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A NEW INTENSITY MEASURE THAT ACCOUNTS FOR THE EFFECTS OF SPECTRAL ACCELERATION, DURATION, AND SPECTRAL SHAPE

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Abstract

The effects of ground motion duration and the shape of the spectrum after the structure softens are not accounted for in structural design. The design code recommends that buildings be designed based on the spectral acceleration at the structure's period from the maximum considered earthquake (MCE). Recorded ground motions scaled to the MCE spectral acceleration can result in a wide variety of nonlinear structural responses. To reduce the variation in structural response at a particular ground-motion intensity, a new intensity measure is formulated to account for the combined effects of spectral acceleration, ground-motion duration, and the response spectrum shape. The intensity measure includes a new measure of spectral shape that integrates the spectrum over a period range that depends on the structure's ductility.

The paper demonstrates the efficiency of the IM in predicting collapse of deteriorating single and multiple degree-of-freedom systems. This efficiency is attributable to the inclusion of ground-motion duration and the ductility dependence of the spectral shape measure. Finally, the new IM's efficiency is compared to several existing spectral shape intensity measures.

Keywords: spectral shape, ground-motion duration, intensity measure, structural collapse analysis

1. Introduction

In the design of new structures and the evaluation of existing ones, it is important to understand how key characteristics of both earthquake ground-motions and structures are likely to affect structural demands. The effects of spectral acceleration and of structural force-deformation characteristics are already considered in current building codes through the design response spectrum and the response modification factor [1, 2]. Bommer et al. [3] and Hancock and Bommer [4] investigated the influence of duration on structural damage measures (e.g., inter-story drift, absorbed hysteretic energy). Chandramohan et al. [5] and Raghunandan and Liel [6] showed that the ground-motion's duration can affect the minimum design strength needed to avoid collapse. Haselton et al. [7] and Eads et al. [8], among others, have shown the influence of spectral shape on the collapse probabilities of structures. Recognizing these dependencies, recent guidelines [9, 1] have recommended that code-alternative or existing structures be evaluated with ground motions that have similar characteristics to the seismic events that control the hazard at the structure's site.

To help select ground motions for structural analysis, a new scalar intensity measure (IM) is proposed that accounts for the effects of (i) the elastic spectral acceleration at the structure's fundamental period; (ii) the duration of the motion; (iii) the shape of the response spectrum; and (iv) the structure's cyclic force-deformation properties. The new IM is evaluated in terms of efficiency (other key features that make an IM desirable are evaluated in [10]). In particular, the paper evaluates its efficiency in predicting force-reduction factors that lead to collapse in brittle and ductile deteriorating SDOF systems, and in terms of the dispersion of the IM at collapse for 30 archetypical building models [11].

2. Desirable Features of an Intensity Measure

The goal of developing a new intensity measure is to help engineers design or evaluate structures. Tothong and Luco [12] proposed that an IM be evaluated in terms of its efficiency, sufficiency and scalability. Kramer [13] suggested that the IM needs to be predictable using GMPEs. Marafi et. al [10] discusses features that makes an intensity measures transparent, structurally independent, and versatile.

This paper focuses on the new IM's efficiency. Ideally, an efficient IM would correlate perfectly with various measures of building response. In such a scenario, the structure would reach a particular value of an engineering demand parameter (EDP) at the same intensity of the IM for any particular ground-motion record. In this case, only a single analysis would be required to characterize the response of the structure at that level of IM. In practice, an efficient measure will correlate strongly with structural response, so that only a manageable number of computationally demanding, nonlinear dynamic analyses would be necessary to characterize the structure's response.

The IM should also correlate well with a variety of engineering demand parameters. For this reason, the proposed intensity measure will be evaluated with a wide range of ground motions and systems, including (i) a large number of SDOF oscillator systems with a wide range of oscillator frequencies and properties that represent a 'brittle, quickly deteriorating' and 'ductile, slowly deteriorating' systems; and (ii) a set of two-dimensional archetypical buildings models.

