International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:11, 2015

A Three Elements Vector Valued Structure's Ultimate Strength-Strong Motion-Intensity Measure

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***Abstract*—**This article presents an alternative collapse capacity intensity measure in the three elements form which is influenced by the spectral ordinates at periods longer than that of the first mode period at near and far source sites. A parameter, denoted by β, is defined by which the spectral ordinate effects, up to the effective period (2T1), on the intensity measure are taken into account. The methodology permits to meet the hazard-levelled target extreme event in the probabilistic and deterministic forms. A MATLAB code is developed involving OpenSees to calculate the collapse capacities of the 8 archetype RC structures having 2 to 20 stories for regression process. The incremental dynamic analysis (IDA) method is used to calculate the structure's collapse values accounting for the element stiffness and strength deterioration. The general near field set presented by FEMA is used in a series of performing nonlinear analyses. 8 linear relationships are developed for the 8structutres leading to the correlation coefficient up to 0.93. A collapse capacity near field prediction equation is developed taking into account the results of regression processes obtained from the 8 structures. The proposed prediction equation is validated against a set of actual near field records leading to a good agreement. Implementation of the proposed equation to the four archetype RC structures demonstrated different collapse capacities at near field site compared to those of FEMA. The reasons of differences are believed to be due to accounting for the spectral shape effects.

***Keywords*—**Collapse capacity, fragility analysis, spectral shape effects, IDA method.

I. Introduction

NEAR-FAULT forward directivity pulse (FD-pulse) strong motions may induce large displacement and strength demands in structures depending upon the ratio of pule period (T_p) to the first mode period of structures (T_1). Structural damage to buildings, built within a few kilometers away from a fault rupture zone, has long been observed during strong near-fault ground motions [1], [2]. This might be the consequence of near-field pulse-like strong motion inducing large displacement and strength demands in structures.

Traditionally, the term "intensity measure (IM)" is referred to a value or a vector valued that quantifies the effects of a record on a given structure [3]. The spectral amplitude at the first mode period (T_1) has been found to be an effective IM in earthquake engineering problems examples are hazard analysis and incremental dynamic analysis (IDA).

In this paper, attempt is focused to present a three elements vector-valued intensity measure IM applicable to the collapse capacity of structures which reflects: (i) spectral amplitude of the observed record at T_1, (ii) the magnitude, distance or epsilon associated with the strong motion, (iv) the record's spectral ordinates at periods other than the first mode period (T_1). One important and effective element, the spectral shape effects, is added to those of Baker and Cornell [4] which will be shown that are significantly effective in reducing the structure's variability in developing the proposed equation for predicting IM in particular for records at near field site. As mentioned by [5], the pulse-like records, specifically those with $T_p/T_1 = 2$, cause a substantial decrease in the collapse capacity relative to a suite of far-field ground motions. Such results are also observed in this study.

A. Literature Review

It has long been understood that as the structure behaves nonlinearly its periods lengthens and greatly affected by spectral ordinates longer than T_1 [6], [7]. The lengthened periods of structure at site being influenced by FD is considerably more affected by spectral shape resulting in considerably large response demand. For pulse period (T_p) ratio to the first mode period (T_p/T_1) values near 2, the response is relatively large compared to the response from records with shorter-period pulses [3] stated that "this is because $Sa(T_1)$ only measures the intensity of the ground motion at T_1. Baker and Cornell [3] and Tothong et al. [8] mentioned that ground motion pulses with $T_p \approx 2T_1$ may be the most damaging for highly nonlinear systems.

Recently, a number of intensity measures indicator have been proposed for improved prediction of structural response. A vector IM consists of $Sa(T_1)$ and the ground motion parameter [9] have been the focus of recent research. Epsilon is a measure of the difference between a record's spectral acceleration value at a given period and the mean value of a predictive model. Although this IM has been observed to effectively account for spectral shape in ordinary ground motions, it was seen to be ineffective at accounting for the effect of velocity pulses in the ground motions [9]. The reason is that $Sa(T_1)$ only measures peaks in the response spectrum at the first mode period in the presence of velocity pulses and does not significantly affect these peaks at different periods. A based inelastic spectral based intensity measure response values is proposed by Luco and Cornell [10]. It was observed that the IM is effective at predicting the response of structures subjected to pulse-like records.

