A simple spectral shape proxy for far-source sites

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Abstract

This paper presents a spectral shape proxy stems from geometric mean consisting of spectral ordinates at the structure's first mode period to that of much larger period. The proposed model denoted by α_{geo} is normalized by spectral ordinate at $2T_1$ for reducing dispersion and scaling level problem. Another arithmetic mean model, α_{Ar}, is also developed to be used for comparison purpose of the geometric mean model. The 26 RC-SMF structures and 78 far-field ground motions are selected to evaluate the performance of the model as a case study. IDA method is used to calculate collapse capacities of the selected structures. Series of linear relationship are developed among the model values and corresponding structures' collapse capacities demonstrating strong coefficient of determinations (R^2). Performances of the presented models "efficiency" and "sufficiency" aspects are shown to be as strong as those of recently proposed predictor, $SaRatio$, while benefits from simplicity. Utilization of the proposed model are: as an element of vector valued IM, as a collapse capacity predictor for structures at far-source sites, collapse margin ratio for collapse safety evaluation of structures.

1. Introduction

It is well-understood that the structural vibration modes, in particular the structures' first mode period (T_1), elongate during experiencing nonlinear response under large intensity strong motion [1], [2]. Furthermore, the stiffness loss of structure experiencing such nonlinear response is continued until its collapse capacity is achieved. Collapse of a structure implies that the structural system is no longer capable to maintain its gravity load-carrying capacity in the presence of seismic load [3]. Meanwhile, the structures' lengthened first mode period, termed "effective period", get a value much longer than of the fundamental period. Different elongated values of period, in terms of a factor of the first mode period (T_1), have been reported in literatures, examples are: a factor of 1.50-1.70 [4], 2.0-2.5 [5], [6].

For the sake of quantifying strong structure's collapse capacity predictor, it is important to properly identify what features of a ground motion, given a structure, make

it effectively damaging [7]. In this context, several models of collapse capacity indicators have been proposed by investigators during the last decade. Examples are those related to structural vibration modes and elongated periods: Cordova et al. [8], Baker and Cornell [9], and Bojórquez and Iervolino [10], and Eads et al. [11].

In this article, two types of collapse capacity indicators for far-source sites, denoted by *Alpha,* called α_{Ar} and α_{geo} are proposed where the implicit information of spectral shape of a given a ground motion are incorporated. Influence of spectral shape on the collapse capacity of a given ground motion and structure are discussed. The models' performances i.e. efficiency and sufficiency aspects, are evaluated and compared with those of the currently used models.

2. Background

2.1 Importance of problem

It is well-known that as structures experience more nonlinearity, their stiffness get weaker causing the influence of structural vibration modes on inelastic displacement of structure become more destructive (e.g. [11]).

Accounting for ground motion spectral shape characteristics in engineering problems that deals with structural collapse capacity is of high importance. Examples are safety collapse evaluation via collapse margin ratio (CMR), seismic collapse risk assessment of buildings [12], and identifying the ground motion intensity measure (IM).

In general, the representative models of spectral shape found in literature, either in the form of a single parameter, vector valued, or multi-parameter models used to evaluate (explicitly or implicitly) structures' nonlinear response (or collapse capacity) may be categorized into three different groups.

2.2. Epsilon (ε) model

Those models by which epsilon (ε) is introduced as the indirect (or direct) representative of spectral shape [13], [14], [15]. Epsilon is defined as the number of standard deviations by which an observed logarithmic spectral acceleration differs from the mean logarithmic spectral acceleration of a ground-motion prediction (attenuation) equation [15]. Examples are; Goulet et al. [14] that showed the mean collapse safety of a modern 4-story reinforced concrete (RC) frame building (with $T_1 = 1.0s$) subjected to a ground motion set with $\varepsilon(T_1 = 1) = 1.4$ increased by a factor of 1.3-1.7 times

larger than that of a mean ε of 0.4. Similar conclusion has been conducted by Haselton and Baker [13]. Relationships between the logarithmic form of collapse capacity and ε, for far-field sites, have been shown to be associated with correlation coefficient (ρ) values on the order of 0.4 to 0.6, and correlation determination (R^2) from 0.2 to 0.4 [16]. Therefore, ε fails to be interpreted as a direct measure of a specific ground motion spectral shape but a proxy to it as stated by Eads [16]. In conclusion, the epsilon-based intensity measure models suffer from explicitly exploring the influence of spectral shape on nonlinear response (in particular collapse capacity).

2.3. Models with contribution of periods longer than T_1

Those models in which spectral shape is identified by information of spectral ordinates at longer periods than T_1. Examples of these types are as follows,

Cordova et al. [8] defined a parameter as the ratio of spectral acceleration at an elongated period (they recommended $2T_1$) to $Sa(T_1)$ termed R_{Sa}. They found a better estimation of peak structural response than $Sa(T_1)$ alone. A spectral shape predictor model called R_{T_1,T_2} was proposed by Baker and Cornell [9]. They let T_2 vary and choose the value that optimally predicts the response of the structure, concluding that the choice of T_2 is seen to be effective for predicting the response of structures from moderate to high levels of nonlinearity, subjected to ordinary ground motions. The models of this type explore the significant influence of spectral ordinates on the nonlinear response of structures at periods longer than that of the first mode period.

