Design ground motion synthesis based on feature indices considering nonlinear response of structures

(構造物の非線形挙動を考慮した特徴指標にもとづく設計地震動の合成)

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ABSTRACT

Selection of design ground motion is an important and influential aspect of seismic design. The selection of design ground motion is affected by the uncertainties of seismic event and unpredictability of nonlinear response. To enhance the reliability of design ground motion selection, it is inevitable to incorporate the afore mentioned uncertainties in the selection/synthesis of design ground motion. For selection of a representative ground motion out of possible input ground motions, it is necessary to evaluate the effect of ground motions on the structure considering the complexity of nonlinear response. This cannot be done, however, by using conventional indices such as peak ground acceleration (PGA). Thus it is essential to outline a method for the synthesis of design ground motion by considering the effect of uncertainties of seismic event and complexity of nonlinear response of structures.

In this study, we address the selection/synthesis of design ground motion considering the important aspects nonlinear response of structure by feature indices. Due to uncertainty in seismic factors, number of possible ground motions is not limited. The ground motions which are required to be considered for the design of structure are referred to as set of input ground motions. In the proposed method of ground motion synthesis the set of input ground motions are described by feature indices. Concept of damage mechanism based indices is proposed. Since there is not a ground motion which is the most efficient in the presence of uncertainties of structural characteristics a design ground motion is artificially synthesized in an iterative modification process. It is proposed and verified that fluctuation in parameters of indices is effective to cope with nonlinear response of structure.

Chapter 1 gives the review of current situation of design ground motion selection approach. It explains why it is necessary to consider the effect of seismic uncertainties and complexity of nonlinear response of structure in the selection/synthesis of design ground motion. In chapter 2, the design ground motion selection method and approaches are reviewed. A survey of design ground motion selection procedures proposed in literature and used in design codes is carried out. Based on the discussion, the objective of this research work is elaborated.

In chapter 3, the proposed method of ground motion synthesis is outlined. In the proposed method of ground motion synthesis, it is objected to synthesize a design ground motion by considering the effect of a large number of input ground motions and unpredictability of nonlinear response. For this purpose, first, a set of input ground motions that reflect the effect of uncertainty is considered. The set is described by feature indices that take into consideration the effect of ground motions on structural behaviors. Second, the ground motion that represents the set in terms of the feature indices is synthesized as a design ground motion. A scheme to synthesize a ground motion to represent the set is explained. The ground motion is synthesized by iteratively modifying its time-frequency characteristics using wavelet functions to improve the values of feature indexes.

In chapter 4, the efficiency of the ground motion synthesis procedure explained in the previous chapter is explored. The efficiency of the method is discussed in context of design ground motion synthesis for a concrete moment resisting frame. The set of possible ground motions is consist of real ground motions records obtained from K-NET. Each member of concrete moment resisting frame is modeled by using fiber elements in OPENSEES, and same is used to conduct the dynamic nonlinear analysis of structure. Various aspects of proposed method of ground motion synthesis are discussed. For example, it is shown that the synthesized design ground motion is not sensitive to the initial

selected ground motion which is to be modified in the iterative modification process. It is shown that the synthesized ground motion is not sensitive to the sampling of set of input ground motions. The results of numerical simulations show that the synthesized ground motion is robust in context of uncertain structural properties. For enhancement of performance of proposed method of ground motion synthesis, it is required to set a procedure for selection of appropriate indices, and this aspect is discussed in next chapter.

In Chapter 5, concept of damage mechanism based indices is introduced to select the most effective indices out of list of available indices. Conceptually, out of available indices, if some index/indices is/are related with expected damage mechanism(s) of structure, then such indices should be deployed for the selection/synthesis of design ground motions. Because the ground motion tough in terms of such indices would be efficient to trigger the expected damage mechanism, such ground motion should be used as design ground motion. The advantages of using damage mechanism based indices over conventional index and other indices which are less correlated with expected damage mechanisms are explained through a numerical simulation. As in the chapter 4, we use concrete moment resisting frame as target structure and set of input ground motions are recorded earthquakes obtained from K-NET. The results show that reliability of design ground motion selection is considerably enhanced due to inclusion of damage mechanism based indices in selection of design ground motions. Selection of parameters of indices is a critical aspect and discussed in following chapter.

In chapter 6, we discuss the selection of parameters of indices considering the nonlinear response of structure under consideration. In comparison with complexity and unpredictability of nonlinear response, the indices are simple. Indices may not represent the possible ground motions in context of nonlinear response of structure. To improve the performance of index based design ground motion selection approaches, the effect of nonlinear response must be reflected in the ground motion selection. We propose to consider a fluctuation to the parameters of indices to improve the performance of indices to represent the possible ground motion. Because, it is not possible to quantitatively consider the effect of complicated nonlinear response of structure in selection of design ground motions. It is considered that consideration of fluctuation to the parameters of indices will be helpful to evaluate a variety of aspects of ground motions. Therefore it will increase the reliability of selection of required design ground motions. Results of numerical simulations show that appropriate range of fluctuation in parameters of indices is required to cope with nonlinear response of damaged cases.

Chapter 7 summarizes the conclusion of this study. First; feature indices based design ground motion synthesis method is proposed. Feature indices are used to describe the set of input ground motions. Proposed iterative method successfully generates the ground motion which is robust and the generated ground motion is not affected by the size of set of possible ground motion s, initially selected ground motion, etc. Second; concept of damage mechanism based indices is proposed for selection of indices. Damage mechanism based indices are related with expected damage mechanisms. Therefore the ground motion tough in terms of damage mechanism based indices is expected to trigger the expected damage mechanism and hence used as design ground motion. Inclusion of damage mechanism based indices in ground motion selection considerably enhances the reliability of design ground motion selection. Third; it is difficult to quantitatively consider the effect of nonlinear response in selection of design ground motions, so we proposed and verified that consideration of fluctuation in parameters of indices is effective to cope with effect of nonlinear response in selection/synthesis of design ground motions.

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Tauqir Ahmed

September, 2012

Dedication

To My Parents, Family, Brother and Sister

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Chapter 1

Introduction

Selection of design ground motion for nonlinear dynamic analysis is an important and influencing aspect of seismic design. It is difficult to answer that "out a large number of available ground motions, which ground motion is best suited for the design purpose, considering that different ground motions has different affect and also structural properties may get changed during the design life of structure". Consideration of uncertainty of structural parameters is important but it complicates the selection of design ground motions, because slight fluctuations in conditions can lead to significant differences in outputs, especially in the case of nonlinear dynamic analysis. However, for the seismic safety of structures, it is essential to have answer for this problem.

1.1 Ground Motions for Seismic Design of Structures

Ground motions for seismic design are available from records of previous earthquakes and from ground motion simulation approaches. These two sources of ground motions are elaborated here in the following.

A number of simple to complex numerical and empirical relationships are proposed to simulate the ground motions from fault models. [1, 2] Such procedures are intended to produce ground motions considering the active fault around the site. By using these numerical and empirical simulation techniques, it is possible to generate the ground motion corresponding to the input parameters. In the past a few decades, performance of simulation techniques has been improved with advancements in seismology. The advancements in seismology give a helping hand to select appropriate parameters to be used with numerical and empirical simulation techniques for formulation of ground motions.

Available ground motions from past seismic activities are another source of design ground motions. The number of recorded time histories of seismic activity is increasing with densification of seismograph networks [3, 4, 5]. The increasing network of seismograph is meant for monitoring the seismic activates on this globe. These networks result with a number of ground motions data. The ground motion records are useful to explore the seismicity of an area. By inversion analysis [6, 7], detail information of the seismic activates; such as size of fault, strike angle, dip angle etc. can be formulated for future use. Secondly; the recorded time histories of famous earthquakes, such as Kobe earthquake is directly used as input ground motion for dynamic analysis of structure and same is recommended in design codes [8].

1.2 Uncertainty Associated with Sources of Ground Motions

The ground motions available from the simulation techniques and from record of previous earthquakes are an important asset. And this data bank of ground motion is expected to be helpful in getting the reliable design ground motion. Here, in this section we are intended to discuss the reliability of sources of design ground motion in context of applicability of ground motions from such sources for the design of structures.

A numerical simulation generates a ground motion based on considered parameters of fault, assumed properties of transmitting media and considered site conditions. If we use the same input parameters with a different ground motion simulation technique, we will get a different ground motion. In field conditions, the size of fault, location of epicenter, rupture velocity, shear wave velocity, direction of propagation of rupture, etc are uncertain. Since the parameters required for prediction of ground motions cannot be determined accurately, therefore, numerical and empirical ground motion simulation techniques are not able to make perfect prediction of ground motions. Meanwhile, owing to limitation of knowledge and complexity of earthquake phenomenon, numerical simulations cannot reproduce the exact ground motion of earthquakes, ether. So if we consider the uncertainty associated with the input parameters, it ends up with bundles of ground motions, which are of equal importance to be considered for reliable design of structure to have reliable design.

Use of historic earthquakes for the design structure is a common practice. Kobe earthquake (January 17, 1995), El Centro earthquake (May 18, 1940) Kashmir Pakistan earthquake (October 08, 2005) are among those famous earthquakes which are used for the design of structure. The use of recorded seismic activity for design of structure is questioned because of two reasons. First, same earthquake never happen twice therefore use of historic earthquake cannot make the predication of earthquake. Secondly, a large number of ground motions are recorded in the history and each recorded ground motion has different characteristics. Therefore design of structure against different recorded ground motions would be different. Meanwhile, there is no right answer for the question that which recorded ground motion is best suited for the design of structure under consideration.

Selection of design ground motions in context of diversity of design ground motions is discussed in above paragraphs. The selection of design ground is more difficult if the affect of stochastic nature of structural characteristics are considered in selection of design ground motions. Because nonlinear structural response is affected by excitation force, and also structural characteristics affect the structural response.

1.3 Uncertainty of Structural Parameters

There is no knowing of structural response prior to the application of dynamic force on structure. This is because of unpredictability of structural response in nonlinear range, which is governed by the uncertainty of structural parameters, such as stiffness of the structure, yield level of structure, etc. It is important to mention that structural parameters are governed by the characteristics of structural members (beams and columns). The characteristics of the structural member are primarily governed by the material characteristics. Properties of structural member are influenced by a number of factors such as; bond between steel and concrete, surface texture of steel bars, hydration process of cement, residual stresses during the manufacturing and construction stage, imperfection in manufacturing etc. These and other factors will affect the properties of an individual element and modification of structural properties of structural member will affect the response of structure in linear and nonlinear range.

It is difficult to quantitatively consider uncertainty of structural performance. As is mentioned that material properties mainly govern the characteristics of structural members (also material properties controls other factors such as bond between steel and concrete etc). Therefore, in essence consideration of uncertainty in material properties is equivalent to the consideration of complex and complicated mechanism which govern the structural characteristics.

Knowing that structural parameters has uncertainty and structural response will be modified as the structure parameters will get fluctuated, we need to consider the uncertainty of structural performance in deciding the design ground motions.

1.4 Sensitivity of Nonlinear Response of Structures

Nonlinear response of structure is affected by a number of factors. The sensitivity of the nonlinear response to different factors is elaborated here in the following.

Characteristics of individual structural component and properties of excitation force govern the nonlinear response of structures. Structural parameters and excitation force has uncertainty. Uncertainty of excitation force result with a number of ground motions. For efficient design it is required that structure should be safe against such possible ground motion in light of uncertainty of structural parameters.

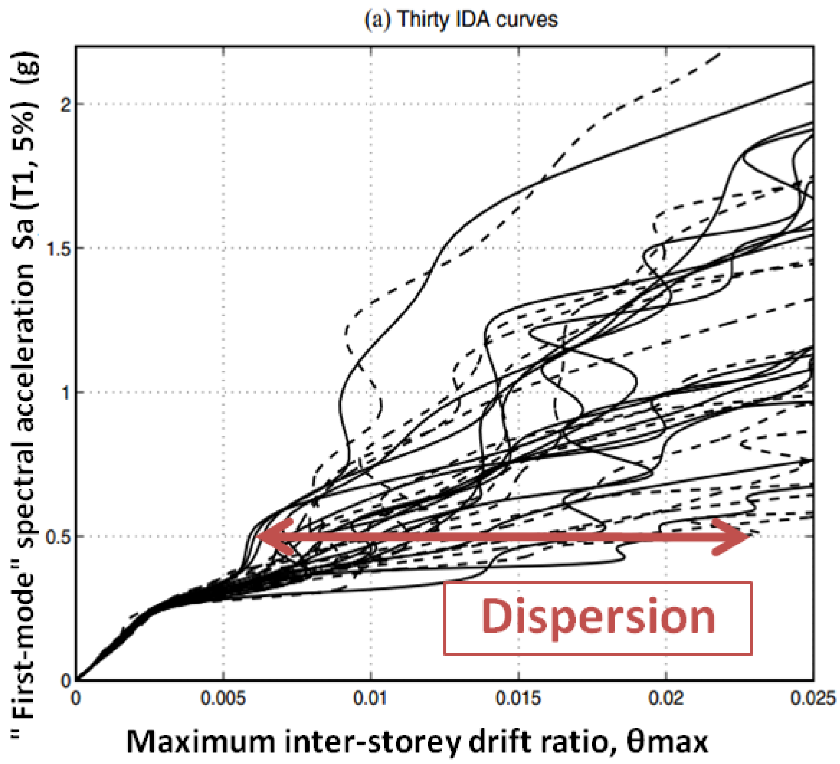

Figure 1.1 Incremental dynamic analysis curves of a moment resisting steel building subjected to thirty different earthquakes [9]

As an example, results of simulation by Cornell and Vamvatisikos [9] are shown in Figure 1.1. In Figure 1.1, the incremental dynamic analysis curves for a five floor steel moment resisting frame are shown. This frame is exposed to thirty different earthquakes. Along horizontal axis, the maximum inter storey drift is plotted. Spectral acceleration is shown on vertical axis. The results in Figure 1.1 are staggered. This is mainly due to differences of characteristics of ground motions. Specifically, if we see at incremental dynamic analysis curves at 0.25 of 'g', the corresponding maximum inter story drift ratios are exactly same for all ground motions. But at 0.5 of 'g', a large dispersion of maximum inter storey drift ratio is observed. Here it is important to note that same structure is exposed to different ground motions. And at 0.5 of 'g' a large dispersion is observed. This reveals that the performance of structure in nonlinear range is complex due to differences in characteristics of ground motions and unpredictability of nonlinear response of structure.

The ground motions are affected by seismic activity and site characteristics. Thus diversity of ground motions is important to consider in structural design. Meanwhile, structural properties are uncertain in nonlinear range. Therefore, theoretically to consider the affect of a ground motion on a structure, it is required to conduct a number of analysis cases. In each case, the nonlinear analysis is needed to be conducted by using different structural characteristics and same ground motions.

More specifically, the following two terms are used to appropriately discuss the effect of different factors on nonlinear response of structures.

1.4.1 Unpredictability of nonlinear response

Realizing the importance of consideration of stochastic nature of structural characteristics in nonlinear range, it is difficult to answer that how a ground motion will affect the structure. Because, response of structure will be different for different structural parameters and this is most likely option due to stochastic nature of structural characteristics. Moreover, unpredictability of nonlinear response is due to realization of the following aspects.

- Non-homogeneity of the material properties
- Effect of performance of joints during nonlinear range
- A variety of possible damage mechanisms and concentration of stresses
- Manufacturing faults and damages due to unexpected loading, etc.

A list of factors is possible, these hinders to predict response of structures in the nonlinear range. Therefore, practically, it is impossible to predict the exact behavior of '*real full scale structure*' in nonlinear range. In this context, the term 'unpredictability of nonlinear response' is used in this work.

1.4.2 Complexity of nonlinear response

Nonlinear dynamic response of structures is function of two aspects.

- Structural properties
- Characteristics of ground motion

The sensitivity of nonlinear response to these two factors can be studied in different ways. Figure 1.2 presents a conceptual layout of possible combinations to study the affect of afore mentioned factors on nonlinear response of structures. Qualitatively, Figure 1.2 shows that there are three ways, in which nonlinear response is being studied.

Firstly, a structure with deterministic parameters is analyzed against a unique ground motion. In this case, it is not possible to get information about how a structure would behave when the structural properties or characteristics of ground motions are modified.

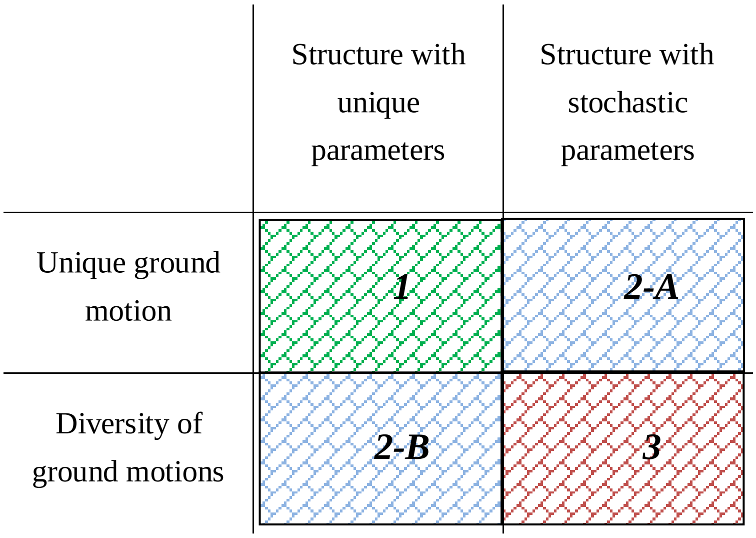

Figure 1.2 Conceptual layout of possible combinations to study the sensitivity of nonlinear response to different factors

Secondly, there are further two groups in second category. In first group, the structure properties are considered as stochastic variable and analyzed against a unique ground motion. This is helpful to study the affect of fluctuating structural properties on nonlinear response of structures. While in second group, a structure with unique characteristics is analyzed against a number of possible ground motions. This is helpful to explore the affect of diversity ground motions on structure.

Thirdly, a structure with stochastic parameters is analyzed against a number of possible ground motions. Here, unpredictability of dynamic nonlinear analysis is raised more, because uncertainty of structural parameters and diversity of ground motions are considered simultaneously. Thus number of combinations of possible ground motions and structures are increased significantly. It is complicated to determine the response of actual '*real full scale structure'*. In this context, the term 'complexity of nonlinear response' is used in this work.

1.5 Intensity Measures and Importance to Consider Uncertainty in Selection of Design Ground Motions

Realizing the importance of consideration of uncertainty of seismic event and complexities of structural response in selection of appropriate design ground motions, we are intended to mention a most common approach for selection of design ground motions. Intensity measures (indices) are used for selection of design ground motions, for example, peak ground acceleration (PGA), etc. if is very difficult that intensity measures can circumscribe the complexities of nonlinear dynamic analysis.

Therefore, it is required to set a modified approach to consider the uncertainty of structural and seismic parameters by which, the reliabilities of having the required design should be shored against the uncertainty of the structural and seismic parameters.

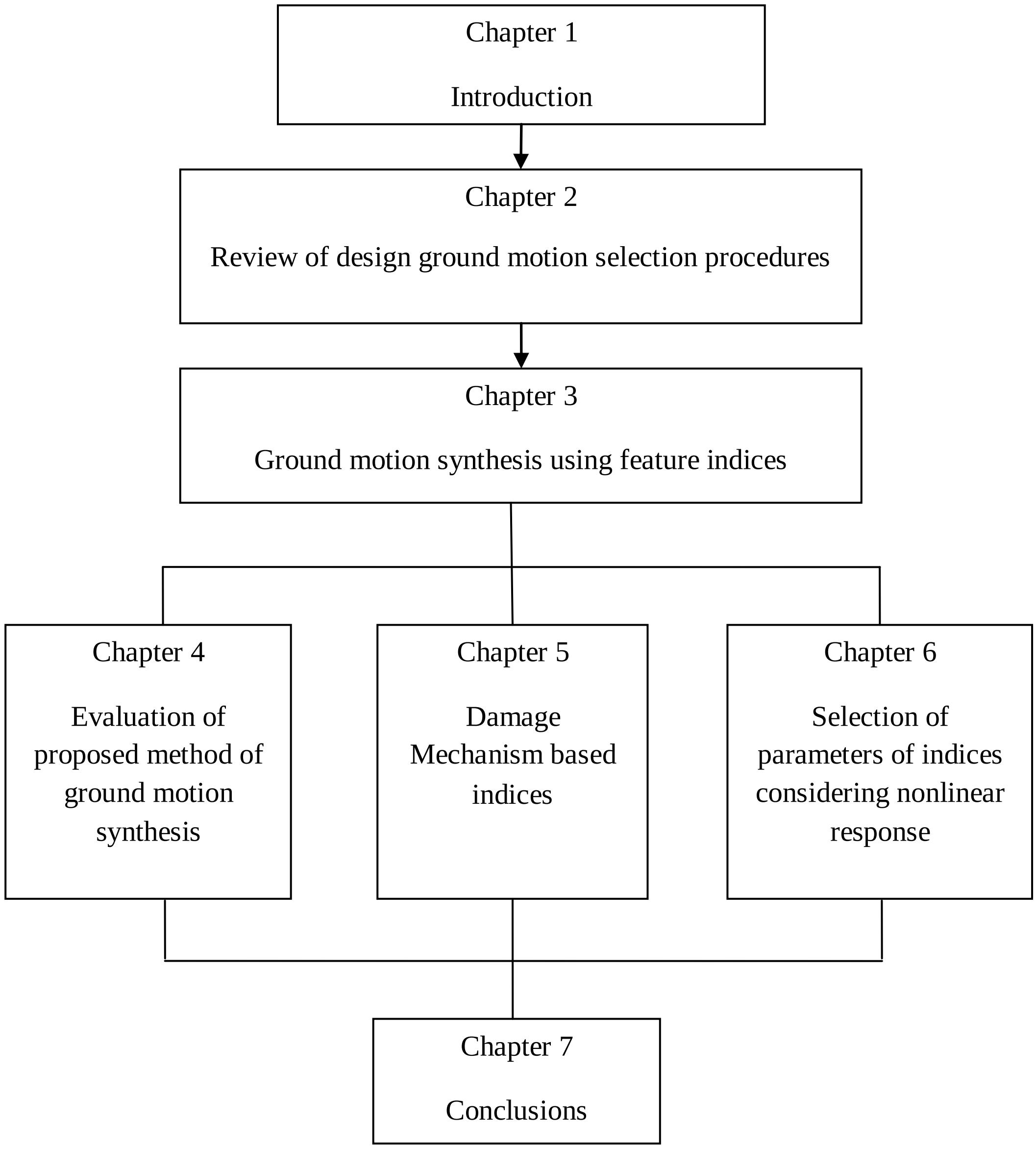

Figure 1.3 Layout of thesis

1.6 Thesis Outline

A layout of thesis is shown in Figure 1.3. Chapter 1 has given a general introduction of importance of consideration of uncertainty in design ground motions selection and the need of having a robust method for synthesis of design ground motion in consideration of uncertainty associated with seismic event and associated with unpredictability of nonlinear response.

Chapter 2 will show a review of current situation of design ground motion selection procedures and practice, and show the objectives of this work.

Chapter 3 explains about the proposed method of ground motion selection by using feature indices. Feature indices are used to represent the set of possible ground motions, which are resulted due to seismic uncertainty.

Chapter 4 shows the details of the application of proposed method of ground motion synthesis for different types of structures and discuss the effectiveness and stability of proposed method of ground motion synthesis.

Chapter 5 is about the damage mechanism based indices, which is a concept to select the most effective indices out of list of available indices. In this chapter, it is shown by numerical simulations that reliability of having a required design ground motion can be increased by using damage mechanism based indices.

Chapter 6 shows the detail of selection of parameters of indices considering the effect of nonlinear response. It is very difficult to quantitatively consider the effect of nonlinear response in selection of design ground motion. We indirectly consider it by giving the fluctuation to the parameters of indices. And it is verified with numerical simulations.

Chapter 7 presents the summary of the current work, conclusions and future work to continue this study.

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Chapter 2

Review of Design Ground Motion Selection Procedures

Realizing the importance of consideration of uncertainty of structural parameters and diversity of ground motions, in this chapter we conduct a survey of present practices and procedure of design ground motion selection and also we surveyed the intensity measures (indices) proposed by the researchers for evaluation of damaging capabilities of ground motions. Some part of this survey is included in M.Sc. thesis of the author [1] and reproduced here in this chapter.

The literature from following areas is explored and summarized in this chapter.

- Present design practice to select the design ground motions.
- Available methods for formulation of ground motions from a fault model.
- Intensity measures for the evaluation of effectiveness of a ground motion.

2.1 Consideration of Uncertainty and Selection of Design Ground Motions in Present Design Practices

In present practice, structural design is completed by using design codes. Relative to the locality of the structure the applicable design code is followed. In each design code factors are specified to increase the load and to reduce the strength of material. In one way or other, these factors aim to coop with the uncertainty. For example, in the first set of general probability-based load combinations for structures [2, 3], one of the load combinations is $\phi R_n = 1.2D + 1.5E + 0.5L$. Here, ϕ is strength reduction factor, thus value of strength reduction factor is less than one $(\phi < 1)$. The strength is reduced to cope with uncertainty of the strength of member, and indirectly consider the uncertainty of structural performance. This approach is retained in present design, such as international building codes [4]. Implementation of factors to consider the uncertainty of occurrence of load and uncertainty of strength characteristics is indirect way to consider the uncertainty of structural performance.

The practice of using amplification factors ground motion do not completely fit in the situations for which performance of the structures in nonlinear range is dominant because nonlinear dynamic behavior of structures are more complicated than can be represented by safety factors. It should be emphasized here that safety factors are not sensitive to the quality of information or simulation results and that they cannot improve the quality of the design by exploiting the quality of available information or simulation results.

With enhancement of computational facilities and availability of sophisticated techniques to conduct the detailed analysis, analysis type is modified from static load analysis to nonlinear dynamic analysis in revised codes. While performance based design is recommended for some special situations. Nonlinear analysis is implemented to check the detail response of structure to assure the performance. Selection of design ground motions is an important and influencing aspect of nonlinear dynamic analysis. But there is no right answer for the question that which ground motion is best suited for the design of structure under consideration.

For efficient design it is required, to formulate a new method, which efficiently considers the uncertainty of nonlinear response of structure and diversity of ground motions in the design process.

2.2 Available Methods for Formulation of Ground Motions

In last few decades, a number of simulation models and empirical relationships are proposed by different researchers to formulate ground motion. These methods are based on the uncertain input parameters. Simulation results from these methods depend on the reliability of the input parameters.

Available methods for the formulation of ground motions from a hypothetical earthquake can be broadly divided into two groups. First group comprises of the methods which are based on attenuation relationships, while the methods which considers the rupture pattern of the fault instead of using attenuation relationships are placed in second groups. In past few decades, some methods are presented to formulate the ground motion by using the attenuation relationship, and these methods also consider the rupture pattern.

<u>The Methods that considers the rupture pattern of fault:</u> In such methods hypothetical seismic fault is divided into sub faults and rupture pattern is considered. As rupture pattern is considered, so the methods of this group explains the phenomenon that the observed waveform at the same distance from source are different according to rupture pattern. Problem of these methods is that these methods have uncertainty on assumption of rupture direction for hypothetical earthquake that have never occurred.

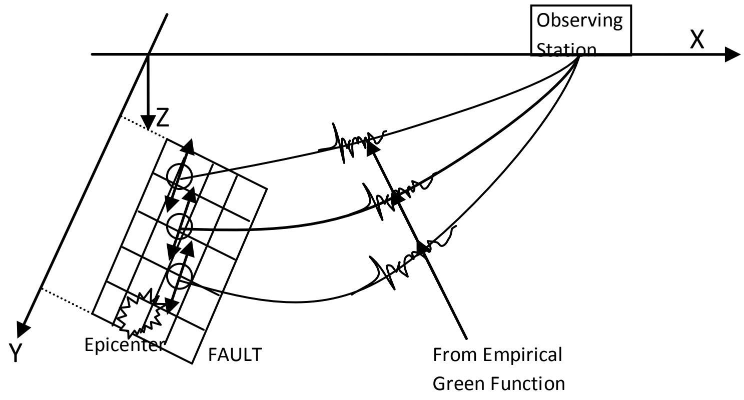

Figure 2.1 Schematic diagram of Empirical Green's method for simulation of ground motion [1]

Using attenuation relationship for ground motion formulation: In such methods, empirical relationship is derived from regression analysis for the observed data. This is an easy way to calculate ground motions and many attenuation formulas are available corresponding to each ground motion index such as peak acceleration, peak velocity, response spectrum and so on [5]. Some attenuation formulas are available which consider the rupture direction also. But the attenuation formulas cannot explain the distribution of strong motion because the actual earthquake has complex rupture process.

Frequently used method for the synthesis of ground motion are listed below with references

Joyner and Boore [6] study the near source attenuation characteristics of horizontal peak ground acceleration for 28 worldwide earthquakes of magnitude 5.0 to 7.7.

Midorikawa and Kobayashi [7] model the fault plane to consist of small sub faults and seismic waves are radiated when rupture front reaches at each sub fault.

Sugito and Kameda [8] work on prediction model for non stationary strong motion of moderate and great earthquakes on the bases of recorded ground motions on rock surface, and in this method engineering bed rock corresponds to the layer where shear wave velocity is in range from 600m/sec to 700m/sec.

In Irikura's method [9]the fault plane of the large event is divided into N X N sub-faults (Fig.2.1) the fault size is taken to match the fault size of a small event used as empirical Green's function. In this method to access the ground motion it is necessary that observed waveform for small event that occurs near hypothetical source is recorded. But it is rare to that necessary waveform was recorded. In this case Green's function is obtained by using numerical calculation or statistical technique.

Fukushima and Tanaka [5] proposes the attenuation formula of peak ground acceleration, which is derived from ground motion data recorded in Japan, United States and in some other countries. This attenuation formula shows good agreement with observed data for the 1995 southern Hyogo prefecture earthquake.

Methods in above paragraphs and other numerical and empirical relationships results into a large number of possible ground motions, which has to be considered in the design process for efficient structural design. In present practice of structural design it is not possible to consider all these ground motion for the design of structures, due to limitation of computational time. To consider all possible ground motions in the design process, it is required to set a new method of ground motion synthesis by which a ground motion can be synthesized, which has all important information of the set of possible ground motions which may face by the structure during design life.

2.3 Intensity Measures for Evaluation of Damaging Capabilities of Ground Motions

For the evaluation of performance of a ground motions, implementation of indices is very well known approach. Broadly, we can divide the indices into two groups, first type of indices are related to the response quantities while second type of indices are related with statistical information of ground motion signal. Both groups of indices are discussed in the following paragraphs.

The response parameters involved in the measure of seismic damage capacity are Hysteretic energy, the acceptable roof drift ratio (D_{rd}) and the maximum roof drift ratio (D_{rm}) [10], while demanded yield strength coefficient and hysteretic energy [11, 12] are also used. Local softening damage index works very well when the centre frequencies are closer to first mode [13]. While a damage index associated with ductility and stiffness degradation is proposed, this relates the stiffness before and after yielding phase [14].

$$D_{K,J}(collapse) = 1 - \frac{K_m}{K_o} \qquad [14]$$

Another damage index is proposed which relates the stiffness of the structure before and after the application of ground motion excitation [15].

$$(DI)_K = 1 - \left(K_{final} / K_{initial}\right) \qquad [15]$$

It is also been shown that for a long duration periodic type of earthquake ground motion, the cumulative effect can be larger than the damage due to the maximum inter story only [16]. And global ductility is also important to control the damage [16]. It is also been shown that ductility and energy criteria do not need any additional parameter in order for relative damage functional to be defined. [17]. PARK and ANG propose 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[18, 19]. This was proposed in 1985 and still most of the researchers use it as basic for comparison of results [20].

Response indices related to ground motions are peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), maximum incremental velocity (IV), maximum incremental displacement (ID)and duration, [11,12] and it is also showed that PGV is a proper intensity measure candidate for deformation demands on SDOF systems[21]. While the PGA PGV duration and ground accelerations are also related to get a representative index I_D [22].

$$I_D = \frac{I_E}{PGA^2}\frac{PGA}{PGV} = \frac{I_E}{PGA.PGV} \qquad [22]$$

$$I_E = \int_0^{t_E} a(t)^2\,dt \qquad [22]$$

While ground motion duration effects on non-linear seismic response of selected SDOF is also studied [23] and stated that; Duration has been found to be insignificant to displacement ductility demand assessment, regardless of oscillation period and backbone. While it considerably affects other demand parameters such as hysteresis ductility and equivalent number of cycles. [23]. Effect of frequency contents of ground motions and fundamental frequency of structure is also studied [24].

SDOF system for each of the first two modes by elastic mode shapes. SDOF corresponding to first mode shows the energy absorbed in the lower part of building and corresponding to second mode shows the energy absorbed in the upper story of the building [25]. While only equivalent SDOF is also used to propose a simplified method for the non-linear seismic damage analysis of planar building structures, referred to as the N2 method [26]. In a report of Johan A. Blume earthquake Engineering centre of Stanford university [27]., it is reported that SDOF systems can be used as indicators for the effect of stiffness degradation on the global (roof) drift of MDOF structures, but they may under predict the amplification at the story level [27].

