PERFORMANCE OF NONLINEAR RESPONSE OF STRUCTURES AS FEATURE INDICES FOR THE SELECTION OF DESIGN GROUND MOTIONS

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For dynamic analysis of structures, selection of ground motion (GM) is a crucial problem. For design, a tough GM should be used. It is difficult, however, to find such GM, because different GM can be the toughest in terms of different aspect. Uncertainty of structural properties complicates the problem. In this paper, an approach is presented to select design GMs out of a set of possible GMs using feature indices which are related with expected damage mechanisms of the structure. Uncertainty of nonlinear response is also incorporated. Quality of the GM selected in this scheme depends on the index considered. This paper discusses the efficiency of various indices through numerical simulations. Results verify the performance of the presented method and clarify several conditions to be taken into consideration.

***Key words**: Design input motion selection, Feature indices, Damage mechanism*

1. INTRODUCTION

GMs to be considered in the design include GM records from the past earthquakes such as 1995 Kobe earthquake, GM records generated by numerical simulation[1), 2)] and those specified by the design codes. However, GMs available from these resources are huge in number, and it is required to select finite (hopefully small) number of GMs to be considered in the design.

In the selection of GMs, a GM that is the “toughest” among possible GMs should be chosen. It is difficult, however, to find such GM, because, due to complexity of nonlinear behavior, the “toughest” GM in terms of one aspect may not be the “toughest” in terms of other aspects.

Additionally, limited knowledge of behavior of structures in nonlinear range and uncertainty of seismic activity make the selection more difficult, because sophisticated techniques such as Nonlinear Seismic Analysis (NSA) are sensitive to change in various parameters.

Due to these reasons, we must admit that the reliability of the design GM is limited due to the existence of uncertainty and unpredictability of both structural response and ground motions.

Realizing that the NSA is essential to look into the structural performance in nonlinear range and the sophisticated techniques to improve the reliability of output of NSA are not free from uncertainty, it is essential to select a GM for NSA by paying due attention to limitations of lack of knowledge of structural response in nonlinear range and uncertainty of structural and seismic activity.

2. OBJECTIVE

A number of available GM selection techniques incorporated indices for the evaluation of effectiveness of GM. But due to complexity of nonlinear dynamic response, variety of structural types, stochastic nature of dynamic characteristics of structures, it is difficult to select the appropriate indices for a general problem of structural design. Authors also proposed a method for the selection of appropriate indices out of available indices, and hence used such indices for selection of design GM[3)]. In that method, selection of indices is based on the correlation of indices with possible damage mechanisms of structure, and GM which is tough in terms of the selected indices would be capable to trigger the possible damage mechanism and hence should be used as design GM. Detail of the efficiency of such indices, however, have not been clarified yet. In this paper, we discuss the performance of various nonlinear response values as indices for the selection of GM in the presence of uncertainty of structural characteristics and ground motion characteristics.

3. STATE-OF–THE-ART: REVIEW OF GM SELECTION USING FEATURE INDICES

The design GMs could be selected from records of past earthquakes[4),5),6)] or those generated by simulation techniques[1), 2)] . In both situations, it is accepted that the “toughest” GM should be employed.

Indices for selection of GM can be classified into two groups. First group consists from statistical information of GMs. The indices based on statistical information of GM signal are linked with peak values in signal, duration of signal, distribution of frequency contents of signal etc. Also included are peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), maximum incremental velocity (IV), maximum incremental displacement (ID) and duration.[7)] It has also been shown that PGV is a proper intensity measure candidate for deformation demands on SDOF systems.[8),] G. Manfredi proposed representative index I_D which relates the PGA, PGV, duration of GM and ground accelerations .[9)]

The second group of indices is related with response of simple structural systems[10)]. Park and Ang proposed in 1985 that seismic structural damage is expressed as a linear combination of the damage caused by excessive deformation and that contributed by repeated cyclic loading effect.[11)] This index is frequently used to quantify nonlinear response of strucutres.[12)] Some damage indices are proposed in terms of ductility and stiffness degradation due to damage experienced by the structure.[13)] Selection of the design GM by taking into account the structural nonlinear response and characteristics of GMs simultaneously, such as response of a single degree of freedom (SDOF) system of natural frequency similar to natural frequency of multi degree of freedom system is an efficient way to quantify the efficiency of GM for that structure. A number of procedures are available to get an equivalent SDOF system for multi degree of freedom system[14)]. In all such techniques, global stiffness and yield strength of the structure is assessed to get the equivalent SDOF system.

Credibility of index-based GM selection methods and evaluation of structural performance by indices is deteriorated due to two reasons. One is that, there is no single index that can perfectly evaluate various aspects of characteristics of nonlinear behavior of structures. The other is that index values are affected by uncertainty of structural characteristics.

4. SELECTION OF DESIGN GROUND MOTION USING DAMAGE-MECHANISM-BASED INDICES

The design GM should be relatively strong or influential for the behavior of the structure in concern, compared to other possible GMs. It should be admitted, however, that there is no knowing how a GM would affect the structure before that is actually applied to the structure.

To handle this problem, we first consider possible damage mechanisms. Then we selected feature indices that are supposed to be associated with the mechanisms. Selection of design GMs out of a set of possible GMs are conducted using these feature indices. It is expected that GMs which are strong in terms of these indices are expected to be influential for the target structure.

(1) Damage-Mechanism-Based Feature Indices

Effectiveness of the indices presented by various researches is conditioned with the selection of proper index for the problem under consideration. In this paper, the knowledge of such indices is incorporated to measure the effectiveness of GMs by appropriately selecting the indices.

The indices should be simple and stable. Most of them are defined using response of simple spring mass systems. Such indices cannot be an exact representation of nonlinear response of structural systems, due to the following reasons:

- Due to complexity of nonlinear response and uncertainty of structural characteristics, behavior of the structure can be different when structural characteristics change.
- Mechanism of behavior of simple system may not be identical with that of the structure.
- Different GM is considered as strong in terms of different indices.