A vector-valued IMs for pulse-like near-fault ground motions is proposed by Baker and Cornell [3]. The IM consists of the parameters $Sa(T_1)$ and $R(T_1, T_2) = Sa(T_2)/$

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International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:11, 2015

$Sa(T_1)$, where T_1 is constrained to equal the first-mode period of the structure and T_2 is chosen to include important characteristics of the spectral shape.

B. Why Three Elements of Vector Valued IM

It is a common practice that the collapse capacity of a given structure due to a single strong motion is obtainable through a process of scaling the motion being applied on the structure so that causes the building to become dynamically unstable, as evidenced by excessive drifts. Representing the spectral ordinate at the first mode period of the structure $Sa(T_1)$ as its collapse capacity is a matter of challenge. The reason is that a specified $Sa(T_1)$ value may be attenuated to different strong motions associated with different magnitudes, distances. Baker and Cornell [4] added a new parameter "epsilon", as a constraint, to attribute this strong motion to the specified magnitude and distance. However, the problem seems not to still be answered due to the fact that there may be different single strong motions being associated with identical $Sa(T_1)$ while different spectral ordinates at periods other than that of T_1. Notably, different spectral ordinates at longer periods than T_1, may lead to different collapses of the given structure. Therefore, another more constraint is needed to reduce such set of strong motion to that of being associated with a specified $Sa(T_1)$ value. This article intends to present a collapse capacity "in the traditional $Sa(T_1)$ form" being accounted for the effects of the spectral ordinates at longer periods up to the effective period ($2T_1$) as the third element of the above stated vector valued IM.

II. Spectral Shape

Haselton et al. [6] and FEMA P695 [7] focused on the consideration of the spectral shape through the parameter ε for the purposes of collapse assessment through nonlinear dynamic analysis. Haselton et al [6] stated that rare high-intensity ground motions have a peaked spectral shape that should be considered in ground motion selection of a set of ground motions that is specific to the building's fundamental period and the site hazard characteristics.

Haselton and Baker [11] stated that "the tendency of high-ε ground motions to have a peaked spectral shape will be an important consideration in the results below. Baker and Cornell [4] concluded that the effect of ε is at least as great as that of magnitude or distance."

"Research also shows that this peaked spectral shape significantly increases the collapse capacity when the peak of the spectrum is near the fundamental period of the building ($T_{1,struct}$) and we scale the ground motions based on ($T_{1,struct}$) [11]-[13]."

The definition of spectral shape in this article is quite different from those above mentioned. It will be shown that a single strong motion associated with identical spectral ordinate at T_1, $Sa(T_1)$ but different spectral ordinates at longer periods than T_1, leads to quite different collapse capacities, in particular those at near field site being affected by forward directivity (FD).

A. Effects of Spectral Ordinates at Longer Periods on Structure's Collapse

The near-source dynamic FD consequence through which most energy from the rupture arrives in a single coherent long-period of motion occurs when the fault rupture propagates toward a site, at a velocity nearly the wave velocity. Buildings at site a few kilometers away from a fault rupture zone, has long been observed during strong near-field ground motions [1], [2]. Due to scarcity of the above stated three types of recorded near-fault ground motions, there is interest in developing synthetic ground motions for near-fault sites predicting the directivity and fling-step pulses, in double and single forms respectively (e.g., [14]-[16]).

Several empirical models, within the last decade, have been proposed by researchers to essentially 'correct' the predictions of GMPEs for directivity effects (e.g., [17]-[20]).

In this section, the influence of spectral ordinates at longer periods other than that of T_1 on structure's collapse is shown to be an effective at far field records particularly at near field site being influenced by forward directivity (FD) effects. For this purpose, four pairs of single records being associated with identical spectral amplitudes at T_1, without scaling, which different values at the effective period at e.g., $2T_1$ are selected. An archetype RC structure already has been used by [6] is subjected to the selected strong motions and their collapses are calculated using the incremental dynamic analysis method. The element stiffness and strength deterioration is accounted for. Table I lists the earthquake names and stations, the magnitudes and distances, the structure's period, the epsilons calculated from Abrahamson and Silva Attenuation Equation [21], the identical spectral amplitudes at the record's pairs, the different $Sa(2T_1)$ values, and finally their collapses. As seen, the collapses reduces (pair No. 1, 0.62 against 1.09, a reduction of 43%) as the result of an increase in the $Sa(2T_1)$ (0.06 against 0.13, an increment of 2.17%). As another example, in the pair No. 4, an increase in $Sa(2T_1)$ (0.05 against 0.12, an increment of 240%) comes up with a decrease of 54% in collapse (1.875 against 1.025).This is the major key point of this article.

