ambraseys and Melville (1982), Berberian (1994) which studied the seismicity of Iranian plateau in detail. Instrumental events after 1900 are recorded by various local and global institutions and research centers with different range of seismic network coverage. Historical and instrumental seismic events are essentially associated with uncertainties in location and magnitude. In present study, after collecting earthquake catalogue from different references (ISC 2016, IRSC 2016), it is tried to determine epicenter and magnitude of the events by the lowest uncertainty according to the coverage of the seismic network of the recording agency.

To homogenize the earthquake catalogue, magnitude of all events is declared as moment magnitude. Lower bound of events' magnitude is determined as 4.0 by assessment of the catalogue completeness with the maximum curvature procedure. Upper bound of events' magnitude is also determined as 7.9 by historical data and empirical relations.

To calculate the seismicity parameters of the sources, it should be assured that the events of the catalogue are mutually independent. To satisfy this assumption of poisonian random processes, time and location window method (Gardner and Knopoff 1974) is applied to decluster the events of the catalogue. Subsequently, seismicity parameters are calculated by consideration of events' uncertainty based on the method proposed by Kijko and Sellevoll (1992).

Empirical ground motion prediction equations reflect the attenuation of strong ground motion parameters such as peak horizontal acceleration or peak vertical acceleration as a function of seismic event's features such as magnitude and epicentre. These equations are essentially based on the recorded seismic events and speaking precisely, they are site dependent. Hence, selection of appropriate equation for probabilistic seismic hazard assessment has an important role in reliability of the results. In the present study, to be able to generalize the findings, the attenuation relation of Campbell and Bozorgnia (2008) has been used probabilistic seismic hazard assessment. This relation is worldwide and some of Iranian strong motion data have been used in their original regression database.

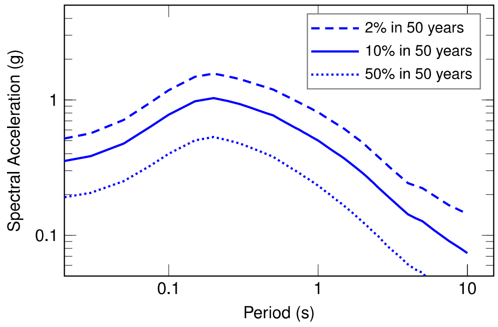

Fig. 3 Uniform hazard spectrum with 2%, 10% and 50% exceedance probability in 50 years (corresponding to 2475-, 475- and 72-year return period respectively) in the studied site

After designation of the attenuation relation, probabilistic seismic hazard analysis is performed for the assumed stiff soil site condition with $V_{s30} = 285\ \mathrm{m/s}$ (ASCE 2010) in three hazard levels with 2, 10 and 50% exceedance probability in 50 years (corresponding to 2475-, 475- and 72-year return period respectively). The results are shown as uniform hazard spectrum in Fig. 3.

4. Optimal record selection procedure

At the present study, record selection and scaling procedure is formulated as an optimization problem by means of the metaheuristic harmony search (HS) algorithm. In this algorithm, searching for the optimal solution of an engineering problem is simulated as the best harmony search process by the musicians (Lee and Geem 2005). In this way, initially a series of solution vectors (namely harmony memory) is randomly created with the possible values of the variables. Next, in a repetitive process, a new solution vector (namely new improvisation) is developed with combination of the values stored in the harmony memory and all possible values for each component of the solution vector. If this vector is qualified as a "good solution", it will be saved in the harmony memory. Hence, the chance of finding the best solution increases in successive iterations. The improvisation process continues till reaching a predefined fitness level for the best solution or a predetermined number of iterations.

To avoid deviation from the main subject of the present study, more description on the HS algorithm and its application in the record selection procedure can be found in related researches such as Shahrouzi and Sazjini (2012). Here, only the main aspect of this process is clarified briefly.