Table 2.1 Maximum acceleration list of major earthquakes observation records at THU building [30]

Date	Magnitude	1st Floor (max acc.) cm/sec²		9th Floor (max acc.) cm/sec²		Area name	
		NS	EW	NS	EW		
1978/2/20	6.7	170	114	421	298	Miyagi-Ken Oki	
1978/6/12	7.4	258	203	1040	523	Miyagi-Ken Oki	
1998/9/15	5.2	138	451	190	379	Miyagi-Ken Southern	
2003/5/26	7.1			231	264	Miyagi-Ken Oki	
2003/7/26	6.2	33	27	98	102	Miyagi-Ken Northern	
2003/9/26	8.0			29	22	Tokachi Oki	
2005/8/16	7.2	87	81	329	287	Miyagi-Ken Oki	
2008/5/8	7.0	19	22	261	226	Ibaraki-Ken Oki	
2008/6/14	7.2	88	70	392	293	Iwate- Miyagi-Ken inland	
2008/7/24	6.8	59	77	275	367	Iwate-Ken North Coast	
2011/3/9	7.2	37	34	171	89	Sanriku Oki	
2011/3/11	9.0	207	216	594	617	Off Pacific Coast Tohoku	Phase -A
		333	330	508	728		Phase-B
2011/3/19	6.1	15	18	34	56	Ibaraki-ken Northern	
2011/4/11	7.0	72	70	141	172	Fukushima-ken Southern	
2011/4/12	6.4	24	28	43	84	Fukushima-ken Oki	
2011/4/23	5.5	17	27	23	57	Fukushima-ken Oki	
2011/7/10	7.1	21	18	95	58	Sanriku Oki	
2011/7/23	6.5	10	11	50	42	Miyagi-Ken Oki	
2011/7/25	6.2	48	62	106	99	Ibaraki-ken Northern	
2011/7/31	6.4	36	31	70	45	Fukushima-ken Oki	

Both the structural dynamics characteristics and ground motion characteristics are to be considered to get a most unfavorable ground motion [10, 11, and 18]. And a seismic reliability model is also proposed which consider the uncertainty associated with both the structural properties and the seismic excitation [28]. By different researcher attempts are made to select strong-motion records that can be scaled to achieve compatibility with site-

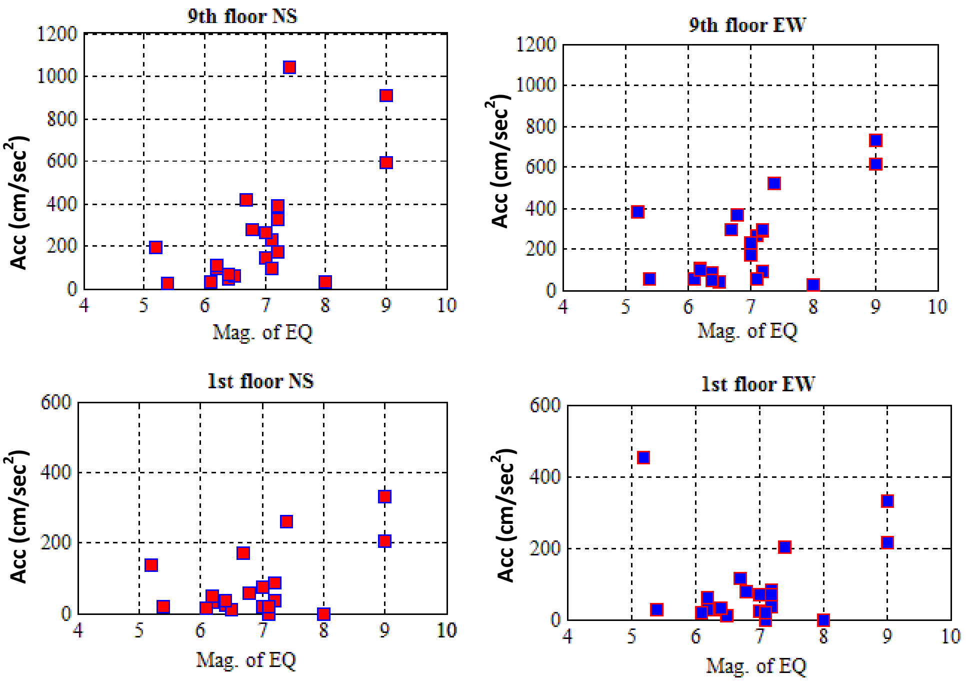

Figure 2.2Distribution of magnitude of earthquakes and maximum floor acceleration (1st and 9th floor in NS and EW direction) from an instrumented building at Tohoku University [30]

response spectrum [29]. The demand index relationships are also presented which take into account a variety of structural and site parameters [20].

It is to be noticed that indices are very simple and may not be able to circumscribe the uncertainty of nonlinear response and diversity of ground motions. In this context, as an example a study is summarized here for the reference. An instrumented nine floor reinforced concrete building is studies against different earthquakes since 1978 [30]. The list of floor accelerations in north south and east west direction for fist and ninth floor are presented in Table 2.1. The results shown in Table 2.1, reveals that acceleration response of building is recorded for all major earthquakes since 1978.

To ease the visualization of the correlation of recoded acceleration with the seismic event (if exist), the distribution of first and ninth floor acceleration is plotted in Figure 2.2. In Figure 2.2, magnitude of earthquakes is plotted along horizontal axis and floor acceleration is plotted along vertical axis. It is clear from Figure 2.2, that floor acceleration has no exact correlation with magnitude of earthquakes. Therefore it is important to mention that due to uncertainty of nonlinear response and diversity of ground motions, it is not expected that definite relationship exists between the response of structure and seismic event.

2.4 Objectives of This Study

In view of the literature survey, the available methods of design ground motion selections do not rationally consider the effect of nonlinear response and effect of uncertain seismic parameters in selection of design ground motions. Meanwhile, a good number of indices are proposed in the literature for selection of design ground motions. But, such indices cannot *perfectly* consider the effect of nonlinear response in selection of design ground motions. So the objectives of this study are here in the following

- To set a method for synthesis of design ground motion rationally considering the uncertainty of seismic and structural parameters by using feature indices.
- In this method we have to use the feature indices, we need to propose a method for selection of appropriate feature indices out of list of available indices.
- To propose a method for selection of feature indices out of list of available indices, which are appropriate to quantify the effect of ground motion on structures in context of nonlinear response of structures.
- To propose a method for selection of indices parameters considering nonlinear response of structures.

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Chapter 3

Ground Motion Synthesis Using Feature Indices

3.1 Introduction

Ground motion simulation techniques and records of ground motions result with a data bank of ground motions. Consideration of such ground motions are required to enhance the seismic performance. On the other side, the dynamic structural parameters (for example natural time period, yield force level etc) are uncertain. Owing to which, different dynamic structural parameters yield different computation results and different designs of the structure, especially when nonlinear behavior of the structure is considered. Therefore, uncertainty of parameters can undermine the reliability of design. To reduce the effect of uncertainty, the number of simulations needs to be increased. However, to pursue economical efficiency, the number of simulations needs to be reduced. To avert such a trade-off, it is proposed to consider an input ground motion for the nonlinear dynamic analysis that represents a large number of possible ground motions and considers the uncertainties of structural and seismic parameters. Such a design ground motion can be considered to reflect the information contained in many possible ground motions, including the effect of uncertainty of structural parameters, and on the basis of this input, which does not require thousands of nonlinear dynamic analyses of the structures, an efficient design exploiting all available information can be developed.

Realizing the importance of synthesis of design ground motion in context of set of possible ground motions, feature indices based design ground motion synthesis is proposed [1]. The details of the proposed method of ground motion synthesis are summarized here in the following [1].

In proposed method of ground motions, the set of ground motions and structures are described by feature indices that are associated with dominant factors of the nonlinear dynamic behavior of structures [1]. The ground motion that is superior in terms of such indices would serve as a good design ground motion. It is difficult to find a ground motion which is simultaneously dominant in terms of multiple indices. It is required to artificially synthesize a ground motion, which is efficient in terms of required number of indices. It is possible to synthesize the required ground motions from scratch, or by modifying an existing ground motion for required performance. The latter option is used in the proposed method of ground motion synthesis. In this method, Wavelet functions are use to modify the time-frequency characteristics of ground motion and generates a ground motion that satisfies the required condition to represent the set. In the proposed method of ground motion synthesis, feature indices are used to describe the set of possible ground motions.

3.2 Description of a Set of Ground Motions by Feature Indices

It is impossible to consider all possible ground motions to accommodate the effect of uncertainty. Therefore, a set of possible ground motions is considered, and it is described by using appropriate feature indices. A similar approach is utilized in some applications such as damage detection [2, 3]. Finite numbers of indices may not perfectly define the set, but careful selection of indices will enable sufficient description of the set. Features should be carefully selected based on knowledge of structural engineering. It would be appropriate to use conventional indices such as response acceleration and response velocity of a single-degree-of-freedom (SDOF) system, rather than newly developed indices, because the reliability and eligibility of conventional indices have been tested for years. For selection of most appropriate feature indices out of a list of available indices, concept of damage mechanism based indices is proposed, and discussed latter in chapter 5.

Since uncertainty lies in the structural parameters, by giving Gaussian noise to material properties, a set of structures is introduced and described by using indices corresponding to the dominant features. No index is known to determine the nonlinear behavior of damaged structures perfectly, but it should suffice to simply use conventional features, such as the natural period of the first mode when an ordinary structural system is treated. If the structure has characteristics that require special attention, additional indices should be adopted accordingly.

Based on the preceding discussion, features that would be important in evaluating the strength of ground motions are adopted, such as peak displacement response of a system with the appropriate natural period. Some factors are reported to be useful for damage evaluation [4, 5, 6], and they could be considered in the selection of features. It is possible to use more than one index, and this will make the estimation of strength of ground motion more reliable.

Once feature indices are fixed, the ground motion that is the largest in terms of these indices can be regarded as representing the set of possible ground motions and regarded as suitable for design purposes. It does not ensure such ground motion actually exists, because the ground motion that is the largest in terms of an index for one structure may not be the largest when different structures are considered, it is a likely option due to uncertainty of structural characteristics. This is also the case when more than one index is considered. The largest ground motion in terms of one index may be inferior to other ground motions in other indices. This problem can be handled by purposively synthesizing artificial ground motion. Such ground motion is not real seismic ground motion, but it should suffice for design purposes. To avoid producing intolerably unrealistic ground motions, ground motion is synthesized by modifying existing ground motion. If a ground motion different from the original is used, a different synthesized ground motion will be obtained. This should be accepted because there is no unique right answer for the problem.

3.3 Main Steps in Synthesis of Design Ground Motions

Three steps are involved in state-of-the-art procedures of design ground motion synthesis. First, from scratch or by modifying an existing ground motions, a limited number of ground motions are formulated. Second, out of formulated ground motions, a relatively efficient ground motion is selected for modification in next step. Third, the process of modification is iterated until the required ground motion is synthesized. As an essence, the ground motion synthesis procedures involve the selection of ground motion in iterative modification.

The proposed method of ground motion synthesis to get the representative ground motion by simultaneously considering uncertainties of the structural parameters and diversity of ground motions mainly comprises of three steps.

- Generation/formulation of possible input ground motions.
- Preparation of structural details and selection of feature indices.
- Step by step modification of time frequency characteristics of a ground motion to synthesis the required design ground motion. These three steps are discussed in the following.

3.4 Set of Input Ground Motions

3.4.1 Concept of set of input ground motions

The ground motions to be faced by the structure during the design life of the structure are not available. Probabilistically, we can formulate a set of ground motions by considering different factors, such as;

- Location of active faults around the site, and using numerical and empirical techniques to formulate the ground motion
- Recorded time history of past earthquakes
- Selection of ground motions considering the site effect, etc.

It should be accepted that the ground motions, which would be faced by the structure during the design life will not be included in the set of possible ground motion, but conceptually, if the structure design is completed by considering the effect of set of possible ground motions then the structure would be safe against the seismic activities faced by the structure during the design life. Hereafter, such set of ground motions is referred to as set of input ground motions.

Selection of set of input ground motions is a detailed research topic. In this work, intentionally, we selected the set of input ground motions so that it contains wide variety of ground motions.

3.4.2 Formulation of set of input ground motions

To generate possible input ground motions, a variety of numerical and empirical methods are available, such as attenuation relationship [7], empirical Green's function method [8], and strong motion simulation of large earthquakes [9]. Different methods generate different ground motions. Even same ground motion simulation technique should generate different ground motions, if the uncertainty of fault parameters is taken into account. Consideration of different methods of ground motion simulation will increase the number of simulated ground motions by many folds. Such simulated ground motions result into ground motions which are candidate to be design ground motion. Ground motion records of past earthquakes are another source of ground moutons.

The ground motions available from records of past earthquakes, results of numerical and empirical techniques are huge in number and generate a large pool of ground motions required to be considered for the design of structure. This pool of ground motion is not limited to a certain number of ground motions. On the other hand, practically we cannot go for infinite number of ground motions.

For selection of ground motion for design of structure we may pick up ground motions from that pool by considering different criteria, such as power of the ground motions, comparing geotechnical data of design site and soil profile at recording station, distance to some active faults around the design site. We can reduce the number of ground motions selected out of the pool, but it is not possible to conduct nonlinear analysis for all selected ground motions. At the same time it is important to consider these ground motions for the design of structures. All such ground motions which are required to be considered for the design of structure are regarded as a set of possible ground motions.

3.5 Feature Indices for Ground Motion Synthesis

Indices are used to describe the set of input ground motions. Indices presented by various researches are found to be effective to measure the damage of the structure. In this work, we incorporate the knowledge of such indices to measure the effectiveness of ground motions. For example, P. Fajfar in N2 method [10] uses the response of equivalent SDOF system for the non-linear seismic damage analysis of planar building.

The indices are expected to show the relative damaging capabilities of ground motion. So the function of index is to describe the set of input ground motions. The indices are not objected to reproduce the complicated nonlinear response of structure.

3.5.1 Challenges in selection of feature indices

Due to complexity of nonlinear response and simplicity of indices, it should be accepted that

- A ground motion is strong in terms of one index while another ground motion will be efficient in terms of other indices.
- The superiority order of ground motion will be altered as the structural characteristics will be changed.

To avert the afore mentioned limitations, we take following actions in the proposed method of ground motion synthesis

a) Damage Mechanism Based Indices:

The most suitable feature indices to represent the set of possible ground motions are evaluated by paying attention to possible damage mechanism of structure. The indices which are expected to be correlated with possible damage mechanisms are selected. The ground motions which are efficient in terms of these indices will be most effective to excite the corresponding damage mechanisms, hence such ground motions should be considered for the design of structure.

Here the possible collapse pattern/mechanism should be accessed, considering physical characteristics of structures such as material of structure, width to height ratio of building, variation of stiffness along the height etc. Damage patterns observed in the past earthquakes should be referred. Detail of damage mechanism based indices is further elaborated in chapter 5.

b) Fluctuation in the Parameters of Indices to Consider Nonlinear Response and Effect of Structural Uncertainties:

A fluctuation to the parameters of indices is considered to cope with uncertainty of nonlinear response. We add fluctuation not to reproduce the complicated nonlinear response of the structure. It is assumed that consideration of fluctuation to the parameters of indices will be helpful to enhance the efficiency of indices to represent the damaging capabilities of design ground motions.

The amplitude of fluctuation added to the index parameters is not easy to specify. Comparing the simplicity of indices and uncertainty of nonlinear response, it is not a good option to fix the value of fluctuation. We need to specify the range of fluctuation suitable to cope with complexity of nonlinear response and we try to evaluate an optimum range of fluctuation to the parameters. The detail of selection of parameters of indices, considering the nonlinear response is further elaborated in chapter 7.

3.6 Iterative Procedure of Design Ground Motion Synthesis

Once the set of input ground motions is formulate, the indices are selected, the fluctuation to the parameters of indices are decided. Next important step is modification of ground motion and synthesis of design ground motion in iterative modification.

3.6.1 Importance of modification of ground motion

It is difficult to find a ground motion which can describe the set of input ground motions, because

- Dynamic parameters of structure are uncertain, thus a ground motion may not exceed beyond the set of input ground motions if the uncertainty of structural parameters are incorporated.
- A ground motion is efficient in terms of an index while another ground motion is efficient in terms of other index.

These shows that it is rare to find a ground motion out of set of input ground motion, which can exceed in terms of multiple indices. Therefore, we need to artificially synthesize a design ground motion of required performance

In comparison to set possible ground motions, a ground motion amplified by an amplification factor can increase the performance in terms of selected indices for all possible structure, but such a ground motion tends to be redundantly strong, and leads to highly uneconomical solution, because characteristics of structures are not considered in the formulation of target structure. In the proposed method, the design ground motion is synthesized in step by step modification process and care is taken to avoid the redundantly strong ground motion.

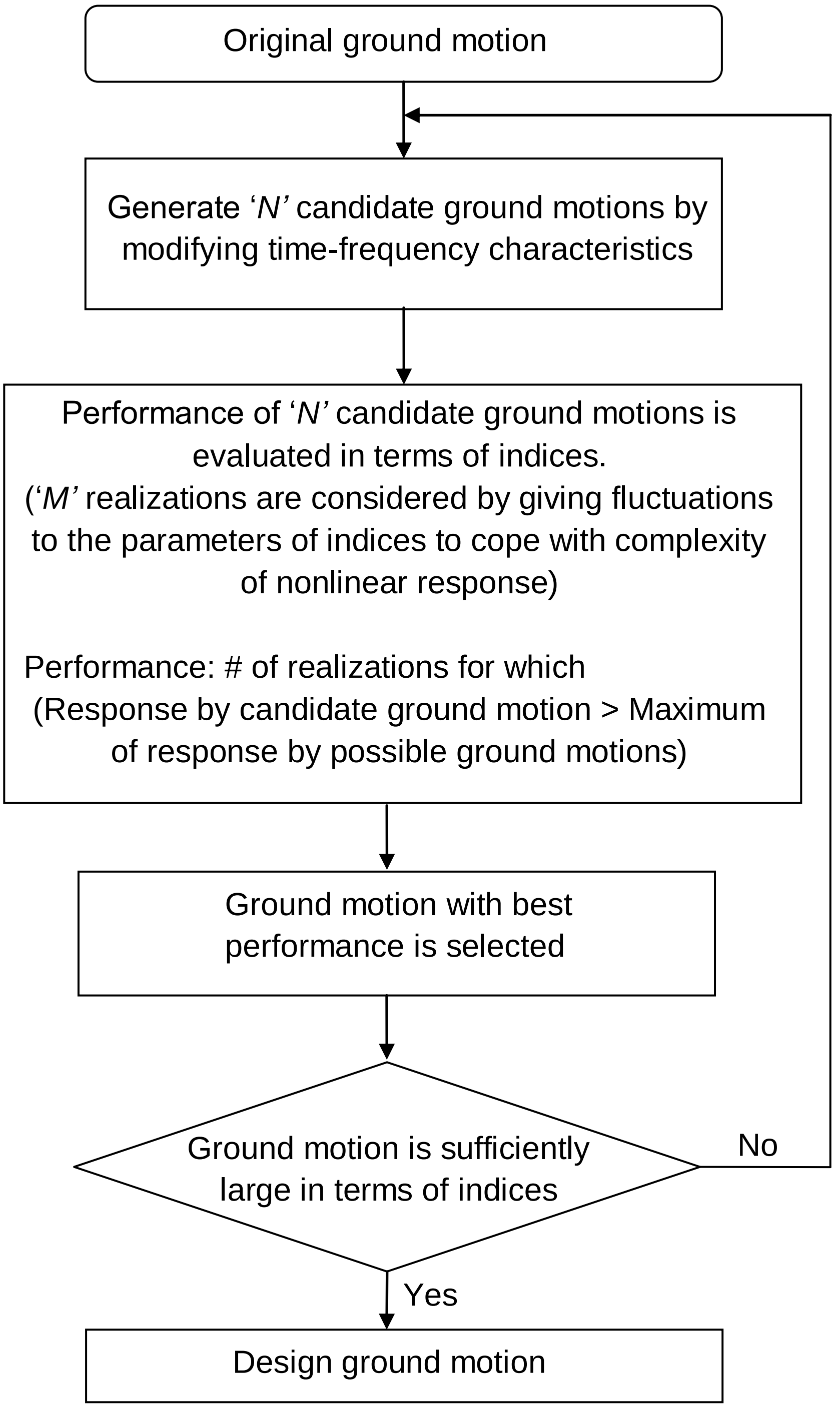

Figure 3.1Iterative procedure of synthesis of design ground motion [1]

3.6.2 Step-by-step modification process for synthesis of design ground motion

Design ground motion is synthesized in a step by step modification process. Schematic diagram of proposed method of ground motion synthesis is shown in Figure 3.1 [1].

In synthesis process a ground motion is randomly selected out of input ground motions and frequency components are modified by using wavelets. In each modification, 'N' ground motions are formulated, hereafter referred to as candidate ground motions. The performance of each candidate ground motion is evaluated by using feature indices. To incorporate the uncertainty of nonlinear response and effect of degrading properties of structure, 'M' realizations of indices are considered by giving fluctuations to the parameters of indices. In each modification a candidate ground motion which shows most improvement is selected for the modification in the next step, and here after referred to as selected candidate ground motions. The process of modification by using wavelet is iterated until ground motion becomes strong enough in terms of selected indices. The details of modification of ground motion by using Morlet wavelet [11, 12] are discussed in the following.

3.6.3 Modification of ground motions by Morlet Wavelet

In synthesis of ground motion, modification of ground motion to have the required performance is an important step. Amplification of ground motion by a small factor is a simple solution to the problem of increasing the performance of ground motion. But in this process the ground motion is factored without considering the structural properties, which are most influential to the nonlinear response of structure, such as natural time period, yield force level, etc.

In the proposed method of ground motion synthesis, wavelet transform is used to rigorously consider the influencing dynamic properties of structure in the modification of ground motion. Wavelet transform is advantageous, because in wavelet transform function is localizes in both space and scaling. This help us to modify the ground motion signal at desired locations, this aspect is described in following.

It is possible to alter the frequency contents of a signal in given range of time. Due to simplicity of application, Morlet wavelet (Figure 3.2) is most famous in the family of mother wavelet. The Morlet-Grossmann definition of continuous wavelet transform [11, 12] for a 1-D signal $f(x) \in L^2(R)$ is,

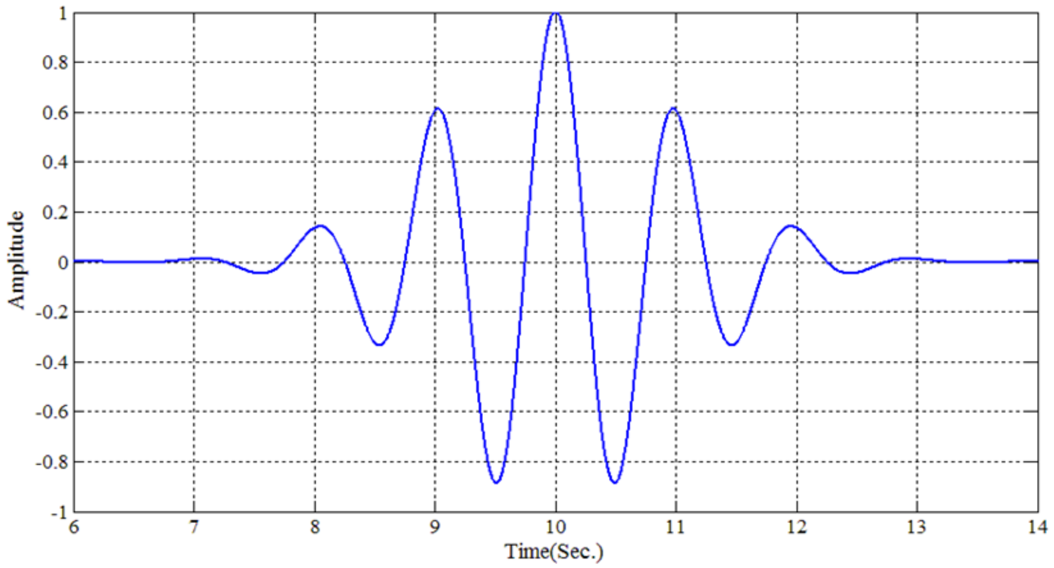

Figure 3.2Morlet Wavelet (peak value is shifted at time = 10 Sec.)

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(x)\psi \left(\frac{x-a}{a}\right) dx \tag{3.1}$$

Morlet wavelet is used to modify the time frequency characteristics of the ground motion signal. The components of ground motion are modified which are most influential in dynamic nonlinear response of structure, such as frequency components of ground motion which are similar to the natural vibration period of structure. This modification is expected to be more effective, when applied at time corresponding to maximum response. But, it is not a good option to modify the unique frequency component at a specific time, the explanation of this aspect and the measures taken in the proposed method of ground motion synthesis are discussed in the following.

a) Frequencies of ground motion signal to be modified by wavelet

The natural period of the structure will be fluctuated due to uncertainties of structural characteristics, and also during the progressive damage of the structure the time period will also be modified. Therefore, as structure properties are modified, it is required to modify a range of frequency components. This aspect is considered in proposed method of ground motion synthesis, and a range of frequency components is modified.

b) Location along time axis to add wavelt for maximum efficiency

Due to uncertainty of nonlinear response it is difficult to certain about the time corresponding to the max response, but still a range of time can be specified among which most of structures yields peak responses.

c) Modification by wavelet and formulation of candidate ground motions

In these scenarios it is required to reinforce a range of frequencies in a specific interval of time. To efficiently incorporate the afore mentioned aspects in proposed method of ground motions synthesis, at each modification step, a number of ground motions are formulated by randomly modifying the frequencies of ground motion (among the range of frequencies which is required to be modified) at randomly selected time (among the time interval, at which frequencies are required to be modified). In this process at each modification step a group of candidate ground motions is resulted.

3.6.4 Selection of updated ground motion

In each modification step, a group of candidate ground motions is formulated by modifying the time frequency characteristics of original ground motion signal by wavelet transform. Out of candidate ground motions, a ground motion which shows increase performance is required to be selected for modification in next step.

Feature indices are deployed to select the most improved ground motion out of candidate ground motions (formulated by wavelet transform). Candidate ground motions are represented by feature indices. Parameters of indices are fluctuated to cope with uncertainties of nonlinear response. By importing fluctuation to the parameters of indices (e.g. fluctuation to natural period if response of bilinear SDOF is used as index), the candidate ground motions are evaluated against a limited number of realizations (e.g. M realization of bilinear SDOF system).

Number of realizations is not influencing to the performance of final synthesized ground motion. Because in each modification step, the parameters of indices are fluctuated, due to which the effect of number of realizations is minimized. So, a small number of realizations in each step will yield a ground motion which would efficiently represent the uncertainties of structural response and would be helpful to represent the candidate ground motions. This aspect will be elaborated in chapter 4.

Performance of each candidate ground motion is evaluated. The ground motion which gives maximum response in terms of feature indices for selected number of realizations is picked for modification in next process. This process is repeated until a ground motion is formulated which shows the required response in terms of feature indices. Such ground motion is design ground motion.

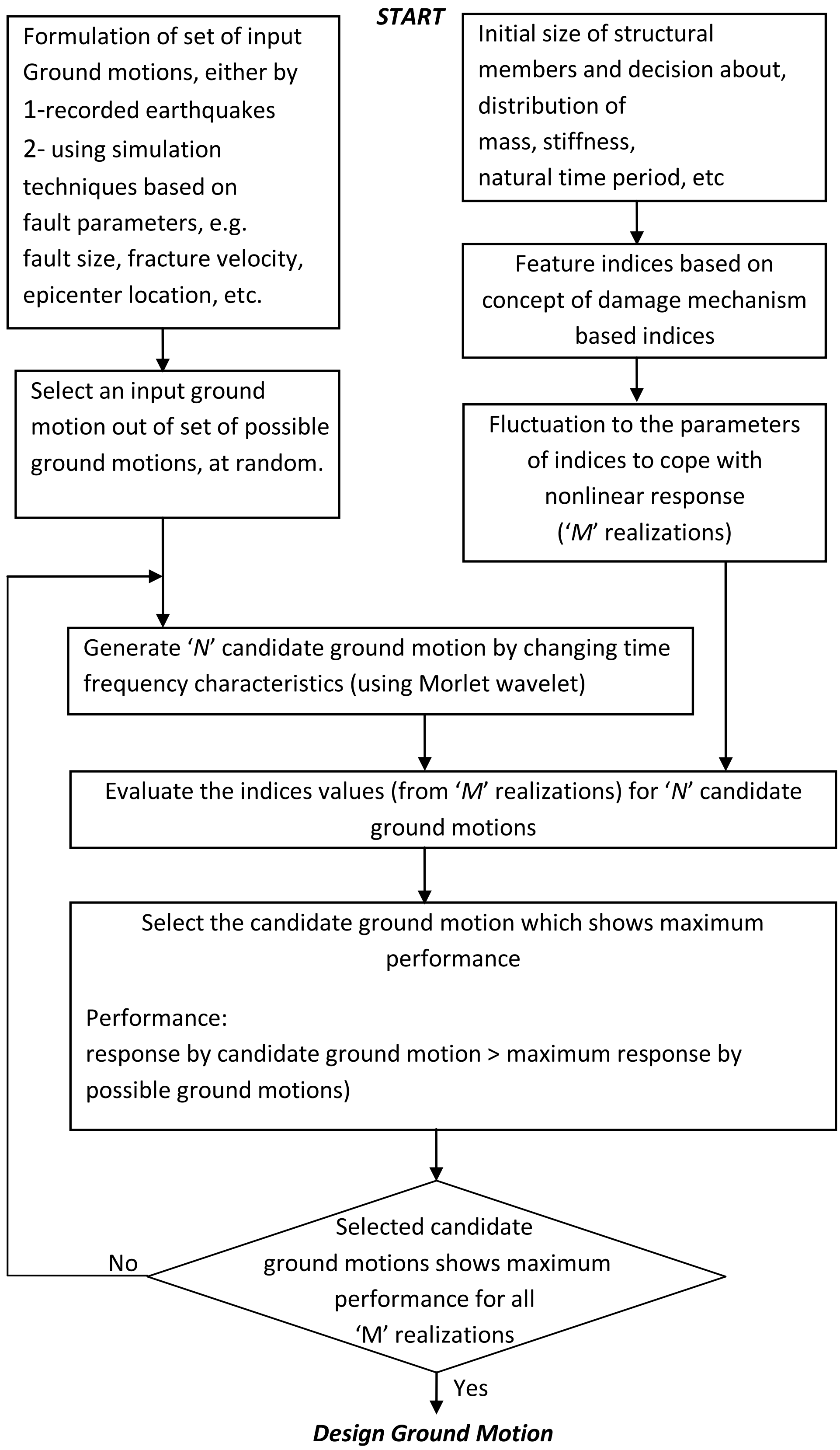

Figure 3.3Schematic diagram of proposed method of ground motion synthesis

In this process, the design ground is synthesized by using feature indices, and here feature indices are used to describe the set of possible ground motions and it is expected that the synthesized ground motion has the information of the set of possible ground motions.

Synthesis process to formulate the ground motion by the proposed method is elaborated in Figure 3.3.

3.7 Sequential Steps of Proposed Method of Ground Motion Synthesis

For synthesis of ground motion, proposed method of ground motion synthesis consists of following steps

- Formulate the set of possible input ground motions. This can be done in either by using the record of previous earthquakes or by using ground motion simulation techniques. For both approaches, further details are here in the following.
- The network of seismographs is spreading and densifying with the passage of time, this data bank of ground motions is helpful to formulate the set of possible ground motions. Based on source to fault distance, site characteristics, magnitude, etc, we can formulate the set of ground motions which is required to be consider for the design of structure under consideration.
- The development in the numerical and empirical techniques of ground motion techniques enables us to generate the ground motion based on parameters of fault, such as size of fault, location of epicenter, fracture velocity, etc. These input parameters are uncertain, and a number of ground motions will be resulted due to consideration of uncertainties associated with such parameters. This leads to a set of input ground motions, which are required to be considered for the design of structure.
- Select the appropriate sizes of structural which are prerequisite to model the structure.
- Decompose the expected structural damage into damage mechanisms. For example, for a bridge pier, the expected damage will be due to oscillation in first mode. So oscillation in first mode is damage mechanism which wills significantly contribute in total damage of this structure.
- Select the index/indices based on concept of damage mechanism based indices (explained in chapter 5). The indices which are related with expected damage mechanism are termed as damage mechanism based indices. Damage mechanism based indices are objected to evaluate the effect of ground motions on structures. It is difficult to find a single index which can reflect the effect of input ground motion. A group of indices can efficiently serve the purpose.

- Consider fluctuation to the parameters of indices to cope with uncertainty and complexity of nonlinear response (detail is discussed in chapter 6). Due to simplicity of indices and uncertainty of nonlinear response, it is not possible to quantitatively consider the effect of nonlinear response in selection of design ground motion. Alternatively we propose to consider a fluctuation to the indices parameters.
- Select a ground motion out of set of possible ground motion, at random.
- Modify the time frequency properties of selected ground motion, in modification process, most influencing components of the ground motion are to be reinforced.
- Wavelet transform is most effective technique to reinforce the required frequency contents in the specific range of time. By modifying time frequency characteristics, a limited number of ground motions are to be formulated, here after referred to as candidate ground motions.
- The candidate ground motions are to be evaluated by using feature indices. Evaluate the candidate ground motions (formulated by wavelet transform) by using feature indices. Here, it is required to consider a limited number of realizations of indices in evaluation of the candidate ground motions.
- Select the ground motion which shows maximum performance. Select the candidate ground motion which shows maximum performance. Performance is the number of cases for which the responses by candidate ground motion is larger than the maximum of responses by possible ground motions.
- If any candidate ground motion shows maximum performance for all number of realizations then that candidate ground motion will be design ground motion.
- If none of the candidate ground motion shows maximum performance for all number of realizations then the candidate ground motion which shows maximum improvement, is to be selected for modification in next iteration.
- Selected candidate ground motion is to be modified again by wavelet transform and candidate ground motions are to be formulated.
- The iteration process is repeated, until the candidate ground motion yields maximum response for selected number of realizations of indices.
- Candidate ground motion yielding the target response for selected number of realizations of indices is representative of the set of possible ground motions and is expected to be toughest for the structure.

3.8 Distinct Properties of the Proposed Method of Ground Motion Synthesis

In proposed method of ground motion synthesis, design ground motion is synthesized in interactive modification process. In general, the distinct properties of the proposed method of ground motion synthesis are summarized in the following.

3.8.1 Consideration of structural uncertainty and diversity of ground motions

A variety of procedures are available for the simulation of ground motions. In such procedures, a set of known parameters of source fault and intermediate transmitting media is used as input. Performance of simulated ground motion depends on the reliability of the input parameters, which are highly uncertain. Considerations of uncertainties of input parameters result with a large number of ground motions, for them it is not possible to conduct nonlinear analysis of the structures. On the other side, it is necessary to consider the characteristics of structures in selection of design ground motions. Therefore, it is essential to simultaneously consider the uncertainties of seismic event and structural response in synthesis of design ground motion. The proposed method of ground motions synthesis is efficient in afore mentioned aspects.

In proposed method, a ground motion is synthesized by accepting the uncertainties of ground motions. A set of possible ground motions is formulated to consider the diversity of ground motions. The uncertainty of structural performance in nonlinear range is considered by considering a range of parameter of feature indices.

3.8.2 Ground motion synthesis based on feature indices

Index-based design ground motion selection approach has been widely accepted [13] and a number of simple to complex indices are proposed [13, 14]. Most of indices are based on the information of ground motion signal such as peak acceleration and duration of ground motion. Some other indices consider the effect of structural characteristics [4, 5]. Here, in this proposed method of ground motion synthesis, instead of using an index based on information of ground motion signal (e.g. PGA etc), we select the important aspects of nonlinear response of structure and used them to select the preferred index out of available indices.