2.4. Models with contribution of periods shorter/longer than T_1

Those models by which spectral ordinates at T_1 are combined with those at shorter/longer periods as the representative of the spectral shape. Examples are as follows,

Bojórquez and Iervolino [10] presented spectral shape called N_P that is defined as the ratio of the average (in geometric mean form) value of the spectral accelerations over a period range of T_1 to $2T_1$, showing that use of N_P parameter significantly improved the prediction of the maximum interstory drift ratio. Eads et al. [11] proposed a spectral shape model incorporating the geometric mean of the spectral acceleration values between the periods of $(a \cdot T_1)$ and $(b \cdot T_1)$ shown by Eq. (1) expressed as:

$$SaRatio = \frac{Sa(T_1)}{Sa_{avg}(T_1 \cdot [a,b])} \qquad (1)$$

Where, "a" and "b" are non-negative constants such that $a \leq b$, and $Sa_{avg}(T_1.[a,b])$ is the geometric mean form of spectral acceleration values between the periods $a.T_1$ to $b.T_1$ [16]. She found that $SaRatio$ is much better correlated with the collapse capacity than when using N_p and ε [11].

3. Objectives and motivation

A limited number of collapse capacity predictor models accounting for ground motions' spectral shape are found in literature; e.g. $SaRatio$ [11] and N_p [10] which are certainly useful. This study attempts to present a simple two parametric spectral shape proxies with strong performances including explicit information of spectral ordinates at the first mode period (T_1) and at longer period ($T_{\text{effective}}$). The major objectives of this study are as follows,

- To demonstrate the geometric mean spectral shape characteristic influence on quantifying the structures' collapse capacity.
- To show that the performance of geometric mean for spectral shape proxy is similar to those of the arithmetic mean form.
- To evaluate the performance of presented model i.e. "efficiency" and "sufficiency" by comparing with those of currently used model e.g. $SaRatio$ [11].

It is important to note that the conclusions drawn later should be interpreted in the context of the assumptions made as follows,

- The "efficiency" and "sufficiency" of the proposed spectral shape-based models are demonstrated through a case study including 26 reinforced concrete (RC) special moment frame (SMF) buildings subjected to the 78 far-field ground motions [17].
- Two items should be strongly pointed out; a) near-source ground motion problems i.e. directivity and fling step effects and b) contributions of spectral ordinates at periods shorter than T_1 to presented spectral shape proxy are not considered in this study. Extending the presented model to other types of structures, other resisting systems and materials, need much work to be done.

4. Basic concept of spectral shape

4.1. Spectral shape definition

It is quite postulated that structural responses such as nonlinear displacement at collapse capacity are strongly influenced by ground motion characteristics and dynamic properties of structure. These two factors are simply visible in a ground motion linear response spectrum for a SDOF system. In other words, spectral ordinates in a response spectrum reflect the contribution of ground motion amplitudes and corresponding frequency content on their values in a linear behaviour of a SDOF system. Furthermore, it is quite understood that MDOF systems are associated with several vibration periods (shorter and longer than the first mode period) which are elongated during nonlinear response of structures. And, it is the spectral ordinates corresponding to extended periods longer and smaller than the first mode period (T_1), that predominantly contribute the nonlinear response such as structural collapse circumstance. The shape of spectral ordinates' envelope of a given structure at periods shorter and longer than the first mode period associated with linear and nonlinear responses is termed "spectral shape".

4.2. Influence of spectral shape on collapse capacity

In order to demonstrate influence of spectral shape on the collapse capacity, given a structure, which traditionally is represented by $Sa_{col}(T_1)$, an 8-story structure with the first mode period of $1.80s$ is selected and its collapse capacity against two ground motions are calculated using IDA method (see Fig.1). As seen, while the spectral ordinates of the two ground motions at T_1 are similar ($0.31g$) their collapse capacities, $Sa_{col}(T_1)$, are different ($2.13g$ and $1.00g$) due to the difference in their spectral shape effects.
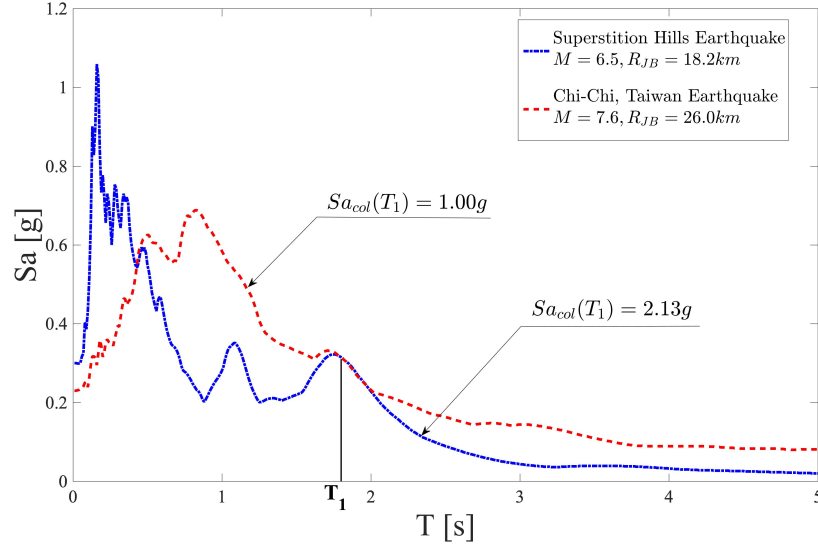
Figure 1. Unscaled response spectra with identical $Sa(T_1 = 1.80) = 0.31g$ for 8-story building.