In the present study, the harmony search algorithm optimizes the selection and scaling of the records to find the best match of the mean response spectrum of the selected records and the conditional mean spectrum. The records are scaled such that their spectral acceleration responses (per 5% damping ratio) in the period range of $[0.2T_1, 1.5T_1]$ do not fall below the 90% of the corresponding values in the conditional mean spectrum; T_1 is the period of the first natural mode of the structure. The records are selected from

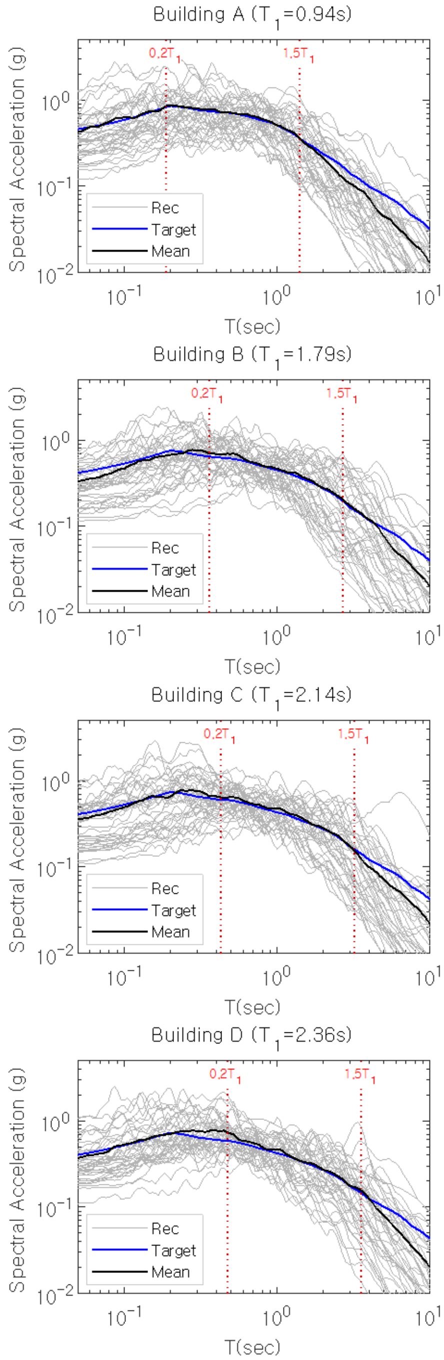

Fig. 4 Mean response spectrum of the selected record sets for the quadruple structural models. Vertical dashed heavy gray lines indicate the period range of matching interval

a set with more than 3000 records of earthquake events with moment magnitude ranging from 4.0 to 8.5 adopted from the PEER NGA records (PEER 2010). To quantify the similarity of the mean response spectrum of the selected records and the conditional mean spectrum, the object function of the optimization problem is defined as following

$$Object\ Function = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\frac{SA_{wm}(T_j) - SA_{target}(T_j)}{SA_{target}(T_j)}\right)^2} \times 100 \tag{4}$$

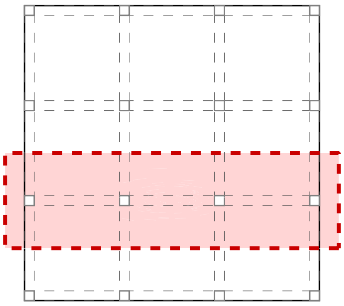

Fig. 5 Typical floor plan of the studied structural models adopted from Haselton and Deierlein (2007). The dashed red box shows the moment-resisting middle frame that its seismic responses are discussed in the present study

Table 1 General specifications of the structural models

Parameter	Value
Seismic design category	*D* (based on IBC (2003))
Bay width	6.1 m (20 ft)
Ground floor height	4.57 m (15 ft)
Other floors' height	3.96 m (13 ft)

that $SA_{wm}(T_j)$ is the weighted average spectral acceleration at the period of T_j, $SA_{target}(T_j)$ is the spectral acceleration in the target spectrum (i.e. conditional mean spectrum) at the period of T_j, and n is the number of discontinuous periods considered in the matching period interval. For each one of the quadruple structural models namely building A, B, C and D, 40 records are selected and scaled by this algorithm. Fig. 4 shows the mean response spectrum of the selected records along with the response spectrum of the individual selected records and the conditional mean spectrum. In each plot, conditional mean spectrum represents the values of the spectral acceleration conditioned on the $S_a(T_1)$ with 10% exceedance probability in 50 years. The details of the structural models are explained in the next section. The remarkable similarity of the mean response spectrum of the selected records and the target spectrum reflects the potential advantage of the harmony search optimization algorithm.