In the proposed method, the effect of nonlinear response is considered to select the indices. Therefore, it is expected that the performance of the proposed method of ground motion synthesis will increased as compared to conventional indices.

3.8.3 Feature indices to describe the affect of ground motions on structures

It is not possible to know the effect of ground motions on structure prior to the analysis. Meanwhile, it is not possible to conduct the nonlinear analysis for a large number of ground motions. Therefore, in proposed method of ground motion synthesis, feature indices are used to describe the effect of ground motions on the structure. The similar approach is utilized in some application such as damage detection [2, 3]. Ground motion dominant in terms of feature indices is selected.

Selecting good indices is prerequisite in the proposed method. For selection of appropriate indices, we propose the concept of damage mechanism based indices. The indices associated with expected damage mechanism are termed as damage mechanism based indices. Therefore such indices are expected be efficient to evaluate the damage caused by the input ground motion in context of structure under consideration.

3.8.4 Consideration of effect of nonlinear response in synthesis of design ground motion

Nonlinear response is very complicated and indices are as simple as response of simple spring mass system. Therefore, it is no possible to quantitatively consider the effect of nonlinear response in selection/synthesis of design ground motions. Indirectly, in this method we consider a fluctuation in parameters of indices. Consideration of fluctuation to the parameters of indices is helpful to evaluate a variety of aspects of grounds motion in context of uncertainty of nonlinear response.

In the proposed method of ground motion synthesis, the indices are equipped with the characteristics of nonlinear response. Therefore, the performance of the synthesized ground motion is expected be higher as compared to ground motion selection by using conventional index, where affect of nonlinear response is not considered.

3.8.5 Modification by wavelet transform

To reinforce the characteristics of ground motions in step by step modification process, Wavelet transform is used. This transform helps us to localize a function both in space and scaling. Therefore use of wavelet transform makes it easy to reinforce the frequencies, which are coherent with the dynamic characteristics of the structure.

In the proposed method of ground motion synthesis, the characteristics of ground motion are modified by considering the dynamic characteristics of the structures. This helps to efficiently synthesize a ground motion, which is dominant in response relative to set of possible ground motions.

3.8.6 Step-by-step modification of ground motion

In present practice of structural design, design ground motion selection by matching a response spectrum is a common approach, for which ground motion is amplified by using small factors. In such process of ground motion selection, the structural parameters are not incorporated. Therefore the selected ground motion may lead to an economically redundant design without specifying the reliability level. To aver this situation, in proposed method of ground motion synthesis, a ground motion is synthesized by iterative modification. In each modification step the important characteristics of nonlinear response are consider to modify the ground motions. Meanwhile, the attention is paid to avoid the redundantly large ground motion. The modification of ground motion is iterated until a ground motion is obtained which represent the set of possible ground motions.

3.9 Summary

There are various reliable methodologies and data available for the estimation of strong ground motion. Since different methods and different data sets yield different ground motions, a robust analysis has to consider a huge number of possible ground motions, most of them equally worth consideration. Because of inherent uncertainty, choosing one ground motion most suitable for design purposes is difficult, especially when nonlinear dynamic analysis is utilized, because the decision will vary with the change of conditions such as input motions or structural parameters.

Here, we present a simple scheme to generate a design ground motion considering all such ground motions. In the scheme, a set of possible ground motions is considered, and the set is described by feature indices that are associated with the effect of ground motions on the nonlinear behavior of structures. A ground motion that represents the set in terms of the indices should be suitable for the design. Such a ground motion can be generated from a ground motion by iteratively modifying the time-frequency characteristics of the original ground motion by using wavelet functions.

The performance of this proposed method of ground motion synthesis is elaborated in chapter 4, and robustness of the scheme under larger uncertainty is discussed.

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Chapter 4

Evaluation of Proposed Method of Ground Motion Synthesis

4.1 Introduction

In proposed method of ground motion synthesis, design ground motion is synthesized in an iterative modification process. In this process time frequency characteristics of a randomly selected ground motion is modified. Proposed method of ground motion synthesis is elaborated in chapter 3. We have tested the proposed method of ground motion synthesis for different type of structures and for different sets of ground motions. We also discuss the effectiveness of proposed method of ground motion synthesis [1, 2, 3, 4]. Here in this chapter of thesis, we mainly reproduce and summarize our published results [1, 2, 3, 4] for following purposes.

- To stream line the findings from application of proposed method of ground motion synthesis in various conditions of structural types and for different sets of input ground motions. For some cases set of ground motions is consist of input ground motions from record of previous earthquakes, while in other cases the set of input ground motions is formulated based on fault parameters by suing simulation techniques
- To discuss the effectiveness of proposed method of ground motion synthesis by simultaneously considering the uncertainties of nonlinear response and diversity of ground motions.
- To show the stability of the proposed method of ground motion synthesis in context of a practical example, design ground motion is synthesized for a moment resisting concrete frame. The moment resisting concrete frame is modeled as really as possible by considering uncertainty of material properties and by using detailed models to characterize the steel and concrete fibers.

Firstly, the proposed method of ground motion synthesis is applied to a relatively simple case. Design ground motion is synthesized for a pier structure, which is referred to as a target structure hereafter. Pier structure is a concrete structure and objected to support the elevated road way. A ground motion representing a set of possible ground motions is synthesized by using the proposed method of ground motion synthesis. The generated ground motion is applied to the target structure and its performance is discussed.

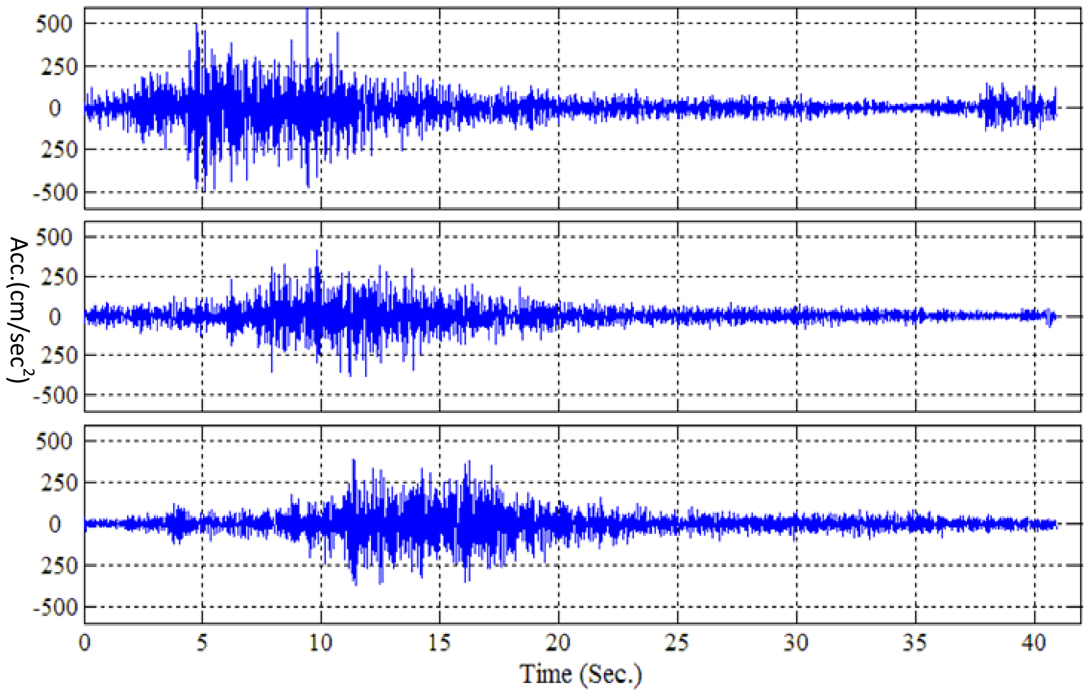


Figure 4.1 Three ground motions formulated by Empirical Green's Function method.[1]

4.2 Problem Setup

4.2.1 Generation of possible ground motions

Possible ground motions are generated assuming uncertainty in some of the fault parameters, using the empirical Green's function (EGF) method [5]. The EGF method uses strong motion records of small earthquake events as Green's function to synthesize ground motion attributable to a large earthquake. It integrates the strong motion records of small events over the fault plane considering the rupture process. The fault plane is divided into segments equivalent in size to that of small events. The ground motions to be generated from individual segments are replaced by the small-event records. By taking a summation of these records both in time and space domains, the ground motion of the large event is generated.

The 2005 Miyagiken-Oki earthquake (M 7.2) in Japan is simulated. Aftershock records of the same earthquake obtained by K-NET [6] are used as the small-event record. Fault parameters are assumed as listed in the Table 4.1. S wave velocity and fracture velocity are assumed to have uncertainty with 5% Gaussian noise. In this simulation, uncertainty is assumed only in these parameters because it suffices the purpose of generating a variety of

Table 4.1Fault Parameters used to formulate the set of possible ground motions by using Empirical Green's Functionmethod (Mean Values) [1]

Fault size	Length = 31.8, Width = 38 (km)
Epicenter (on fault)	X = 31.8, Y = 19 (km)
S wave velocity	3.0 (km/sec)
Fracture velocity	2.1 (km/sec)

ground motions. Discussion about whether the presented scheme is applicable when the variety of ground motions is attributable to the fluctuation of other seismic parameters is beyond the scope of this simulation. Nine hundred ninety-nine ground motions are generated, and they are regarded as possible ground motions. Among the generated ground motions, time histories of three ground motions that have relatively large peak accelerations are shown in Figure 4.1. The histogram in Figure 4.2 shows that peak ground acceleration of the generated ground motions are distributed over the range of 300 to 650 cm/sec^2. Although they are synthesized using the same ground motion record as Green's function, considerable diversity is observed.

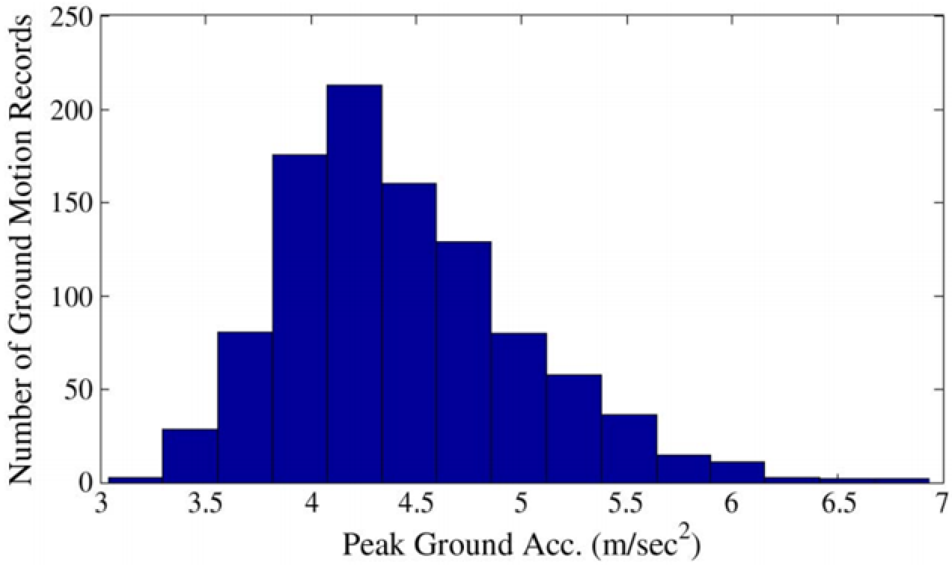


Figure 4.2 Histogram of maximum acceleration of set of input ground motions formulated by Empirical Green's Function [1]

4.2.2 Target structure

As the target of application, a simple multi degree-of-freedom (MDOF) model is assumed, modeling an 11-m-high pier of elevated roadway as shown in Figure 4.3. The column consists of 40 layers of elements, and each layer is meshed by using 10×10 elements. The model consists of 40×10×10 elements in total. For simplicity, the mass is concentrated on four nodes. The top mass corresponds to the weight of deck slab (including the weight of supporting girders etc) and other three masses to the column. Natural periods of the system in the elastic range are 0.63, 0.48, 0.27, and 0.087 seconds. Bilinear nonlinearity is assumed as the material property in which Young's modulus reduces to 20% of the initial value after

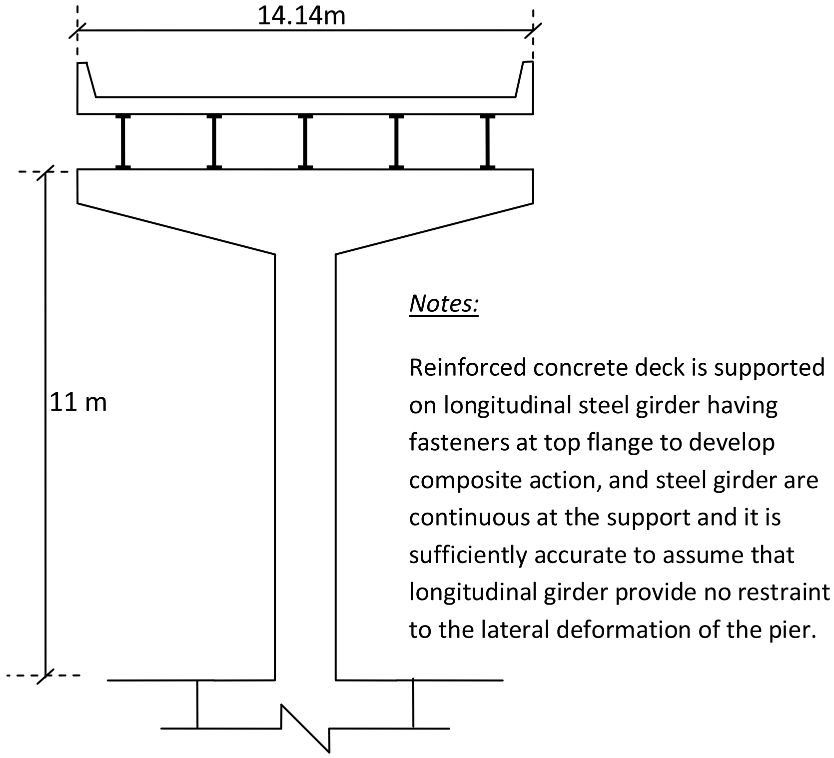


Figure 4.3Dimensions of bridge Pier used in used in numerical simulation[1]

yielding. Because of the distribution of stress along the section, the hysteresis curve of the force-displacement relationship does not exhibit a simple bilinear relationship. Uncertainty is assumed in structural parameters of the target model described above. Gaussian noise with the standard deviation of the 7% and 2% of the mean value is added to the stiffness and the yielding force, respectively. Dynamic analysis of the target model is conducted using the OpenSees Software [7].

The response of nonlinear SDOF systems is used as the feature indices to describe the set of the input ground motions. The SDOF system has a natural period identical to the first mode of the target structure, and exhibits bilinear properties. It yields at the same acceleration level as the target structure. Parameters of the SDOF model have the same uncertainty as the parameters of the target structure. Response of the system is regarded as a feature index to describe the effect of the input motions on the target structure, considering the uncertainty of structural parameters.

As mentioned previously, feature indices are used not to predict the behavior of the target structures, but to describe the set of possible ground motions from the viewpoint of how they affect the behavior of structures. Response of a nonlinear SDOF system is expected to serve as a good index because it takes into consideration the response of the first mode and also the effect of nonlinearity.

4.3 Ground Motion Synthesis Based on Feature Indices

The procedure to synthesize the ground motion that represents the set of possible ground motions starts with the selection of the indices to be considered. Two cases are presented. One case adopts peak response displacement of nonlinear SDOF systems as an index, and the other considers two indices of peak displacement and peak velocity of nonlinear SDOF systems. In both cases, fluctuation is given to the parameters of SDOF systems and 1,000 realizations of nonlinear SDOF systems are used to consider structural uncertainty.

Since it is impossible to find a ground motion that exceeds all possible ground motions in terms of selected indices, the ground motion is generated by an iterative update of one possible ground motion. In each update, the ground motion should be modified so that it can efficiently increase the values of selected indices, that is, peak response values of nonlinear systems. It is fulfilled by paying attention to the time-frequency characteristics of the ground motion. Time-frequency characteristics of the ground motion are modified by using Morlet wavelet functions [8, 9]. The procedure for synthesis of design ground motion is schematically shown in Figure 4.4 and elaborated in the following.

First, the target time and target frequency to be amplified is determined based on the property and response of the nonlinear system. A wavelet that takes the peak value at the target time and frequency is then generated and added to the candidate ground motion. If the structural system is linear, the target frequency should be equal to the natural frequency and the target time should be the time at which the response hits the peak. In this problem, however, target time and frequency cannot be determined exactly because of the nonlinear behavior of the system and uncertainty of the structural parameters. Therefore, 10 candidate ground motions are generated by randomly fluctuating the target time and frequency, and one of them is selected.

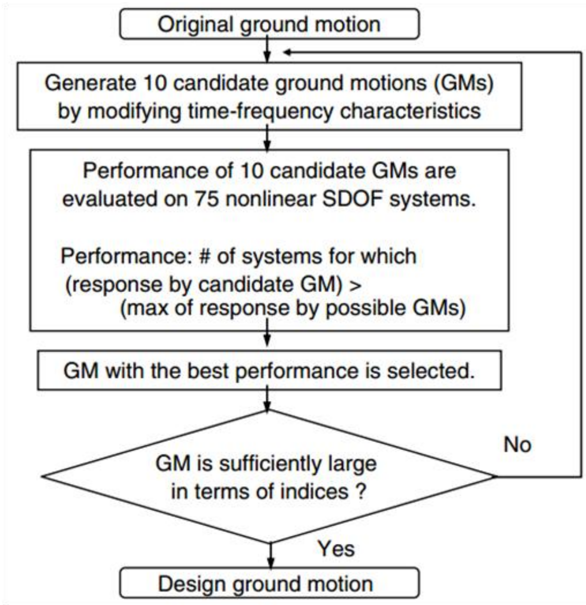


Figure 4.4 Simplified flow of iterative procedure for design ground motion synthesis [1]

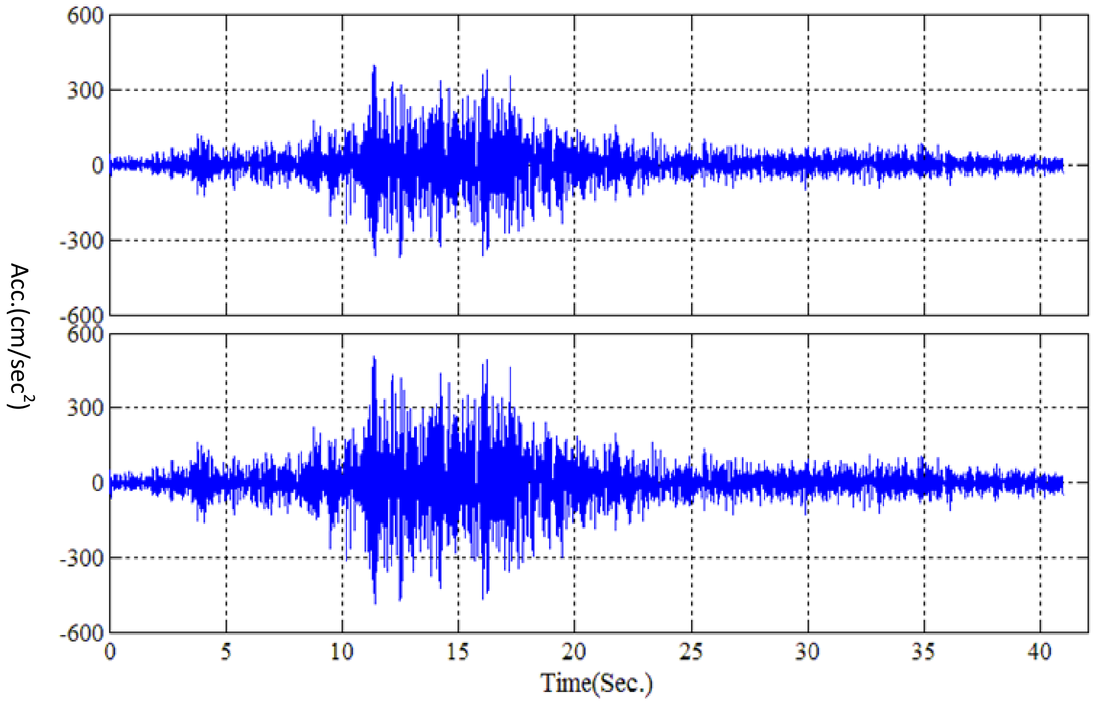


Figure 4.5 (Top) Ground motion Synthesized by proposed method of ground motion synthesized using one index (Bottom)Factored ground motion for comparison[1]

The generated ground motions are compared based on the feature indices as follows. Out of 1,000 realizations of nonlinear SDOF structures reflecting the structural uncertainties, 75 realizations are randomly selected. The number of realizations is counted for which the nonlinear response induced by the candidate ground motion (formulated by modifying time frequency characteristics) is larger than that by all possible ground motions. (In this simulation, all 999 ground motions are considered, but if the number of possible ground motions is huge, this could be conducted using a randomly selected finite number of ground motions.)

The ground motion that exhibits the largest number among the 10 candidate ground motions is adopted as the updated ground motion.

This procedure is iterated until the updated ground motion becomes strong enough to become the largest in terms of feature indices among all possible ground motions for all 75 realizations. The generated ground motion is expected to surpass most of possible ground motions in terms of feature indices, and it represents the set of possible ground motions.

4.4 Simulation Results

4.4.1 Case 1: Considering a single Index

In the first case, peak response displacement of a nonlinear SDOF system is considered as a single index. Time history of the synthesized ground motion is shown at the top in Figure 4.5.

If the synthesized ground motion indicates much larger response values compared with real seismic ground motions, it would lead to overly conservative seismic design. To assess this aspect of the synthesized ground motion, the ratio of the peak response of as SDOF caused by *j*th motion to that caused by the synthesized ground motion is defined as

$$R_{\delta,j} = \frac{\text{peak response displacement of a SDOF by } j^{th} \text{ ground motion}}{\text{peak response displacement of a SDOF by synthesized ground motion}} \qquad 4.1$$

where $j = 1 \cdots 999$. If $R_{\delta,j} < 1$, it indicates that the synthesized ground motion is stronger than the j^{th} ground motion in terms of peak response displacement. $R_{\delta,j}$ is plotted against the number of candidate ground motions in Figure 4.6. The plot shows that the ratio is less than 0.9 in most cases, which indicates that displacement capacity required by the synthesized ground motion is larger than those by possible ground motions by 10% or more.

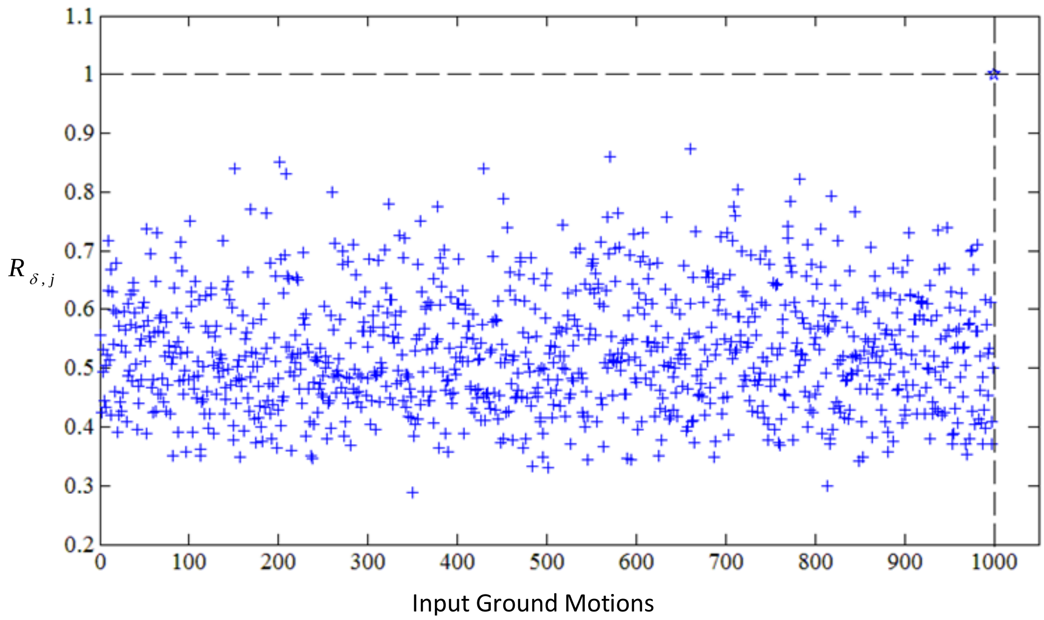


Figure 4.6 Distribution of $R_{\delta,j}$ for set of possible ground motion, UNIT value on vertical axis corresponds to synthesized ground motion [1]

It indicates that the synthesized ground motion is sufficiently strong in terms of SDOF realizations. It also implies that the generated ground motion is redundantly demanding with the margin of 10%.

The reason for the redundancy becomes clear when the uncertainty of structural parameters is considered. In the simulation, 1,000 SDOF realizations are used to cope with uncertainty of structural parameters, and their response against 999 candidate ground motions and the synthesized ground motion are calculated. As in Equation 4.1, the ratio of the peak response of the *i*th SDOF realization caused by the *j*th ground motion to that by the synthesized ground motion is discussed. To find the largest response induced by the possible ground motions, the ratio of the maximum value of peak displacements of the *i*th SDOF realization caused by 999 ground motions to that caused by the synthesized ground motion, is defined as

$$R_{\delta}^{i} = \frac{\text{max.of peak response diaplacement of } i^{th} \text{ structure caused by all ground motions}}{\text{peak response displacement of } i^{th} \text{ structure by synthesized ground motion}} \quad 4.2$$

where $i = 1 \cdots 1{,}000$. Figure 4.7 plots R_{δ}^{i} against 1,000 SDOF realizations. In the figure, many of the ratios are less than unity. This implies that the margin observed in Figure 4.6 is necessary when uncertainty is to be considered.

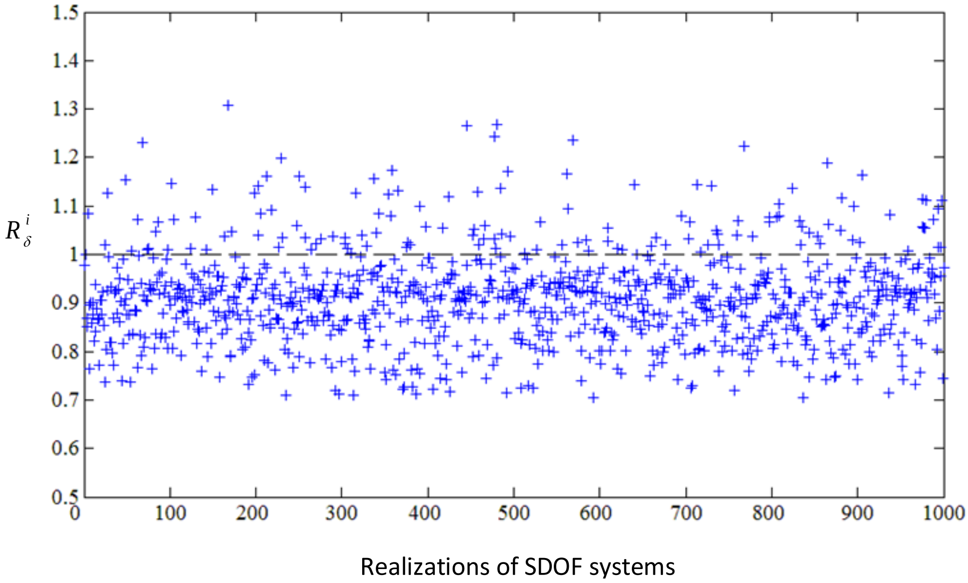


Figure 4.7 Distribution of R_δ^i from 1000 realizations of SDFO structures [1]

As a reference, a factored ground motion is generated by amplifying the original ground motion. The amplification factor is determined as follows. Among all combinations of 1,000 nonlinear SDOF realizations and 999 ground motions, the number of combinations is counted in which the peak response displacement is larger than that by the factored ground motion. The number, which is denoted by N_C, can be considered the quantitative representation of the reliability of the factored ground motion, because small N_C indicates low exceeding probability, that is, a high level of safety. The value of N_C decreases as the amplification factor increases from 1.0 to 1.7, as is shown in Figure 4.8. Figure 4.8 also shows N_C counted for the synthesized ground motion. The ground motion factored by 1.3 has almost the equivalent safety level as the synthesized ground motion and is used as the reference. The time history of the factored ground motion is shown at the bottom in Figure 4.5.

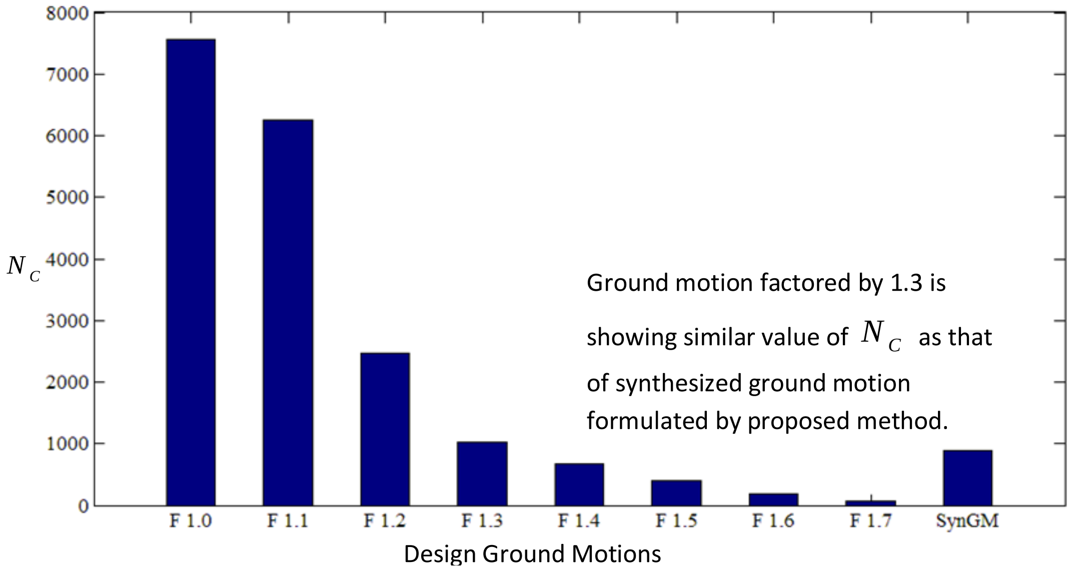


Figure 4.8Values of N_C for factored ground motions and ground motion synthesized by using one index [1]

Performance of the factored and the synthesized ground motions are compared considering the target multi degree of freedom (MDOF) structure. They are compared in terms of displacement and velocity responses of the top mass and the bending moment at the critical section. As in Equation 4.1, the ratio of the peak displacement of the top mass by the *j*th ground motion to that by the synthesized ground motion is defined as

$$R_{\delta,j}^{MDOF} = \frac{\text{peak respsone dispalcement of top mass by } j\text{th ground motions}}{\text{peak respsone dispalcement of top mass by sunthesized ground motion}} \tag{4.3}$$

Similarly, ratios $R_{V,j}^{MDOF}$ and $R_{b,j}^{MDOF}$ are defined as velocity response of top mass and the bending moment at the critical section, respectively.

Figure 4.9a shows the values of $R_{\delta,j}^{MDOF}$ and $R_{V,j}^{MDOF}$. The synthesized ground motion, which is generated considering the displacement response as an index, is sufficiently large in terms of the response displacement of the target structure, compared with all other candidate ground motions. In terms of response velocity, considerable number of ground motions make the ratio larger than 1.0. Figure 4.9 b shows $R_{b,j}^{MDOF}$ and $R_{V,j}^{MDOF}$, illustrating that the synthesized ground motion yields a sufficiently large bending moment compared with most of possible ground motions.