Consequently, spectral shape is an important factor and should be incorporated into any parameter (or model) which acts as a ground motion spectral shape proxy model (e.g. [11]). In other words, spectral ordinates whose energy exhibit in ground motions and predominantly affect the structural nonlinear response, should be incorporated into proxy model. Having said, in the absence of exact extended period information and for the sake of simplicity, the predominant periods longer than the first mode period (T_{eff}) up to $2T_1$ are incorporated into the proposed spectral shape proxy. However, it is argued that spectral ordinates at periods less than T_1 (higher mode contribution) improve collapse prediction [16] particularly in irregular structures, which are not considered in this study.

5. Proposed spectral shape model ($Alpha$)

In this article attempt is focussed on the mean value of spectral ordinates, started at the first mode period $Sa(T_1)$ up to that at two times the first mode period $Sa(2T_1)$, as extended period. This period range ($T_1 \sim 2T_1$) has also been recommended by Cordova et al. [8] and Baker and Cornell [9] explaining that it is common to take into account the spectral ordinates at two points, T_1 and the extended period $2T_1$ on the recording response spectrum in intensity measure model.

The proposed spectral shape proxy stemmed from the mean spectral ordinate presented by two spectral ordinates at T_1 and $2T_1$ in geometric form $\sqrt{Sa(T_1).Sa(2T_1)}$

normalized by $Sa(2T_1)$ for the sake of reducing data sparseness problem and independency from scaling levels of the records expressed as:

$$\alpha_{geo} = \frac{\sqrt{Sa(T_1).Sa(2T_1)}}{Sa(2T_1)} = \sqrt{\frac{Sa(T_1)}{Sa(2T_1)}} \qquad (2)$$

However, as the arithmetic mean form is very similar to geometric mean but sensitive to extreme spectral ordinates (i.e., very high or very low) [16] for the sake of comparison, this form of spectral shape indicator (α_{Ar}) is also developed and used in this study.

$$\alpha_{Ar} = \frac{\frac{1}{2}[Sa(T_1) + Sa(2T_1)]}{Sa(2T_1)} \qquad (3)$$

It is interesting to be mentioned that, the second model is mathematically similar to that of Eads [11] (see Eq. (1)). Assuming special values of $a = 1$ and $b = 2$ (corresponding to periods at T_1 and $2T_1$) in $Sa_{avg}[T_1.(a,b)]$, which can be shown mathematically that:

$$\text{geometric mean}[Sa(T_1), Sa(2T_1)] \approx Sa_{avg}[T_1.(1,2)] \qquad (4a)$$

or quantitatively,

$$\sqrt{Sa(T_1).Sa(2T_1)} \approx Sa_{avg}[T_1.(1,2)] \qquad (4b)$$

This is simply shown by multiplying both sides of relation (4) to $\sqrt{Sa(T_1).Sa(2T_1)}$ which gives Eq. (5) expressed as:

$$\frac{\sqrt{Sa(T_1).Sa(2T_1)}}{Sa(2T_1)} \approx \frac{Sa(T_1)}{Sa_{avg}[T_1.(1,2)]} \qquad (5)$$

Meaning that, α_{geo} model values $\approx SaRatio$ model values. The approximate equality of Eq. (4b) for an individual and a group of far-field ground motion is shown in Fig. 2. This figure graphically displays a comparison between values of $Sa_{avg}(T_1.[1,2])$ and $\sqrt{Sa(T_1).Sa(2T_1)}$ for 4-story building with the first mode period

of $1.16s$ corresponding to an individual earthquake (Fig. 2a) and a set of 39 pairs of ground motions (78 individual far-field records), which the horizontal line is representative for the median values of the model (Fig. 2b). As seen in the figure, there is a subtle difference in the values of mentioned parameters, less than 5% both for Fig. 2a and 2b. Moreover, dispersion of each model in Fig. 2b is $\sigma = 0.41$ and $\sigma = 0.42$ for $Sa_{avg}(T_1.[1,2])$ and $\sqrt{Sa(T_1).Sa(2T_1)}$ respectively (only 2% difference).
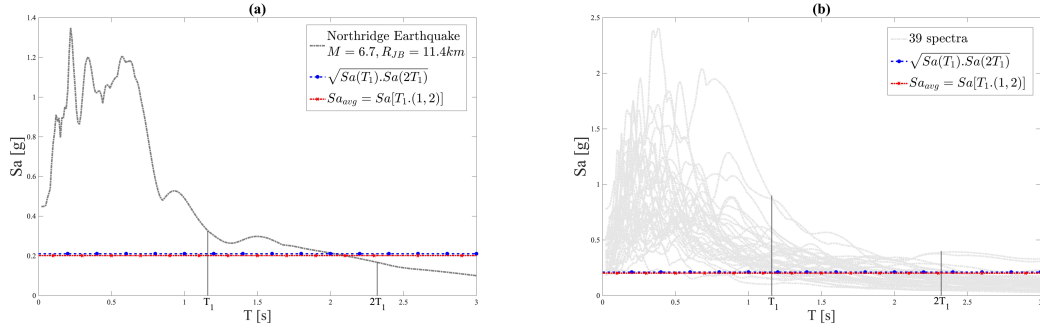