3. Existing IMs for Duration and Spectral Shape

Other authors have investigated the effects of ground-motion duration and spectral shape. Bommer et al. [3] found that the effects of durations are more pronounced in structures that are susceptible to low-cycle fatigue and who also undergo strength and stiffness degradation with dynamic loading. They also showed that using IMs that account for spectral shape with duration intensity measures decouples the two effects on structural response. Hancock and Bommer [4] later took an alternative approach by comparing the effects of duration using spectrally matched records.

Chandramohan et al. [5] found that, compared with other measures, significant duration (D_s) was the most suitable IM for ground-motion duration. Significant duration is defined as the time between two target values of the integral, $\int_0^{t_{max}} a_g(t)^2 dt$, where a_g is the ground acceleration, and t_{max} is the total duration of the record. Chandramohan et al. found that D_s correlates well with structural collapse capacity, it is unaffected by ground-motion scaling, and it is not correlated to other common IMs. Bommer et al. [3] and Chandramohan et al. [5] both evaluated other IMs for duration (e.g. bracketed duration) that are not considered in this paper due to their lack of scalability.

De Biasio et al. [14] evaluated several intensity measures that account for the effects of spectral shape. Those summarized here have many of the identified desirable features. Cordova et al. [15] developed an IM based on spectral acceleration, $S^*(T_n)$, where T_n is the fundamental period of the structure. S* accounts for spectral shape by multiplying the spectral acceleration by the square root of $S_a(2T_n)$ over the $S_a(T_n)$. De Biasio et al. showed that the intensity measure S* correlated with building response. However, the spectral shapes for ground motions and the effective period of nonlinear structures can vary greatly, and this measure does not include the effects of peaks occurring at periods other than the two considered.

Baker and Cornell [16] introduced an IM that quantifies the spectral shape by computing the geometric mean of a series of spectral accelerations, $S_{a,geo}$. Bojórquez et al. [17] found that, if c_iT_n were taken at consistent intervals between T_n to $2T_n$, the resulting intensity measure better correlated with structural collapse. Eads et al. [8] found that c_iT_n computed between $0.2T_n$ to $3T_n$, resulted in an intensity measure that accounted for higher mode effects and nonlinearity. This approach resulted in lower dispersions in the prediction of the IM to cause collapse of numerous building models with various ground motions sets. De Biasio et al. [14] showed similar trends through another intensity measure, ASA_R, which also quantifies the spectral shape in terms of values at several period ranges.

4. A New Intensity Measure

The proposed ground-motion intensity measure combines the spectral acceleration at the first natural period of a structure, a measure of the ground-motion duration, and a measure of the shape of the ground-motion elastic response spectrum:

$$IM_{comb} = S_a(T_n) * IM_{dur}^{C_{dur}} * IM_{shape}^{C_{shape}} \tag{1}$$

where, $S_a(T_n)$ is the spectral acceleration at the fundamental period of interest (T_n), IM_{dur} is the IM for duration, and IM_{shape} is the IM for spectral shape. The empirical exponent C_{dur} accounts for the structure's sensitivity to IM_{dur}, and the C_{shape} exponent accounts for its sensitivity to IM_{shape}. Once the IMs have been selected, the exponents are found by regression analyses.

In this paper, $S_a(T_n)$ was computed for a damping ratio of 5%. IM_{dur} was taken as the significant duration (D_s), computed as the time interval between 5% and 95% of the maximum value of the integral. For the ground motion sets considered, this time interval resulted in a marginal benefit to the IM's efficiency compared to other intervals (e.g., 5%-75%).