Figure 4.9 also shows the ratios of the response values induced by the factored ground motion to those by the synthesized one, which is given by replacing the "*j*th ground motion" in the numerator of Equation 4.3 with "factored ground motion." The factored ground motion is obtained so that it has the same level of safety in the presence of uncertainty of ground motion and structural parameters. It exhibits good performance, giving the ratios of about 1.0, 1.4, and 1.05 in response displacement, response velocity, and bending moment, respectively. The synthesized and the factored ground motions are almost the same in response displacement and bending moment. As for the response velocity, however, only the factored ground motion exhibits sufficiently large value. This indicates that if response velocity is an important factor for the safety of target structures, sole consideration of response displacement was not enough to show the advantage of the synthesized ground motion and it would be appropriate to use multiple indices

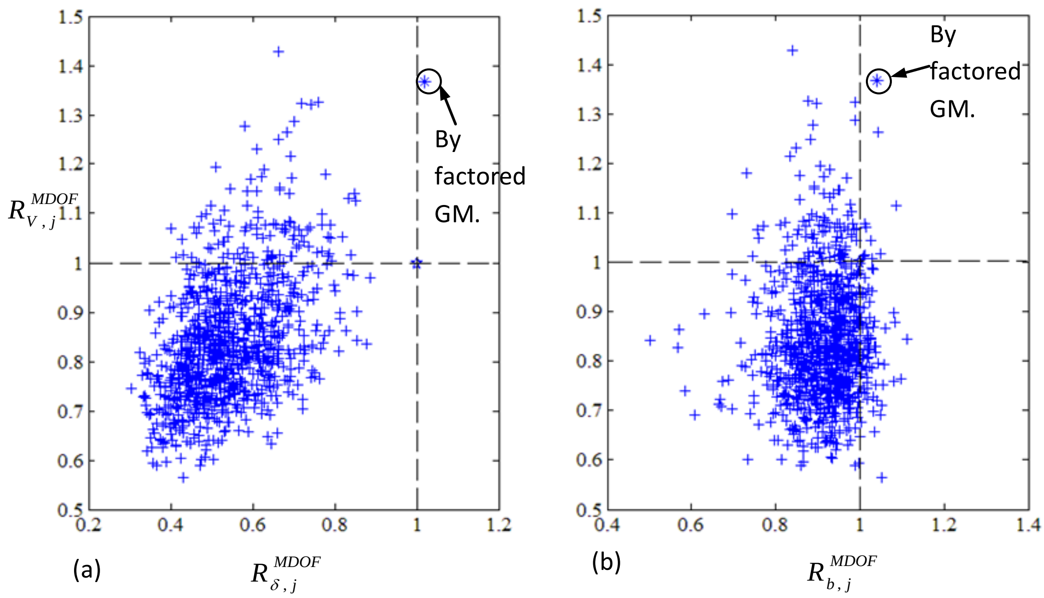


Figure 4.9(Left) Distribution of $R_{V,j}^{MDOF}$ and $R_{\delta,j}^{MDOF}$ for MDOF structure against set of possible ground motions (Right)Distribution of $R_{V,j}^{MDOF}$ and $R_{b,j}^{MDOF}$ for MDOF structure against set of possible ground motions, UNIT value on horizontal and vertical axis corresponds to Synthesized ground motion [1]

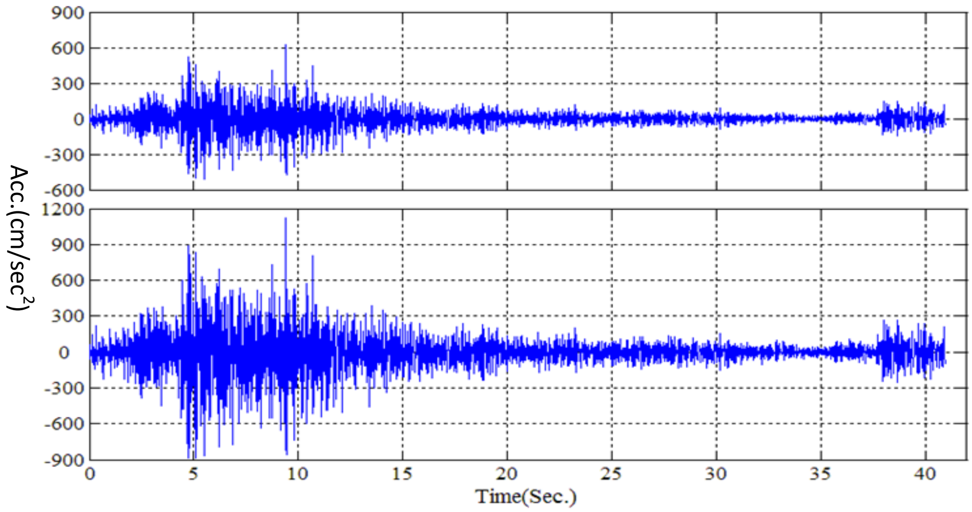


Figure 4.10 (Top) Ground motion Synthesized by proposed method of ground motion synthesized using two indices (Bottom)Factored ground motion for comparison[1]

Case 2: Considering two indices

Another simulation is presented to discuss the performance of the ground motion synthesized by considering two indices: peak displacement response and peak velocity response of nonlinear SDOF systems. The same uncertainty in the ground motions and structural parameters is assumed as was in the single-index case. Time history of the synthesized ground motion using two indices is shown at the top in Figure 4.10.

The ratio of the peak response caused by the *j*th ground motion to that caused by the synthesized ground motion, as given in Equation. 4.1, is defined for the response displacement ($R_{\delta,j}$) and response velocity ($R_{V,j}$) and is plotted in Figure 4.11. All results give the value less than 1.0, indicating that the synthesized ground motion is sufficiently demanding. It is observed that there is redundancy in response displacement, whereas the response velocity ratio exhibits a small margin.

The performance of the synthesized ground motion in the presence of parametric uncertainty in both ground motions and structures is discussed. As in Equation 4.2, the ratio of the maximum of peak displacements of the *i*th structure caused by all possible ground motions to that by the synthesized ground motion is defined. The ratios of displacement response and velocity response are denoted by R_δ^i and R_V^i , respectively. Figure 4.12 plots their distributions. Most of the ratios of the response velocity R_V^i are less than 1.02. The ratios of displacement response R_{δ}^{i} are sensitive to uncertainty, and they are distributed over the wider range, some exceeding 1.0 by 20%. This indicates that the redundancy of response displacement in Figure 4.11 is actually necessary to ensure safety because the displacement response of the current problem is highly sensitive to the uncertainty of input motions

Performance of the synthesized ground motion is compared with that of the factored one, which is supposed to ensure the same level of safety. Figure 4.13 shows the number of combinations of SDOF realizations and possible ground motions for which peak displacement of the structure caused by the ground motion is larger than that by the factored and the synthesized ground motions. The comparison shows that the ground motion factored by 1.8 has an equivalent safety level as the synthesized ground motion. The time history of the ground motion factored by 1.8 is shown at the bottom in Figure 4.10.

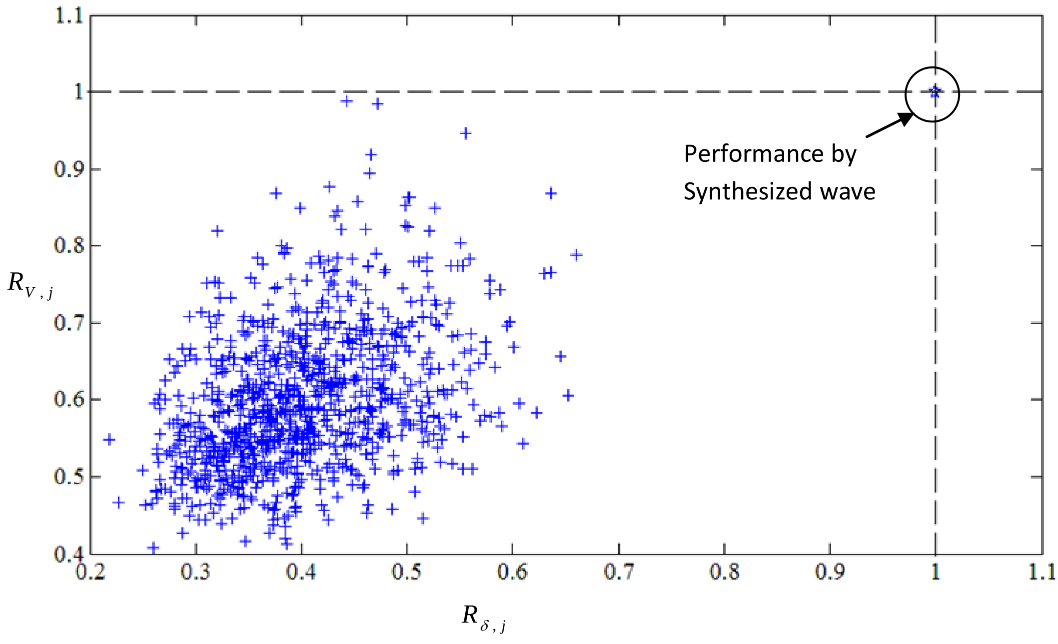


Figure 4.11 Distribution of $R_{\delta,j}$ against $R_{V,j}$ for set of possible ground motions, UNIT value corresponds to deterministic SDOF against synthesized ground motion [1]

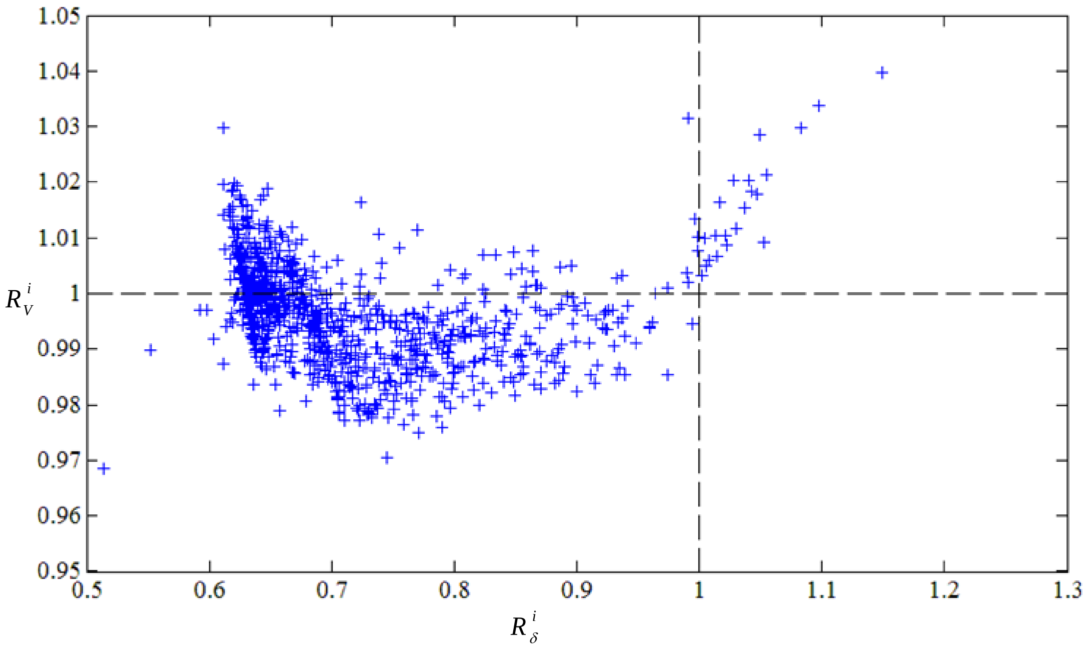


Figure 4.12Distribution of R_δ^i *and* R_V^i *for set of possible ground motions and ground motion synthesized by proposed method of ground motion synthesis [1]*

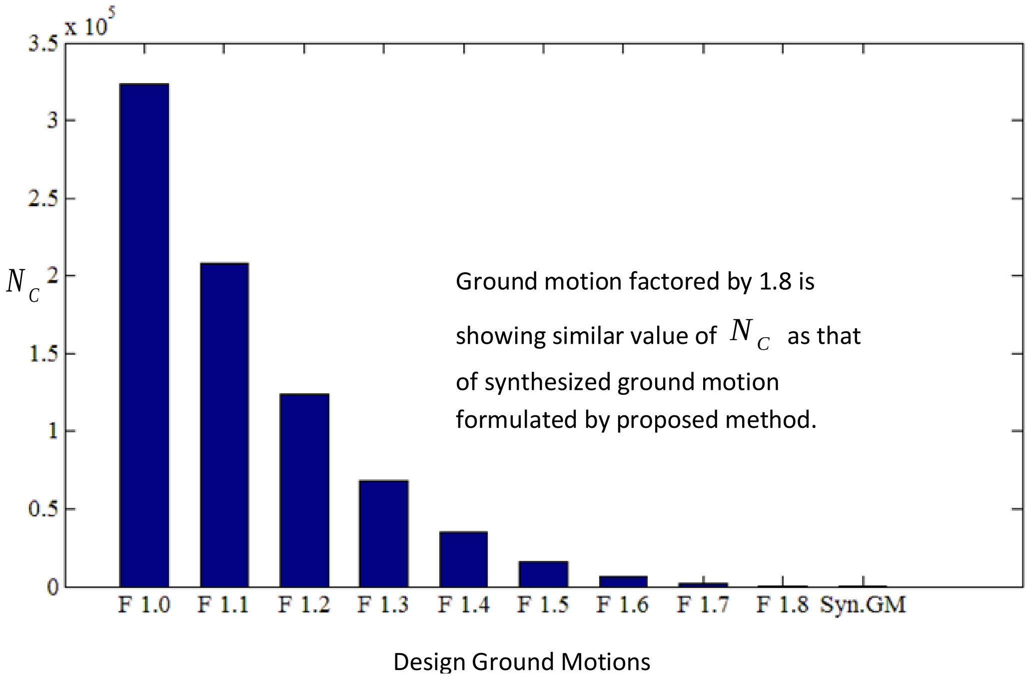


Figure 4.13Values of N_C *for factored ground motions and ground motion synthesized by using two indices [1]*

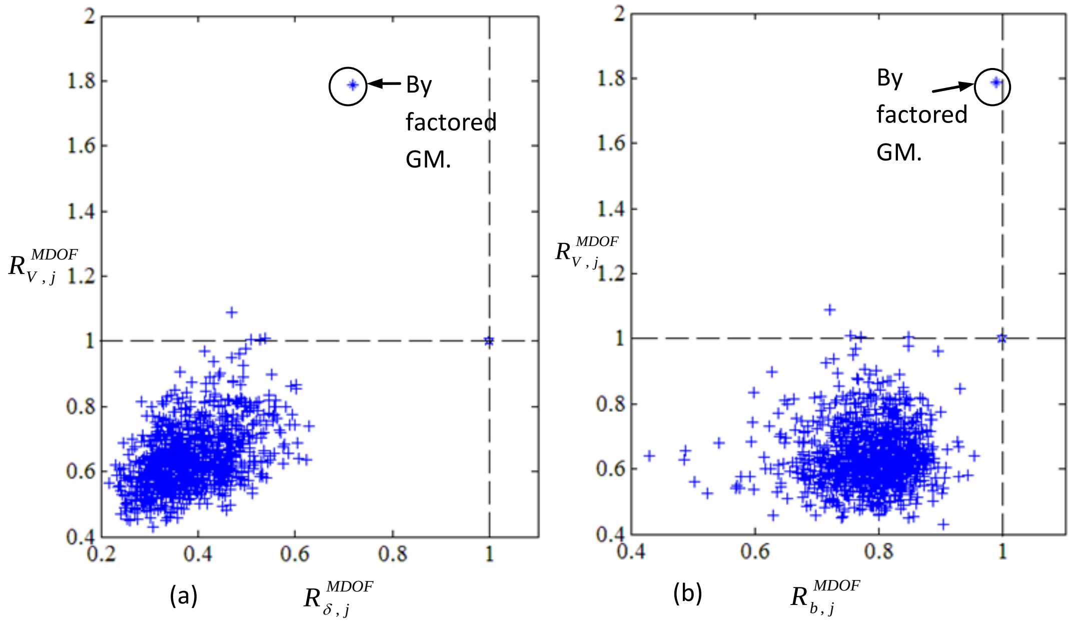


Figure 4.14(Left) Distribution of $R_{V,j}^{MDOF}$ and $R_{\delta,j}^{MDOF}$ for deterministic MDOF structure against set of possible ground motions, (b)Distribution of $R_{V,j}^{MDOF}$ and $R_{b,j}^{MDOF}$ for deterministic MDOF structure against set of possible ground motions, unit value corresponds to synthesized ground motion using two indices) [1]

The synthesized, factored, and possible ground motions are applied to the target MDOF structure. The ratio of the response displacement by each ground motion to that by the synthesized ground motion $R_{\delta,j}^{MDOF}$ is defined as in Equation 4.3. Similarly, the ratios $R_{V,j}^{MDOF}$ and $R_{b,j}^{MDOF}$ are defined for the response velocity of the top mass of the target structure and peak bending moment at the critical section, respectively. Figure 4.14a shows the distribution of $R_{\delta,j}^{MDOF}$ and $R_{V,j}^{MDOF}$, and Figure 4.14b shows $R_{b,j}^{MDOF}$ and $R_{V,j}^{MDOF}$. These figures reveal that most ratios are less than 1.0. The response of the target structure induced by possible ground motions is not likely to exceed the values estimated by the synthesized ground motion in response displacement, response velocity, and bending moment. There exists wide margin of redundancy in response displacement. Figure 4.14a also shows that the ratio induced by the factored ground motion is less than 1.0 for the response displacement, whereas it is as high as 1.8 for the response velocity, indicating that the factored ground motion is less demanding in terms of response displacement and more demanding in terms of response velocity.

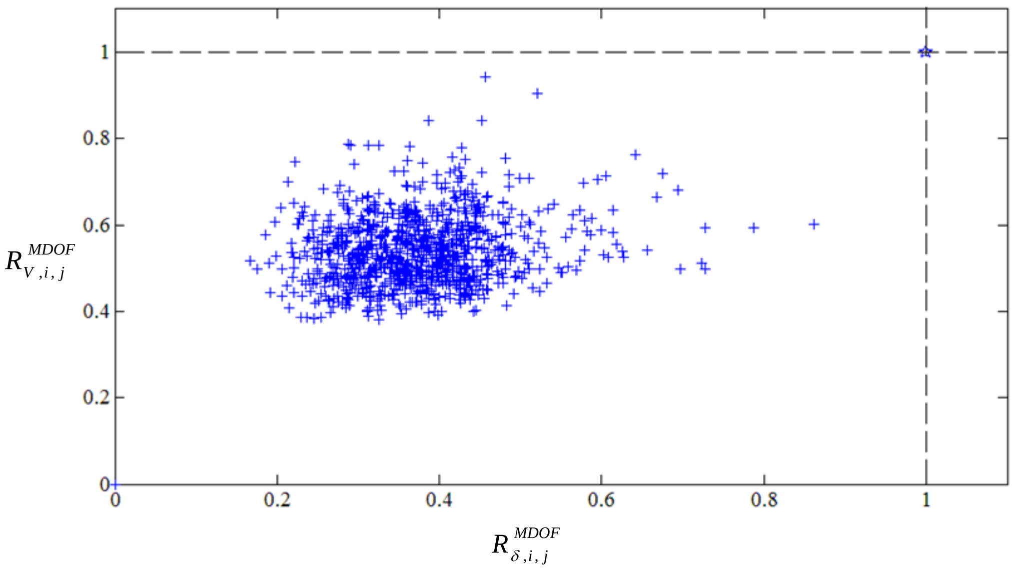


Figure 4.15 Distribution of $R_{V,i,j}^{MDOF}$ against $R_{\delta,i,j}^{MDOF}$ for 2000random combinations of target structure and possible ground motions, Unit Value corresponds to response of target structure (with deterministic parameters) against synthesized ground motion [1]

Considering the performance of the synthesized ground motion in the presence of uncertainty of structural parameters of the target MDOF structure, attention is paid to response displacement and response velocity, because it is in these factors that the factored and the synthesized ground motions are clearly different. One thousand structures are considered, changing parameters of target MDOF structures. The peak response displacement of the top mass of the ith structure, induced by the jth ground motion, is compared with that by the synthesized ground motion. The ratio is given as

$$R_{\delta,i,j}^{MDOF} = \frac{\text{peak response diaplacement of top mass of } i^{th} \text{ structure by } j^{th} \text{ ground motion}}{\text{peak response displacement of top mass of deterministic structure by synthesized ground mot}} \qquad 4.4$$

Ratio of the peak velocity response $R_{V,i,j}^{MDOF}$ is also defined in the same manner. Figure 4.15 plots the ratios for a randomly selected 2,000 combinations of structures and ground motions. The figure indicates that most of both of these ratios are less than 1.0, which indicates that the target MDOF structure designed with the synthesized ground motion would show good performance even when structural parameters have uncertainty. Some give the ratio of 0.8 or larger in terms of response displacement. This implies that the redundancy observed in Figure 4.14a contributes to ensuring the performance under uncertainty.

4.5 Efficiency of Synthesized Ground Motion in Context of Uncertainty of Structural Parameters

Structural performance in nonlinear range is affected by a number of factors. We assume variation in structural parameters to cope with uncertainty of nonlinear response. But, it is difficult to evaluate the range of uncertainty of structural parameters, therefore it is necessary that the proposed method of ground motion synthesis must be stable to change in structural parameters. Afore mentioned aspects of proposed method of ground motion synthesis are evaluated [2] and reproduced here in the following.

To validate the effectiveness of the proposed method of ground motion synthesis in context of uncertainty of structural parameters, here a more detailed model of bridge pier is used in numerical simulation. Bridge pier is modeled by using steel and concrete fibers. The simulation conditions are described in the following

4.5.1 Simulation conditions

- *Set of input Ground motions:* Similar to the previous case, the set of possible ground motions were formulated considering the fault parameters. The detail is given in section 4.2.1.
- *Design ground motion synthesis:* Design ground motion is synthesized by using two indices. The displacement and velocity response of SDOF are used as indices. Ground motion is synthesized similar to the previous case. The detail has explained in section 4.2.3
- *Parameters to show the effectiveness of the synthesized ground motion:* we consider the absolute maximum displacement and velocity response of the top of concrete pier and bending moment at the critical section of pier as factors to validate the effect of ground motions on structures.

4.5.2 Efficiency of synthesized ground motion in comparison of set of possible ground motions

To validate the performance of synthesized ground motion to represent the ground motions generated by the fault model in terms of nonlinear response values, efficiency of synthesized ground motion is discussed for following conditions

- Design ground motion is synthesized by using indices, but efficiency of synthesized ground motion is to be evaluated in context of bridge pier structure (bridge pier structure is modeled in OpenSees by using fibers of concrete and steels). This aspect is required to be discussed because, design GM is synthesized by using indices, but actually, the ground motion is to be used for the analysis and design of structure.

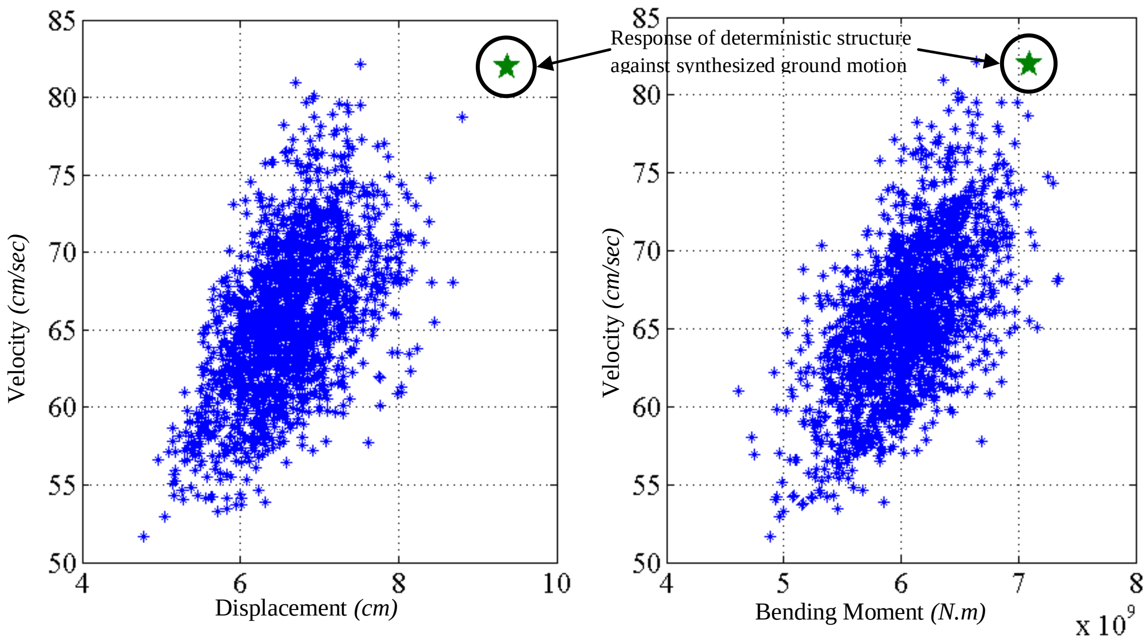


Figure 4.16Absolute maximum displacement and velocity response of top of concrete pier and bending moment at bottom of concrete pier for 2000 random combination of uncertain structures and possible ground motions due to uncertainty of fault parameters. [2]

- Performance of synthesized ground motion is to be compared with set of possible ground motions, in context of application to structure.
- Performance of synthesized ground motion is to be discussed in context of uncertainty of structural parameters.

Figure 4.16 shows the absolute maximum displacement response, velocity response and bending moment at the critical section of pier for a randomly selected 2,000 combinations of structures and ground motions. Structural model based on mean values of structural properties is referred to as deterministic structure hereafter. The response of deterministic model against the synthesized ground motion is also plotted in Figure 4.16. Figure 4.16 clarifies that the response of deterministic structure against the synthesized ground motion is dominating the response of random combination of possible ground motions and uncertain structures. It is important to mention that, although the bending moment was not considered as an index during the synthesis process, the synthesized ground motion also dominates in terms of bending moment.

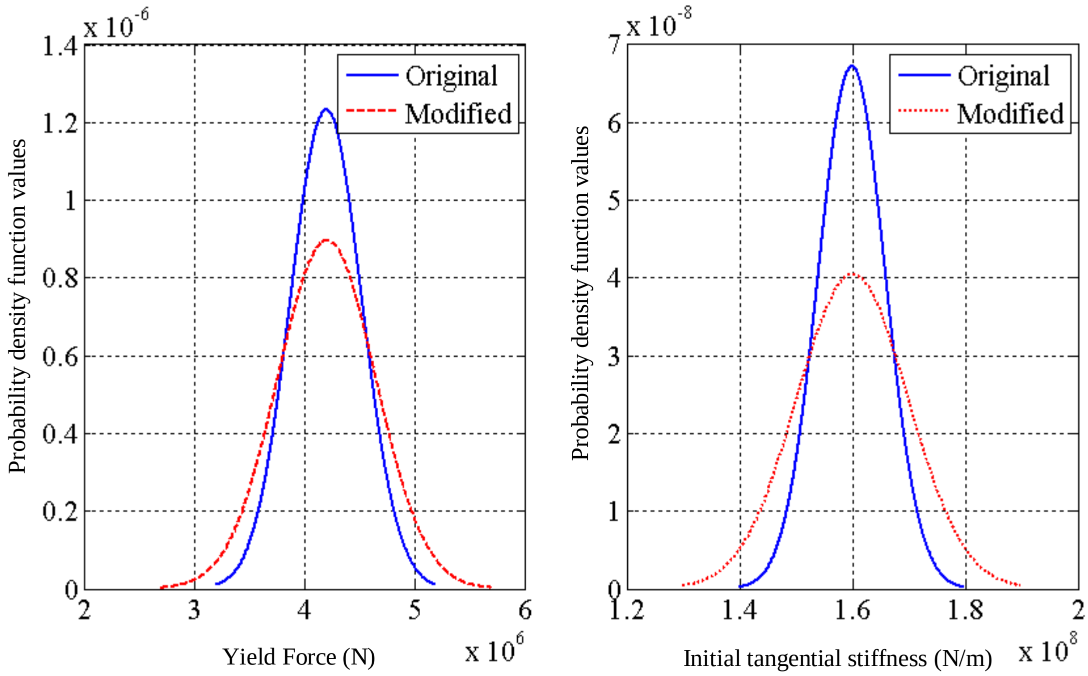


Figure 4.17Smoothed probability density function to show the distribution of original and modified range of yield force and stiffness of pier structure. [2]

This means that designing the deterministic structure against the synthesized ground motion by the proposed method is equivalent to analyzing a quite large number of structures against a suite of simulated ground motion due to uncertainty of fault parameters.

4.6 Robustness of the Synthesized Ground Motion

Let us remind that uncertainty range of seismic and structural parameters is difficult to evaluate. It is important that the proposed method of ground motion synthesis should not be sensitive to the change of uncertainty range of structural and seismic parameters. To validate this aspect of the proposed method, another set of structures is assumed by modifying the uncertainty range for stiffness and yield stress level of structure. The original and modified probability density function for the stiffness and yield force level of structure are plotted in Figure 4.17. The standard deviation for yield force is modified from 7% to 15% and 7% to 11% for stiffness of structure.

Similar to previous case, absolute maximum displacement response, velocity response and bending moment at the critical section of concrete pier for a randomly selected 2,000 combinations of structures and ground motions are plotted in Figure 4.18. The response of deterministic structure against the synthesized ground motion is also plotted on Figure 4.18.

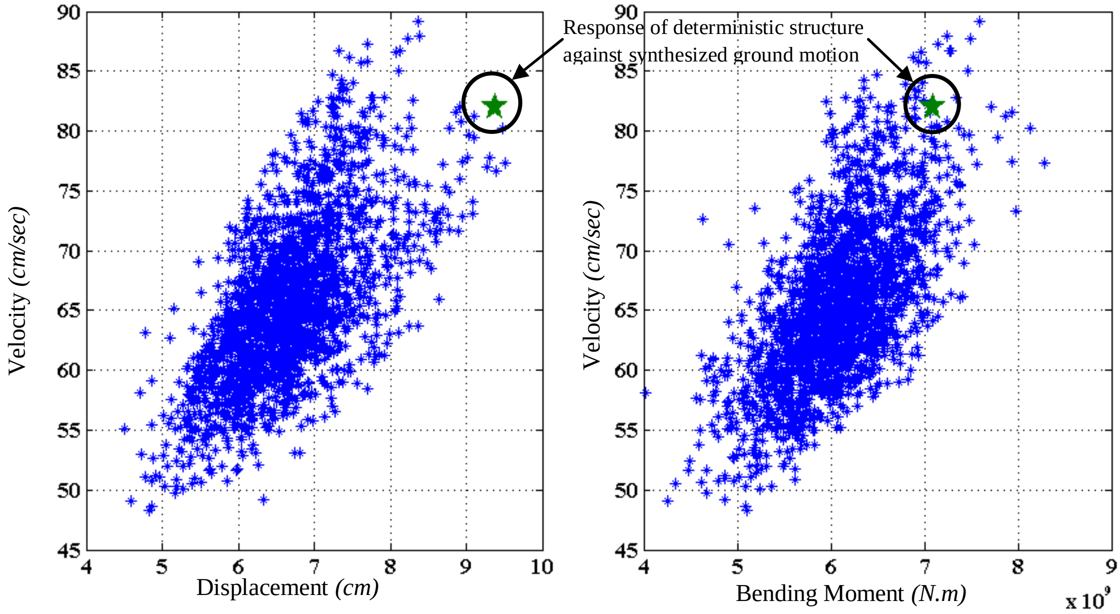


Figure 4.18Absolute maximum displacement and velocity response of top of concrete pier and bending moment at bottom of concrete pier for 2000 random combination of uncertain structures against modified structural parameters and possible ground motions due to uncertainty of fault parameters. [2]

Figure 4.18 shows that the nonlinear response of deterministic structure against the synthesized ground motion is reasonably dominant over the random combination of ground motions and structures. It should be noted that the structure models in the random combinations of Figure 4.18 posses the structural properties with the modified uncertainty range, which was not considered during the synthesis of design ground motion.

This validates that design ground motion simulated by the proposed method is efficient to represent the fault parameters in terms of nonlinear response values and proposed method is robust against the vagueness of uncertainty of uncertain parameters.

4.7 Design Ground Motion Synthesis for Concrete Frame

The effectiveness of the proposed method of ground motion synthesis is discussed in context of a bridge pier structure in previous section. The set of ground motions was formulated by using fault model. Here, performance of the proposed method of ground motion synthesis is elaborated for more complicated problem. Design ground motion is synthesized for a concrete frame for following conditions.

- Target structure is a five floor moment resisting concrete fame.
- The set of possible ground motions is composed of real ground motion records of previous earthquakes.

The detail of set of possible ground motions and modeling of target structure are in the following.

4.7.1 Possible ground motions

Set of possible ground motion is considered for the design of structures to enhance the reliability of structural performance. 2,000 ground motion records from past earthquake events are obtained from K-NET [6]. Actual ground motion records are used in order to discuss the applicability of the presented scheme for real ground motions. The ground motion records are factored so that their peak ground acceleration values are ranging between 600cm/sec^2 to 800cm/sec^2.

To discuss the affect of set of possible ground motions on synthesized ground motions, ground motion is synthesized by considering a set of 500 ground motions, which are randomly selected from 2000 possible ground motions. Performance of the synthesized ground motion is elaborated in context of the set of possible ground motions used in the synthesis process and also in context of the set of possible ground motions which are not considered in the synthesis process.

4.7.2 Structural model

Design ground motions are synthesized for a moment resisting concrete frame, elevation of the frame is shown in Figure 4.19and sectional details are shown in Table 4.2. This structure here after referred to as target structure. The dead load for the nonlinear analysis 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[7].

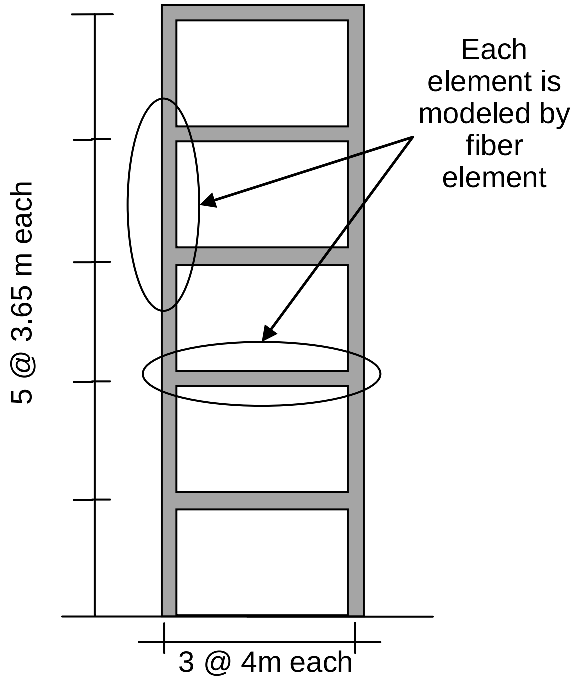


Figure 4.19Elevation of concrete frame [3]

Table 4.2Detail of beam and column sections [3]

	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*

Elements of frame are modeled by using unidirectional steel and concrete fibers. Figure 4.20 and Figure 4.21 elaborates the discretization of structural member into steel and concrete fibers. The steel and concrete fibers 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`[10] model is used to model confined and unconfined concrete. The stress strain curve for concrete model is shown in Figure 4.22. Tensile strength of concrete is also considered in this model. Parameters to model stress strain curve for concrete are summarized in Table 4.3.