5. Structural models

The focus of the structural analysis in the present study, is not essentially the assessment of the responses of a certain category of buildings but is the evaluation of the structural behavior of common structural models. In such way, the results can be generalized for similar structures. For this purpose, four structural models are adopted from the research of Haselton and Deierlein (2007). These models are special moment resisting reinforced concrete 2D frames designed based on the provisions of ACI 318-05 (2005). Fig. 5 shows the typical plan of the studied three-bay models. The number of stories varies in the models and is 4, 8, 12 and 20 in the structural models A, B, C and D respectively. These structural models are represented by the ID1008, ID1012, ID1014 and ID1021 respectively in

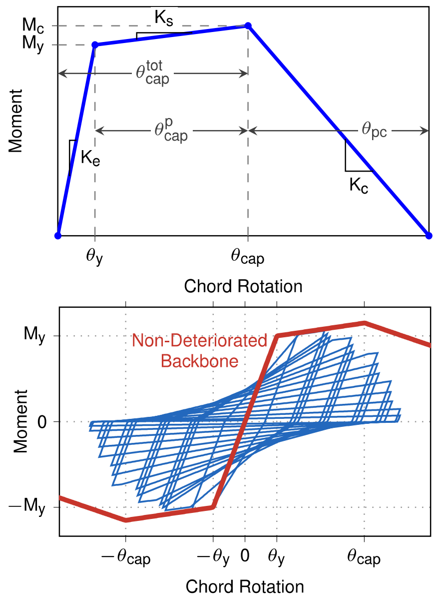

Fig. 6 Nonlinear moment-rotation behavior incorporating the strength and stiffness deterioration in Ibarra-Krawinkler model under monotonic (top) and cyclic loading (bottom)

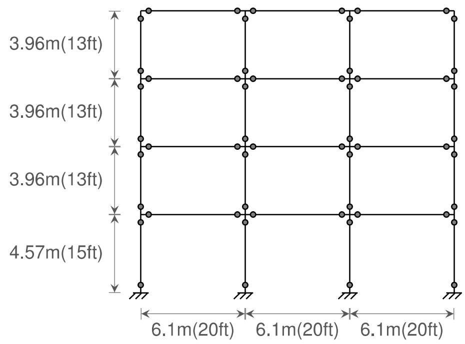

Fig. 7 Elevation view of the building model A with four story and three bays. The filled circles in both ends of beam and column elements indicate the potential plastic hinges

Haselton and Deierlein (2007). Some general specifications of these models are presented in Table 1.

In the studied structural models, to simulate the inelastic behavior, concentrated plasticity models (plastic hinges in both ends of beams and/or columns) have been adopted and the beam and column elements are assumed to be linear elastic. Nonlinear characteristics of plastic hinge material follow the model proposed by Ibarra *et al.* (2005) which incorporates strength degradation and stiffness deterioration. Fig. 6 shows a typical monotonic and cyclic nonlinear moment-rotation curve for the nonlinear hinge models. Fig. 7 shows the elevation of the structural model A with four stories and three bays along with the potential plastic hinges. Modeling and analysis of the structures is performed by the OpenSEES software (OpenSEES 2017).

6. Structural analysis result and discussion

Aforementioned structural models have been analyzed under the records selected based on the spectral shape IM to

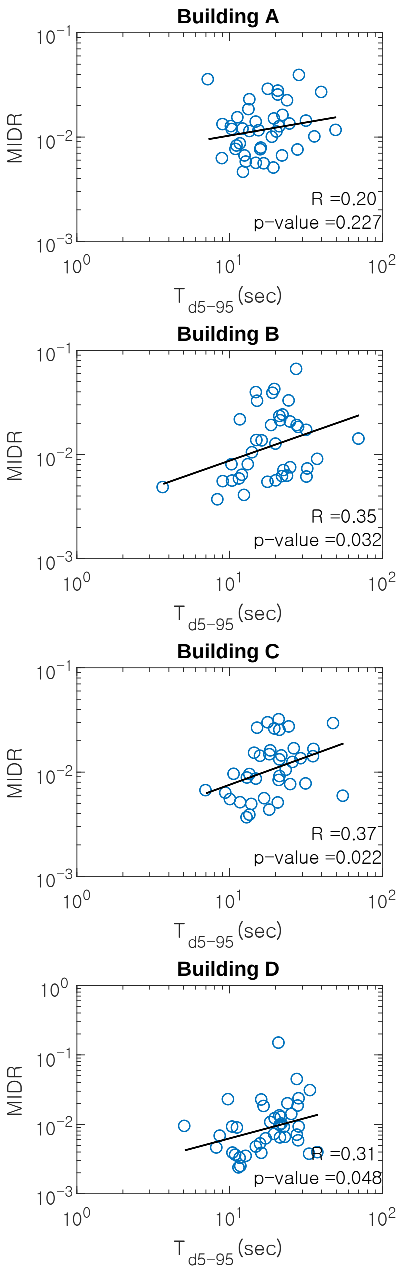

Fig. 8 Maximum inter-story drift ratio (MIDR) versus the strong ground motion duration in structural models