Figure 2. Graphically illustration of the two proposed spectral shape-based collapse capacity proxies over (a) Northridge Earthquake (b) 39 pairs of far-field ground motions for a 4-story RC building ($T_1 = 1.16s$).

Table 1 summarizes the same procedure for five buildings with different stories. Closeness of the median values between the two models are quite visible confirming the approximate equality of Eq. (4b).

Table 1. Values of $\sqrt{Sa(T_1).Sa(2T_1)}$ and $Sa_{avg}(T_1.[1,2])$ for 39 pairs of ground motion corresponding to five buildings

Story No.	$T_1[s]$	$\sqrt{Sa(T_1).Sa(2T_1)}$		$Sa_{avg}(T_1.[1,2])$	
		Median [g]	Dispersion (σ)	Median [g]	Dispersion (σ)
2	0.63	0.42	0.39	0.40	0.43
4	1.61	0.21	0.42	0.22	0.41
8	1.71	0.12	0.48	0.11	0.50
12	2.09	0.09	0.53	0.09	0.55
20	2.36	0.07	0.53	0.07	0.60

It will be shown that calculating $Sa_{avg}[T_1.(1,2)]$ in Eads model [11] requires identification of broad range of spectral ordinates from aT_1 to bT_1 (with period interval of say 0.01s and for comparison purpose in this study from T_1 up to $2T_1$), meanwhile, the proposed model ends up with similar values while benefits from model simplicity in

that only spectral ordinate information at the two periods of T_1 and $2T_1$ suffices to be identified.

Fig. 3 represents the ratio of α_{geo} over $SaRatio$ corresponding to the 26 structures and 39 pairs of far-field records studied in this paper. The ratios of the two model values in Fig. 3 reflect the closeness of the two model values demonstrating that more than 60% of the results are between 0.9 and 1.1.
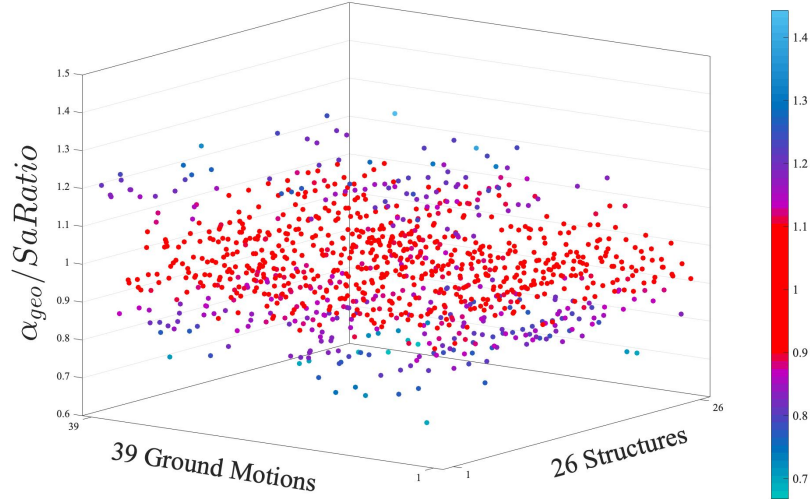

Figure 3. Illustration of $\alpha_{geo}/SaRatio$ values with respect to 39 records and 26 buildings.

6. Case study

6.1. Structural models

Performances of the two proposed proxy models are demonstrated by implementing over a number of selected structures. To this end, 26 RC-SMF structures are selected as case study. However, it is not claimed that the proposed model ends up with strong performance in other types of resisting systems and materials.

The 26 reinforced concrete (RC) special moment frame (SMF) buildings (from 2 to 20 stories) which have already been designed according to the provisions of ASCE 7-02 and ACI 318-05 [18], [19] (see Table A) for a high seismic region are used to explore the performance of the proposed spectral shape-based predictor. The reason that the RC-SMF structural systems are selected in this study is the simple availability of structures' information and the possibility of modelling severe deterioration of the selected RC frames which is of high importance. To this end, a two-dimensional three-bay model is selected for each of the 26 RC-SMF building systems [20] and the OpenSEES structural

analysis platform (OpenSEES) [21] is used for performing dynamic analysis of structures. The behavioral effects in beams, columns and beam-column joints in the ductile moment resisting systems used are considered to sufficiently capture those that govern the collapse behavior.