Considering these issues, in this paper, we take following procedure:

- We consider a range of properties of indices in order to discuss the influence of uncertain structural characteristics of the target structure, when evaluating the values of feature indices.

- We use multiple feature indices that are supposed to be associated with possible damage mechanisms of the structure. The indices are utilized to represent quantitatively the characteristics of GMs. GMs which are efficient in terms of these indices are considered to be likely to trigger damage on the structure.

(2) Conditions for the Selection of Design Ground Motions

The design GM should be selected so that probability (P) of occurrence of damage(D)under the condition that the structure is designed against some GM(GM) is smaller than a certain value $(\bar{P})$.

$$P = prob(D|GM) < \bar{P} \tag{1}$$

The value of probability (P) depends on the selected design GMs. Since we cannot know the influence of a GM on the structure in advance, we need to select design GMs randomly from those GMs which satisfy the specified conditions (C). Therefore we should consider the probability that Equation (1) is satisfied when GM is randomly selected based on the condition (C). This probability can be regarded as reliability(R), which can be written as

$$R = prob[\{prob(D|GM < \bar{P})\}|C] \tag{2}$$

In this procedure, feature indices are used in the condition (C). If design GMs are selected based on multiple indices, which consider various possible damage mechanisms, reliability (R) is expected to be higher than the one selected by using conventional schemes. The reliability will be improved, if the multiple indices consider wider aspects of damage mechanisms in the structure.

The exceedance probability of feature indices is incorporated to evaluate the effectiveness of GMs. The probability of the *i*-th GM among possible GMs in terms of indices $k = 1,2,3, ...$

$$p_i = prob(v_n^1 > v_i^1 \| v_n^2 > v_i^2 \| \ldots) \tag{3}$$

where v_i^k denotes the value of the *k*-th index against the *i*-th GM, and *n* is the number of GMs. For the *i*-th GM, if exceedance probability in terms of feature indices $(p_i)$is small, the probability of occurrence of damage due to the *i*-th GM, $prob(D|GM)$, is also expected to be small. This leads to the condition (C) for the selection of design GMs.

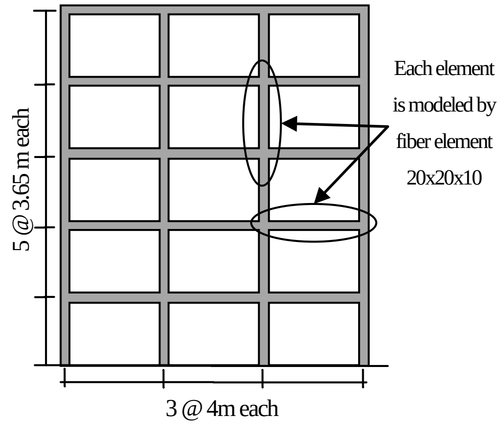


Figure 1 Elevation of concrete frame

For example, we can select a GM for which exceedance probability in terms of indices, p_i, is close to a certain value, say $\bar{p}$, which can be taken identical with $\bar{P}$ in Equation (1), as:

$$p_i \cong \bar{P} \tag{4}$$

Reliability of the GM selected by this scheme depends on the quality of selected indices.

Let us discuss about this aspect through numerical simulations in the following sections.

5. NUMERICAL SIMULATIONS

Here we discuss the performance of the GM selected using feature indices. Design GMs which satisfy the condition are selected for a two dimensional five story three bay concrete frame out of a number of GMs. Performance of GMs selected using different indices in the representation of condition (C) is compared.

(1) A Set of Possible Ground Motions

To formulate the set of possible GMs to be considered for the design of structures to enhance the reliability of structural performance, the 450 GM records from past earthquake events are obtained from K-NET[4]. It would be possible to generate such ground motions using numerical techniques. We use actual GM records, in order to discuss the applicability of the presented scheme for real ground motions. The GM records are factored so that their peak ground acceleration values are ranging between 600cm/sec^2 to 800cm/sec^2.

Table 1 Detail of beam and column sections

	Width [cm]	*Depth [cm]*	*Reinforcement*
Column	*38*	*38*	*19mm dia. 22 bars uniformly distributed on all faces*
Beam	*30*	*38*	*Top. 19 mm dia. 7 bars Bot. 19 mm dia. 7 bars*

(2) Structural Model and Uncertainty of Structural Performance in Nonlinear Range

Design GMs are selected for a moment resisting concrete frame, elevation of the frame is shown in Figure 1 and sectional details are shown in Table 1. This structure here after referred to as target structure. The dead load for the nonlinear analysis (NA) is contributed by the self weight of members beam, columns, concrete slab and weight of floor finishes. Nonlinear dynamic analysis is conducted by using OPENSEES[15)]

Elements of frame are modeled by using unidirectional steel and concrete fibers, which are characterized by stress strain relationships. To characterize stress strain curve for the fibers of concrete and steel different models are available as recipes in OPENSEES. Among material models available on OPENSEES, `Concrete02` model is used to model confined and unconfined concrete. The stress strain curve for concrete model is shown in Figure 2. Tensile strength of concrete is also considered in this model. Parameters to model stress strain curve for concrete are summarized in Table 2.

Similarly, material model `Steel02`[15), 16)] of OPENSEES is used to characterize the stress strain behavior of steel fiber. In this model we can control the transition from linear to nonlinear stage. The stress stain curve for this steel model is shown in Figure 3, the model parameters are tabulated in Table 3.

In order to consider the fluctuation of material property, we assume material properties of elements are independent stochastic variables. Yield strength of steel, modulus of elasticity of steel and compressive strength of concrete are considered as stochastic variables. Parameters of stochastic properties are listed in Table 4. (Material property of concrete model is a function of compressive strength of concrete, and it is affected by the change of compressive strength.)