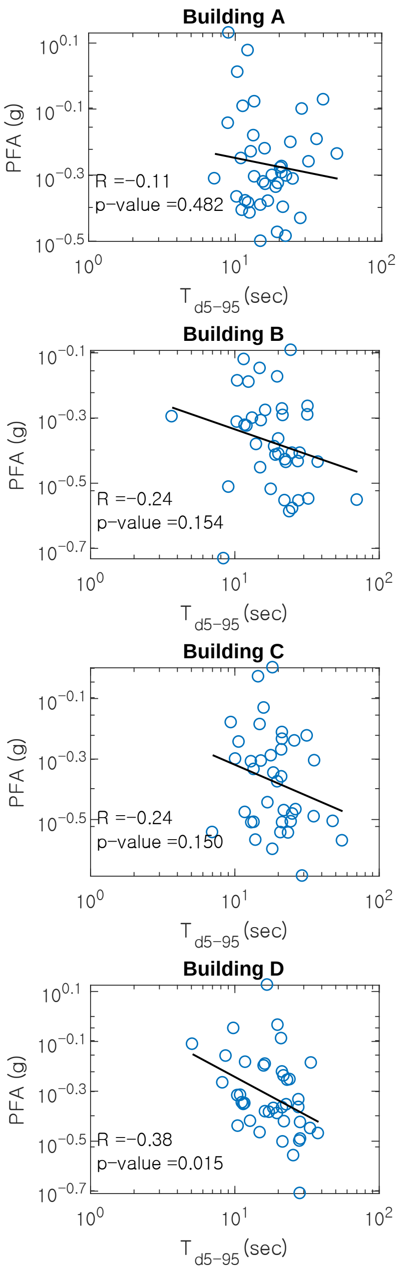

Fig. 9 Peak floor acceleration (PFA) versus the strong ground motion duration in structural models

assess the sufficiency of this IM in prediction of the instantaneous and cumulative structural responses or demand parameters. In this way, reminding the concept of sufficiency of the IM, the hypothesis of “the spectral shape could sufficiently predict the structural responses” can be explored more in detail. The results are presented and discussed in the current section. The secondary IM selected to assess the sufficiency of the primary IM, is the significant duration (T_{d5-95}, as defined by Trifunac and Brady 1975).

The first demand parameter discussed here is the maximum inter-story drift ratio (MIDR) which is a good indicator of the overall performance of the structure. Fig. 8 shows the variation of the MIDR values versus the significant duration of the strong ground motion records. As mentioned in previous researches (Bradley 2010), in most cases, the relation of the structural response parameters with the strong ground motion parameters is a log-log relation; hence, here, a logarithmic scale has been used for the horizontal and vertical axes in the plots. In each plot, along with the scatter data points, the linear trend of the data resulted from curve fitting is plotted and the correlation coefficient and the p-value for the linear regression are reported. Based on the statistical principles, the p-value less than 0.05 indicates a significant correlation between the response parameter and the intensity measure. As inferred from the Fig. 8, in all structural models except the low-rise building A, the MIDR has a relevant correlation with T_{d5-95} intensity measure. Also, the p-values are less than 0.05 for all building except the building A. These facts