6.2. Ground motion selection

A set of 78 far-fields ground motions [20] including the general far-field set of 44 records presented by FEMA-P695 [12] are considered in this study. All the selected records are converted into the geometric mean form [23] using Eq. (6) expressed as:

$$Sa_{GM} = \sqrt{Sa_X . Sa_Y} \qquad (6)$$

In which Sa_X and Sa_Y are spectral acceleration in X-direction and Y-direction respectively, and Sa_{GM} is the geometric mean of the mentioned components.

6.3. Incremental Dynamic Analysis (IDA)

The well-known Incremental dynamic analysis (IDA) method is used to calculate collapse capacities of the structures (e.g. [22]). IDA has recently emerged as a powerful means to study the nonlinear response of structures; all the way from elasticity to final global dynamic instability [24]. IDA is used to assess the collapse capacity of a structure under a set of ground motions [25]. They define the collapse capacity of the structure in terms of the ground motion intensity at which collapse occurs.

In brief, an IDA analysis involves performing a series of nonlinear dynamic structural analysis through which the intensity of the candidate ground motion is increased by means of scale factors ending up with the global collapse capacity of the structure through applying scaled motions over the given structure. Graphically, the collapse capacity of a structure is displayed by plotting the spectral acceleration at the fundamental period of the given structure, $Sa(T_1)$, with 5% damping ratio as intensity measure (IM), against the maximum structure's interstory drift as damage measure (DM). The global collapse capacity is considered to be reached when a small increase in the ground motion scale factor generates a large increase in the structural response. Alternatively, the onset of global dynamic instability is recognized as the point at which the local slope of the IDA curve decreases to equal or less than 20% of the initial slope of the IDA curve (e.g. [26]). The general idea is that the flattening of the curve is an indicator of dynamic instability.

Vamvatsikos and Cornell [27] proposed a global collapse criterion where the maximum interstory drift (θ_{max}) in IDA analysis equal to 10% (close to global collapse).

7. Efficiency and sufficiency aspects of *Alpha* parameter

7.1. Evaluation of procedure

In general, the prerequisite of a link between two datasets is their trend strength through posing the correlation between them. In this study coefficient of determination (R^2) is used as trend strength.

R^2 value is simply achievable by performing a regression analysis between the two desired datasets, which are spectral shape proxy (α_{geo}) corresponding to the record's set in natural logarithmic form ($Ln\alpha_{geo}$) and the selected structures' collapse capacities represented by $Sa_{col}(T_1)$, in $LnSa_{col}(T_1)$ form.

7.2 Efficiency

An efficient spectral shape indicator is one whose trend poses a robust correlation coefficient (ρ) or coefficient of determination (R^2) (or small standard deviation). The selected 26 RC-SMF structural systems (from 2 to 20 stories) are used to calculate the structures' collapse capacities represented by $LnSa_{col}(T_1)$. These buildings are subjected to a general set of 78 far-field ground motions and their corresponding collapse capacities are calculated using IDA method. The response spectra corresponding to 78 records are converted into GM forms by Eq. (6) and their α_{geo} parameters are calculated. Furthermore, series of linear relationships among the two datasets of $LnSa_{col}(T_1)$ and $Ln\alpha_{geo}$ are developed and their corresponding coefficient of determinations (R^2) are calculated. For evaluating the proposed model through comparison issue, the same process is followed to calculate those of arithmetic form of mean value $\frac{1}{2}(Sa(T_1) + Sa(2T_1))$, and Eads approach assuming $a = 1$ and $b = 2$.

Fig. 4 shows plots of the three linear relationships fitted among $LnSa_{col}(T_1)$ (the collapse capacities of a 8-story RC-SMF building) and three models, $Ln\alpha_{Ar}$, $Ln\alpha_{geo}$, and $LnSaRatio$. The developed linear relationships along with the corresponding correlation coefficient are also shown at the top left panels. As seen, coefficients of determination are 0.88, 0.90, and 0.85 for α_{Ar}, α_{geo}, and $SaRatio$ respectively.

Results in the forms of the 26 structures' ID and R^2 values corresponding to α_{Ar}, α_{geo}, and $SaRatio$ models are depicted in Fig. 5, together with the models' goodness of fits.

Table 2 also summarizes the correlation coefficient corresponding to collapse capacities for the three models together with the variation of values' ranges.
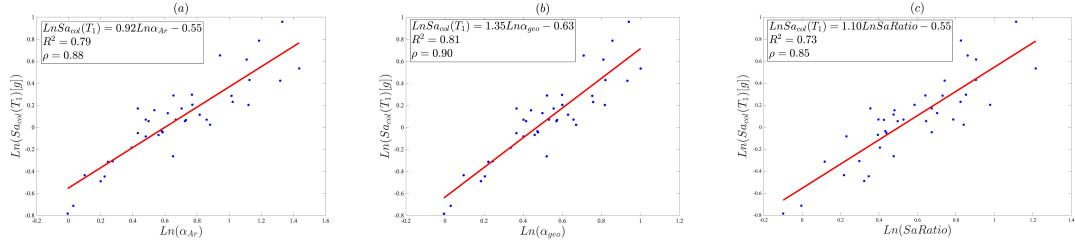