Fig. 1 shows a sample of response spectra used in the analysis process. As seen, both spectral ordinates at T_1 are associated with identical values (without scaling) while different values at $2T_1$.

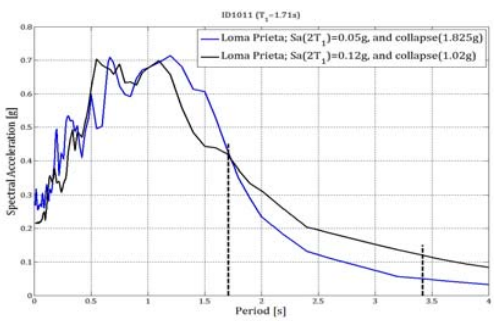

Fig. 1 Comparison illustration of two response spectra being associated with identical $Sa(T_1)$ while different values at $2T_1$

TABLE I
EARTHQUAKE NAMES, STATIONS, COLLAPSE SCALE FACTORS, AND THE CALCULATED COLLAPSE CAPACITIES (THE IDENTICAL SPECTRAL AMPLITUDES TOGETHER WITH THOSE OF DIFFERENT VALUES AT, $2T_1$)

No.	EQ	M	R (km)	T_1 sec	$\varepsilon_{A.S.}$	$Sa(T_1)$ (g)	$Sa(2T_1)$ (g)	collapse SF	CC $Sa(T_1)$ (g)
1	Northridge	6.7	26.45	1.71	0.9	0.21	0.06	5.25	1.09
	ImperialValley	6.5	22.03	1.71	0.9	0.21	0.13	2.97	0.62
2	Northridge	6.7	17.15	1.71	1.6	0.48	0.06	3.20	1.49
	Loma Prieta	6.9	27.93	1.71	2.0	0.50	0.13	1.77	0.89
3	Kobe, Japan	6.9	22.5	1.71	1.5	0.41	0.04	4.56	1.86
	Northridge	6.7	15.6	1.71	1.3	0.41	0.1	2.06	0.86
4	Loma Prieta	6.9	77	1.71	2.8	0.42	0.05	4.31	1.825
	Loma Prieta	6.9	27.6	1.71	1.7	0.42	0.12	2.46	1.025

EQ. Earthquake name, M: Magnitude, R: closest distance, CC: Structure's Collapse Capacity

B. Fragility Function (Curve)

The fragility function (curve) is a useful method to calculate the probability of structure's collapse (normally in CDF form of log-normal distribution) given the record set, engineering demand parameter set (EDP), spectral amplitude (at T_1) in this study, to which each is subjected. The fragility curve is used to relate the median collapse capacity IM to the archetype structure's collapses in the first step and thereafter to the hazard-leveled target extreme event's spectral amplitude at T_1.

III. PROPOSED COLLAPSE CAPACITY PREDICTION

A prediction equation is developed with the help of a parameter, denoted by, β, by which the effects of spectral ordinates at longer periods on collapse are effectively taken into account and is explained here.

A. β Parameter Definition

β parameter is defined as the ratio of the moment area of the trapezoidal shape (ABCDE) to that of the rectangular shape (ABDE) about the $Sa(2T_1)$ (DE in Fig. 2), given an strong motion, the fundamental period of a structure (T_1), and the effective period ($2T_1$). This parameter is normalized to $Sa(T_1)$ which effectively reduces the variability of the used records and those of the selected structures.

Calculating the moment areas by means of their mass center distances to the $Sa(2T_1)$ gives:

$$\beta = \frac{S_{BCD}\times\frac{2T_1}{3}+S_{ABDE}\times\frac{T_1}{2}}{S_{ABDE}\times\frac{T_1}{2}} \quad (1)$$

where, S denotes the area of the shapes shown in Fig. 2. Substituting the calculated shape areas, $S_{BCD} = (Sa(T_1) - Sa(2T_1)) \times T_1/2$, and $S_{ABDE} = Sa(2T_1) \times T_1$, into (1) and rearranging the forms of equations gives:

$$\frac{\beta}{Sa(T_1)} = \frac{2S_a(T_1)+S_a(2T_1)}{3S_a(2T_1)S_a(T_1)} = \frac{1}{3}\left[\frac{1}{S_a(T_1)} + \frac{2}{S_a(2T_1)}\right] \quad (2)$$