Results of a nonlinear analysis against one of the possible GMs are shown here as an example. Displacement response of floors are shown in Figure 4, while the stress strain curve of steel fiber of an end column of first floor are plotted in Figure 5. OPENSEES calculates the strain of each fiber against the deformation of member. Such strain of columns is used to quantify the effect of

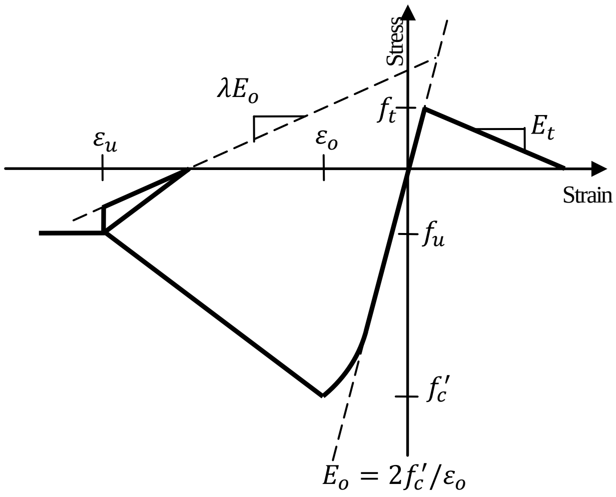


Figure 2 Stress strain model for concrete `Concrete02`[15)]

Table 2 Properties of concrete model `Concrete02`

f_c' = compressive strength of concrete (Mpa) (Subjected to uncertainty)	- 27.57
f_u = ultimate strength of concrete	$0.2 * f_c'$
f_t = tensile strength of concrete	$0.14 * f_c'$
ε_o = strain at compressive strength	-0.003
ε_u = strain at ultimate strength	$5 * \varepsilon_o$
E_o = initial stiffness	$2f_c'/\varepsilon_o$
λ = unloading stiffness to initial stiffness ratio	0.1
E_o = tension softening stiffness	$f_t/0.002$
Ratio of confined to unconfined compressive strength of concrete	1.3

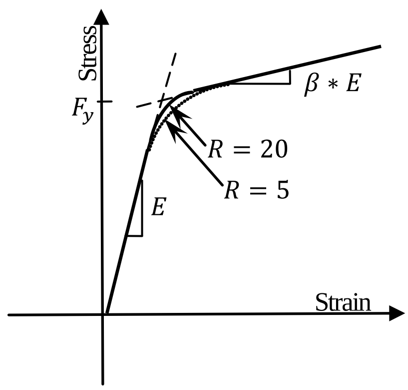


Figure 3 Stress strain model for `steel02`[15), 16)]

Table 3 Parameters of steel model used in simulation

Parameter	*Value*
E	*250 Mpa (subjected to uncertainty)*
F_y	*200,000(subjected to uncertainty)*
β	*0.18*
R	*18*

GM on structure..

(3) Quantification of damage of structure

Let us consider the quantification of severity of damage in the structures. Damage level caused by GMs is assessed by comparing maximum strain experienced by steel rebar of each member of the structure. Let ε_m^i denote the strain of the rebar of the *m*-th structural member when the structure is exposed to the *i*-th GM. Suppose that the *d*-th GM is the design GM, then ε_m^d is regarded as reference value of strain of the *m*-th structural member. Here we define the structure is damaged, if strain of half of columns exceeds the value given for each member by the design GM.

Strength of the design GM can be quantified by considering the probability that the structure designed by the *d*-th GM is damaged when it is exposed to all possible GMs. It can be written as

$$P_d = prob\left[\frac{\sum_{m=1}^{M} \mathrm{Ind}\{\varepsilon_m^n > \varepsilon_m^d\}}{M} > \frac{1}{2}\right] \qquad (5)$$

where M is the number of elements; n is the script to denote GM; ε_m^i denotes the strain of steel bar of the *m*-th structural member caused by the *i*-th GM; and $Ind\{C\}$denotes an indicator function that is given as

$$\mathrm{Ind}\{X\} = \begin{cases} 1, & \text{if condtion X is true} \\ 0, & \text{otherwise} \end{cases}$$

Table 4 Parameters of stochastic material-properties

Properties	Yield Strength of steel rebar (fy) Mpa	Modulus of elasticity of steel rebar (E) Mpa	Compressive strength of concrete (fc') Mpa
Mean	250	200,000	27.5
Standard deviation	5%	3%	7%
Distribution type	Normal	Normal	Normal

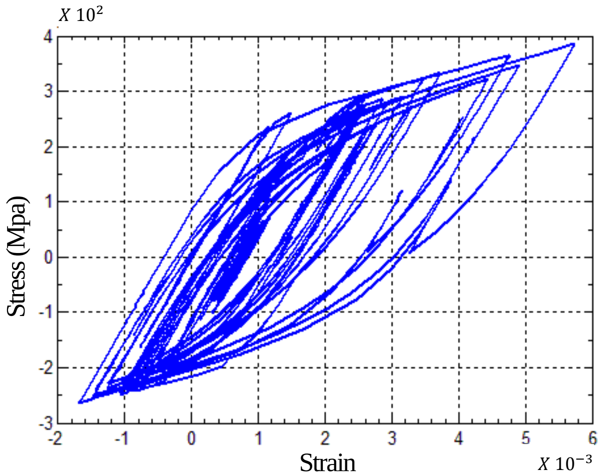


Figure 5 Stress strain response of steel fiber of ground floor column at maximum stressed section