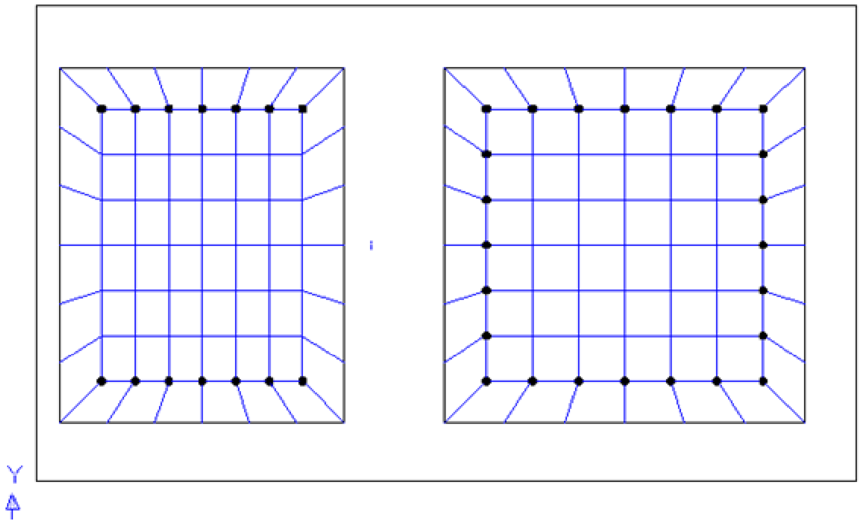


Figure 4.20 Meshing of beam and column (x-section)

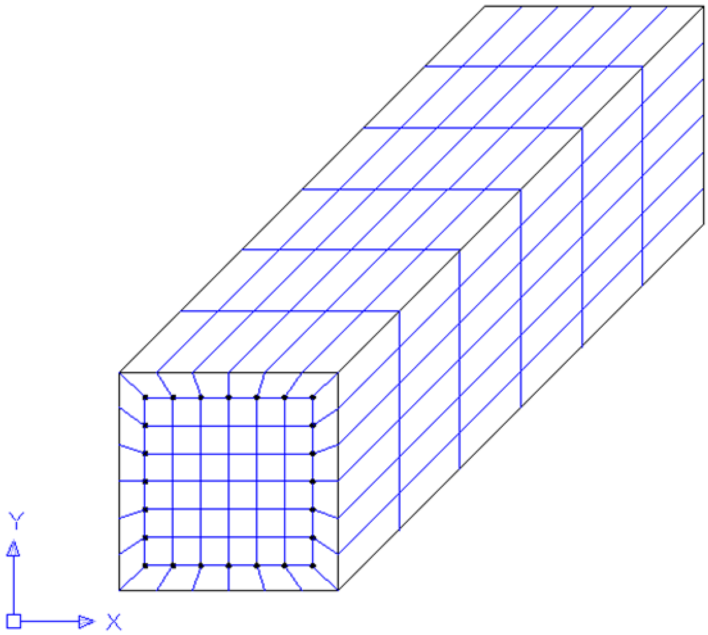


Figure 4.21 3D view of a member of concrete frame

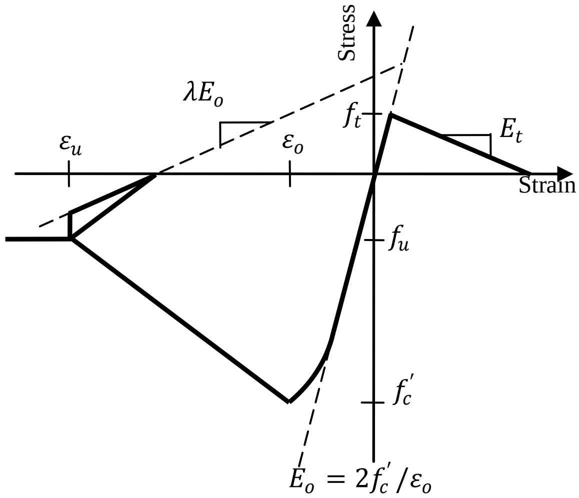


Figure 4.22Stress strain model for`concrete02`[3,7,10]

Table 4.3Properties of concrete model`Concrete02`[3]

$f_c^{'}$ = 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

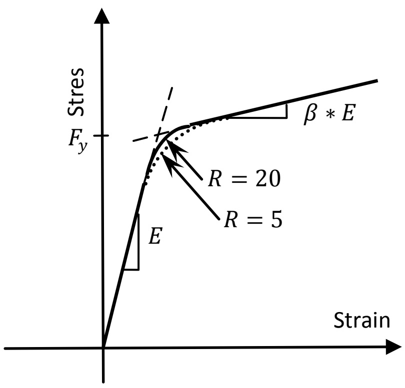


Figure 4.23Stress strain model for`steel02`[3,7]

Table 4.4Parameters of steel model used in simulation[3]

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

Similarly, material model `Steel02` [7] of OpenSees is used to characterize the stress strain behavior of steel fibers. In `Steel02` model we can control the transition from linear to nonlinear stage. The stress stain curve for this steel model is shown in Figure 4.23, the model parameters are tabulated in Table 4.4.

4.7.3 Uncertainty of material properties

The dynamic characteristics of the structure, such as natural frequency, yield force etc, are function of the material and sectional properties of structural members. Theoretically, the material properties are supposed to be a constant, while, practically the material properties of the member would be fluctuating between a minimum and maximum value. This complicates the dynamic response of the structure.

In order to consider the affect of uncertain material properties on structure response, we consider material properties of elements as 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 variables are listed in Table4.5.

Parameters of the fiber model of concrete are function of compressive strength of concrete. As in this simulation, compressive strength of concrete is considered as a stochastic variable, therefore, property of whole structure also varies in a stochastic manner.

We considered a standard deviation in material properties. And as an example we fix the 3%, 5% and 7% standard deviation (STD) in modulus of elasticity of steel, yield strength of steel and compressive strength of concrete respectively. Basically, standard deviation was fixed based on engineering judgment. Here, based on some references, qualitative discussion is

Table 4.5Parameters of stochastic material-properties [3]

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

made in the following regarding the fluctuation considered for the compressive strength of concrete and yield strength of steel.

a) For compressive strength of concrete:

Compressive strength of concrete will be satisfactory if following requirements are meant from 28days compressive strength of concrete.

"A strength test is the result of two cylinder made from fresh concrete and tested at an age of 28 days. Concrete would be considered as satisfactory, if the following requirements are fulfilled

- The average of three consecutive test should not more than or equal to the specified compressive strength of concrete.
- No individual test is more than 3.5 Mpa below the specified strength." [11]

Based on this information, the compressive strength of concrete $\pm 3.5Mpa$ is to be considered while setting the fluctuation to the compressive strength of concrete. In this simulation, $27.5, 21.9$ and $32.8\,Mpa$ are average, minimum and maximum value of compressive strength of concrete respectively.

Thus, in this simulation we consider a fluctuation to the compressive strength of concrete. The fluctuation range is mean value of compressive strength of concrete$\pm$ 5.6 Mpa. By comparing this with acceptance criteria of compressive strength of concrete (which is compressive strength of concrete$\pm$ 3.5Mpa), it is indexes that fluctuation considered in the compressive strength of concrete is realistic.

b) For yield strength of steel:

In this simulation, 19mm diameter bars [designated as 20M] are used, which is equivalent to #6 bars (in FPS system). We use A-36 steel, because it is recommended in most of the building codes. We consider 5% standard deviation in the value of yield strength of steel. To access the appropriate range of fluctuation to the yield strength of concrete, a qualitative comparison is made with the experimental data of 172 bars in the following.

The yield strength of different steel bars for A615 Grade-40 reinforcement is shown in Figure 4.24 [12]. In Figure 4.24, bar size is plotted along horizontal axis and vertical axis represent the yield strength of steel. In Figure 4.24, the values in parenthesis show the number of test.

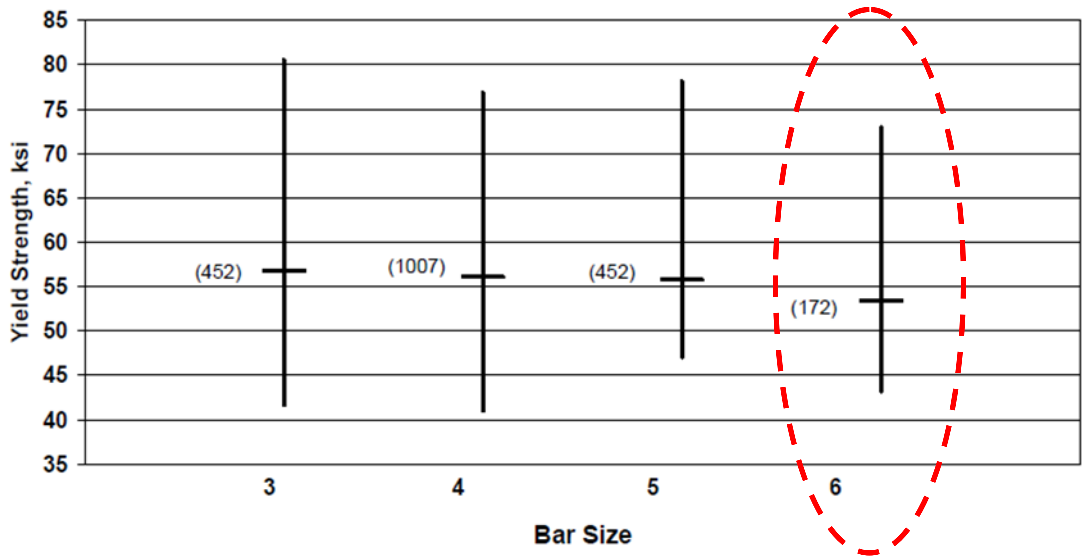


Figure 4.24Mean and range of yield strength for A615 Grade-40 reinforcement. [12]

We use # 6 bars in this simulation. Accordingly the tests results for yield strength of # 6 bars are highlighted by red ellipse in Figure 4.24. These results show that minimum and maximum value of yield strength from experimental data is 78% and 138% of average value of yield strength of steel bars respectively. While, in the simulation, the minimum and maximum values of yield strengths are 83% and 117% of average value of yield strength of steel bars respectively. Quantitatively, this comparison shows that the fluctuation range considered in this simulation is reasonably in good agreement with experimental data.

In context of comparison/evaluation of compressive strength of concrete and yield strength of steel, we assume that fluctuation to the modulus of elasticity is also realistic.

It is to be emphasized that the fluctuation in the material properties is considered to cope with uncertainty of structural performance in nonlinear range and fluctuation in the parameters of indices is not meant for absolute consideration of possible range of material properties. Afore-mentioned qualitative comparison shows that fluctuation ranges considered in material properties are realistic.

OpenSees calculates the strain of each fiber against the deformation of member. Such strain of columns is used to quantify the effect of ground motion on structure.

4.7.4 Quantification of structural damage

Let us consider the quantification of severity of damage in the structures. Damage level caused by ground motions is assessed by comparing maximum strain experienced by steel bars of each member of the structure. Let ε_m^i denote the strain of the bar of the m-th structural member when the structure is exposed to i-th ground motion. Suppose that the d-th ground motion is the design ground motion, then ε_m^d is regarded as reference value of strain of the m-th structural member. The structure is regarded as damaged, if strain of half of members exceeds the value given for each member by the design ground motion.

Strength of ground motion can be quantified by considering the probability that the structure designed by the ground motion is damaged when it is exposed to all possible ground motions. It is written as

$$P_d = prob\left[\frac{\sum_{m=1}^{M} \mathrm{Ind}\{\varepsilon_m^n > \varepsilon_m^d\}}{M} > \frac{1}{2}\right] \qquad 4.5$$

Where M is the number of elements; n is the script to denote ground motion; and $Ind\{C\}$denotes an indicator function that is given as

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

4.7.5 Conditions for synthesis of design ground motion

(1) Number of indices: To compare the effect of indices and number of possible ground motions on synthesized ground motion, we compare two cases in which ground motion is synthesized by different indices. In first case ground motion is synthesized by using single index, displacement response of SDOF corresponding to first mode is used as index. In second case ground motion is synthesized by using two indices, indices are displacement response and dissipated energy by SDOF corresponding to first mode of structure.

(2) Size of sampled sub set of ground motions: In both cases ground motion is synthesized by using a sub set of 500 ground motions out of a set of 2000 possible ground motions. The set of 500 possible ground motions is randomly selected out of set of 2000 possible ground motions, and here after referred to as a sub set of possible ground motions.

4.7.6 Synthesis of design ground motion

Design ground motion is synthesized by using the proposed method. In synthesis process a ground motion is randomly selected out of 500 ground motions and frequency components are modified by using wavelets. In each modification, 10 candidate ground motions are formulated. The performance of each candidate ground motion is evaluated against 50 SDOF realizations. (In case of bridge pier, 75 SDOF realizations were used). In each modification step, a candidate ground motion which shows most improvement is selected for the modification in the next step, and here after referred to as selected candidate ground motions. The process of modification of ground motion by wavelet transform is iterated until ground motion becomes strong enough for SDOF realizations.

We compare the performance of ground motions synthesized in aforementioned two cases in the following sections.

4.8 Computation Results

Ground motion is synthesized by using single index for first case, and a sub set of 500 possible ground motions out of a set of 2000 possible ground motions is used in synthesis process.

Ground motion is synthesized using displacement response of SDOF system as index. First, the effectiveness of synthesized ground to represent the set of possible ground motions is discussed in the following.

4.8.1 Effectiveness of synthesized ground motion

Ground motion is synthesized by using displacement response of SDOF system as an index. The proposed method of ground motion synthesis is objected to have such a design ground motion which can represent a set of possible ground motions. During synthesis process, it was avoided to have a redundant ground motion.

In this simulation, ground motion is synthesized by modifying time frequency characteristics of a randomly selected ground motion in an iterative modification process. The acceleration time history of synthesized ground motion is compared with acceleration time history of initial randomly selected ground motion (which was iteratively modified) in Figure 4.25. The zoom part of ground motion histories in Figure 4.25 shows that the synthesized ground motion is not drastically modified in the synthesis process. This reveals that proposed method of ground motion synthesis do not produce a completely different

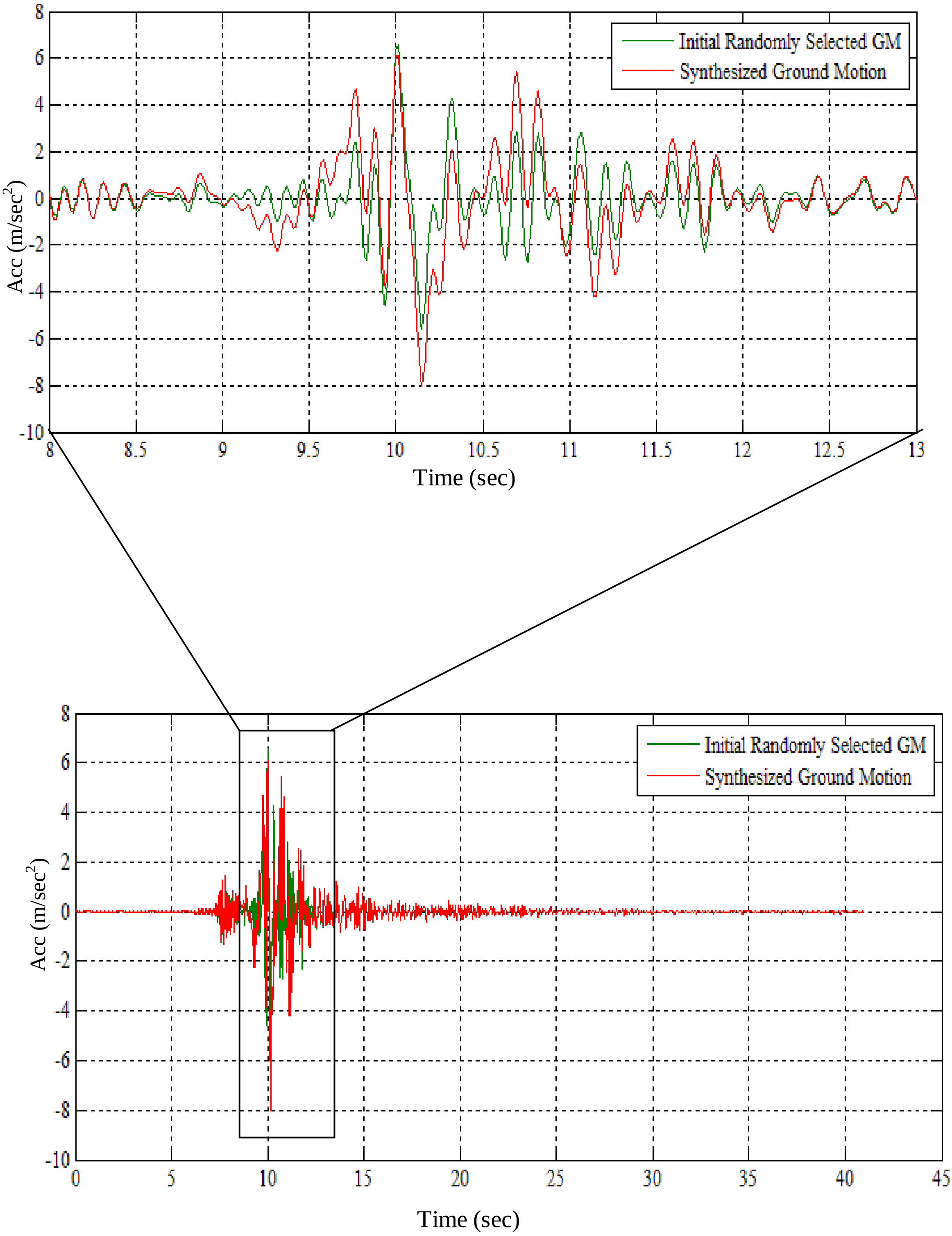


Figure 4.25 Initial selected ground motion and synthesized ground motion

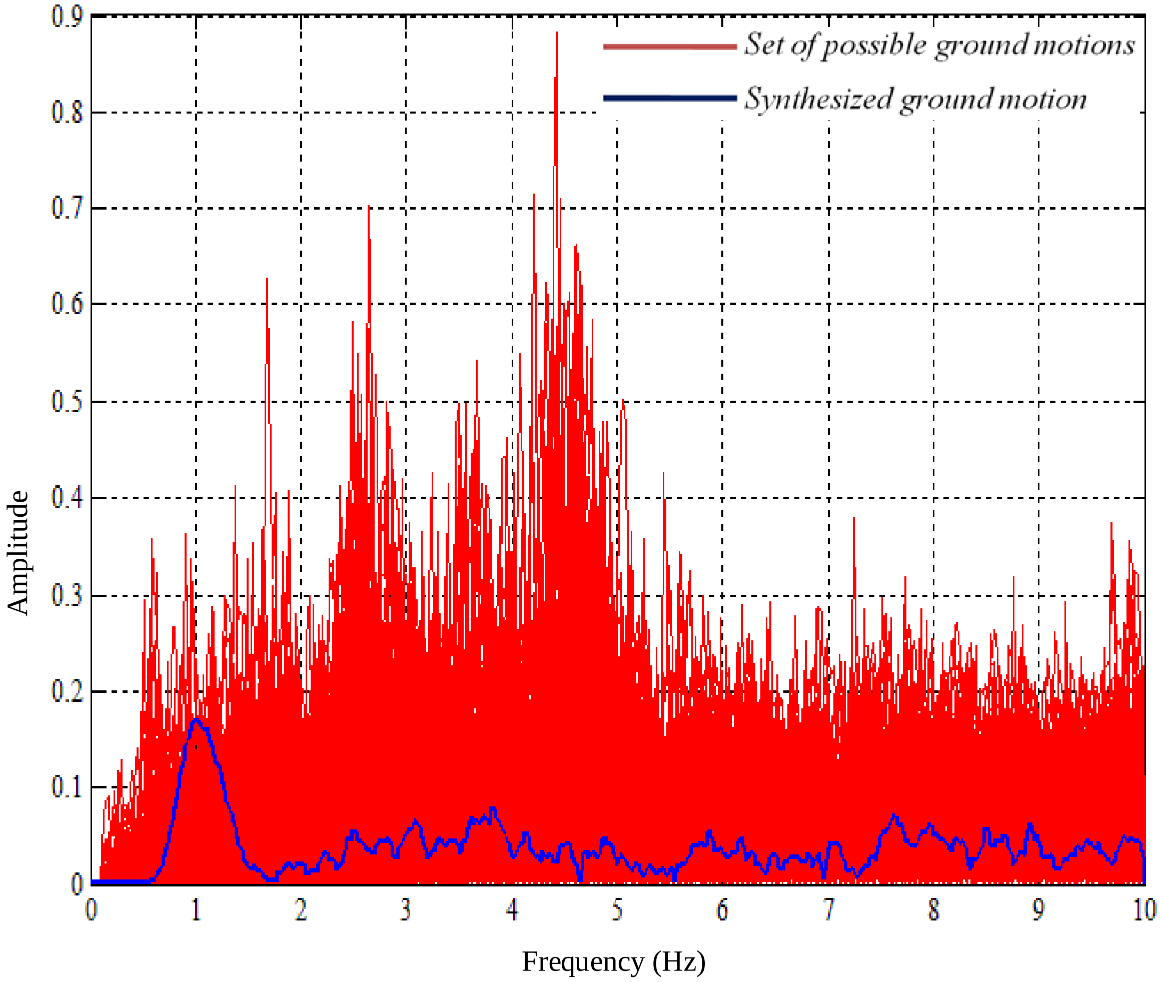
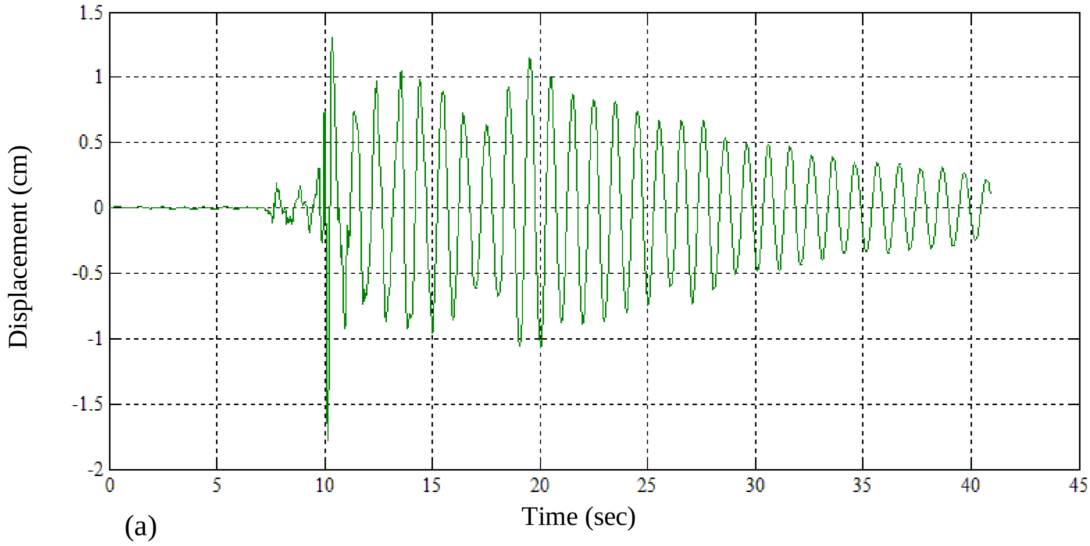


Figure 4.26 Frequency distribution of set of possible ground motions and synthesized ground motion

ground motions. Moreover the characteristics of the synthesized ground motion are compared with set of possible ground motions in the following.

To evaluate the characteristics of synthesized ground motion in comparisons of set of possible ground motions, the frequency distribution of synthesized ground motion and set of possible ground motions are plotted in Figure 4.26. In Figure 4.26, frequencies are plotted along horizontal axis and amplitude is shown along vertical axis. Figure 4.26 shows that in context of frequency characteristics, the proposed method of ground motion synthesis do not produce a redundant ground motion as compared to set of possible ground motions.



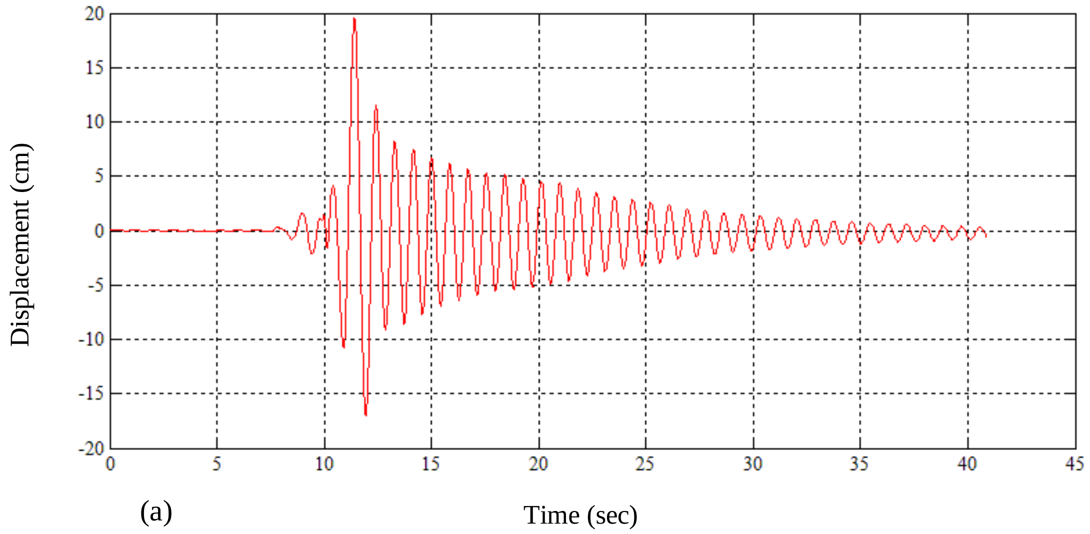


Figure 4.27Displacement response of SDOF system subjected to (a) initial selected ground motion (b) synthesized ground motion

To evaluate the performance of synthesized ground motion against the single degree of freedom (SDOF) system and concrete frame model. The synthesized ground motions and initial selected ground motion (which is modified in iterative procedure to synthesize the design ground motion) are applied to SDOF system and concrete frame model and the resultant displacement are plotted in Figures 4.27, 4.28 and 4.29. In Figures 4.27, 4.28 and 4.29, horizontal axis shows the time and vertical axis shows the displacement. By analyzing the results shown in Figures 4.27, 4.28 and 4.29, it is clear that the synthesized ground motion do not yield redundant displacements in SDOF nor in the concrete frame model.

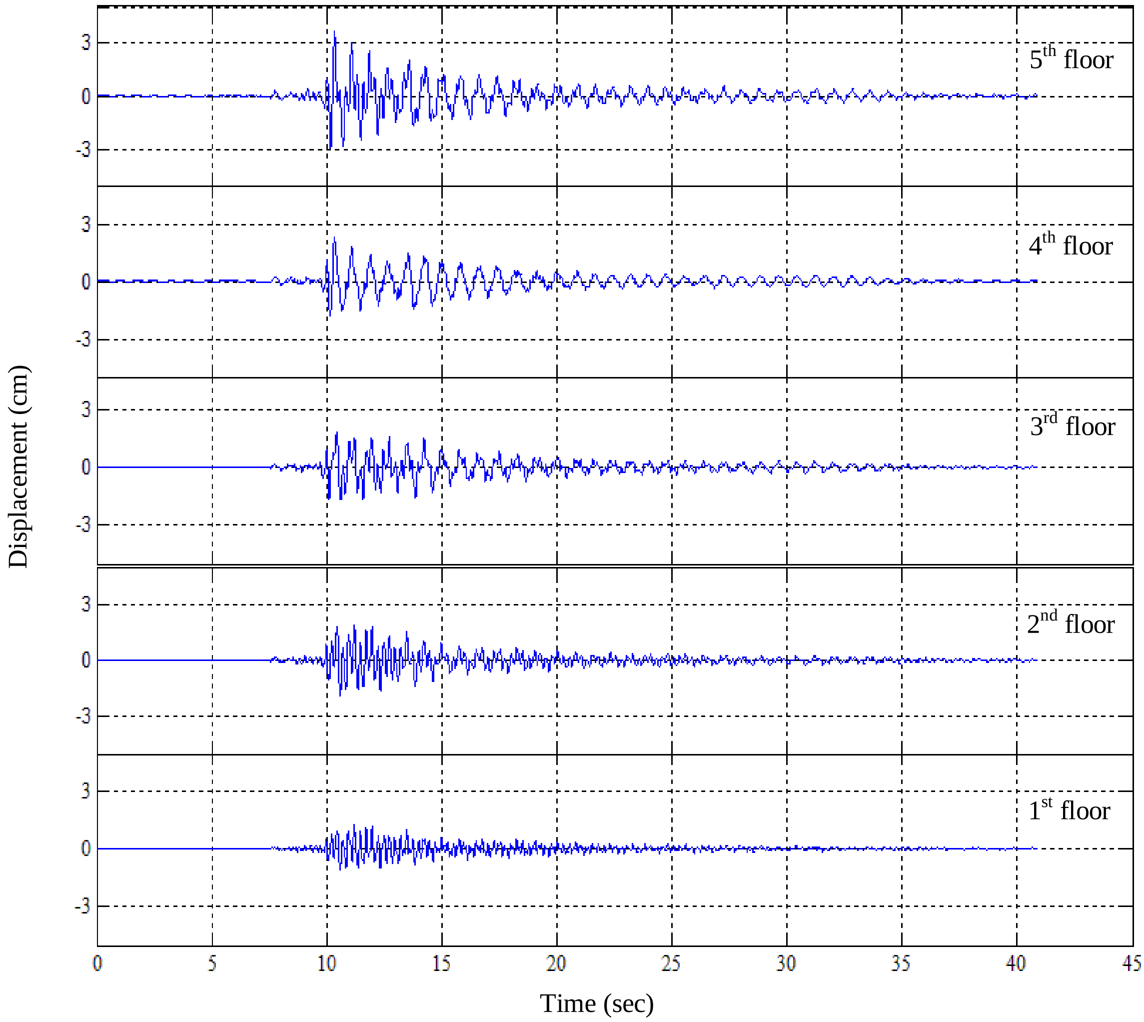


Figure 4.28Floor displacement of moment resisting concrete frame subject to randomly selected ground motion which is used in step by step modification process to synthesize design ground motion

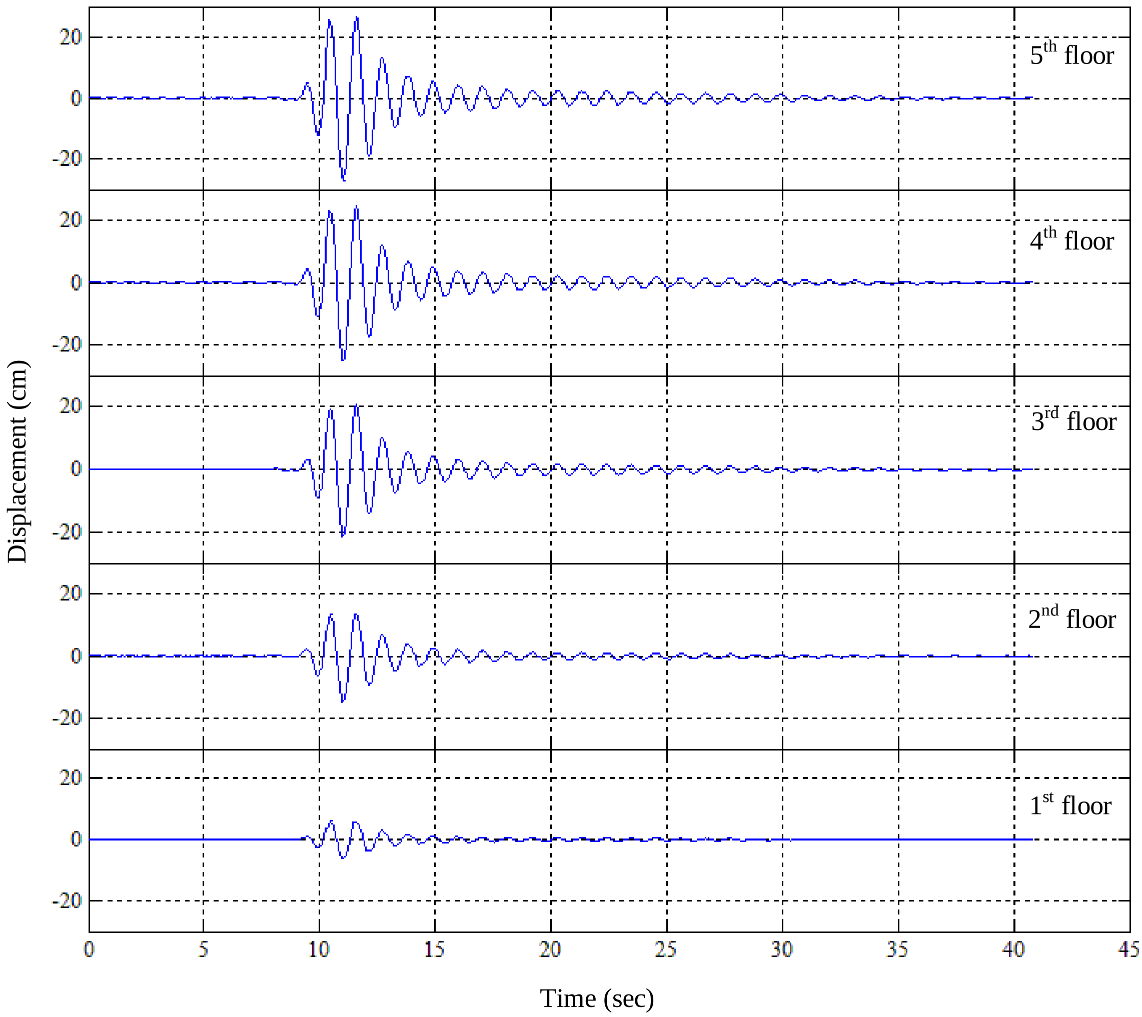


Figure 4.29Floor displacement of moment resisting concrete frame subject to synthesized ground motion

The performance of synthesized ground motion is discussed in context of initial randomly selected ground motion (which is iteratively modified to synthesize the design motion). In the following, the effectiveness of synthesized ground motion would be explored for a complicated structural system which is modeled with high degree of freedom and fluctuation is assumed in the material properties of the members. Dynamic analysis is conducted by using finite element based program OpenSees.

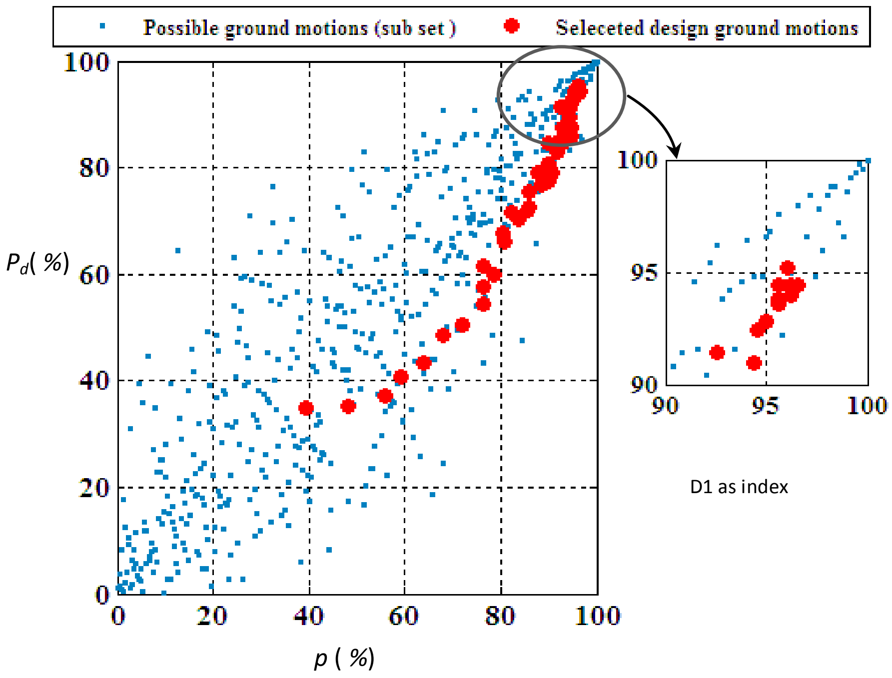


Figure 4.30 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for synthesized design ground motion and sub set of possible ground motions (ground motion is synthesized by one index) synthesized by using indices [3]

4.8.2 Effectiveness of the proposed step by step ground motion synthesis process

Target structure is exposed to selected candidate ground motions and also to sub set of possible ground motions. Probabilities of structural damage and exceedance probability in terms of indices are introduced to discuss the performance of ground motions against concrete structure and in terms of index respectively.