A. Performed Regression Analyses

Getting together the above stated 8 structure's properties, the 28 pairs of spectral amplitudes at T_1 and $2T_1$ corresponding to the strong motion set, a collapse capacity equation is established. A MATLAB code is developed involving OpenSees, an open-source platform developed by PEER [22], by which the element stiffness and strength deteriorations are taking into account [23]. The proposed near field prediction equation permits to meet the hazard leveled target extreme event (2% chance in 50 year). The robust correlation coefficient obtained from regression processes confirms the reliability of the selected variables of the 8 structure's properties and the strong motion's characteristics (Table II).

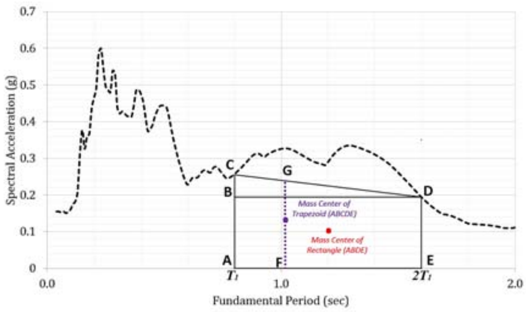

Fig. 2 The spectral amplitudes at T_1 and $2T_1$ associated with the mentioned shapes

TABLE II
THE CORRELATION COEFFICIENTS OBTAINED FROM THE FITTED LINEAR CURVES OF THE 8 RC ARCHETYPE STRUCTURES

NO. of Structure	Structure's ID	Structure's Period[s]	No. of Stories	Correlation coefficient
1	1001a	0.56	2	0.93
2	2064	0.66	2	0.90
3	1003	1.12	4	0.89
4	1004	1.11	4	0.89
5	1009	1.16	4	0.92
6	1012	1.80	8	0.94
7	1014	2.14	12	0.89
8	1021	2.36	20	0.87

The developed near-field equation is used to predict the collapse capacity of a given structure corresponding to the predetermined hazard-leveled extreme event at a near-field site and is expressed as:

$$M_{mean} = Exp\left[1.875 + \frac{0.613}{T_1} + 0.956 \times LN(RDR_{ult})\right] \quad R^2 = 0.98 \quad (3)$$

where, RDR, T_1 are the roof displacement ratio obtained from a push-over procedure [7] and the fundamental period respectively, and M_{mean} is the mean value of the 8 fitted line slopes corresponding the eight regression analysis procedure.

A regression analysis is performed among two sets of data consisting of the 28 calculated scaling factors (SFs) for each structure hence, $8 \times 28 = 224$ data, associated with 224 $\frac{\beta \times M_{mean}}{Sa(T_1)}$, parameters where M_{mean} is the fitted line slope corresponding to each structure. In other words, each structure is associated with specified fitted line slope (M) and 28 scaling factors. The obtained linear relationship is expressed as:

$$SF = 0.9717 \left[\frac{\beta}{\mathrm{Sa}(T_1)} \times M_{mean}\right] + 0.7;\ R^2 = 0.76 \tag{4}$$

The parameter $[\beta\ /\ \mathrm{Sa}(T_1)]$ can be related to a θ parameter, often less than unity, an FD-pulse indicator, which reflects the effects of FD-pulse spectral ordinates at loner periods than T_1 up to the effective period $(2T_1)$. Calculating the area mass center of the trapezoidal shape (Fig. 2), the spectral ordinate corresponding to this point (Fig. 2), and dividing by $Sa(T_1)$ gives the θ parameter which mathematically comes up with (5) expressed as:

$$\theta = \delta + \frac{1}{3} \times \frac{(1-\delta)(2+\delta)}{(1+\delta)};\ where\ \delta\ is,\ \ \delta = \frac{Sa(2T_1)}{Sa(T_1)} \tag{5}$$

The parameter θ Value (which is less than unity) represents the contribution of spectral ordinates at longer periods up to the effective period $(2T_1)$ other than that of T_1.