Figure 4. Display of linear relationships between natural logarithm of the collapse intensity and a) α_{Ar}, b) α_{geo}, and c) $SaRatio$ models for the 8-story RC building.
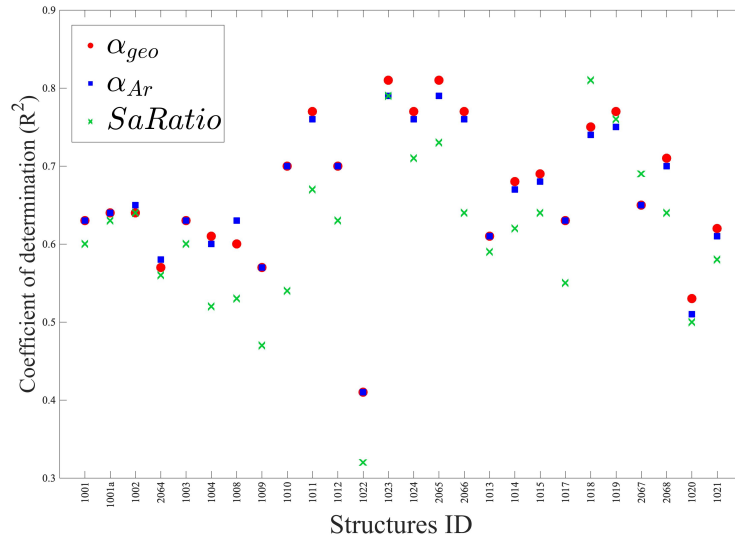

Figure 5. Display of R^2 values for 26 RC structures with respect to α_{Ar}, α_{geo}, and $SaRatio$ models.

Table 2. Summary of correlation coefficients between the collapse capacities and the three models; α_{Ar}, α_{geo}, or $SaRatio$ for 26 buildings.

$\rho(LnSa_{col}(T_1), Ln\alpha_{Ar})$		$\rho(LnSa_{col}(T_1), Ln\alpha_{geo})$		$\rho(LnSa_{col}(T_1), LnSaRatio)$	
Mean	Range	Mean	Range	Mean	Range
0.80	0.64~0.89	0.82	0.64~0.90	0.78	0.57~0.90

7.3. Sufficiency

Sufficient spectral shape indicator is one that renders the seismically induced structural collapse capacity independent of the earthquakes' magnitudes (M) and source to site distances (R) [28]. Sufficiency of the model is evaluated through performing two series of calculations outlined as follows,

Two linear relationships are developed between the two datasets of M and R versus residual of $LnSa_{col}(T_1)$ where M and R are the earthquakes' magnitudes and corresponding distances to the causative faults respectively where are used in the first step of *Alpha* calculation. The residuals existing in the trends between the general set of 78 far-field recordings and the collapse capacities of the 26 RC-SMF structural systems are calculated. *P*-value criterion is used to evaluate the independency of structural collapse capacities with respect to the earthquakes' magnitudes and source to site distances. *P*-value and the confidence interval criteria are just different ways of summarizing the same statistical information, which the close link between *p*-values and confidence intervals is quite obvious [29]. *P*-value of less than 0.05 (the threshold between sufficiency and insufficiency) indicates that model is not sufficient with respect to the ground motion parameter of interest. Summary of *p*-values including mean and range corresponding to 39 pairs of earthquakes' magnitudes and distances for α_{Ar}, α_{geo}, and $SaRatio$ models are listed in Table 3.

Table 3. Sufficiency illustration of three indicators, α_{Ar}, α_{geo}, or $SaRatio$, with respect to earthquakes' magnitudes and distances.

	α_{Ar}		α_{geo}		$SaRatio$	
	Mean	Range	Mean	Range	Mean	Range
p-value Magnitude (M)	0.59	0.07~0.85	0.57	0.06~0.9	0.64	0.16~0.98
p-value Distance (R)	0.69	0.09~0.95	0.71	0.07~0.96	0.71	0.25~0.99

As seen, in this circumstance, none of *p*-values corresponding to the earthquakes' magnitudes (M) and distances from site-to-causative fault (R) is less than 0.05. It reflects that the proposed model satisfies the sufficiency criterion and acts as an independent parameter from the earthquakes magnitudes and corresponding distances.

8. Use of the proposed model

This article is not intended to present a new intensity measure model; and preferably recommend a simple friendly used model. Intensity of a ground motion, given a structure, could be quantified by a property called Intensity Measure (IM) considered both as a scalar measure and vector-valued one [10]. Shome and Cornell [30] have demonstrated that $Sa(T_1)$, as the representative of IM, is more efficient than PGA. Vamvatsikos and Cornell [27] compared the record-to-record variability of the IDA curves obtained from representing PGA and $Sa(T_1; 5\%)$ as the IM of a 9-story steel moment-resisting frame with fracturing connections using similar suite of 30 ground motions belonging to a narrow magnitude and distance bin. They showed that PGA is deficient relative to $Sa(T_1; 5\%)$. Some researchers have also found that $Sa(T_1)$ is not very efficient for structures and incorporating periods less than T_1 improve the structural nonlinear response (e.g. [31], [32]).