A new measure of spectral shape (IM_{shape}) has been developed [10] that accounts for the differences in period elongation between brittle and ductile structures. Haselton et al. [7] showed that ductile structures are more susceptible to spectral shape effects. To account for this dependence, IM_{shape} is calculated over a period range that depends on its ductility demand, if that is known, or alternatively, on the structures ductility capacity. A new IM_{shape}, denoted SS_a, is defined using the integral of the ground-motion response spectrum (damping ratio of 5%) between the fundamental period of the building (T_n) and the nominal elongated period (αT_n), as shown in Figure 1. To make IM_{shape} independent of scale, the integral is then normalized by the area of a rectangle with height of $S_a(T_n)$ and width of $(\alpha\text{-}1)T_n$.

$$IM_{shape} = SS_a(T_n, \alpha) = \frac{\int_{T_n}^{\alpha T_n} S_a(T)\, dT}{S_a(T_n)(\alpha - 1)T_n} \tag{2}$$

where αTn is computed as a multiple of the secant stiffness of the structure at maximum displacement resulting in $\alpha = C_\alpha\sqrt{\mu}$ where C_α is set to 1.3 (variations are discussed in [10]), and μ is the system's displacement ductility factor. In practice, the assumed value of μ used in SS_a's computation would only need to be approximate, because the results are not sensitive to this assumption. For example, this value could also be taken as the ductility capacity of the system determined from the seismic response modification factor from ASCE/SEI 7-10 [1]. Using the structures ductility in SS_a results in a more efficient IM. The following sections discuss the efficiency of IM_{comb}.

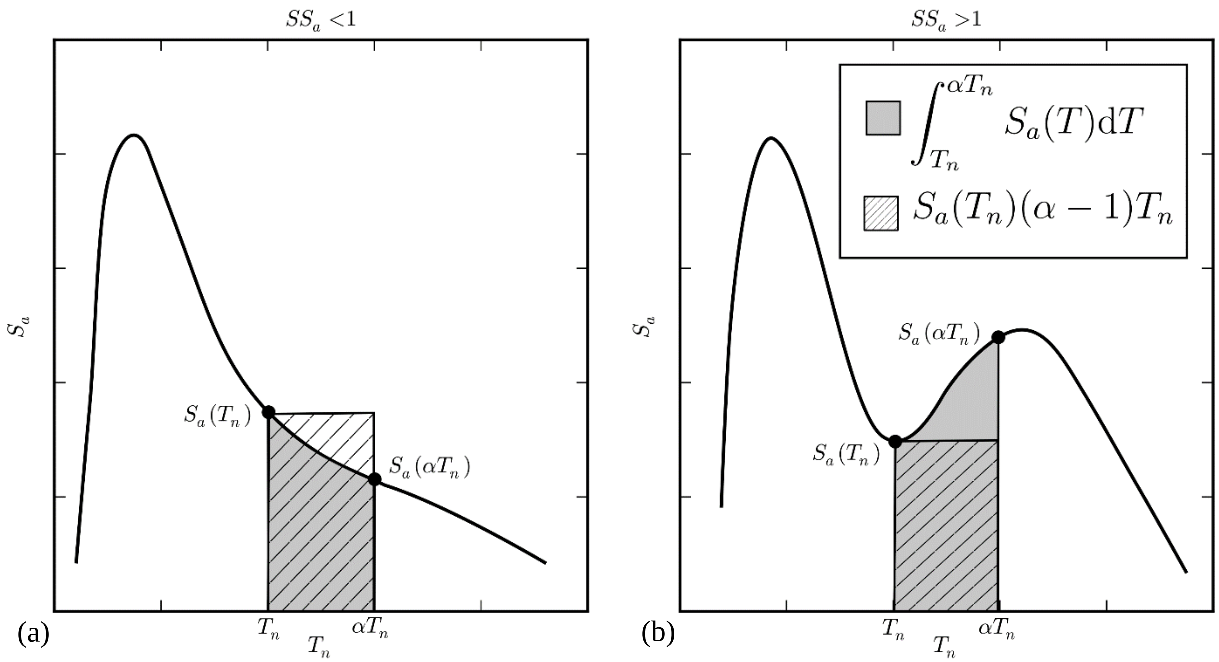


Figure 1 – Graphical depiction of (a) SS_a less than 1 and (b) SS_a greater than 1.