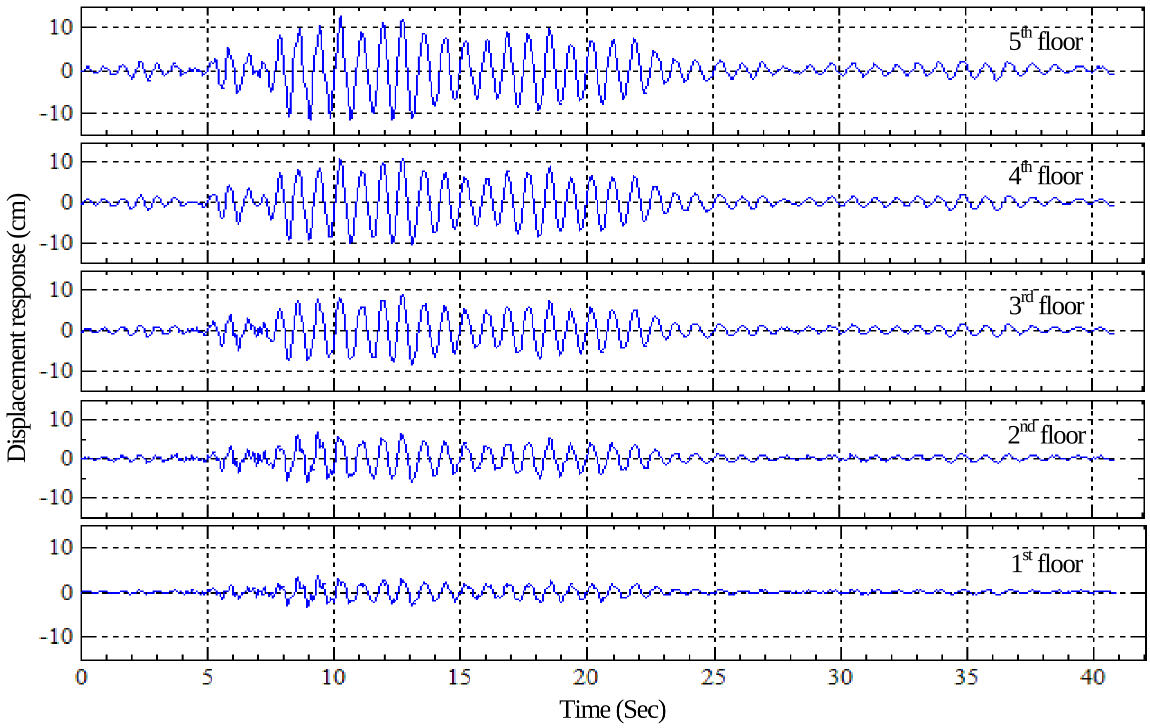


Figure 4 Displacement response of concrete frame against a random GM out of set of possible GMs

(4) Possible Damage Mechanisms

For the target structure, it is assumed that the ultimate failure will be contributed by one of the following three damage mechanism or combination of them.

- Excessive deformation of structure due to oscillation in the first mode: The most probable damage is due to excessive deformation of structure when structure is oscillating in the lower order modes.
- Damage due to maximum inter-story drift: The failure of this concrete frame could be caused by excessive inter-story drift. The GMs, whose frequency contents are closer to those of higher modes of the structure, will trigger such damage. In such case, damage of the structure will not be limited to lower part of the structure.
- Damage due to cyclic nature of GM: Failure can be caused by the accumulation of damage due to cyclic excitation force. Damage at each story could be quantified by the amount of energy dissipated at that story level.

It is important to mention that damage of a structure is not caused by a unique mechanism, but that rather it is due to combination of some mechanisms. The indices which are associated with these damage mechanisms are supposed to be appropriate tools to use in the selection of design GMs, because GM which will be tough in terms of these indices will be efficient to trigger the damage mechanism and hence should be considered as design GM. Let us discuss the selection of appropriate indices to consider the damage mechanisms in the next section.

(5) Candidate Indices and Efficiency of Candidate Indices

This section compares the performance of feature indices that are supposed to be associated with the damage mechanisms listed above. Eight candidate indices are considered. Four of them are response values of the bilinear SDOF systems whose natural period corresponds to the first mode of the target structure, such as displacement response (D1), velocity response (V1), acceleration response (A1) and dissipated energy (E1). Remaining four indices are those of the SDOF system corresponding to the second mode of target structure. They are displacement response (D2), velocity response (V2), acceleration response (A2) and dissipated energy (E2) .

Excessive deformation of the structure due to oscillation in the first mode is first possible damage mechanism. Let us refer to the displacement of top node of concrete frame as an evaluation factor I. Target structure, which is discussed in Section 5.2, is exposed to a set of possible GMs and value of *I* is evaluated. Relative exceedance probability of the *j*-th GM (P_j) as compared to other GMs is

$$P_j = prob(I_n > I_j) \tag{6}$$

Since the set of GMs is fixed, P_j is regarded as normalized rank of the *j*-th GM in terms of damage index among those possible GMs and can be evaluated as

$$P_j = \frac{\sum_{n=1}^{N} Ind\{I_n > I_j\}}{N} \tag{7}$$

where, *N* is number of GMs, and $Ind\{C\}$ is an indicator function as defined earlier.

Values of eight indices are evaluated for set of possible GMs. As properties of SDOF systems are function of uncertain structural characteristics, it is important that indices should reflect the uncertain structural characteristics. SDOF systems are used to evaluate the GMs in context of target structure, but we cannot know the exact relationship between the values of parameters of SDOF system and that of target structure. Thus we consider noise to the parameters of SODF system. For each GM, a set of 10 SDOF systems is formulated by randomly selecting the properties out of the selected range of SDOF parameters, and the average of ten results is used as the value of each index. These indices are used to define the exceedance probability of each of possible GMs. Similar to Equation (6), exceedance probability of *j*-th GM in terms of index *k* is defined as

$$p_j = prob(k_n > k_j) \tag{8}$$

Since the set of GMs is fixed, and p_j is regarded as the normalized rank of the *j-th* GM in terms of index *k*, among possible GMs. It is expressed as

$$p_j = \frac{\sum_{n=1}^{N} Ind\{k_n > k_j\}}{N} \tag{9}$$

For each of possible GMs, the rank in terms of evaluation factor (I) and in terms of eight candidate indices are evaluated from Equations (7) and (9), respectively, and plotted in Figure 6.