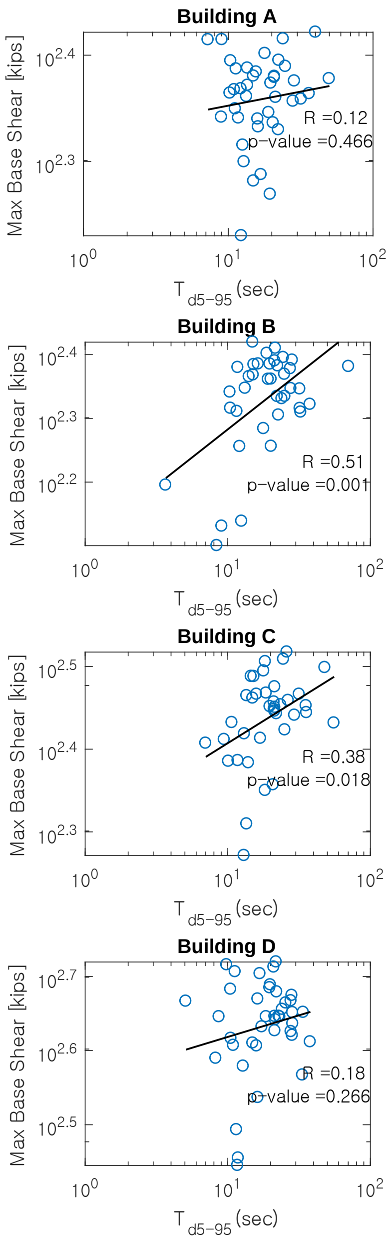

Fig. 10 Maximum base shear versus the strong ground motion duration in structural models

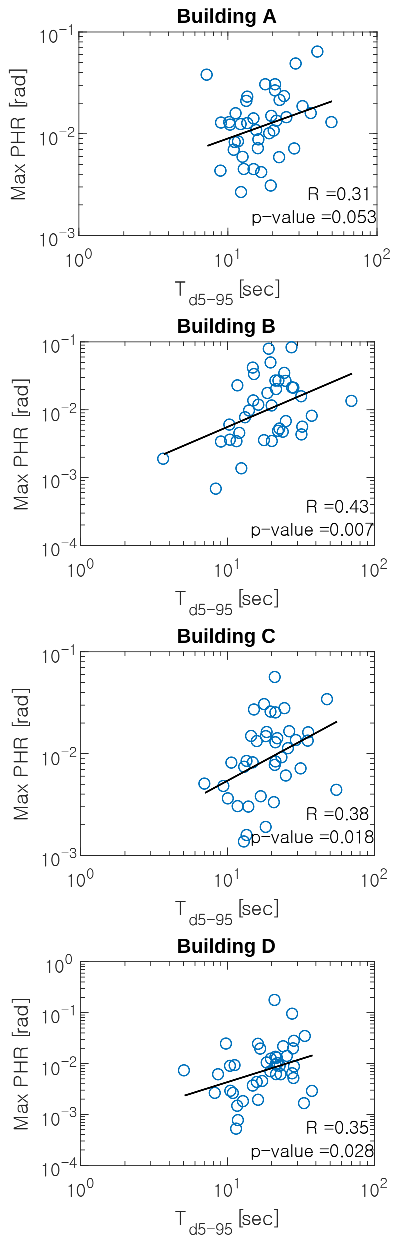

Fig. 11 Maximum plastic hinge rotation versus the strong ground motion duration in structural models

demonstrate the improper sufficiency of the record selection method based on the CMS.

Next demand parameter assessed to explore the sufficiency of the spectral shape, is the peak floor acceleration (PFA) which generally has not reported as important as MIDR in previous researches in describing the global performance and damage state of the structure. Fig. 9 shows the PFA values versus the significant duration of the records for different structural models. As can be seen, according to the low absolute values of the correlation coefficient and the high p-values reported for all structural models except the building *D*, one can claim that this demand parameter does not really correlate with the duration. This means that the spectral shape is more sufficient than the significant duration in predicting the peak floor acceleration demand.

Maximum base shear is the next global demand parameter assessed in this research. Fig. 10 illustrates the variation of the maximum base shear versus the significant duration of the records in the various building models. As inferred from this plots, this response parameter has scattered distribution so that no systematic order can be found about its correlation with the significant duration. For model building *A* and *D*, maximum base shear and significant duration has a relatively low correlation coefficient and a high *p*-value while for building *B* and *C*, the response parameter and the IM has a high value of correlation coefficient and a low *p*-value. However, data scatter in for all building except the model *C* reassure the unsystematic correlation of the demand parameter with the significant duration. This fact accentuates the sufficiency of the spectral shape in prediction of maximum base shear of