5. Evaluating the Intensity Measure using Deteriorating SDOF Systems

To ensure that IM_{comb} is efficient, it should also correlate with the results of nonlinear dynamic collapse analyses of deteriorating systems. The force-deformation behaviors of the deteriorating SDOF systems were modeled using the peak-oriented deteriorating model [18] as implemented in OpenSees [19]. Two sets of SDOF models were developed to represent 'brittle, quickly deteriorating' and 'ductile, slowly deteriorating' systems. The values of the model parameters (shown in Table 1) were similar to those proposed by Haselton et al. [20] and Ibarra et al. [21], based on their calibration of the model with experimental results. To capture the effects of spectral shape at various periods (0.1-3s), the SDOF oscillators had varying initial elastic stiffnesses and were subjected to both ground motions sets. Previous studies have incorporated p-delta effects by rotating the backbone curve of the nonlinear spring. In this study, p-delta effects have not been explicitly incorporated in the analysis, but rather, are incorporated into the assumed elastic, post-yield and post-capping stiffness values.

Table 1. Model parameters used for the Ibarra et al. [18] peak-oriented deterioration model.

Ibarra Model Parameter	Brittle, Quickly Det.[1]	Ductile, Slowly Det.[1]
Post-yield stiffness	0.03 K_e[1]	0.03 K_e[1]
Post-capping stiffness	-0.1 K_e[1]	-0.1 K_e[1]
$\delta_{cap.}/\delta_y$	4	8
$\gamma_{s,c,a}$	25	100
γ_k	50	200
Residual strength	≈ 0	≈ 0

Notes: [1]Critical damping (ξ) is equal to 5%, and rate of deterioration (c) is equal to 1.0
K_e = elastic stiffness of the oscillator, $\delta_{cap.}/\delta_y$= ratio of the capping displacement to the yielding displacement, $\gamma_{s,c,a}$ = cyclic deteriorating parameter for yield strength, post-capping strength, and acceleration reloading stiffness, γ_k = cyclic deterioration parameter for the unloading stiffness

Using an incremental dynamic analysis (IDA) [22], the spectral acceleration at collapse ($S_{a,c}$) was computed as the point where the system reached its residual strength and had negligible stiffness. IDA curves are developed for a ductile and brittle oscillator subjected to the 78 ground motion records in the expanded FEMA set, scaled incrementally until collapse. These motions are commonly used in FEMA P695 [23] and compiled by Haselton et al. [11]. To normalize the building response parameter, $S_{a,c}$, so that the oscillators at various periods could be compared, the results are summarized in terms of the relative intensity, R_c [21]. R_c was computed as the ratio of $S_{a,c}$ for a given ground motion to the yield strength of the system normalized by the weight of the structure, shown as,

$$R_c = \frac{S_{a,c}}{\eta g} \tag{3}$$

where $\eta = \frac{F_y}{mg}$, F_y is the system strength, m is the mass of the structure, and g is the gravitational acceleration. R_c quantifies the ground-motion's intensity on a particular system [21].

5.1 Efficiency of Estimates of R_c

Efficiency can be quantified through the dispersion of the IM's intensity that causes collapse for a particular system using a set of ground motions. A relationship of R_c with IM_{comb} can be established where SS_a in IM_{comb} is computed using values of α that depend on the structure's properties:

$$\alpha = C_\alpha \sqrt{\delta_c/\delta_y} \tag{4}$$

where C_α is found to be optimal at 1.3 (variations are discussed in [10]), and δ_c/δ_y is determined from the system's backbone curve, defined in Table 2 lists the values of the C_{dur} and C_{shape} exponents for both representative systems, optimized for two ground-motion sets. The second set, is compiled by Raghunandan et al. [24], consists of 77 earthquake records, 42 of which are long-duration recordings from large magnitude subduction events, and the remaining 35 are short-duration recordings selected from the FEMA set. This ground motion set is referred to as the crustal/subduction set.