Baker and Cornell [33] introduced Sa_{avg} as an intensity measure by defining it as a geometric mean of the spectral acceleration ordinates at set of periods, which has been used by several authors (e.g. [10], [11], [34]):

$$Sa_{avg}(T_1, \ldots, T_n) = \left(\prod_{i=1}^{n} Sa(T_i) \right)^{\frac{1}{n}} \qquad (7)$$

where $T_1, \ldots, T_n$ are the n periods of interest that T_1 need not refer to the first-mode period of the structure [33].

Eads et al. [11] considered $Sa_{avg}(T_1.[a, b])$ as intensity measure in their works by comparing it with $Sa(T_1)$ for estimating likelihood of structural collapse and concluded that Sa_{avg} is a good scalar IM for evaluating collapse capacity of a structure.

This paper recommends that the geometric form of the spectral ordinates $Sa(T_1)$ and $Sa(2T_1)$, which was also introduced by Cordova et al. [8] could be used by Eq. (8) as intensity measure due to its simplicity expressed as:

$$Sa_{geo} = \sqrt{Sa(T_1).Sa(2T_1)} \qquad (8)$$

For purpose of demonstrating the IM usage and as an example, three different models are considered as IM for computing collapse capacity of an 8-story building.

$Sa_{geo,col}$ (this study), $Sa_{avg,col}$ (Eads et al. [11]), and the most prevalent one, $Sa_{col}(T_1)$, are those models which are selected for this aim. The dispersion (σ) of an 8-story structure obtained from three existing models at predicting collapse intensity are compared in Fig. 6, which are displayed in each individual figure. Collapse level of each 26 studied structures are also calculated according to each IM model and summary of the results in the form of dispersion value are provided in Fig. 7. As it is shown in Fig. 6 and Fig. 7, closeness of values in dispersion of $Sa_{geo,col}$ and $Sa_{avg,col}$ with considerable difference from $Sa_{col}(T_1)$ are quite apparent.
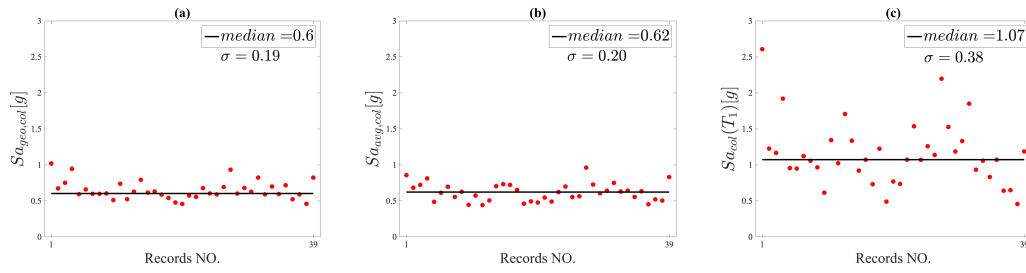

Figure 6. Collapse capacity intensity of 8-story building for individual records a) $IM = Sa_{geo}$, b) $IM = Sa_{avg}$, and c) $IM = Sa(T_1)$. Horizontal black lines indicate median values of a, b, and c plots.
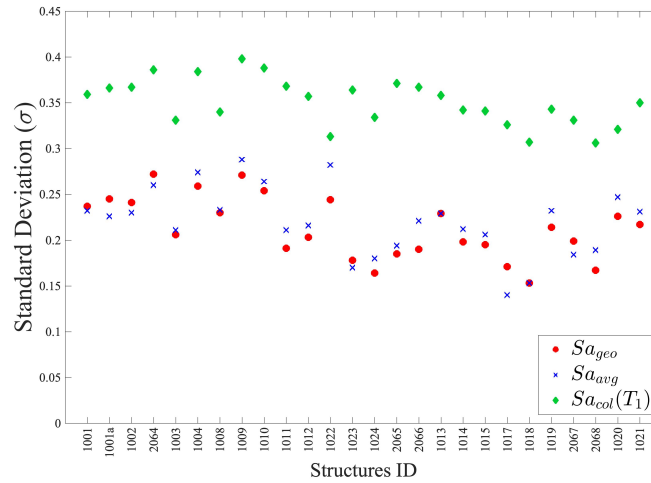

Figure 7. Standard deviation values (σ) with respect to 26 RC structures and the three IM models in the form of logarithmic values.

9. Discussion

As already stated, epsilon (ε) is related only to a single spectral ordinate at the fundamental period T_1, thus fails to account for the effects of those at periods much longer than T_1 (e.g., $2-2.5T_1$) [11], [9]. Eads et al. [11] demonstrated that $SaRatio$, as a

collapse capacity predictor, is much stronger than the other existing models such as ε or N_p. It was shown that α_{geo} model performances i.e. efficiency and sufficiency aspects are slightly stronger than $SaRatio$ model.

It should be noted that in Eads et al. model, see Eq. (1), numerous values for a and b could be selected to consider a broad domain of ground motion's spectrum. However as Eads demonstrated in her thesis [16], finding optimum values of a and b which might be result in best correlation coefficients (ρ) does greatly increase computational effort. As was shown, taking into account the spectral ordinates at first mode period (T_1) and two times of T_1, ($2T_1$), which are also recommended by Cordova et al. [8], Baker and Cornell [9], and Bojórquez and Iervolino [10], does not considerably influence the spectral shape effect on efficiency, sufficiency, and calculation of collapse capacity.