The collapse capacity of a given structure is simply calculated by multiplying the corresponding scaling factor to the hazard-levelled target spectral amplitude, $Sa(T_1)$, (2% chance in 50 year, MCE strong motion) (4) estimated at the site of interest expressed as:

$$Sa_{Col}(T_1) = SF \times Sa_{MCE}(T_1) \tag{6}$$

In practice, substituting the structure's first mode period (T_1) and RDR in (3) gives the $M(mean)$ parameter. The term $\frac{\beta}{Sa_{MCE}(T_1)}$ corresponding to the hazard-level MCE strong motion and that of at $Sa(2T_1)$ are calculated. Equation (4) is used to calculate the corresponding SF, and finally (6) is used to predict the collapse capacity corresponding to the structure. The spectral shape indicator θ parameter is calculated by means of (5). Consequently, the proposed vector valued IM composed of three elements, $[Sa(T_1), \varepsilon, \theta]$, is predicted. Since $Sa(2T_1)$ is often smaller than $Sa(T_1)$ even in Non-pulse strong motion, θ parameter also comes up with the values less than unity which is significantly influenced by the FD-pulse value. It is important to note that we have presented the concept of the problem and the methodology of collapse prediction of a given structure and the problem is but applicable to a family of structures having different structural resisting systems. Consequently, the presented methodology should be extended considering a large numbers of structures having different types of resisting systems and structural types.

IV. Validation, Results, and Discussion

The proposed methodology is validated against the actual two sets of records consisting of a FD-pulse set and a Non-pulse set (Table III). A 4-story archetype RC structure is used to demonstrate the validation of the proposed methodology. The whole procedure of calculating the collapse capacities are followed and the results are outlined in Table IV. The mean collapse capacities corresponding to each set are shown at the last row of Table III. As seen, good agreements between the results of this study (in spite of a 7.5% differences) and those of the actual records confirm the validity of the proposed methodology.

TABLE III
The Selected Earthquake Information and the Mean Value of the Calculated Collapse Capacities

NO.	Earthquake	M	R	$Sa(T_1)$	$Sa(2T_1)$	CC
	FD-pulse Records subset					
1	Northern Calif-03	6.5	27	0.31	0.2	1.24
2	Imperial Valley-06	6.5	0.7	0.35	0.26	1.85
3	Imperial Valley-06	6.5	7.3	0.4	0.21	1.26
4	San Fernando	6.6	1.8	0.91	0.35	2.28
5	Tabas, Iran	7.3	2	0.92	0.5	1.46
	Non-Pulse Records subset					
6	Imperial Valley-06	6.5	8	0.37	0.15	1.76
7	Kocaeli, Turkey	7.5	5	0.38	0.25	1.04
8	Nahanni, Canada	6.8	10	0.5	0.12	2.36
9	Northridge-01	6.7	12	0.51	0.28	1.3
10	Northridge-01	6.7	8	1.07	0.26	2.57
	MEAN			0.57	0.26	1.71

M: Magnitude
R: closest distance
CC: Structure's Collapse Capacity

TABLE IV
The Predicted Collapse Capacity of A 4-Story RC Structure

Story	ID	T_1	RDR_{ult}	$Sa(T_1)$	$Sa(2T_1)$	$\beta/Sa(T_1)$	CC
4	1008	0.94	0.047	0.572	0.26	3.17	1.59

T_1: Structure's first mode period, RDR_{ult}: Ultimate Roof Displacement Ratio, $Sa(T_1)$: Spectral amplitude, CC: Structure's Collapse Capacity

The results are presented within two series of data. The first one is the linear relationships obtained from performing the regression procedures for each structure. 8series of fitted lined are developed among the structure's SF and 28 parameters leading to robust correlation coefficients (28 parameter are used because our methodology is based on geometric mean values) (Fig. 3).

The second result series are the calculated collapse capacities as the outcomes of the proposed prediction (6). The developed equations are implemented upon the three archetype structures to demonstrate its effectiveness. The obtained results are briefly outlined in Table V. Table V lists the story numbers of the 3 archetype structures used, Their RDRs and periods, spectral amplitudes at T_1. The spectral amplitudes at $2T_1$ together with those of collapse capacities, as the major contribution of this study are shown in two comparable columns together with those of FEMA [7]. These (in GM forms) are as follows:

1) The collapse capacities corresponding to the 14 strong motions being influenced by forward directivity pulse effects are shown under named FD-pulse.
2) The collapse capacities corresponding to the 14 strong motions where have not been influenced by FD are shown under named Non-pulse.