The value of $R^{2,}$ indicates the goodness of fit and also corresponds to the square of the sample correlation coefficient (r^2) in a simple linear regression model. The standard error of the estimate (in log-space), SE_{ln} quantifies the dispersion of the estimate and relative standard error (in log-space), RSE_{ln}, normalized the standard error by the mean of the estimate. The fit using the exponents C_{dur} and C_{shape} are then shown for the two individual ground motion sets in terms of the values of R^2, SE_{ln} and RSE_{ln}. The standardized beta coefficients for the 'ductile' systems, $\hat{\beta}_i^s$, are 21% larger for D_s and 54% in SS_a relative to the 'brittle' system, suggesting that the collapse of ductile structures is more sensitive to the shape of the spectrum and duration. The period of ductile systems elongates more than those of brittle systems before they collapse, making them more sensitive to the shape of the spectrum. This observation is consistent with those of Haselton et al. [7].

Table 2. Optimum C_{dur} and C_{shape} for IM_{comb} for 'brittle' and 'ductile' systems.

Coefficient	Brittle, Quickly Det.		Ductile, Slowly Det.	
	FEMA	Cru/Sub	FEMA	Cru/Sub
C_{dur}	0.07		0.11	
C_{shape}	0.49		0.72	
$\hat{\beta}^{s}_{dur}$	-0.14		-0.17	
$\hat{\beta}^{s}_{shape}$	-0.51		-0.79	
R^2	0.26	0.27	0.65	0.60
SE_{ln}	0.30	0.36	0.27	0.31
RSE_{ln}	0.31	0.33	0.18	0.19

Figure 2 plots the predictor variable R_c with respect to IM_{comb} (computed using the optimized C_{dur} and C_{shape} exponents in Table 2), normalized by S_a. The expected value of the response variable, $E(R_c)$, from the linear regression model is plotted along with the 95% prediction intervals (PI, 95% confidence that R_c lies within this interval). The dispersion can be quantified by the PI, or alternatively, by the relative standard error of the estimate (in log-space) from the regression model (RSE_{ln}). As expected, the R^2 statistics are larger for 'ductile' systems (0.65 and 0.60) than for 'brittle' systems (0.26 and 0.27) for both ground-motions sets. In addition, R_c decreases with increasing IM_{comb}/S_a. This analysis demonstrates that IM_{comb} correlated well with collapse of ductile systems.

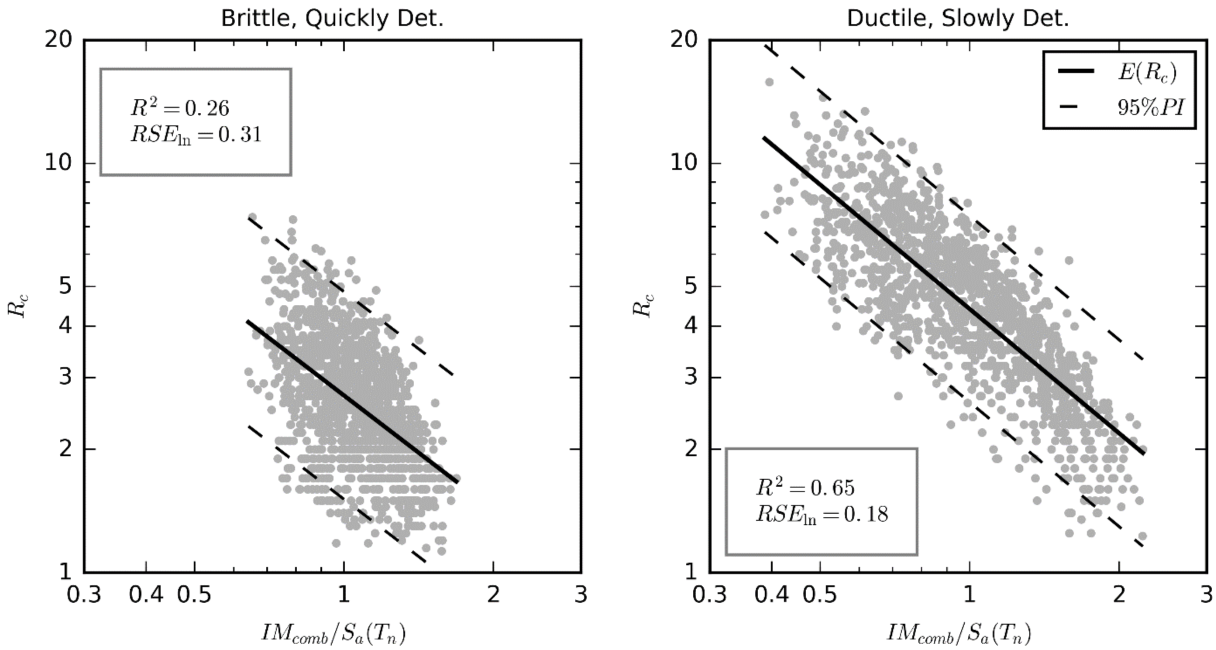
6. Evaluating IM_{comb} Using Analyses of Building Collapse