Coefficient of covariance (CoV), which is given for two indices X and Y as

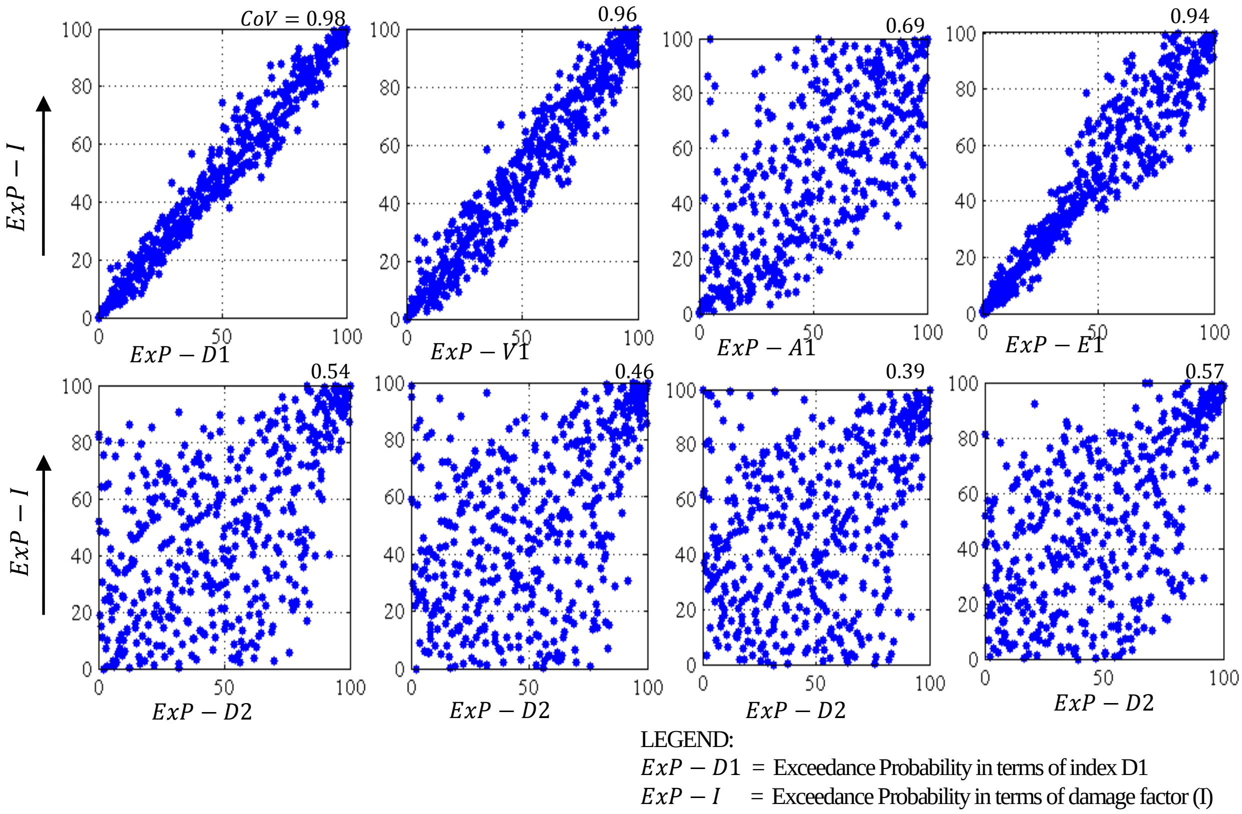


Figure 6 Exceedance probability of damage quantification factor in MDOF for possible damage mechanism against the exceedance probability in terms of eight candidate indices

Table 5 Coefficient of covariance for the distribution of exceedance probability of possible damage mechanism and exceedance probability of eight candidate indices

Indices / Damage Quantification factor	Indices based on response of SDOF corresponding to first mode of MDOF					Indices based on response of SDOF corresponding to second mode of MDOF			
	Disp. (D1)	Vel. (V1)	Acc. (A1)	Disp. Energy (E1)		Disp. (D2)	Vel. (V2)	Acc. (A2)	Disp. Energy (E2)
Disp. of top node of MDOF	0.98	0.96	0.69	0.94		0.54	0.46	0.39	0.57
Drift at 5th floor	0.52	0.55	0.45	0.51		0.75	0.72	0.68	0.78
Drift at 4th floor	0.80	0.84	0.60	0.76		0.79	0.72	0.64	0.79
Drift at 3rd floor	0.91	0.89	0.68	0.89		0.44	0.36	0.30	0.48
Drift at 2nd floor	0.94	0.93	0.67	0.91		0.61	0.54	0.48	0.65
Drift at 1st floor	0.85	0.85	0.61	0.83		0.69	0.62	0.56	0.72
Disp. Energy at 5th floor	0.15	0.16	0.20	0.19		0.43	0.41	0.41	0.50
Disp. Energy at 4th floor	0.57	0.61	0.44	0.55		0.81	0.77	0.71	0.82
Disp. Energy at 3rd floor	0.46	0.42	0.39	0.51		0.12	0.07	0.06	0.18
Disp. Energy at 2nd floor	0.70	0.70	0.51	0.69		0.51	0.46	0.41	0.56
Disp. Energy at 1st floor	0.33	0.35	0.26	0.34		0.49	0.50	0.49	0.53

$$C^R(X,Y) = \frac{C(X,Y)}{\sqrt{Var(X)Var(Y)}} \tag{10}$$

where $C(X,Y)$ denotes the covariance. CoV is calculated for each of eight indices, and mentioned on sub-plots of Figure 6 correspondingly. It is clear from Figure 6 that CoV values are in accordance with the scatter of plot. For example, plot for D1 is least scattered and corresponding value of CoV =0.98 which is the highest among eight indices. Hence, D1 is most correlated with first possible damage mechanism. Values of CoV for eight indices are tabulated in the first row of Table 5.