Probabilities of structural damage: Probabilities of structural damage (P_d) for both sub set of possible ground motions and selected candidate ground motions are formulated by using the concept discussed in section 4.7.4 and by employing equation 4.5.

Exceedance probability in terms of index: Exceedance probability or normalized rank (p) of the i-th GM (p_i) in terms of index x^1 is formulated as

$$p_i = \frac{\sum_{n=1}^{N} \mathrm{Ind}\{x_n^1 > x_i^1\}}{N} \qquad 4.6$$

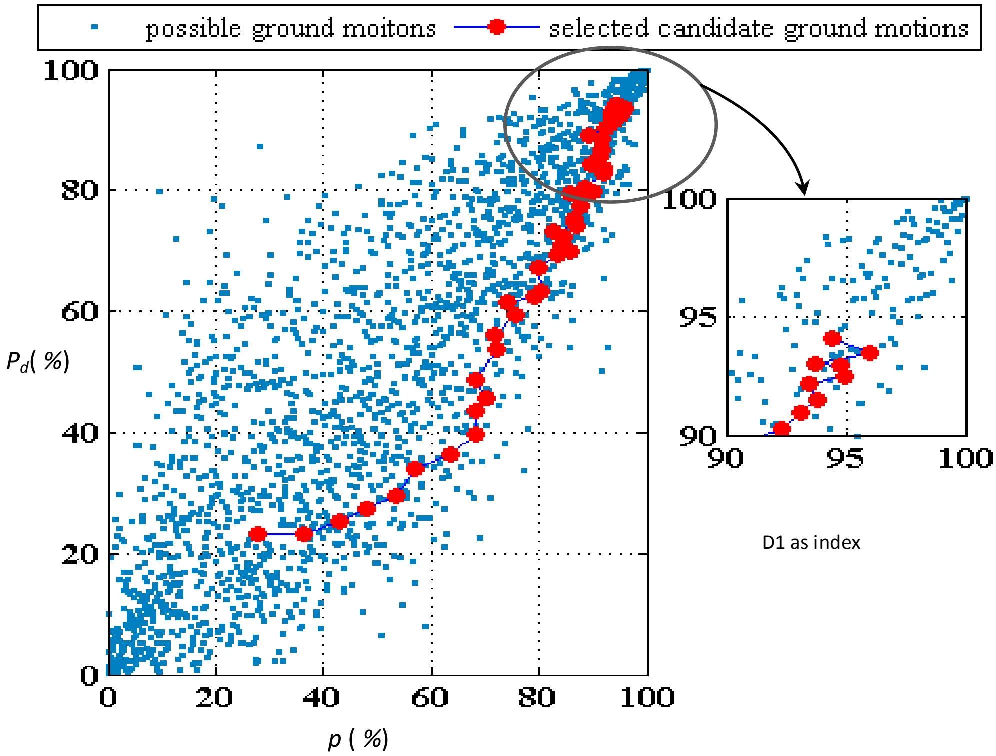


Figure 4.31Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for synthesized design ground motion and set of possible ground motions (ground motion is synthesized by one index and sub set of possible ground motions)[3]

where, N is number of possible ground motions. Figure 4.30 shows the distribution of probability of structural damage (P_{d}) and exceedance probability in terms of indices (p) for sub set of possible ground motions. The same probabilities($P_{\mathrm{d}}$and p) are formulated for the selected candidate ground motions in context of sub set of possible ground motions and traced on Figure 4.30.

Firstly, track of red dots corresponds to the step by step modification of a random ground motion. (It is to be noticed that probabilities ($P_{\mathrm{d}}$and p)for initial randomly selected ground motion had smaller than 40%). It shows the effectiveness of the proposed method to iteratively modify the ground motion.

Second, the zoomed part of the Figure 4.30 shows that the performance of the synthesized ground motion is increased to 95%. Improvement of performance from 40% to 95%

indicates that the proposed method is reliable in terms that it can synthesize a ground motion which is representative of possible ground motions considered in the synthesis process.

Third, the increase in performance of synthesized ground motion to 95% shows that the synthesized ground motion is among the prominent ground motions, but synthesized ground motions do not produce redundant result.

4.8.3 Consideration of a sub set of possible ground motions

Since it is impossible to generate all possible ground motions, synthesized ground motion must be representative of ground motions which are not considered in the synthesis process. To evaluate the effectiveness of synthesized ground motion in that context, the probabilities (P_d and p) are formulated by using set of 2,000 possible ground motions and presented in Figure 4.31. Similar to Figure 4.30, P_d and p are formulated for the selected candidate ground motions considering 2,000 possible ground motions and traced on Figure 4.31. Figure 4.31 verifies the promising performance of synthesized ground motions against such set of possible ground motions which was not fully considered in the synthesis process.

It is to be highlighted that in this simulation example, the ground motions are synthesized by using the sampled set of possible ground motions (500 ground motions), not all of the possible 2000 ground motions.

4.8.4 Effect of indices on synthesized ground motion

To elaborate the effect of indices on synthesized ground motion, here we discuss the ground motions synthesized by using one and two indices.

Case 1: Displacement response of SDOF corresponding to first mode of structure (Let D1 denote this index.) is deployed as a single index for synthesis of design ground motion. The effectiveness of the synthesized ground motion in perspective of modification in step by step synthesis process and effect of set of possible ground motions are discussed in sections4.8.1, 4.8.2 and section 4.8.3.

In Figures 4.30 and 4.31, the track of red dots corresponds to the step by step modification of a random ground motion. Acceleration response of SDOF corresponding to the first mode of the structure is not involved in the synthesis process. We explore the suitability of acceleration of SDOF as an index for the synthesis process. Probabilities in terms of acceleration response of SDOF system are formulated by using equation 4.6.

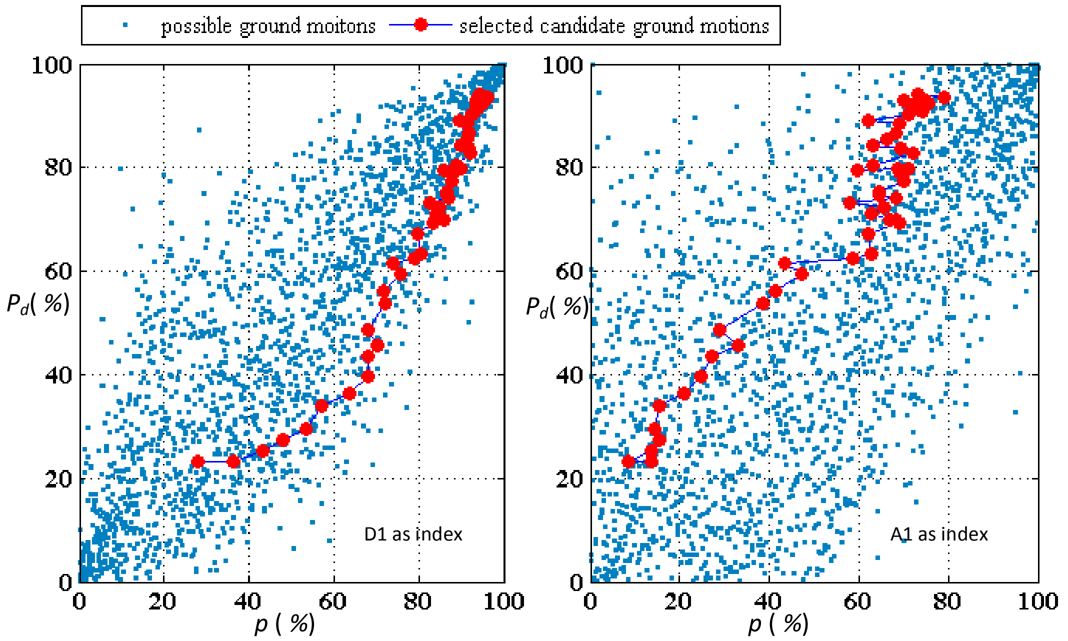


Figure 4.32Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for synthesized design ground motion and set of possible ground motions [3]

Distributions of probabilities of structural damage against the exceedance probabilities in terms of displacement and acceleration responses are plotted in Figure 4.32 (a) and Figure 4.32(b) respectively.

Form Figure 4.32 (b), the enhancement of exceedance probability in terms of acceleration response is up to 75 %. This shows that acceleration response of SDOF corresponding to first mode is not very efficient, but it does up to some extent.

Case 2: From the zoomed part of Figure 4.25 and Figure 4.26, the enhancement is up to 95%. To further improve the performance of synthesized ground motion, we synthesize a design ground motion by using two indices, which are displacement response and energy dissipated by SDOF corresponding to first mode of structure. (They are denoted by D1 and E1, respectively.) The reasons for including these indices for synthesis of design ground motion is that degrading of the stiffness cannot be properly represented by displacement response of structure, but it can be represented by dissipated energy of SDOF.

Design ground motion is synthesized by using a sub set of 500 possible ground motions, but efficiency of selected candidate ground motions is elaborated in perspective of set of 2000 possible ground motions.

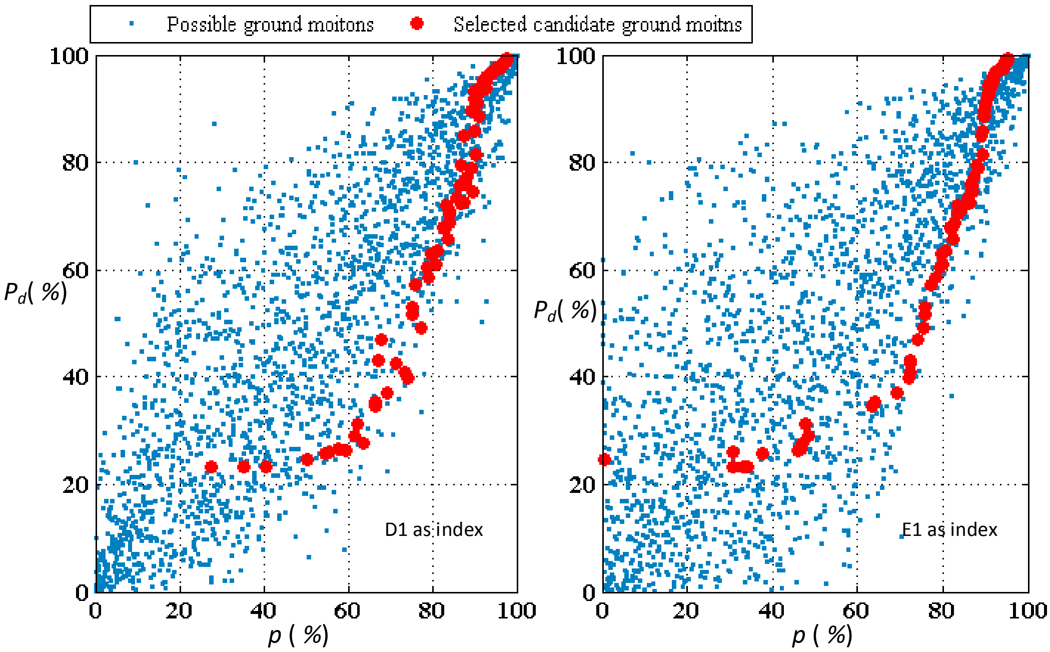


Figure 4.33Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for synthesized design ground motion and set of possible ground motions (ground motion is synthesized by two indices and sub set of possible ground motions) [3]

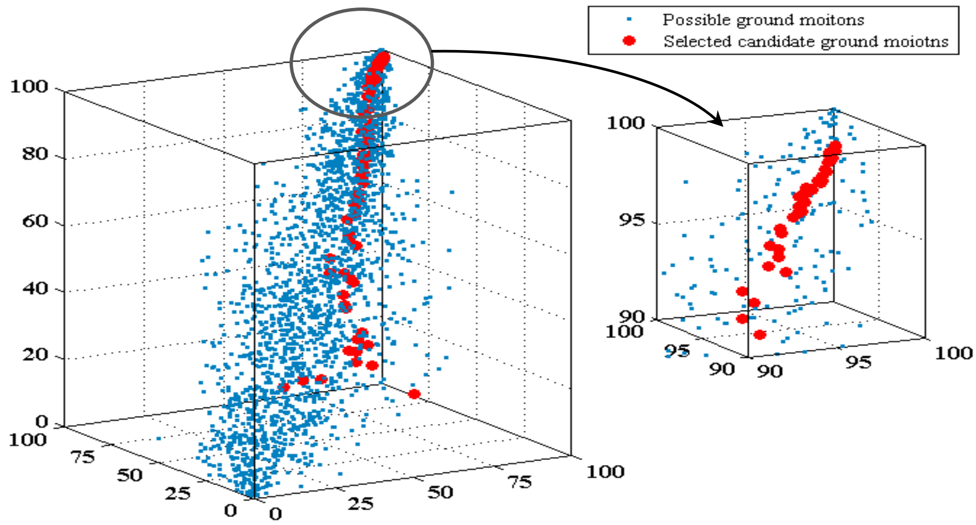


Figure 4.34 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for synthesized design ground motion and set of possible ground motions (ground motion is synthesized by two indices and sub set of possible ground motions) [3]

Similar to the first single index case, (discussed above), probability of structural damage and exceedance probabilities in terms of indices are formulated for selected candidate ground motions and for set of possible ground motions, and presented in Figures4.33 and 4.34.

Figure 4.33 shows the distribution of probability of structural damage against the exceedance probability in terms of indices. While, 3D plot in Figure 4.34 shows the distribution of probability of structural damage against the exceedance probabilities in terms of both indices used in synthesis process. The zoom in part of Figure 4.34 shows the enhancement of synthesized ground motion up to 98%.

Figure 4.33 and Figure 4.34 show the track of red dots going well up to top of vertical axis. Steepness of the track of red dots is an important difference as compared to first case. In later case steep track shows that selected candidate ground motion is efficiently improves as compared to the first case because we used more appropriate indices.

4.9 Summary

In this chapter, the effectiveness of the proposed method of design ground motion synthesis is discussed. Design ground motion is synthesized for three different conditions, which includes two bridge pier and one five-floor moment resisting concrete frame. For bridge pier cases the set of possible ground motions is formulated by simulation of fault. While for concrete frame the record of previous earthquakes is used to formulate the set of possible ground motions. The results of numerical simulations verify the applicability of proposed method of ground motion synthesis in different conditions. Various aspects of proposed method of ground motion synthesis are explained, such as proposed method of ground motion synthesis is not affected by the initial ground motion (which is to be modified in step by step iteration process), the synthesized ground motion is robust in terms of sampling of possible input ground motions and also in context of uncertainty of structural parameters. The efficiency of the design ground motion synthesized is compared with a factored ground motions. These and similar other factors verifies the suitability of proposed method of ground motion synthesis to have reliable design ground motion in context of diversity of ground motions and uncertainty of nonlinear response of structures.

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Chapter 5

Damage Mechanism Based Indices

5.1 Introduction

In the proposed method of ground motion synthesis, indices are used to quantify the damaging capabilities of ground motions. At each modification step of proposed method of grounds motions synthesis, a ground motion is to be selected out of candidate ground motions (candidate ground motion are formulated by reinforcing the time frequency characteristics by wavelet transform). This reveals that in proposed method of ground motion synthesis, selection of ground motion is involved, which is done by using feature indices. Therefore, in this chapter, we discuss about the improvement of the ground motion selection by introducing a mean for selection of appropriate indices.

Selection of ground motion out of a number of ground motions is important to discuss from following two perspectives.

- In proposed method of ground motion synthesis, selection of ground motions out of candidate ground motions is involved at each modification step. Therefore, to enhance the performance of proposed method of ground motion synthesis, it is necessary to propose an effective mean to select the ground motion out of a number of ground motions.
- To avoid the cumbersomeness of synthesis process, for relatively simple cases of design (such as structure in low seismicity area), Design Engineers prefer to select a design ground motion out of a number of possible ground motion. Therefore, this discussion of an effective mean to select the ground motion out of a number of ground motions will be equally applicable for aforementioned scenarios.

In the selection of ground motions, a ground motion that is the “toughest” among possible ground motions should be chosen. It is difficult, however, to find such ground motion, because, due to uncertainty of nonlinear behavior, the “toughest” ground motion 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 structural analysis are sensitive to change in various parameters.

Due to these reasons, we must admit that the probability of selection of required design ground motion is limited, specifically, due to the existence of uncertainty of structural response and diversity ground motions.

Realizing that nonlinear structural analysis is essential to look into the structural performance in nonlinear range and the sophisticated techniques to improve the performance of output of nonlinear structural analysis are not free from uncertainty, it is essential to select a ground motion for nonlinear structural analysis by paying due attention to limitations of lack of knowledge of structural response in nonlinear range and diversity of ground motions.

A number of available ground motion selection techniques incorporated indices for the evaluation of effectiveness of ground motion. But due to uncertainty of nonlinear dynamic response, variety of structural types, stochastic nature of dynamic characteristics of structures, it is difficult to select appropriate indices for a general problem of structural design.

We proposed the concept of damage mechanism based indices for selection of appropriate indices out of available indices, and hence used such indices for selection of design ground motion [3]. In this method, selection of indices is based on the correlation of indices with possible damage mechanisms of structure, and ground motion which is tough in terms of the selected indices would be capable to excite the possible damage mechanism and hence should be used as design ground motion.

In this chapter, the concept of damage mechanism based indices is elaborated and we discuss the performance of various nonlinear response values as indices for the selection of ground motion in the presence of uncertainty of structural characteristics and diversity of ground motions.

5.2 Design Ground Motion Selection Using Indices

For nonlinear dynamic analysis of structure, it is accepted that the “toughest” ground motion out of possible ground motions should be used as design ground motion. Meanwhile, in the selection of design ground motion, it is inevitable to consider the uncertainties and unpredictability of earthquakes [7]. Thus, most of the ground motion selection methods (specifically, those specified in the codes) take probabilistic approach in essence [8, 9]

Performance of design ground motions are influenced by the uncertainties of structural response. we need to take into consideration that it is not a linear problem, In that context, matching response spectrum[10,11], using genetic algorithms [12,13], structure specific ground motions [14,15,16] and use of indices [17] are main categories of ground motion selection procedures (available in literature) to cope with the uncertainties of structural response.

The details of indices for selection of design ground motion are discussed in chapter 2, and summarized here to clarify the advantage of having of a large number of indices in the literature. Meanwhile, challenges in selection of appropriate indices for the case under consideration are also highlighted.

Indices for selection of ground motion can be classified into two groups. First group consists from statistical information of ground motion signal. The indices based on statistical information of ground motion signal are linked with peak values in signal, duration of signal, distribution of frequency contents of signal, peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), maximum incremental velocity (IV), maximum incremental displacement (ID) and duration [17]. It has also been shown that PGV is a proper intensity measure candidate for deformation demands on SDOF systems [18], G. Manfredi proposed representative index$I_D$which relates the PGA, PGV, duration of ground motion and ground accelerations [19].

The second group of indices is related with response of simple structural systems [20], 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 [21]. This index is frequently used to quantify nonlinear response of structures [22]. Some damage indices are proposed in terms of ductility and stiffness degradation due to damage experienced by the structure [23].Selection of the design ground motion by taking into account the structural nonlinear response and characteristics of ground motions 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 ground motion for that structure. A number of procedures are available to get an equivalent SDOF system for multi degree of freedom system [24]. In all such techniques, global stiffness and yield strength of the structure is assessed to get the equivalent SDOF system.

Index-based ground motion selection methods have limitations. First, there is no single index that can perfectly evaluate various aspects of characteristics of nonlinear behavior of structures. Second, index values are affected by uncertainty of structural characteristics.

5.3 Selection of Design Ground Motion Using Damage-Mechanism-Based Indices

The design ground motion should be relatively strong or influential for the behavior of the structure in concern, compared to other possible ground motions. It should be admitted, however, that there is no knowing how a ground motion 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 ground motions out of a set of possible ground motions are conducted using these feature indices. Therefore, it is expected that ground motions which are strong in terms of these indices will be influential for the target structure [25].

5.4 Damage-Mechanism-Based Indices

Effectiveness of the indices presented by various researches is conditioned with the selection of proper index for the problem under consideration. Here, the knowledge of such indices is incorporated to measure the effectiveness of ground motions 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 uncertainty of nonlinear response and uncertainty of structural characteristics, behavior of the structure can be different when structural characteristics change.
- Behavior of simple system may not be identical with that of the structure.
- Different ground motion is considered as strong in terms of different indices.

Considering these issues, here we take following procedure:

- We consider a range of parameters of indices in order to consider 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 ground motions. Ground motions which are efficient in terms of these indices are considered to be likely to trigger damage on the structure.

5.5 Selection of Design Ground Motion

In the selection of ground motions, a ground motion that is the "toughest" among possible ground motions should be chosen. It is difficult, however, to find such ground motion, because, due to uncertainties associated with nonlinear behavior of structure, the "toughest" ground motion 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 diversity of ground motions make the selection more difficult, because sophisticated techniques such as Nonlinear Seismic Analysis (NSA) are sensitive to change in various parameters.

Here, we use indices as condition to select the design ground motions. From design ground motion it is expected that probability $(\mathrm{P})$of occurrence of damage(D)under the condition that the structure is designed against that ground motion$(\mathrm{GM})$is smaller than a certain value $(\overline{\mathrm{P}})$.

$$\mathrm{P} = \mathrm{prob}(\mathrm{D}|\mathrm{GM}) < \overline{\mathrm{P}} \tag{5.1}$$

The value of probability(P)depends on the selected design ground motions. Since we cannot know the influence of a ground motion on the structure in advance, we need to select a ground motion which satisfies the specified condition(C).

5.5.1 Indicator of the performance of an index/indices$\boldsymbol{I_C}$

Ground motions are selected based on condition (index values), therefore it is necessary to consider the probability that Equation 5.1 is satisfied when ground motion is randomly selected based on the condition(C). As indices are used in the condition, therefore this probability is used as criteria to evaluate the goodness of index/indices, and regarded as '*indicator of the performance of an index/indices*'I_C and written as

$$I_C = prob[\{prob(D|GM) < \bar{P}\}|C] \tag{5.2}$$

Higher value of I_C shows that index/indices are efficient to select the required design ground motion (GM)

Lower value of $I_C$shows that index/indices are not efficient to select the required design ground motion (GM)

In this procedure, indices are used in the condition (C). If design ground motions are selected based on multiple indices, which consider various possible damage mechanisms, the value of I_C is expected to be higher than the one selected by using conventional schemes.

In this procedure, feature indices are used in the condition (C). If indices are efficient to represent the damage capabilities of ground motions, then probability of having the required design ground motion is higher. Thus, I_C(the indicator of the performance of index/indices) has a direct correlation with the efficiency of an index. In this study, we will use the value of I_C as criteria to evaluate the goodness of an index.

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

$$p_i = prob(v_n^1 > v_i^1 \| v_n^2 > v_i^2 \| \ldots) \qquad \text{Eq. 5.3}$$

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

For example, we can select a ground motion for which exceedance probability in terms of indices, p_i, is close to a certain value, say $\overline{p}$, which can be taken identical with $\bar{P}$ in Equation 5.1, as:

$$\overline{p} \cong \bar{P} \qquad \text{Eq. 5.4}$$

Performance of the ground motion selected by this scheme depends on the quality of selected indices.

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

5.6 Numerical Simulations

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

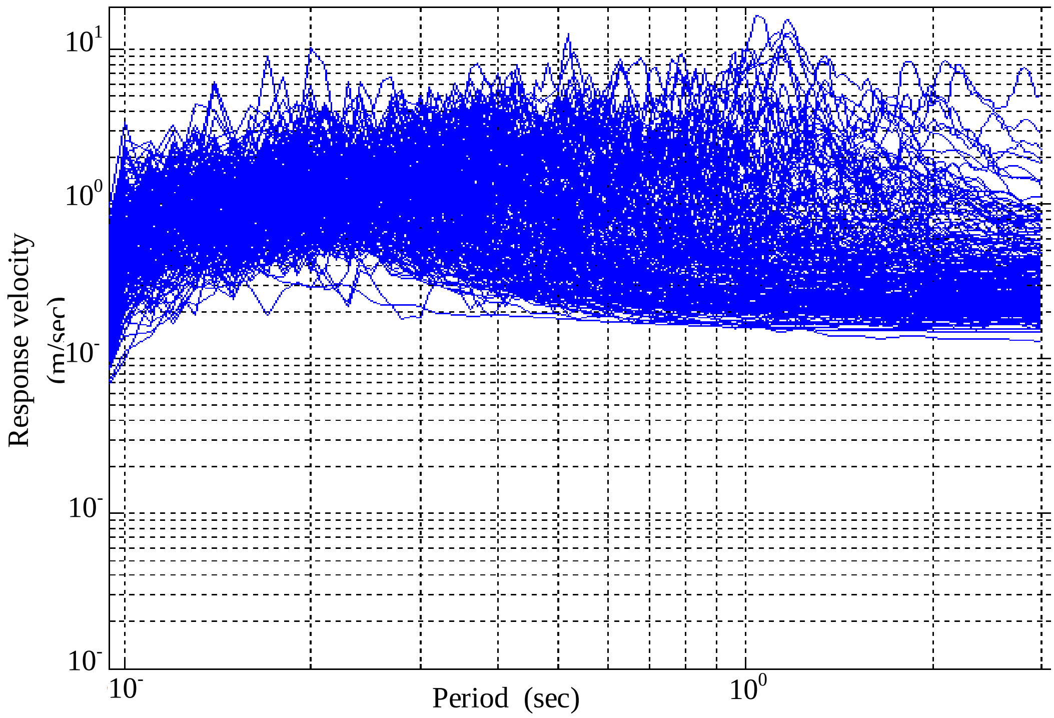

Figure 5.1Response spectrum of set of possible Ground motions[25]

5.6.1 A Set of possible ground motions

A set of possible ground motions is considered for the design of structures. Selection of possible ground motions is difficult, because theoretically infinite number of ground motions is possible. For practical purposes, the number of ground motions can be reduced by applying different filters, such as source to site distance, magnitude of event, etc. Filtered ground motions comprise a set of possible ground motions (out of which design ground motion(s) is/are to be selected). The details of the set of possible ground motions are not circumscribed by the scope of this study. Thus a set of possible ground motions is intentionally selected so that it contains wide variety of ground motions.

To formulate the set of possible ground motions, 450 ground motions records from past earthquake events are obtained from K-NET. It would be possible to generate such ground motions using numerical techniques. We use actual ground motion records, in order to discuss the applicability of the presented scheme to real ground motions. In order to verify the applicability of the proposed scheme under the wide range of variation, ground motions are selected without considering the ground conditions. The ground motion records are factored so that their peak ground acceleration values are ranging between 600cm/sec^2 to 800cm/sec^2. The response spectrums of set of possible ground motions are shown in Figure 5.1.

Each element is modeled by fiber element

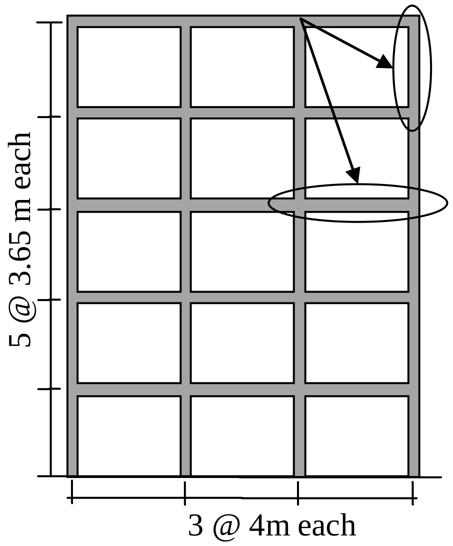

Figure 5.2 Elevation of concrete frame with main dimensions element

Table 5.1Detail of beam and column sections[25]

	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

5.6.2 Structural model and uncertainty of structural performance in nonlinear range

Design ground motions are selected for a moment resisting concrete frame, elevation of the frame is shown in Figure 5.2 and sectional details are shown in Table 5.1. This structure here after referred to as target structure. The dead load for the nonlinear analysis 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 [25].

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` [26,27] model is used to model confined and unconfined concrete. The stress strain curve for concrete model is shown in Figure 5.3. Tensile strength of concrete is also considered in this model. Parameters to model stress strain curve for concrete are summarized in Table 5.2.

Similarly, material model Steel02 [26] 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 Steel02 is shown in Figure 5.4, the model parameters are tabulated in Table 5.3

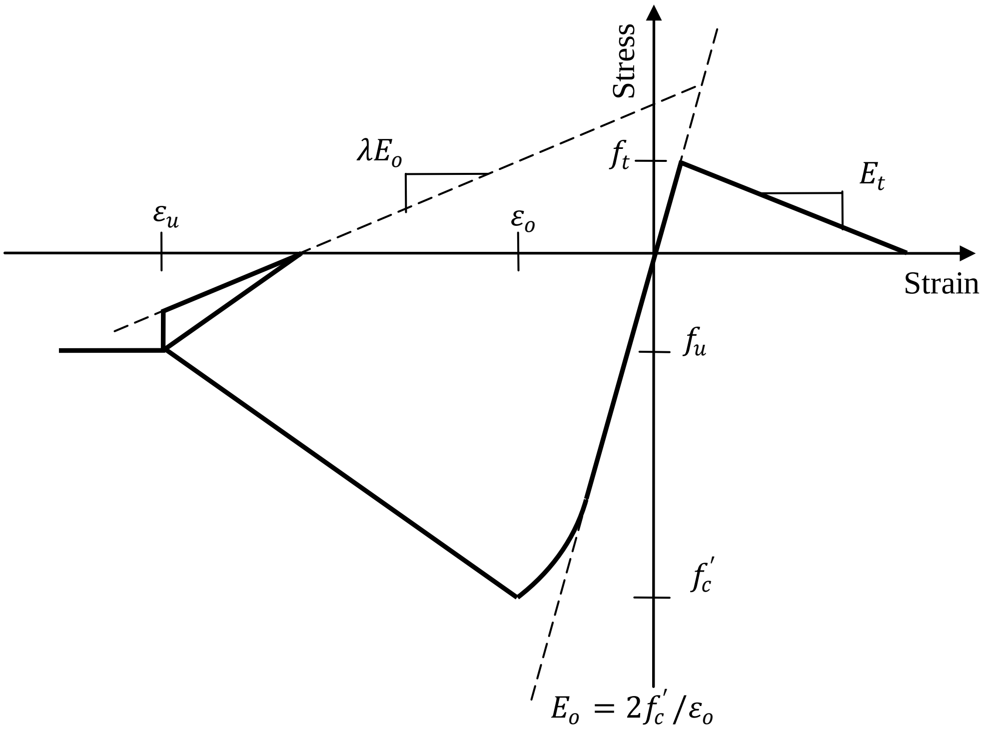

Figure 5.3 Stress strain model for concrete `Concrete02`[25,26,27]

Table 5.2 Properties of concrete model Concrete02 [25, 26, 27]

$f_c^{'}$ = 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

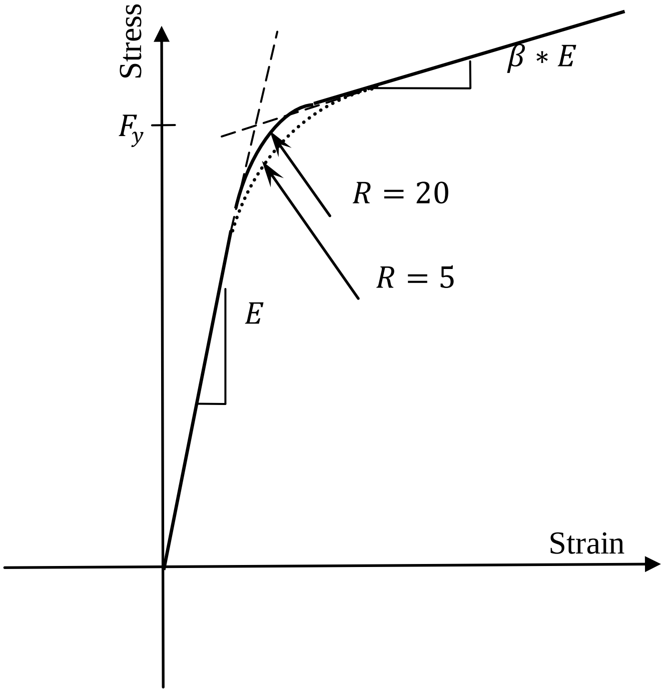

Figure 5.4 Stress strain model for steel `Steel02` *[25,26]*

Table 5.3 Parameters of steel model used in simulation[25]

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

Analysis shows that natural period of the concrete moment resisting frame under consideration is 0.65sec. It is important to mention that multiple factors related to the characteristics of members and properties of materials govern the time period of the structure. Thus in one way or other, we can use time period of the structure to validate the numerical model of structure.

Here, we compare the time period calculated from the model response with the approximate time period estimated by using empirical relationship given in UBC-97, Equation 30-8 [28]. According to UBC-97 (Equation 30-8), time period (*T*) is given as fallow

$$T = C_t (h_n)^{3/4} \quad [28] \qquad \text{Eq. 5.5}$$

Where,

T = natural time period in *Sec*

C_t = 0.0853 for steel moment resisting frames.

= 0.0731for reinforced concrete moment-resisting frames and eccentrically braced frames.

= 0.0488 for all other buildings.

The frame under consideration is moment resisting concrete frame, for which C_t will be0.0853 and height of structure is 18.25 meters. Using these values in Equation 5.5 gives the natural time period as 0.64 seconds. This shows good agreement with the value 0.65sec, which is based on the analysis result. This comparison index that OpenSees model of the structure is realistic.

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 5.4, and distribution of material properties are shown in Figure 5.5and Figure 5.7 (Material property of concrete model is a function of compressive strength of concrete, and it is affected by the change of compressive strength.).