The new IM was evaluated further using the results reported by Haselton et al. [11]. They report the results of the dynamic collapse analysis for 30 MDOF archetypical reinforced concrete (RC) special moment frame buildings (SMF), subjected to the expanded FEMA ground motion set. The IMs at collapse were computed for each of the building models and for a variety of IMs. To compute IM_{comb}, the μ in SS_a, was extracted from the results of nonlinear, push-over analyses [11]. Instead of the ductility demand, the system ductility, μ_T, was used instead. It was calculated as the ratio of the ultimate roof displacement (80% of the structure's yield base-shear) to the effective roof yield displacement.

6.1 Efficiency of IM_{comb} at Collapse

Efficiency was assessed based on the dispersion of the IM at collapse using mean of the natural-log standard deviation (σ_{ln}) of the IM computed at collapse for the 30 archetypes. When SS_a was computed using $\mu=\mu_T$ for each archetype, the mean σ_{ln} of IM_{comb} at collapse was equal to 0.271 (Table 3). The exponents (C_{dur} and C_{shape}) used to compute IM_{comb} were optimized for the collapse results of the combined 30 archetypes.

The average value of μ_T for the 30 archetypes was 9.2. To simplify the computation of SS_a, a value of $\mu=8$, was used for all of the frames, which is the seismic response modification factor given in ASCE/SEI 7-10 for RC-SMF systems [1]. With this assumption, the mean σ_{ln} of IM_{comb} at collapse increased to 0.275, which was only slightly larger than the value computed using $\mu=\mu_T$. These results suggest that the mean value of σ_{ln} is insensitive to small changes of μ, so only an approximate estimate of μ is necessary.



(a) (b)

Figure 2. R_c with respect to $\frac{IM_{comb}}{S_a(T_n)}$ for (a) 'brittle, quickly deteriorating' system and (b) 'ductile, slowly deteriorating' system for the FEMA ground motion set.

To illustrate the impact of the smaller dispersion of the IM at collapse, Figure 3(a) shows the empirical cumulative distribution of the IM for a particular building archetype along with its fitted collapse fragility function. Both IM_{comb} and the commonly used $S_a(T_n)$ are shown in Figure 2. To allow direct comparison of the results, the IMs have been normalized by the median value of the IM at collapse, $IM_{col,50}$, so that a value of one corresponds to collapse of half of the structures. Figure 3(b) shows the dispersion in the fitted collapse fragility functions of all 30 archetypes was smaller for IM_{comb} than for $S_a(T_n)$. As shown in Table 3, the mean $\sigma_{\ln}$ for IM_{comb} was 0.275, whereas it was 0.404 for $S_a(T_n)$ and 0.401 for S_a computed at twice the initial period to account for structural softening. These results show that the mean $\sigma_{\ln}$ was around 31% lower for IM_{comb} than for $S_a(T_n)$ or $S_a(2T_n)$.

7. Comparing Efficiency of IM_{comb} to Efficiencies of Other Shape IMs

Table 3 compares the efficiency of the proposed IM_{comb} with existing shape IMs and with variations of the new IM for the expanded FEMA set. Table 3 describes each of the IMs; the equation that defines it; and the period range over which the spectral shape intensity measure was evaluated. The comparisons are made in terms of R^2 for R_c in deteriorating systems. For the collapse results for 30 frames, the results are compared in terms of the mean dispersion of the intensity measure at collapse.