For the second and third possible damage mechanisms, the maximum inter-story drift and dissipated energy are used as quantification factor. Similar to the first damage mechanism, values of CoV are evaluated for these damage mechanisms and tabulated in row two to eleven of Table 5. For second and third damage mechanism, it is clear from Table 5 that at different floor levels different indices are effective to consider these damage mechanisms. Thus multiple indices are required to represent these damage mechanisms.

6. COMPARISON OF PERFORMANCE OF GM SELECTED BY VARIOUS INDICES

This section discusses how reliability of the GM is affected by the property of indices used in the selection of GM. We consider three types of combination of indices and compare the performance of the selected GMs.

(1) Reliability of GM selected by indices

Here we consider the reliability of selected GM. Reliability *R* is defined in Equation (2) and it is determined by the condition *(C)*. In the following example, we consider the case where $\bar{P} = 40\%$. Condition (*C*) can be given as Equation (4). If the index is perfectly correlated with the behavior of the target structure, it should be satisfied that $\bar{p} = \bar{P}$. If qualities of the indices are good, this equation should be satisfied by relatively small error.

Exceedance probability, or normalized rank of the *i*-th GM (p_i) in the set of possible GMs, is evaluated by Equation (3). When single index x^1 is used in the selection of the design GM, for example, it is given as

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1\}}{N} \tag{11}$$

Then the GM that satisfies Equation (4) should be selected. In the numerical simulation, as design exceedance probability (DEP) value is taken as 40%, GMs with the exceedance probability within the range of $40 \pm 5\%$ in terms of indices are selected. Similarly, when two indices are considered, the exceedance probability is given as

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1 \| x_n^2 > x_i^2\}}{N} \tag{12}$$

and when three indices are considered, given as

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1 \| x_n^2 > x_i^2 \| x_n^3 > x_i^3\}}{N} \tag{13}$$

Probability of occurrence of structural damage, P_d , is evaluated by Equation.(5) and the procedure of evaluation is described in section 5.3.

(2) Reliability of GM Selected by Indices Associated with the First Mode of the Structure

Let us first consider the indices that are response values of SDOF system with the natural frequency identical with that of the target structure. Considered indices are D1, V1 and E1, or displacement response, velocity response and dissipated energy of the SDOF system. Table 5 shows that CoV of D1, V1 and E1 are at the almost same level for all three damage mechanisms.

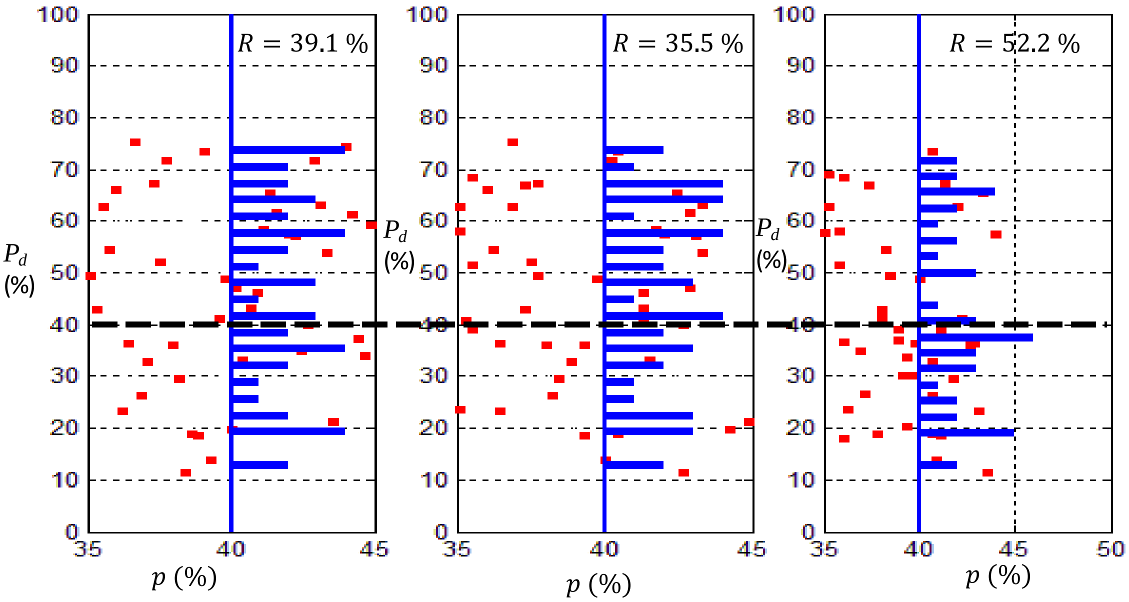
For the selected GMs, probability of structural damage occurrence, P_d , is plotted against the exceedance probability in terms of index D1 in Figure 7 (a).

The GM, for which probability of structural damage occurrence is less than 40%, is considered to have the intended performance. The reliability is given as *R* = 39 %. It indicates that if you select the GM solely based on index values, D1, probability that the selected GM satisfies the condition is 39%.

Figure 7 (b) shows the results when two indices, D1 and V1, are used. For this case, reliability is given as *R*=35.5%.