Bianchini [35] recommended at least spectral ordinates at 10 periods are required to compute Sa_{avg}, therefore, from the time cost view the presented models are much more simpler and user-friendly.

As was shown, influence of spectral shape on collapse capacity depends upon the amount of spectral ordinate difference at T_1 and $2T_1$ and such difference is the major factor that causes different collapse capacity.

The proposed spectral shape indicator α which is defined as the Square Root Ratio of Spectral Ordinates (SRRSO) at T_1 to that at $2T_1$ called α_{geo}, is associated with strong performance over the selected structures (see case study section). As seen in Fig. 1, the spectral shape indicator value (α_{geo}) with respect to Superstition Hills earthquake is 2.84 against that of Chi-Chi earthquake, which is 1.75. It reflects that the structure's collapse capacity is increased as α_{geo} increases. In other words, α_{geo} somehow demonstrates the collapse capacity strength of structures used in the case study.

Existing method of seismic hazard analysis is based on probabilistic/deterministic estimation of hazard-levelled extreme event i.e. $Sa(T_1)$ (with 2% chance in 50 year which corresponds to collapse prevention) (e.g. [19]). Recognizing that spectral ordinate at T_1 does not properly represents influence of those of the other longer periods on collapse capacity, accounting for spectral shape characteristic in collapse capacity proxy is remarkably significant [8]. Meanwhile, for the reason that estimation of $SaRatio$ needs quantification of a broad number of spectral ordinates at periods from T_1 to $2T_1$ (at least ten values in geometric mean form [35]), more simplicity of the proposed

collapse capacity proxy, given a structure and a ground motion in comparison with that of Eads, $SaRatio$, is quite clear.

It was shown that the proposed geometric mean form of spectral shape proxy is associated with similar performance to arithmetic mean. Since the geometric mean-based attenuation relations are becoming more popular and the geometric mean form is less sensitive to extreme spectral ordinates (i.e. very high or very low) [16], dealing with geometric mean forms of spectral shape proxy potentially makes the use of spectral shape more feasible, which was used in proposing α_{geo}.

10. Conclusion

A two parametric geometric mean-based spectral shape proxy model consisting of two spectral ordinates at the first mode period (T_1) and extended period ($2T_1$) called α_{geo} is proposed. The model stemmed from geometric mean value $\sqrt{Sa(T_1).Sa(2T_1)}$ normalized by $Sa(2T_1)$ for the purpose of reducing dispersion and scaling independency. Meanwhile, in addition to the proposed geometric mean form of spectral shape indicator another arithmetic mean form (α_{Ar}) is developed demonstrating that the geometric form is associated with similar performance.

The spectral shape indicator and corresponding collapse capacities of a set of 26 RC-SMF structural systems under the 39 pairs of far-field motions (in geometric mean form) were calculated as a case study using the well-known Incremental Dynamic Analysis (IDA) approach.

The structures' collapse capacities at $Sa_{col}(T_1)$ against the proposed spectral shape proxy are calculated and their performances are comprehensively discussed and evaluated through comparing with those of the existing model e.g. $SaRatio$ parameter. Whilst Eads showed that $SaRatio$ model as a collapse capacity predictor is much stronger than the other existing models such as ε or N_p, it was shown that the performances of the presented model, efficiency and sufficiency aspects are comparable with those of $SaRatio$ model.

The proposed spectral shape proxy deals with only two parameters; $Sa(T_1)$ and $Sa(2T_1)$, therefore, its identification is simpler than those of $SaRatio$ model for the reason that the information of other spectral ordinates are not required.

Examples of implementing the proposed spectral shape proxy in engineering problems are as a collapse capacity predictor, as an element of vector valued IM,

collapse margin ratio, CMR, for collapse safety evaluation of structures, seismic collapse risk assessment of buildings.

It was shown that the structure's collapse capacity is increased as the proposed spectral shape indicator increases i.e. it somehow demonstrates the collapse capacity strength of structures used in the case study.

Finally, the conducted conclusions are subjected to a number of limitations,

- The 26 structural RC-SMF buildings and 78 far-field ground motions used in the case study.
- The contribution of periods shorter than T_1 (higher modes) was not considered.
- It is strongly emphasized that use of the proposed models in the case study are not extendable to all structures having different materials and types of seismic resisting systems more work to be carried out.

11- Acknowledgement

Appendix

Structural models used in this study:

Table A. Structural information of 26 RC SMF frame buildings [20].

Design ID Number	No. of stories	Bay width (ft)	First mode period (T_1) [sec.]
1001			0.63
1001a	2	20	0.56
1002			0.63
2064			0.66
1003		20	1.12
1004			1.11
1008	4		0.94
1009		30	1.16
1010			0.86
1011			1.71
1012			1.80
1022			1.80
2065	8	20	1.57
2066			1.71
1023			1.57
1024			1.71
1013			2.01
1014			2.14
1015		20	2.13
1017	12		1.92
1018			2.09
1019		30	2.00
2067		20	1.92
2067			2.09
1020	20	20	2.63
1021			2.36

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