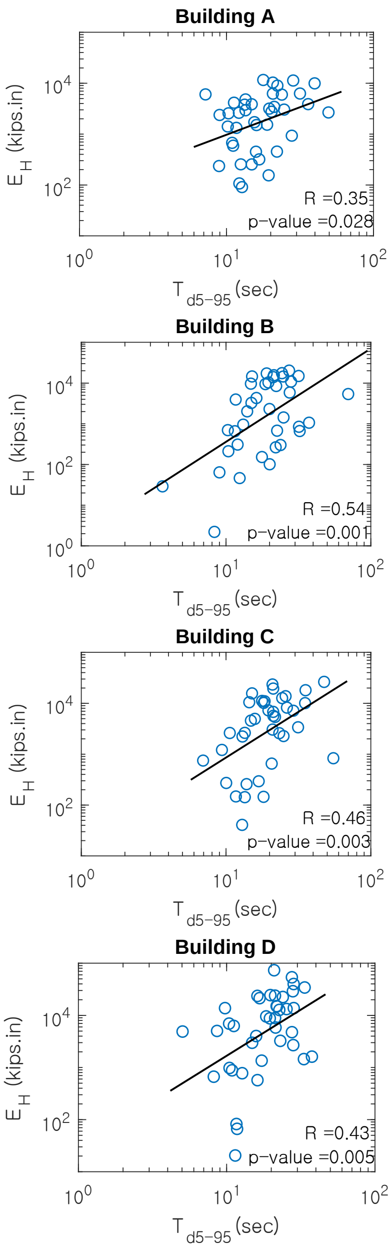

Fig. 12 Dissipated hysteresis energy versus the strong ground motion duration in structural models

the structure.

Fig. 11 demonstrates the variation of the maximum plastic hinge rotation (MPHR) versus the significant duration. The MPHR despite aforementioned response parameter is a local demand parameter which relatively describes cumulative effect of the earthquake load and the damage localization in structural elements. As can be seen in Fig. 11, in all structural models, maximum plastic hinge rotation shows a significant correlation with the strong ground motion duration of the input records. Generally, plastic deformations are sensitive to duration of the seismic excitation while record selection procedure based on the spectral shape does not explicitly account for such properties of the selected strong ground motion records.

Proper performance assessment of the structure may not be possible without exploring the cumulative and energy-based demand parameters (Gupta and Krawinkler 1999). To study the sufficiency of the spectral shape in prediction of such demand parameters, Fig. 12 illustrates the dissipated hysteresis energy in plastic hinges versus the significant duration of the strong ground motion records. As obvious in this figure, among the studied demand parameters in the current study, hysteresis energy shows the most systematic correlation with the significant duration of the records. For all model buildings, data scatter resembles a statistical regression between the demand and the duration of the records. High values of the correlation coefficient and low p-values confirm this fact in quantitative manner. No energy dissipating devices have been used in the structural models, however, if such equipment is utilized to enhance seismic performance of the structure, energy dissipation and the significant duration of the strong motion in the site, should be accounted for in record selection procedure.

7. Conclusions

The present study sets out to explore the sufficiency of the spectral shape intensity measure (speaking precisely, record selection based on the conditional mean spectrum) in prediction of the maximum value and cumulative structural demand parameters. In this way, four special moment resisting RC frames are analyzed under the records selected based on the spectral shape. The record selection is done by the aid of the harmony search algorithm, a metaheuristic optimization algorithm. Next, various structural responses are studied to assess the sufficiency of the spectral shape in prediction of the demand parameters. Findings can be summarized as follows:

• Utilization of the Harmony Search optimization algorithm for selection of limited number of strong ground motion records within a vast number of available ones, resulted in the remarkable analogy of the mean spectrum of the selected records with the target conditional mean spectrum with a slight computational effort.

• The spectral shape intensity measure (as depicted by the conditional mean spectrum) could not reflect all contents of the seismic excitation and is insufficient in predicting some structural demand specially responses associated with cumulative characteristics of the strong ground motion records.

• Previous studies implied the correlation of the structural responses with the significant duration of the earthquake records. So, the significant duration feature of the strong ground motion records is considered as secondary intensity measure and its correlation with the structural responses is examined to explore the sufficiency of the spectral shape in prediction of structural demands.

• Structural responses such as the inter-story drift ratio, plastic hinge rotation and the dissipated hysteresis energy significantly correlate with the significant duration of the earthquake records. This fact accentuates the importance of the duration of the seismic excitation which should be more discussed in future researches.

• Deficiency of the spectral shape in prediction of the structural responses associated with cumulative characteristics of the strong ground motion records is obvious in the studied models. Consequently, for structural systems with special elements such as energy-dissipation devices, this issue may be more crucial and indicates the requirement of more advanced record selection procedures which account for more intensity measures along with the spectral shape.

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