It is important to mention that material properties of individual member of concrete frame are randomly selected from the distribution shown in Figure 5.5 and Figure 5.7. This shows that, in a way or other, the unpredictability of nonlinear response which is attributed due to uncertainty of material characteristics are considered

Table 5.4 Parameters of stochastic material-properties [25]

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

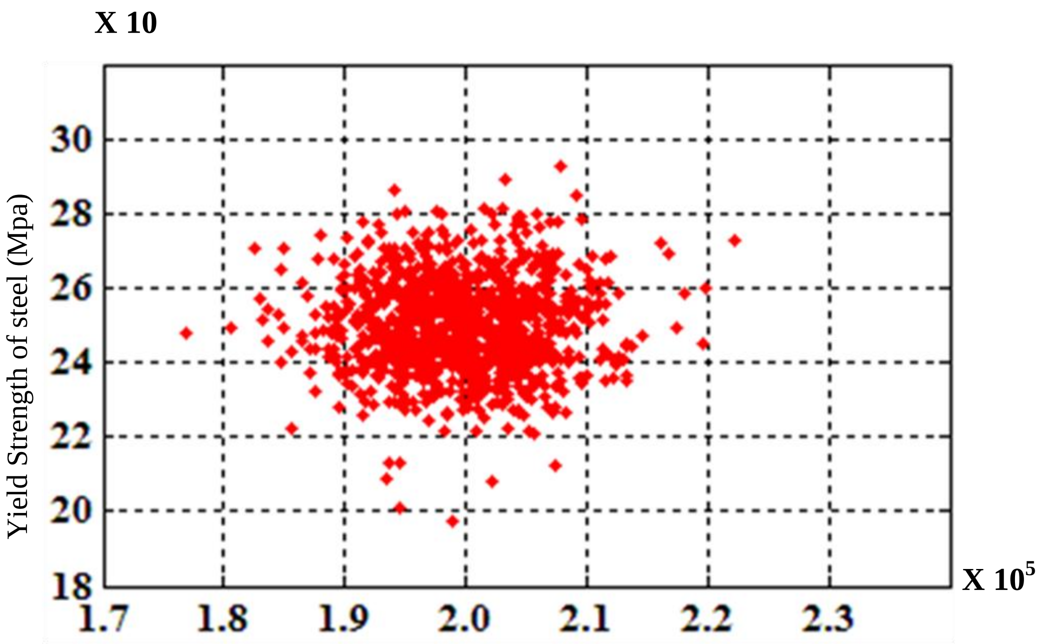

Figure 5.5 Distribution of yield strength of steel bars and modulus of elasticity of steel bars, considered in the numerical simulation

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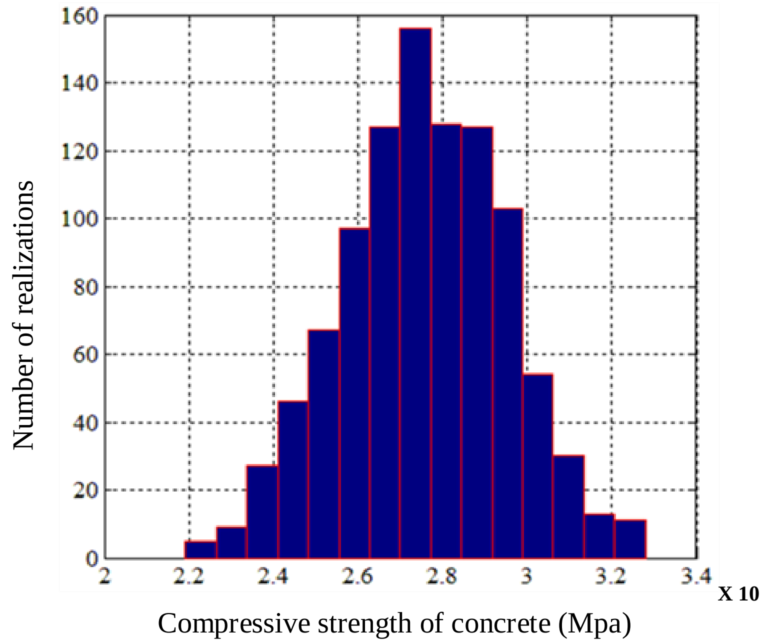


Figure 5.7 Distribution of compressive strength of concrete, considered in the numerical simulation

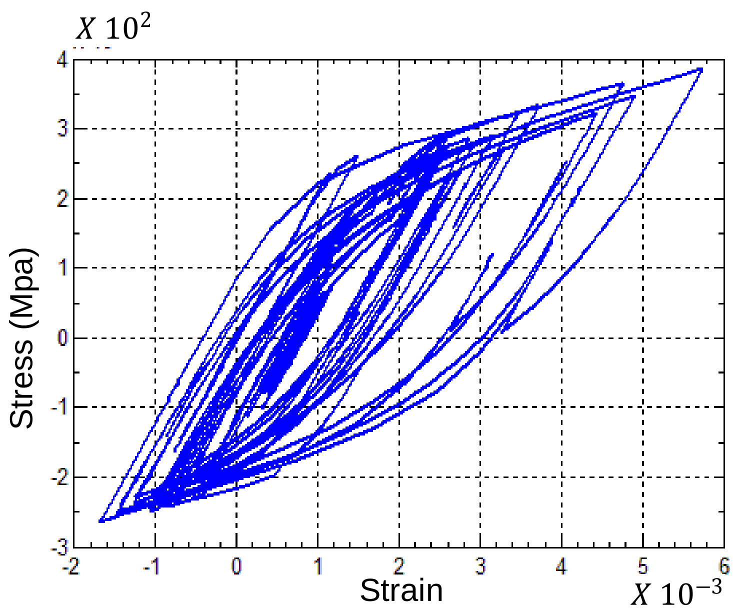


Figure 5.6 Stress strain response of steel fiber of ground floor column at maximum stressed section [25]

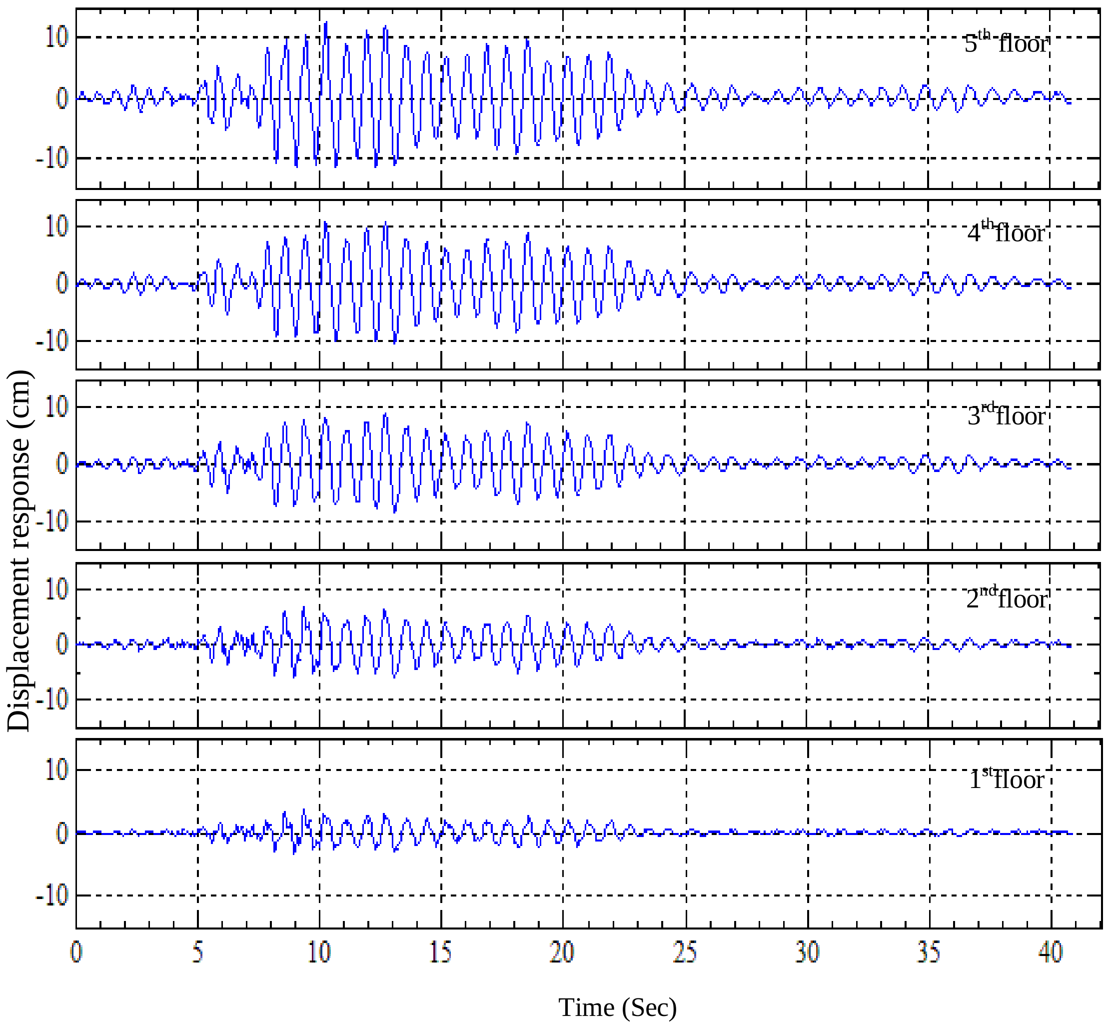


Figure 5.8 Displacement response of concrete frame against a random ground motion out of set of possible ground motions [25]

Results of a nonlinear analysis against one of the possible ground motions are shown here as an example. Stress strain curve of steel fiber of an end column of first floor are plotted in Figure 5.6, while displacement responses of floors are shown in Figure5.8 OPENSEES calculates the strain of each fiber against the deformation of member. Such strain of columns is used to quantify the effect of ground motion on structure.

5.6.3 Quantification of damage of structure

Let us consider the quantification of severity of damage in the structures. Damage level caused by ground motions is assessed by comparing maximum strain experienced by steel rebar of each member of the structure. Letε_m^i denote the strain of the rebar of the *m*-th structural member when the structure is exposed to the *i*-th ground motion. Suppose that the d-th ground motion is the design ground motion, and 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 ground motion.

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

$$P_d = prob\left[\frac{\sum_{m=1}^{M} \mathrm{Ind}\{\varepsilon_m^n > \varepsilon_m^d\}}{M} > \frac{1}{2}\right] \qquad \text{Eq. 5.6}$$

Where M is the number of elements; n is the script to denote ground motion; and $Ind\{C\}$denotes an indicator function that is given as

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

5.6.4 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 ground motions, whose frequency contents are closer to those of higher modes of the structure, will excite 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 ground motion: 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 rather than that 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 ground motions, because ground motion which will be tough in terms of these indices will be efficient to trigger the damage mechanism and hence should be considered as design ground motion. Let us discuss the selection of appropriate indices to consider the damage mechanisms in the next section.

5.6.5 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 ground motions and value of I is evaluated. Relative exceedance probability of the j-th ground motion (P_j) as compared to other ground motions is

$$P_j = prob(I_n > I_j) \qquad \text{Eq. 5.7}$$

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

$$P_j = \frac{\sum_{n=1}^{N} Ind\{I_n > I_j\}}{N} \qquad \text{Eq. 5.8}$$

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

Values of eight indices are evaluated for set of possible ground motions. 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 ground motions 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 ground motion, 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 ground motions. Similar to Equation 5.6, exceedance probability of *j*-th ground motion in terms of index *k* is defined as

$$p_j = prob(k_n > k_j) \qquad \text{Eq. 5.9}$$

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

$$p_j = \frac{\sum_{n=1}^{N} Ind\{k_n > k_j\}}{N} \qquad \text{Eq. 5.10}$$

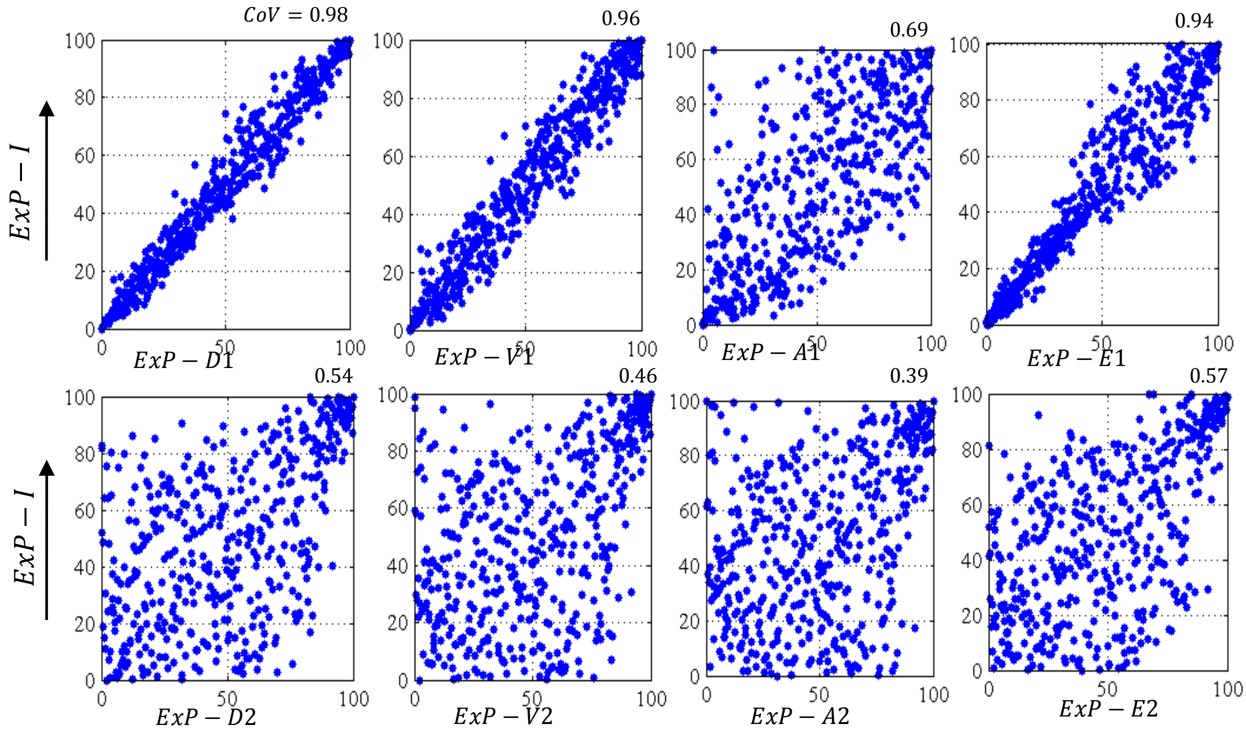
For each of possible ground motions, the rank in terms of evaluation factor (I) and in terms of eight candidate indices are evaluated from Equations 5.8 and 5.10, respectively, and plotted in Figure 5.9.

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

$$C^R(X,Y) = \frac{C(X,Y)}{\sqrt{Var(X)Var(Y)}} \qquad \text{Eq. 5.11}$$

where $C(X,Y)$ denotes the covariance. CoV is calculated for each of eight indices, and mentioned on sub-plots of Figure 5.9 correspondingly. 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 5.5.

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 5.5. To ease the visualization of correlation between indices and possible damage mechanism, the values of correlations shown in Table 5.5 are plotted in Figure 5.10.



LEGEND:

$ExP - D1$= Exceedance Probability in terms of index D1

$ExP - I$= Exceedance Probability in terms of damage factor (I)

Figure 5.9 Exceedance probability of damage quantification factor in MDOF for possible damage mechanism against the exceedance probability in terms of eight candidate indices[25]

It is clear from Figure 5.10 that at different floor levels different indices are effective to consider these damage mechanisms. Thus multiple indices are required to represent these damage mechanisms.

Table 5.5 Coefficient of covariance for the distribution of exceedance probability of possible damage mechanism and exceedance probability of eight candidate indices[25]

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

Coefficient of covariance between percentile in terms of indices and

1- Disp. of top node of FRAME	
D1	0.98
V1	0.96
A1	0.69
E1	0.94
D2	0.54
V2	0.46
A2	0.39
E2	0.57

2- Maximum inter-story drift. **3- Dissipated Energy.**

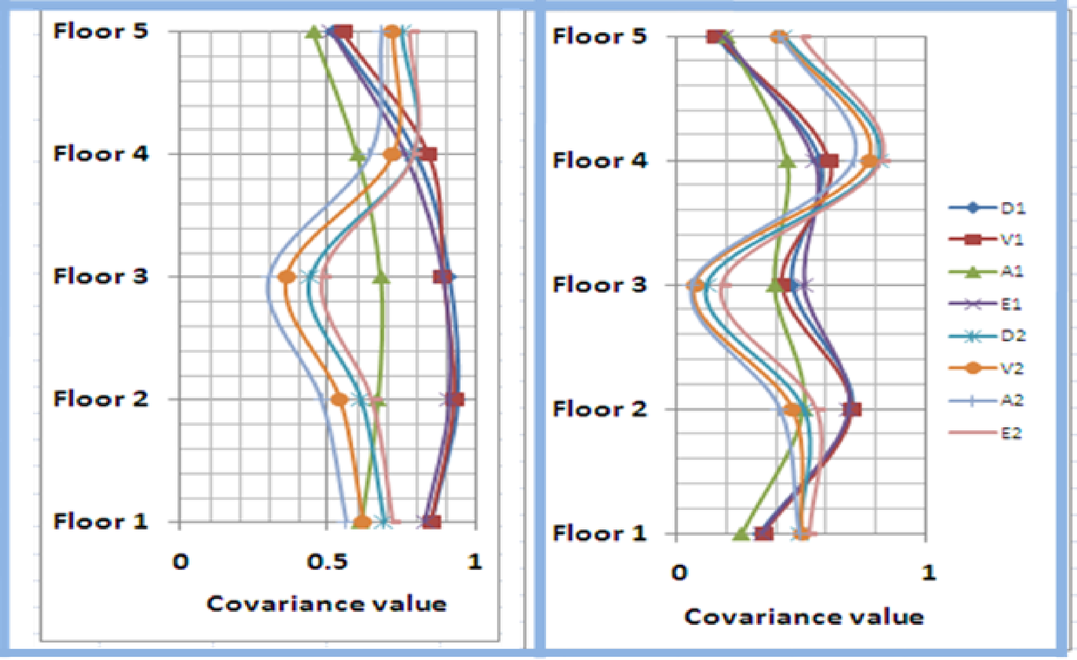


Figure 5.10 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using indices [25]

5.7 Comparison of Performance of Ground Motion Selected by Various Indices

This section discusses how the probability of having required design ground motion is affected by the properties of indices used in the selection of ground motion. We consider three types of combination of indices and compare the performance of the selected ground motions.

5.7.1 Probability of selection of required design ground motions by indices

Here we consider the probability of having required design ground motion. This probability is shown by 'indicator of the performance of an index/indices' (I_C). I_C is defined in Equation 5. 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 5. 4. If the index is perfectly correlated with the behavior of the target structure, it should be satisfied that $\bar{p} = \bar{P}$. This equality will be satisfied with relatively small error, if indices are good

Exceedance probability, or normalized rank of the i-th ground motion(p_i) in the set of possible ground motions, is evaluated by Equation 5. 3. When single index x^1 is used in the selection of the design ground motion, for example, it is given as

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1\}}{N} \qquad \text{Eq. 5.12}$$

Then the ground motion that satisfies Equation 5.4 should be selected. In the numerical simulation, as design exceedance probability (DEP) value is taken as 40%, ground motions 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

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1 \| x_n^2 > x_i^2\}}{N} \qquad \text{Eq. 5.13}$$

and when three indices are considered, given as

$$p_i = \frac{\sum_{n=1}^{N} Ind\{x_n^1 > x_i^1 \| x_n^2 > x_i^2 \| x_n^3 > x_i^3\}}{N} \qquad \text{Eq. 5.14}$$

Probability of occurrence of structural damage, P_d , is evaluated by Equation 5.6 and the procedure of evaluation is described in section 5.6.3.

5.7.2 Ground motion selection by using 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. Similar to Figure 5.10, Figure 5.11 shows the correlation of the indices (D1, V1 and E1) with expected damage. It is clear from Figure 5.11 that CoV of D1, V1 and E1 with three damage mechanisms exhibits same trend. Thus, D1, V1 and E1 are mutually similar. Selection of design ground motions by using D1, V1 and E1 is discussed in the following

For the selected ground motions, probability of structural damage occurrence, P_d, is plotted against the exceedance probability in terms of index D1, given by Equation 5.12, in Figure 5.8 (a). They are plotted by red points. Similarly, in Figure 5.8 to Figure 5.11 relationships between P_d and p_i are shown. In the Figure, black dash-line denotes the targeted design exceedance probability value. If the exceedance probability of the design ground motions is lower than the target, it means “safe” and it is located below this line. To show the distribution of the performance of selected ground motions for full scale structure, histogram of exceedance probability of structural damage is plotted which is represented by blue bars in the Figures.

The ground motions for which probability of occurrence of structural damage is less than 40% (below the black dash line) are considered to have the intended performance. Value of *Ic* is given as *Ic* = 39 %. It indicates that if you select the ground motion solely based on index values, D1, probability that the selected ground motion satisfies the condition is 39%.

Figure 5.8 (b) shows the results when two indices, D1 and V1, are used. For this case, value of *Ic* is given as *Ic*=42.5%.

Finally, design ground motion are selected by using three indices D1, V1 and E1by repeating the procedure as or first case. The results are plotted in Figure 5.8(c) and value of *Ic*52.2%.

These results show that value of *Ic* is not increased due to use of multiple indices, this reveals that the probability of selection of required design ground motions is not considerably increased. This is because all three indices used for selection of design ground motion are mutually similar.

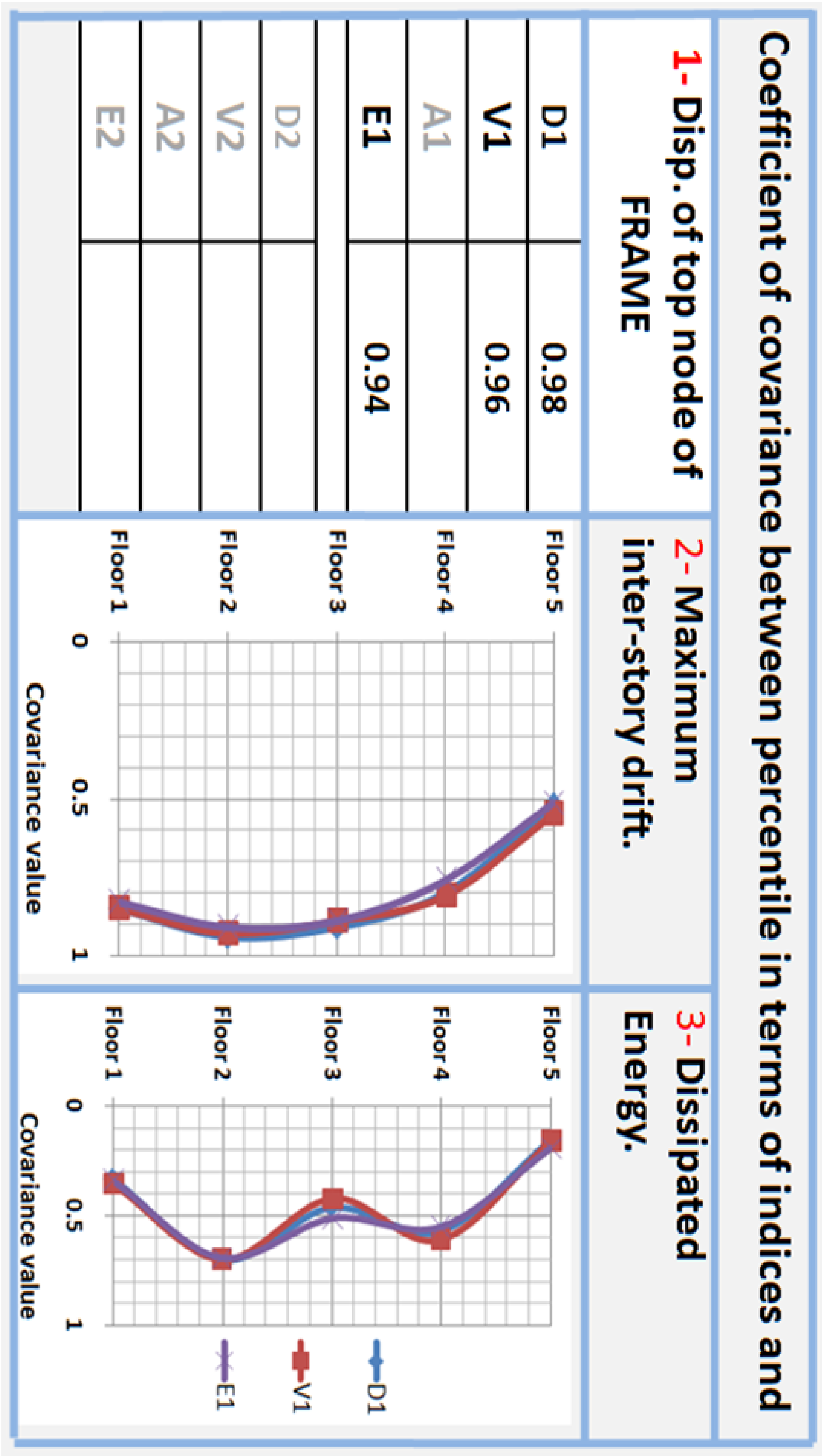


Figure 5.11 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using indices [25]

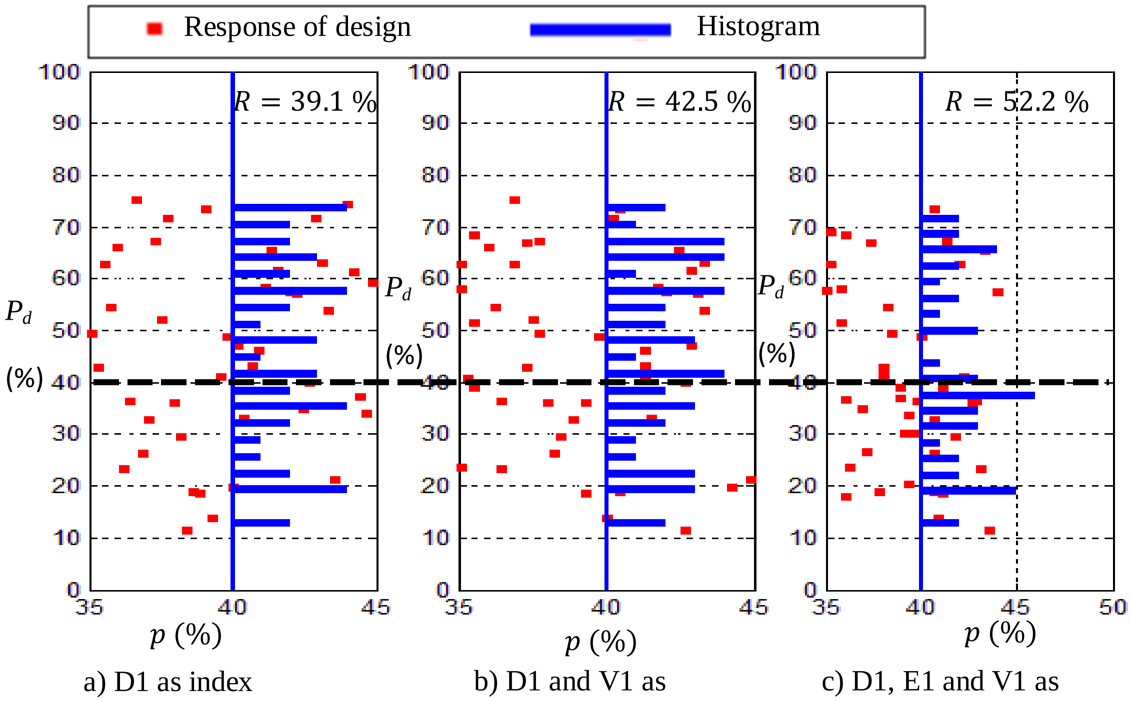


Figure 5.12 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using indices based on first mode (for $\bar{P}$ = 40%) [25]

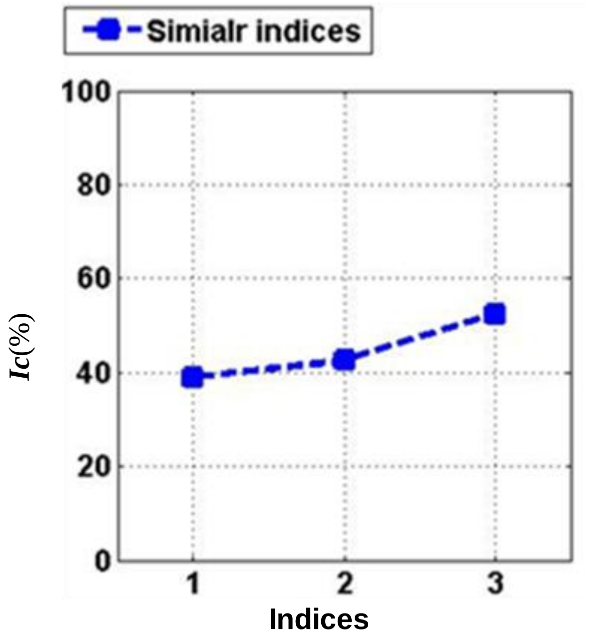


Figure 5.13 Variation of value of Ic with number of indices

5.7.3 Ground motion selection by damage mechanism based indices

In Table 5.5, 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 two to eleven of Table 5.5 and sketched in Figure 5.14. Based on CoV values, the damage mechanism based indices are expected to cover the assumed damage mechanisms. (Show by black line in Figure 5.14). 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 mechanisms, 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 (DMB indices). We discuss the performance of the design ground motion 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 5.9.

Comparison of Figure 5.15 (a) and (b) shows that value of *Ic* 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 ground motion characteristics from those represented by D1, displacement and the first oscillation mode. It indicates that consideration of different aspects enhanced the performance of the selection of design ground motion.

Value of *Ic* is 94.3 % for the case, where D1, E1 and E2 are used as indices for selection of design ground motion, and probability of damage occurrence is plotted in Figure 5.15 (c). 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.

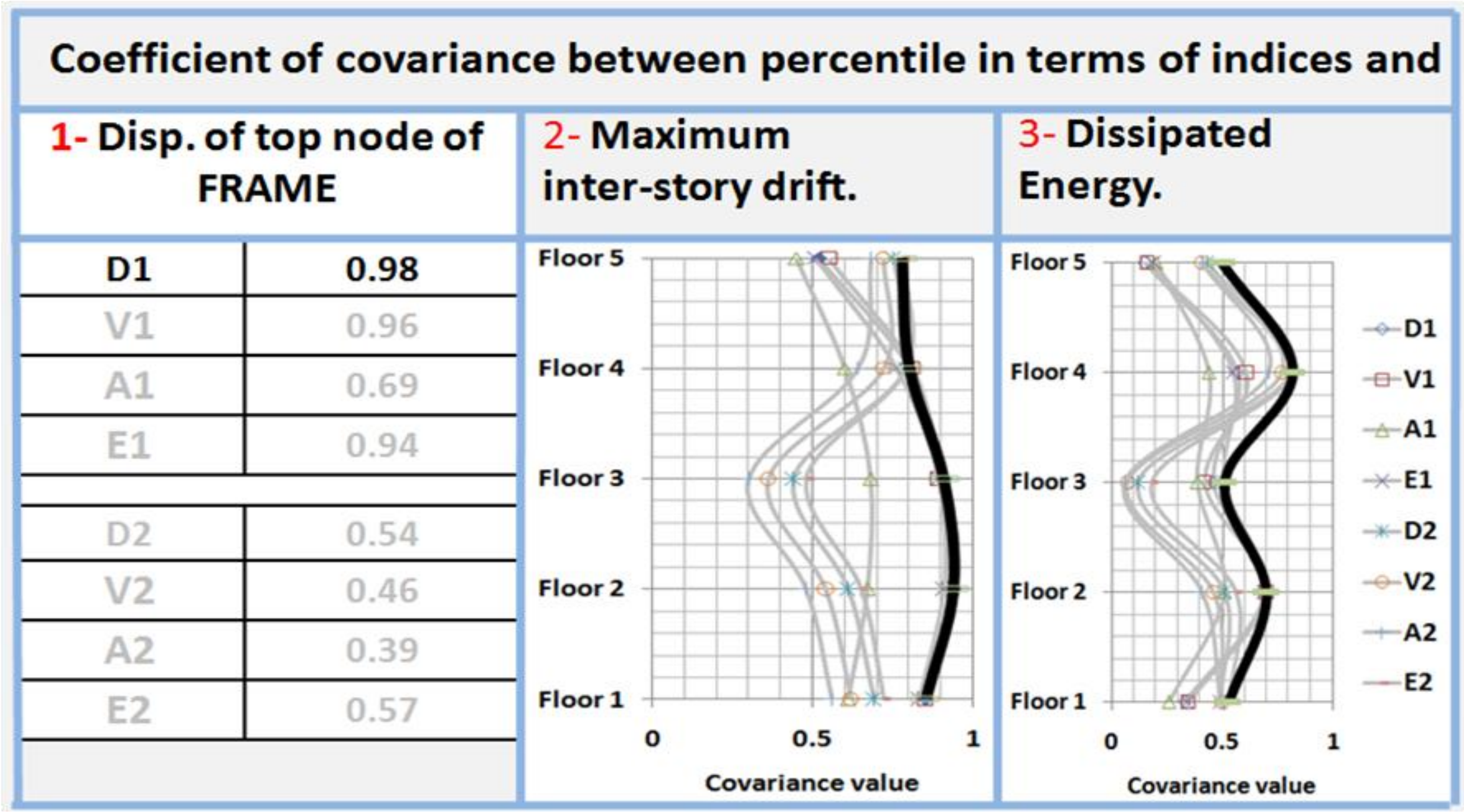


Figure 5.14 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using indices [25]

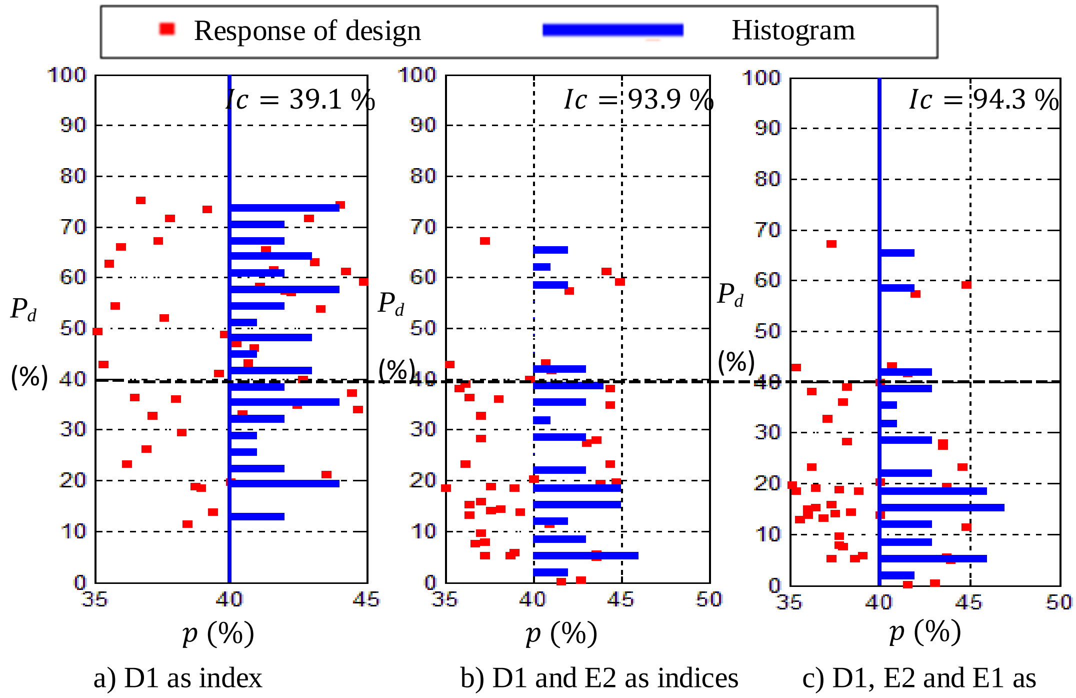


Figure 5.15 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using DMB indices (for $\bar{P} = 40\%$) [25]

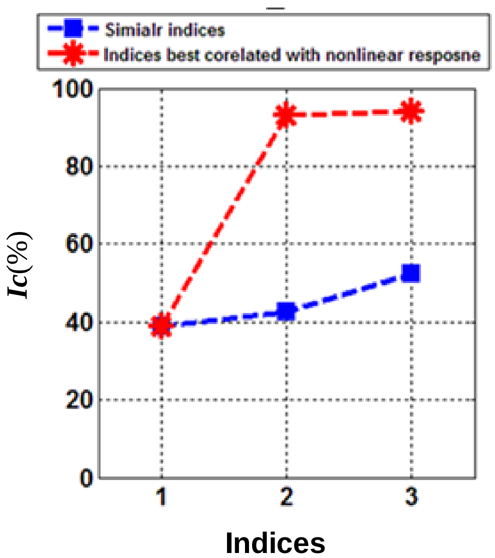


Figure 5.16 Variation of value of Ic with number of indices

Here the value of I_C is increased to 94% as compared to single index (D1 case, for which I_C is 39%). This means that if we select the design ground motion by incorporating the damage mechanism based indices, then there is 94% chances that the selected design ground motion (randomly selected ground motion which fulfill the condition to be design ground motion) shows the required performance in context of target structure.