To evaluate the efficiency of the new spectral shape intensity measure, SS_a must be isolated from duration. For predicting force-reduction factors, the correlation is made directly with SS_a and other normalized (dividing by S_a) measures of shape. For the collapse results of 30 frames, the efficiency of SS_a is evaluated for a variation of the IM that includes the effects of spectral acceleration and shape (but not duration).

$$IM_{SS_a} = S_a * SS_a^{C_{shape}} \tag{5}$$

where C_{shape} is optimized using the dataset.

The effects of including duration can be evaluated by comparing the IM_{comb} and SS_a rows in Table 3. Ground-motion duration had no significant effect on the ductile MDOF frames. The deteriorating SDOF systems (in particular, the brittle one) were more sensitive to duration. A similar spectral shape IM, SS_d, can be computed using the displacement response spectrum. The results are similar using the acceleration response spectrum (SS_a) or the displacement spectrum (SS_d).

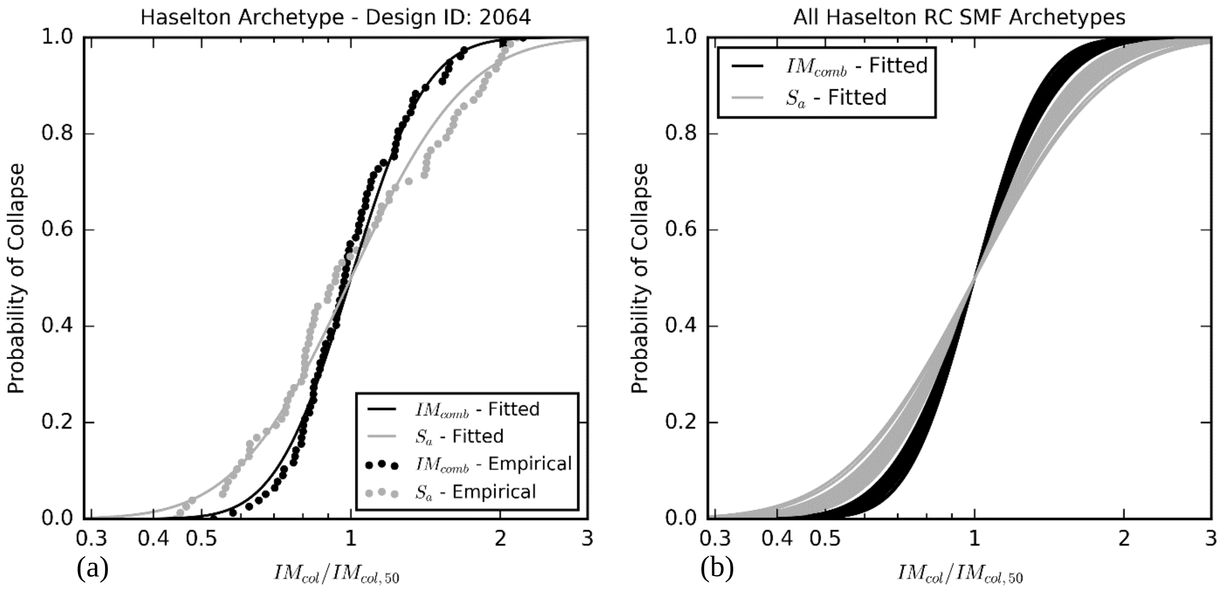


Figure 3. (a) Collapse fragility functions of an RC SMF structural archetype (b) Fitted collapse fragility functions of all Haselton RC SMF archetypes using IM_{comb} and $S_a(T_n)$.

Table 3. IM statistics for the expanded FEMA ground motion set.