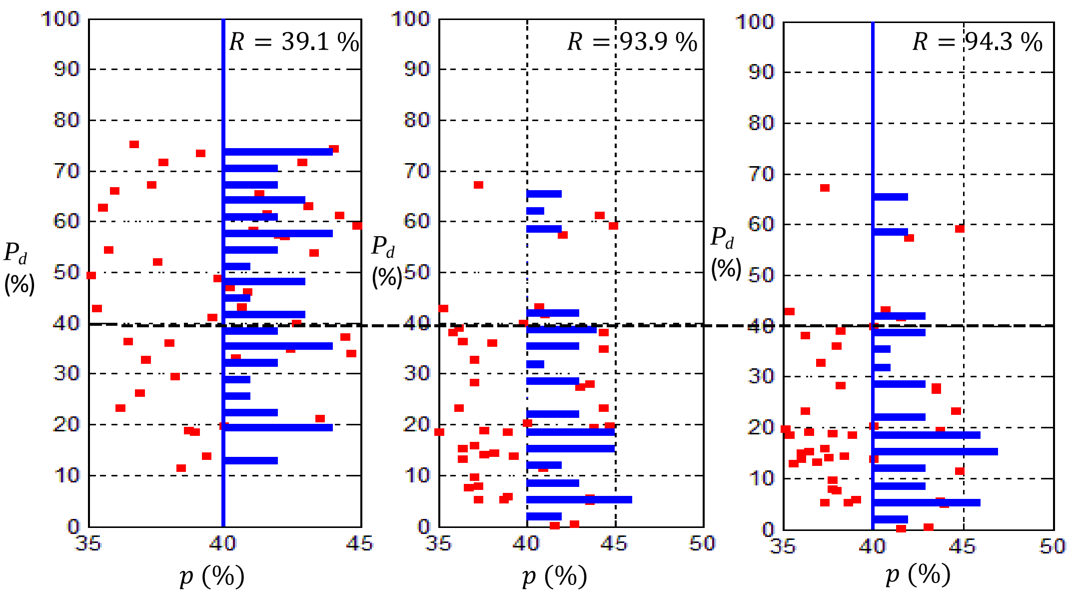
Finally, design GM are selected by using three indices D1, V1 and E1by repeating the procedure as or first case. The results are plotted in Figure 7(c) and reliability *R*=52.2%.

These results show that the reliability of more than one index did not improve the reliability considerably. This is because all three indices considered here are peak response of the same SDOF system.



a) D1 as index b) D1 and E1 as indices c) D1, E1 and V1 as indices

Figure 7 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices



a) D1 as index b) D1 and E2 as indices c) D1, E2 and E1 as indices

Figure 8 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices

(3) Reliability of GM Selected by Indices that are Highly Correlated with the Nonlinear Response

In Table 5, first row shows CoV between the eight indices and first possible damage mechanism, which is damage contributed by excessive deformation of structure due to oscillation in fundamental mode. It is shown that D1 is the most correlated among the candidate indices.

For the second and third possible damage mechanisms, the results are summarized in rows 2 to 1 of Table 5. No single index shows high correlation with the second and third possible damage mechanisms of all floors. It is observed that for the fourth and fifth floor, E2 shows high correlation for both the second and third mechanisms. Also observed is that for the first to third floor, E1 is among the highest for both second and third mechanism, but for the third damage mechanism of the first floor, E2 shows the highest.

From these results, we consider D1, E1 and E2 as highly correlated with the possible damage mechanisms. We discuss the performance of the design GM selected by these indices or combination of these indices, considering the case using one index D1, two indices of D1 and E2 and, three indices of D1, E1 and E2. Probability of damage occurrence and exceedance probability in terms of these indices are presented in Figure 8.

Comparison of Figure 8 (a) and (b) shows that reliability of the design GMs increases significantly from 39 % to 94 % by using two indices D1 and E2 instead of one index D1. It is conjectured that this is because index E2 represents different aspects, dissipated energy and the second oscillation mode, of GM characteristics from those represented by D1, displacement and the first oscillation mode. It indicates that consideration of different aspects enhanced the reliability of the selected GM.

Reliability of the design GMs selected by D1, E1 and E2, whose probability of damage occurrence is plotted in Figure 8 (c), is 94.3 %. The improvement from two-index case is not so large. It is inferred here that aspects considered by an additional index, E1, the dissipated energy and the first mode oscillation, are already covered by indices D1 and E2, and contribution of the E1 is not obvious in that sense. It could be pointed that the value of 94% of the two-index case was already too high to expect further improvement.

In order to verify our conjecture, we also consider the same problem increasing the targeted probability of damage occurrence. Design GMs are selected for DEP value of 60% using the same set of indices. The results are plotted in Figure 9 and they exhibit the same trend, verifying our conjecture.

(4) Reliability of GM Selected by Indices that are Less Correlated with the Nonlinear Response

We also discuss the performance of GMs selected based on the indices whose CoV are relatively low. Considered indices are A1, V2 and A2. Performance of design GMs selected by using three combinations of indices, which are A1 and E1, D2 and V2, and D2 and A2 are evaluated. In each combination, one of the two indices is a less correlated index.

Probabilities of occurrence of damage for them are plotted in Figure 10. The reliability values for the three combinations are 60.5, 50.9, and 57.2%, respectively. This shows that the reliability of design GMs selection is higher than the case with indices associated with the first mode of the structure, which is discussed in section 6.2. It indicates that consideration of wide variety of aspects of GM characteristics could help us to select a design GM with higher reliability, even if the performance of the additional index itself is not so high.

(5) Selection of Indices for the Selection of Design GMs.

Results presented above lead to several conditions for the appropriate indices for the selection of design GM. It can be summarized as follows.

First, as is widely recognized, indices related with possible damage mechanisms are appropriate for the selection of design GMs. Secondly, reliability of the selected GM is improved if wider variety of aspects of GM is considered in the selection of design GMs. As the third point, it can be noticed that if you add new index to the existing indices for the selection of design GM, it would be effective for the improvement of reliability, if that covers different aspects of characteristics of influence of GM on structures. This is the case even if the added index itself does not have strong correlation with the behavior of structures. It also indicates that if newly added index has a good correlation with some damage mechanisms, its inclusion does not improve the reliability considerably, if that aspect is already considered by existing indices.