Table V demonstrates the obtained vector valued collapse capacity IMs for three story RC archetype structures corresponding to FD pulse, non-pulse sets of strong motions. The corresponding epsilons are also shown. The results show the performance of the proposed technology in reducing the structure's capacity being subjected to a FD-pulse set compared to those of non-pulse set. As seen, the FD-pulse strong motions associated with larger spectral amplitudes at $2T_1$ resulted in smaller collapse capacities compared to those of the non-pulses. Interestingly, the θ parameters, representing the spectral shape effects, increase due to an increase of spectral amplitude at $2T_1$ (Table V, 0.823 for FD-pulse against 0.755 for non-pulse, 0.8 for FD-pulse against. 735 for non-pulse, and 0.77 for FD-pulse against 0.74 for non-pulse). The FD-pulse strong motions came up with smaller values compared to those of Non-pulses. In brief, while the collapse capacities corresponding to the FD-pulse strong motions are considerably smaller than those of the Non-pulses, both are associated with smaller values relative to those of FEMA [7]. The results reflect the fact that accounting for the spectral amplitudes at longer periods cause the collapse capacity, as the IM, to be reduced.

It is important to note that our spectral shape definition looks to be different from those of e.g., [6]. In that we mean the spectral shape as the quantities of a family of spectral amplitudes at longer periods (irrespective to that at the first mode period) rather than the single spectral amplitude at T_1 which is traditionally indicated by its epsilon. In other words, we are dealing with a family of epsilon rather than a single one.

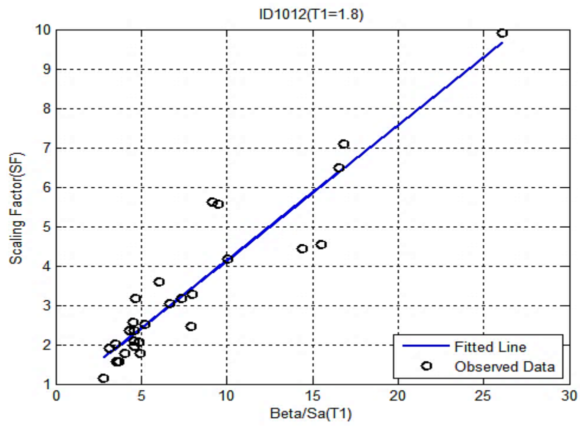

Fig. 3 Displays the fitted linear curve together with the corresponding correlation coefficient ($\rho = 0.93$) as a sample

TABLE V
THE THREE ARCHETYPE STRUCTURE INFORMATION AND THE RESULTS OF IMPLEMENTING THE PROPOSED METHODOLOGY IN THE FORMS OF FS-PULSE AND NON-PULSE SETS OF STRONG MOTIONS COLLAPSE CAPACITIES

Story	T_1 sec	RDR_{ult}	$Sa(T_1)$	$Sa(2T_1)$		$Vector\ valued\ collapse\ capacity$ $(Sa_{Col}(T_1), \varepsilon, \theta)$		
				Non-pulse	FD-pulse	Non-pulse	FD-pulse	FEMA P695
2	0.63	0.076	1.45	0.64	0.89	(3.67,1.51, 0.755)	(3.1, 1.51,0.823)	(4.32,1.51)
4	0.94	0.047	1.17	0.45	0.67	(2.17,1.57,0.735)	(1.8, 1.57,0.8)	(3,1.57)
8	1.71	0.023	0.65	0.26	0.32	(0.94, 1.62,0.74)	(0.87,1.62, 0.77)	(1.25,1.62)

V. CONCLUSIONS

The findings of this study are outlined as follows:

1) The traditional collapse capacity relies on a single spectral ordinate at T_1 represented by, $Sa(T_1)$, and epsilon as its indicator, which seems not to be a sufficient predictor of collapse capacity IM. It is shown that even adding epsilon to $Sa(T_1)$, as a two elements vector valued still doesn't account for the relevant characteristics of strong motion and structure's properties in collapse phase of the structure under study.
2) The spectral shape effects i.e., the spectral ordinates at longer periods (up to the effective period $2T_1$) other than that of T_1, are shown to significantly affect the traditional $Sa(T_1)$ value as IM. The proposed three vector valued collapse capacity, consisting the spectral ordinate at $T_1, Sa(T_1)$, magnitude and distance or epsilon, and θ parameters effectively take into account the influence of spectral shape on $Sa(T_1)$ and reasonably reduce the variability of strong motions as well as those of the structure in predicting IM.

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