IM	Comment	Period range	R^2 for SDOF systems		Mean σ_{ln} of IM at collapse for 30 RC moment frames	
			R_c 'Brittle'	R_c 'Ductile'	$\mu = \mu_T$	$\mu = 8$
S_a	Elastic spectral acceleration using 5% damping	T_n	-	-	0.40	
		$2T_n$	-	-	0.40	
IM_{comb}	Includes, S_a, D_s, and SS_a, Eq. 3	T_n-αT_n	0.35	0.68	0.27	0.27
SS_a	Arithmetic mean using μ dependent period range, Eq. 11	T_n-αT_n	0.21	0.60	0.27	0.28
SS_d	Arithmetic mean of displacement response spectrum using μ dependent period range, Eq. 11[1]	T_n-αT_n	0.20	0.61	0.27	0.28
S*	Accounts for S_a at two periods Cordova et al. [15]	T_n, $2T_n$	0.18	0.55	0.31	
$S_{a,geo}$	Geometric mean using period range as recommended by Bojórquez et al. [17]	T_n-$2T_n$	0.20	0.52	0.34	
$S_{a,geo}$	Geometric mean using period range as recommended by Eads et al. [8]	$0.2T_n$-$3T_n$	0.23	0.58	0.30	
$S_{a,geo}$	Geometric mean using μ dependent period range	T_n-αT_n	0.14	0.57	0.27	0.28

Note: $\alpha = 1.3\sqrt{\mu}$

[1]The IM was computed using SS_d instead of SS_a.

In Table 3, the normalized measures of SS_a, S*, and $S_{a,geo}$ have been transformed into log-scale, and their exponents have been optimized to achieve the largest possible R^2 statistic (or minimum mean σ_{ln} of IM at collapse). $S_{a,geo}$ were computed using period ranges that were recommended by Bojórquez et al. [17] and Eads et al. [8]. SS_a had a higher R^2 (or lower σ_{ln} of IM at collapse) than the existing IMs for all of the analyses but one. For brittle, deteriorating systems, the R^2 was 0.23 for $S_{a,geo}$, whereas it was slightly lower (0.21) for SS_a.

The benefits of using the arithmetic versus the geometric mean of S_a values can be evaluated by comparing SS_a to $S_{a,geo}$ for the same period range. For all analyses, the statistics were preferable for the arithmetic mean (SS_a) than the geometric mean ($S_{a,geo}$). In particular, Table 3 shows that R^2 increased up to 50% for the 'brittle' system (0.14 to 0.21).

8. Conclusions

A new ground-motion intensity measure, IM_{comb}, has been developed to account for the effects of spectral acceleration, duration, and spectral shape. IM_{comb} characterizes ground-motion duration in terms of significant duration, D_s. IM_{comb}, also incorporates a new measure of spectral shape, SS_a, which corresponds to the normalized integral of the response spectrum over a ductility dependent period range. The form of IM_{comb} (Eq. 3) makes it scalable and transparent. The transparency of the IM made it possible to identify the effects of duration and spectral shape on the response of various systems. For example, the spectral shape affected all structures, but in particular, ductile structures.

An efficient IM enables engineers to either evaluate structures with fewer ground motions or to predict structural performance with higher degrees of certainty. Compared with existing IMs, IM_{comb} is more efficient in predicting force-reduction factors for collapse in brittle and ductile deteriorating SDOF systems (R_c). The new IM also results in lower dispersions of the IM at collapse for 30 RC SMF archetypes [11]. The improved efficiency is attributable to the inclusion of duration and a ductility dependent measure of spectral shape. This ductility dependence makes the IM structure specific (i.e., less structure independent).

Though not discussed here, the new IM is versatile enough to evaluate the intensity of recorded and simulated ground motions, even in the absence of GMPEs [10]. To incorporate the IM into traditional PSHA, it would be necessary to develop GMPEs for spectral shape, at which time the predictability of the IM could be evaluated. A sufficient IM enables engineers to select ground motions for nonlinear dynamic analyses of structures without considering source and site parameters. The IM_{comb} is sufficient to parameters like M and R where it's sufficiency is discussed in Marafi et al. [10].

The recommended values of the exponents, C_{dur} and C_{shape} used in IM_{comb} are listed in Table 2. These values have been optimized using SDOF systems of two representative system types. Further work is needed to evaluate the variability of the exponents for a wider variation in structural systems.

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