7. Conclusions

Selection of design GM is a crucial stage in the design process based on nonlinear dynamic analysis of structures. In this paper, we presented a method to select design GMs out of possible GMs by using appropriate indices.

First we define the reliability of the design GM as the probability that the probability of the intended

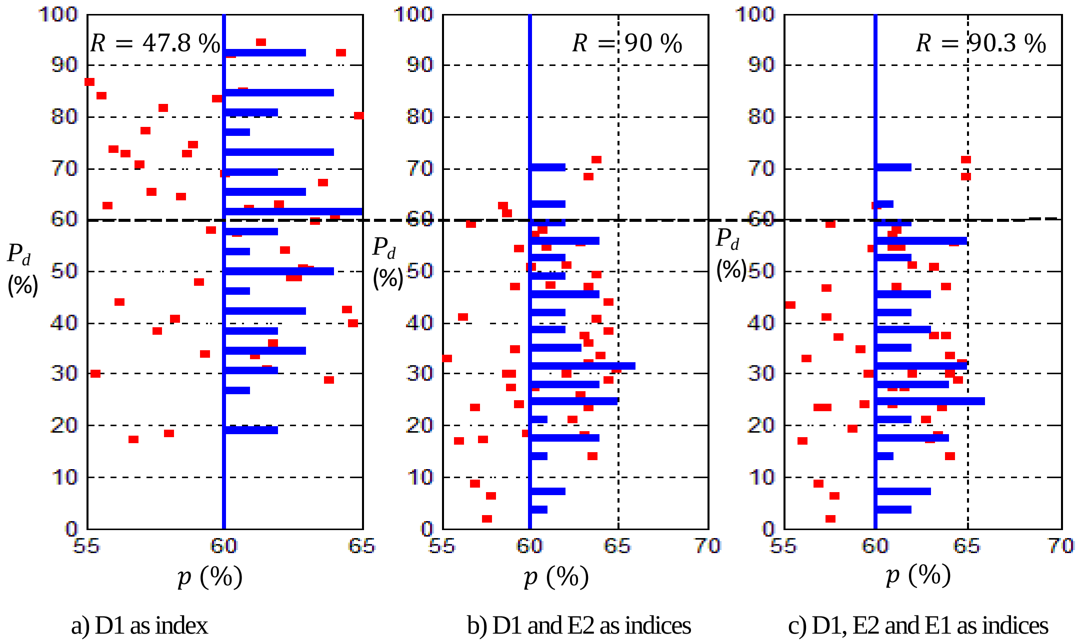


Figure 9 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices

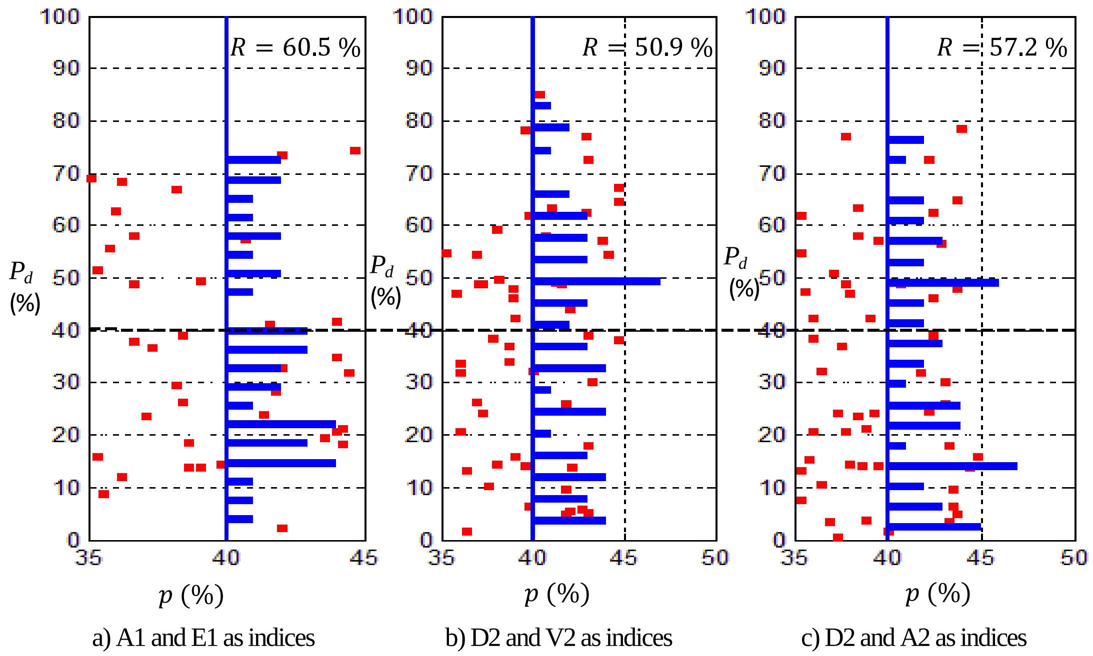


Figure 10 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices

performance is realized when design GM is selected based on certain conditions. We present the scheme to formulate the condition using indices that are associated with GM characteristics of both ground motions and structures. We assume possible damage mechanism which could be inferred from the structure, and then define the index that is supposed to be correlated with them.

Next we consider the performance of the GM selected by those indices. It is shown that no single index could serve as the perfect index that can represent the characteristics of influence of GM on nonlinear behavior of structures. We propose to use more than one index and discuss what kind of combination of should be utilized for the selection of design GM. It is also discussed that how the reliability should be defined using multiple indices.

Numerical simulation is conducted assuming a five story RC moment resisting concrete structure as the target structure. The results indicate several conditions for the indices to be used in the selection of design GMs. Firstly; index corresponding to damage mechanism is efficient for the selection of good design GMs. It is also shown that it is useful to use indices so that it can cover the wider variety of aspects of GM on structural behaviors.

These findings should be further verified through various numerical simulations and investigation of damage of structures in the past earthquakes.

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