To compare the performance of damage mechanism based indices with the first case (in which indices related to first mode was used for selection of design ground motions), the value of *Ic* for both cases are shown in figure 5.16. In Figure 5.16, horizontal axis shows the number of indices used for the selection of design ground motion. Vertical axis shows the value of *Ic*. Increase in value of *Ic* is clearly observed for the DMB indices case. The reason is that, the DMB indices are expected to cover most influential aspect of nonlinear behavior of structure under consideration. Therefore, inclusion of DMB indices increases the probability of selection of required design ground motions.

In order to verify this conjecture, we also consider the same problem with different targeted probability of damage occurrence. Design ground motions are selected for $\bar{P} = 70, 60, 50, 30, 20\%$.The variation of value of *Ic* for these cases are summarized in Figure 5.17 and they exhibit the same trend as is explained for $\bar{P} = 40\%$. Similar to figure 5.12 and Figure 5.15, the distribution of probabilities (P_d and p_i) for these cases are plotted in Figure 5.18 to 5.27. DMB indices are efficient to select the required design ground motion, reason is that, the DMB indices are expected to cover most influential aspect of nonlinear behavior of structure under consideration, therefore, inclusion of DMB indices increases the probability of selection of required design ground motions.

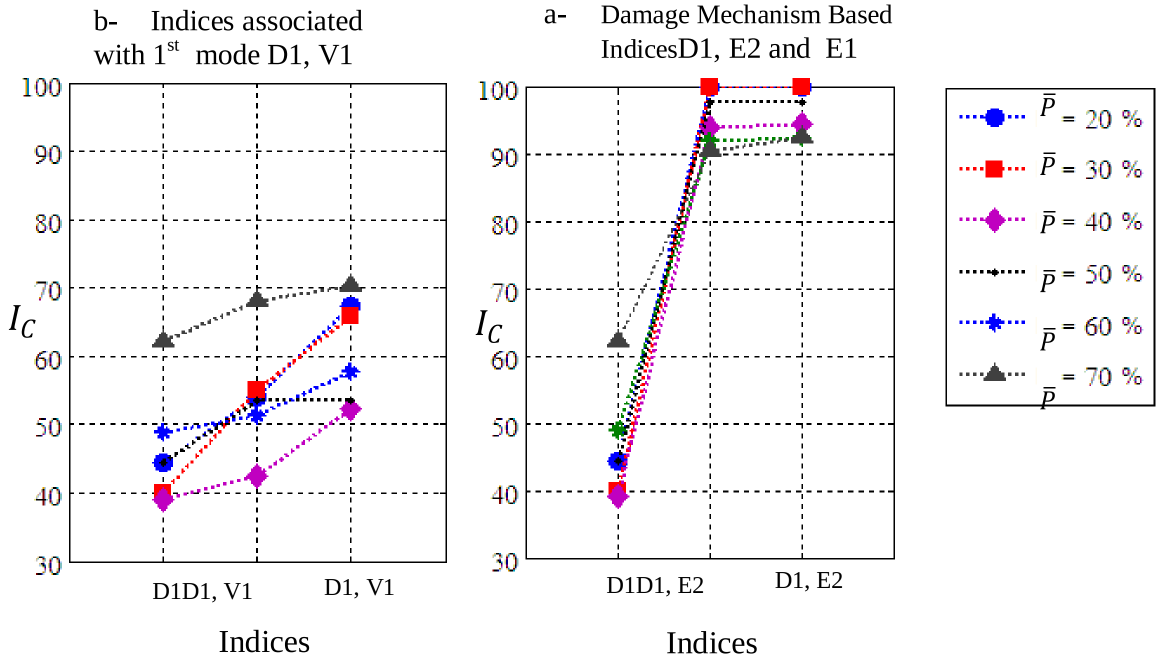
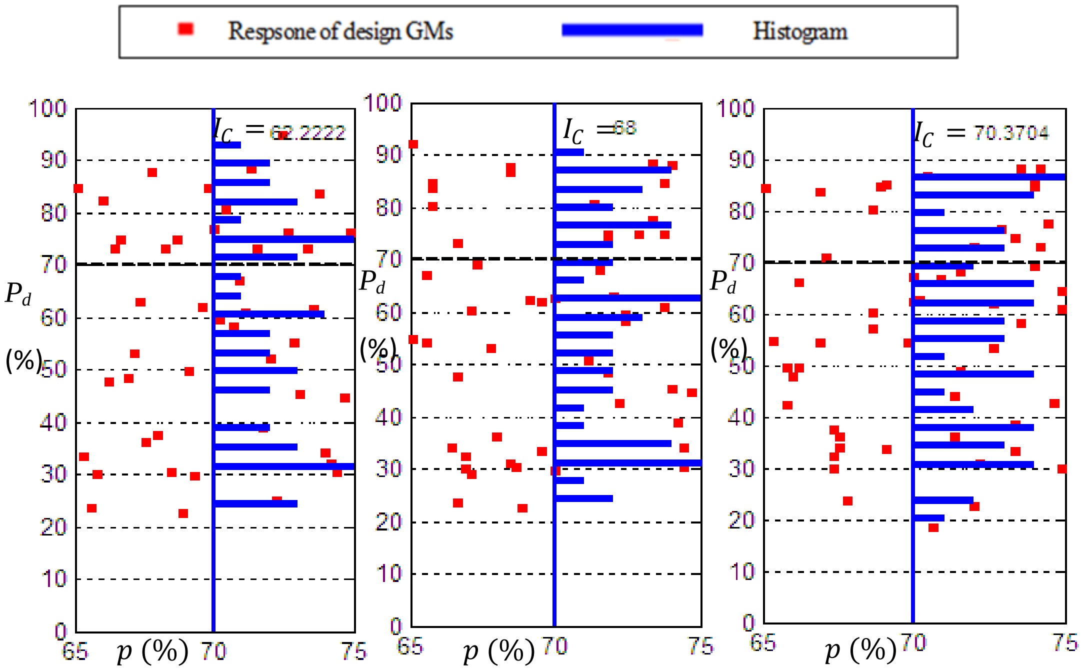
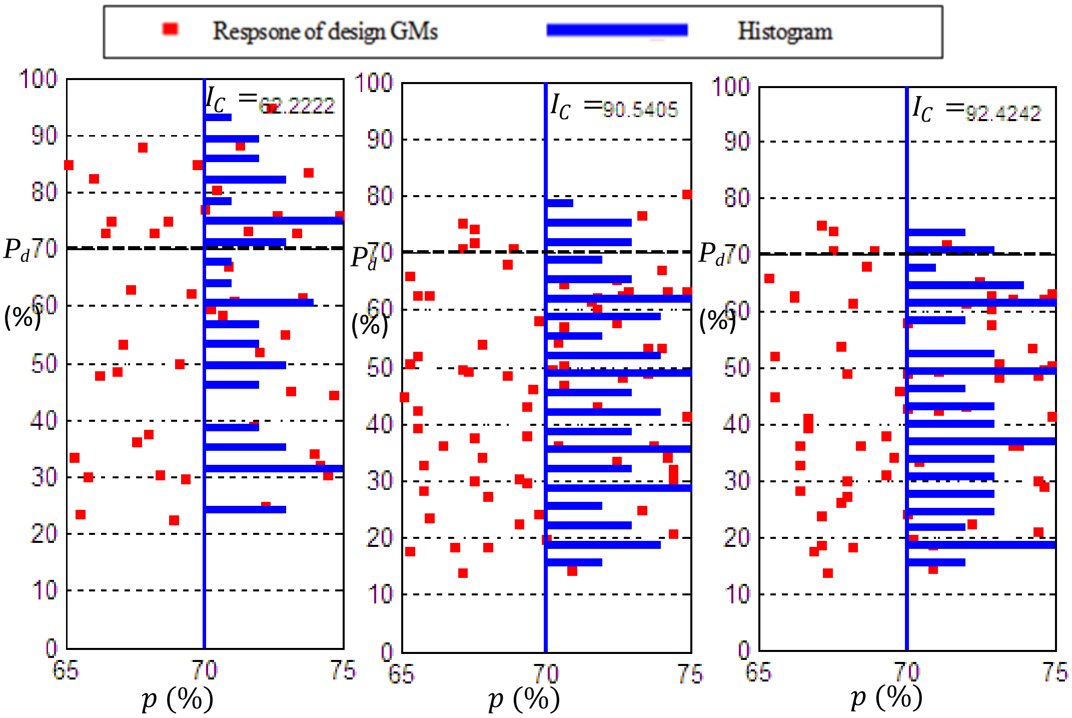


Figure 5.17 Distribution of I_C for different levels of targeted probability of damage occurrence for two set of indices. (a) Indices associated with first mode (b) Damage mechanism based Indices



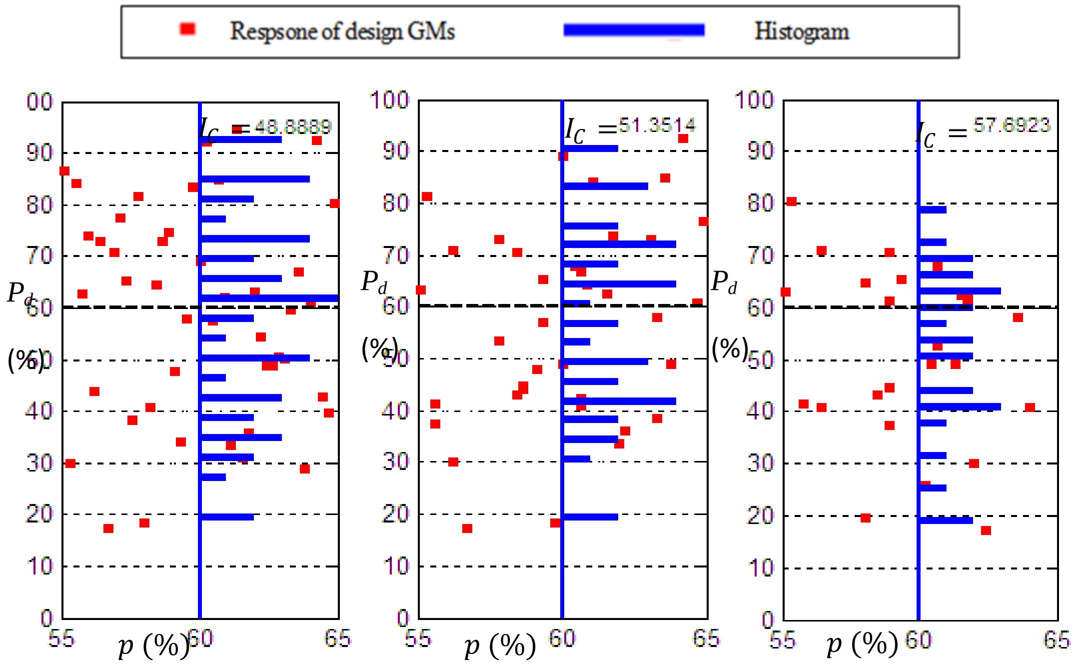
a) D1 as index b) D1 and V1 as c) D1, V1 and E1 as

Figure 5.18 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices based on first mode (for $\bar{P} = 70\%$)



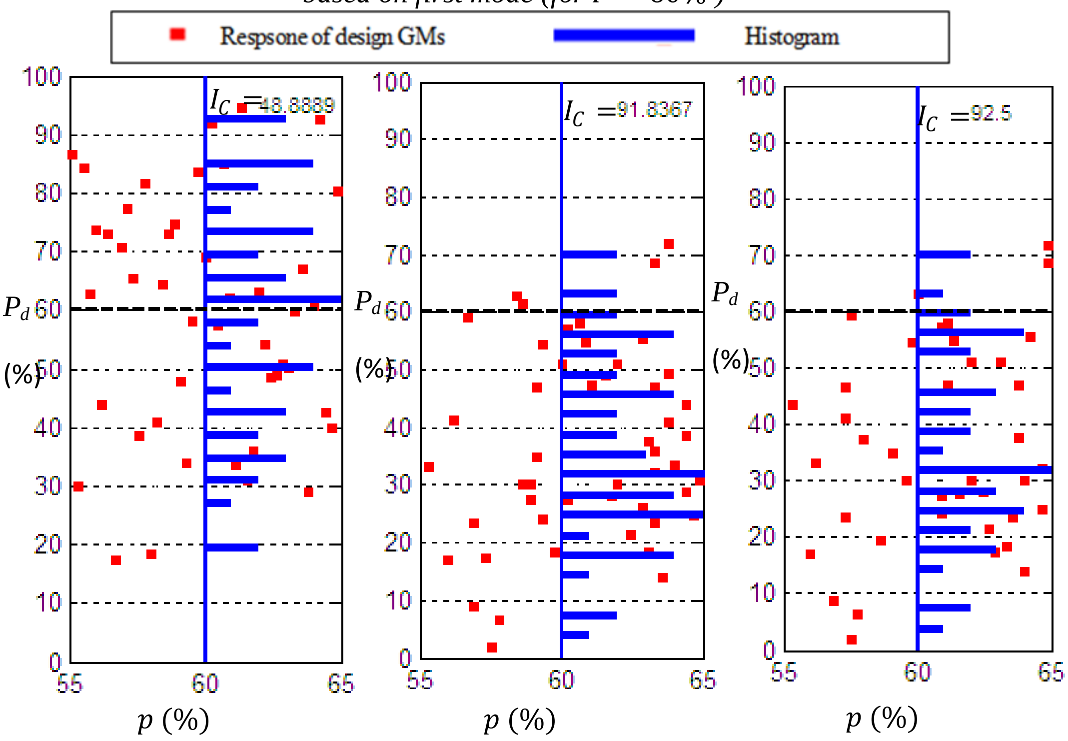
a) D1 as index b) D1 and E2 as indices c) D1, E2 and E1 as

Figure 5.19 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using DMB indices (for $\bar{P} = 70\%$)



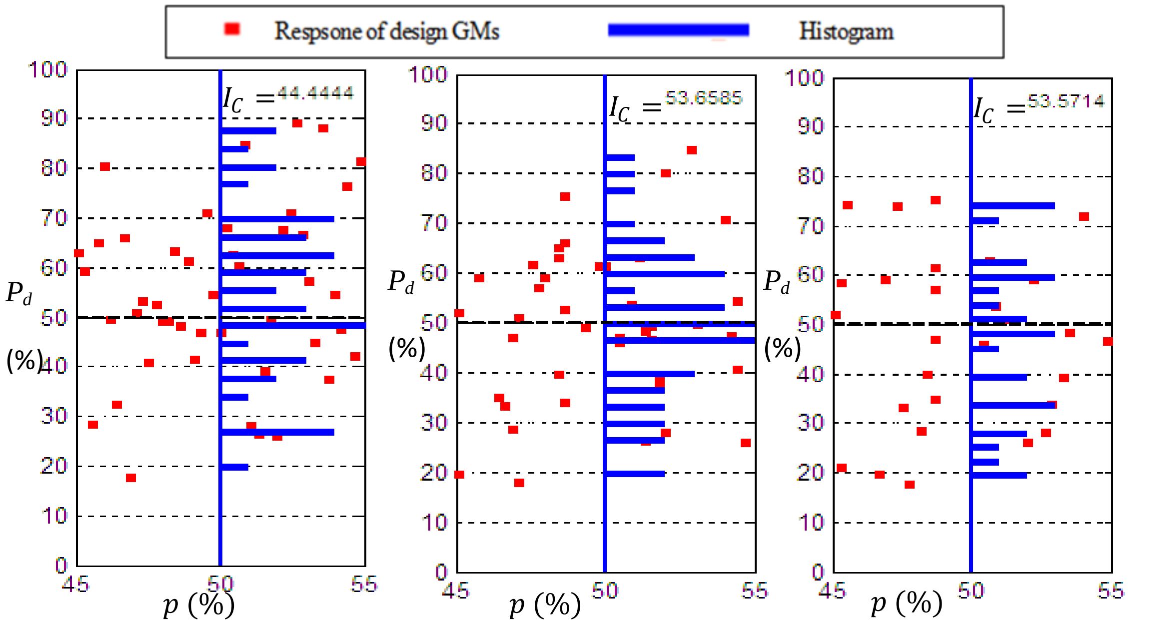
a) D1 as index b) D1 and V1 as c) D1, V1 and E1 as

Figure 5.20 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices based on first mode (for $\bar{P}$ = 60%)



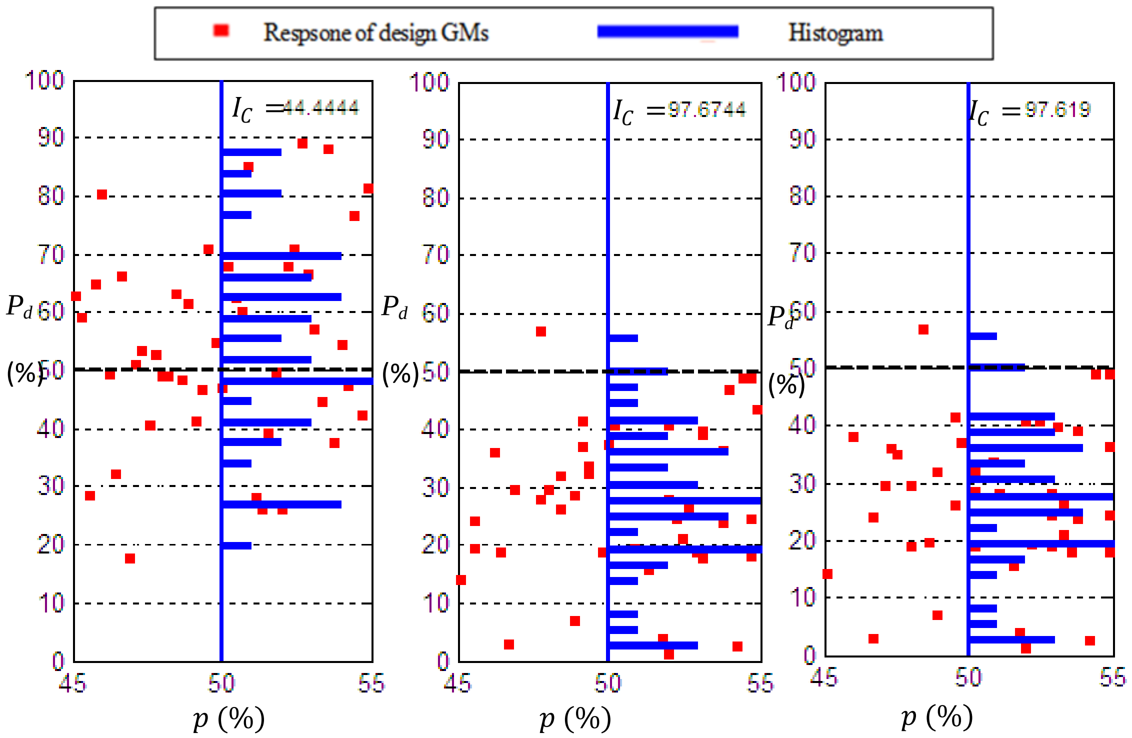
a) D1 as index b) D1 and E2 as indices c) D1, E2 and E1 as

Figure 5.21 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using DMB indices (for $\bar{P}$ = 60%)



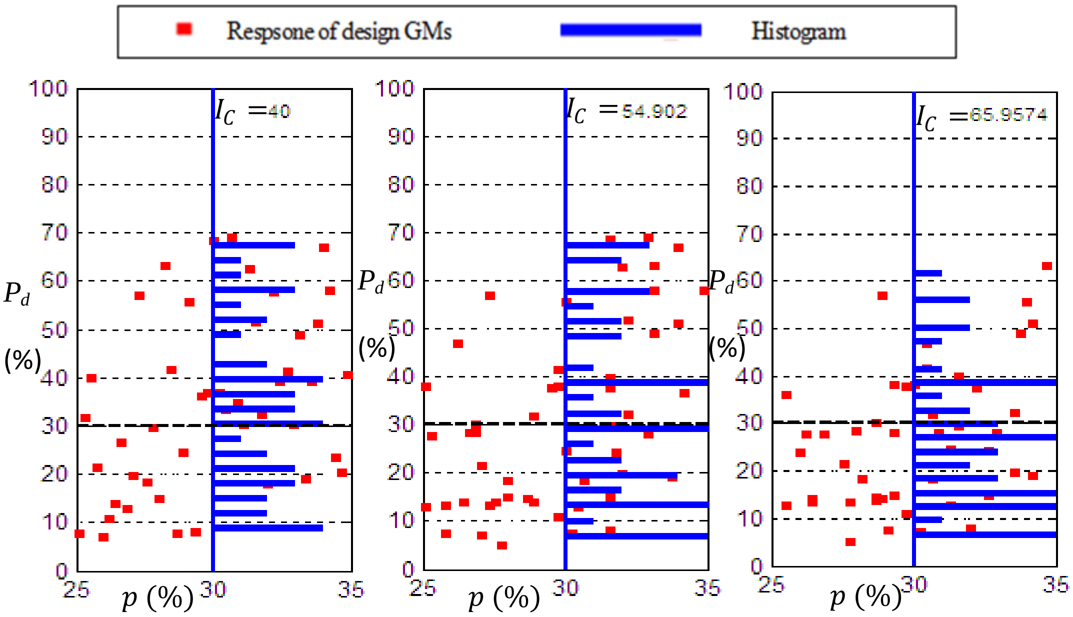
a) D1 as index   b) D1 and V1 as   c) D1, V1 and E1 as

Figure5.22 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices based on first mode (for $\bar{P}$ = 50%)



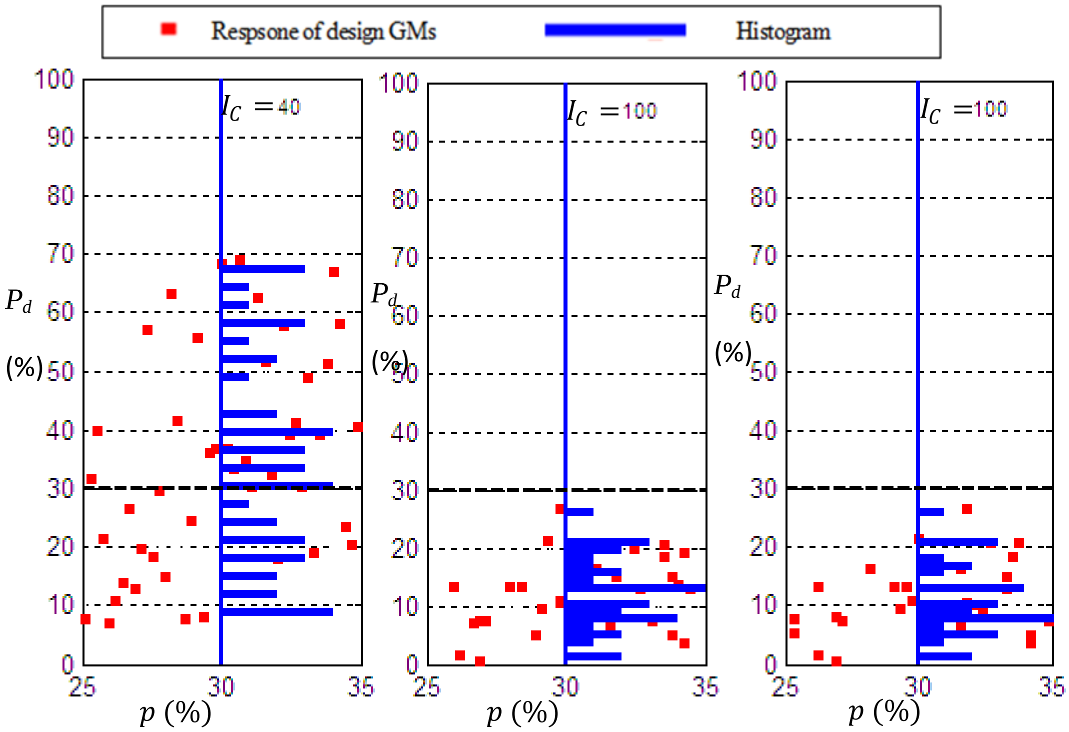
a) D1 as index   b) D1 and E2 as indices   c) D1, E2 and E1 as

Figure5.23Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using DMB indices (for $\bar{P}$ = 50%)



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

Figure 5.24 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices based on first mode (for $\bar{P}$ = 30%)



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

Figure5.25 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using DMB indices (for $\bar{P}$ = 30%)

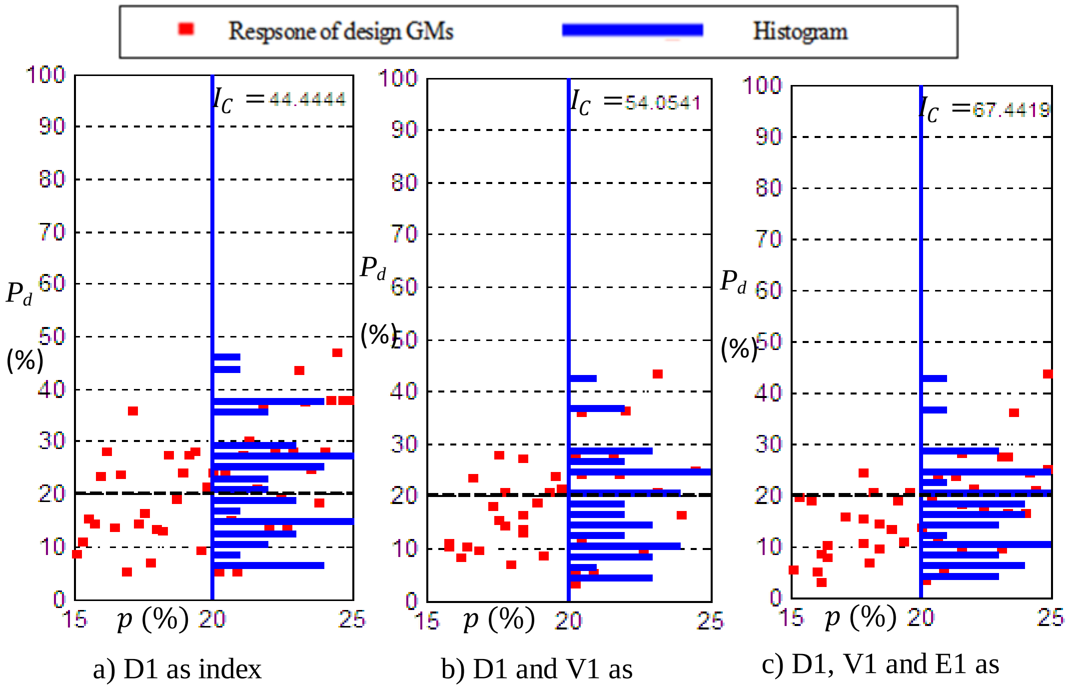


Figure 5.26 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using indices based on first mode (for $\bar{P}$ = 20%)

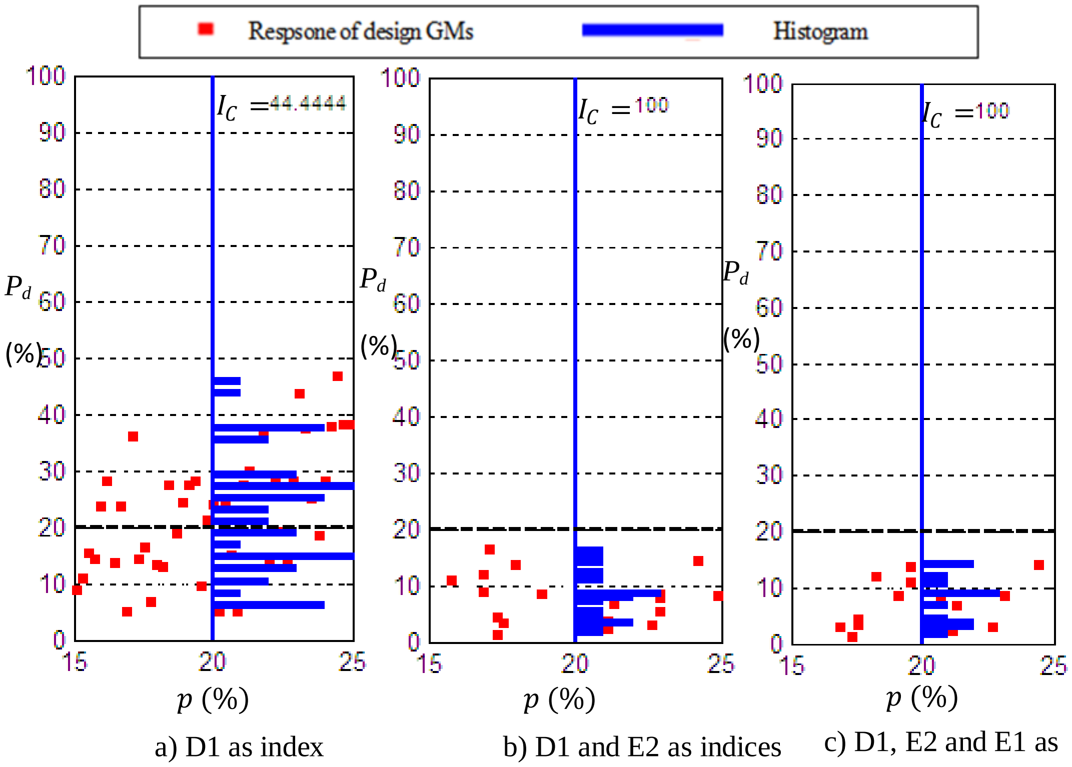


Figure 5.27 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design GMs selected by using DMB indices (for $\bar{P}$ = 20%)

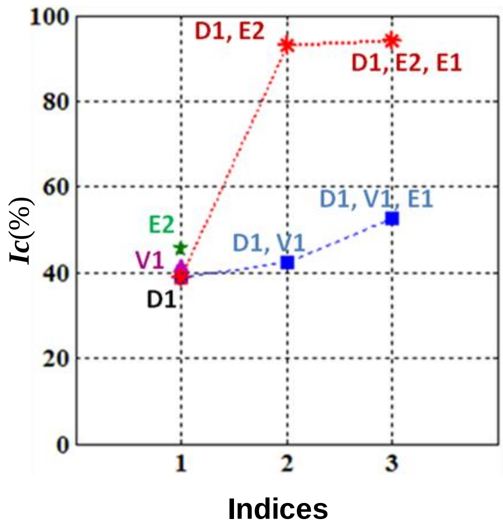


Figure 5.28 Variation of value of Ic with number of indices

5.7.4 Evaluation of performance of DMB indices

In the simulation results, the value of *Ic* is considerably increased due to Inclusion of DMB indices. To check that the increase in value of *Ic* is not due to a single index, here we separately use D1, V1 and E2 for selection of design ground motions. And accordingly the values of *Ic* are evaluated. Similar to figure 5.16, the values of *Ic* are shown in Figure 5.28

Fig.5.28 shows that if indices D1, V1 and E2 are separately used for selection of design ground motion then values of *Ic* are 39%, 41.2% and 47.3% respectively. If combination of D1 and V1 is used for selection of ground motions, then the values of *Ic* is 42.5%. It shows that the value of values of *Ic* is not considerably increased as compared to cases, where D1 and V1 are individually used for selection of design ground motion. The reason is that D1 and V1 are similar and do not cover different aspects of structural damage. Therefore combination of D1 and V1 is not very effective to increase the performance of selection of required design ground motion.

On the other hand, the values of *Ic* is increased to 92% if combination of D1 and E2 (DMB indices) is used for selection of indices. This reveals that the increase in probability of selection of required design ground motion is not solely due to a single index, rather than that the performance of selection of required design ground is increased, because damage mechanism based indices are expected to cover different aspect.

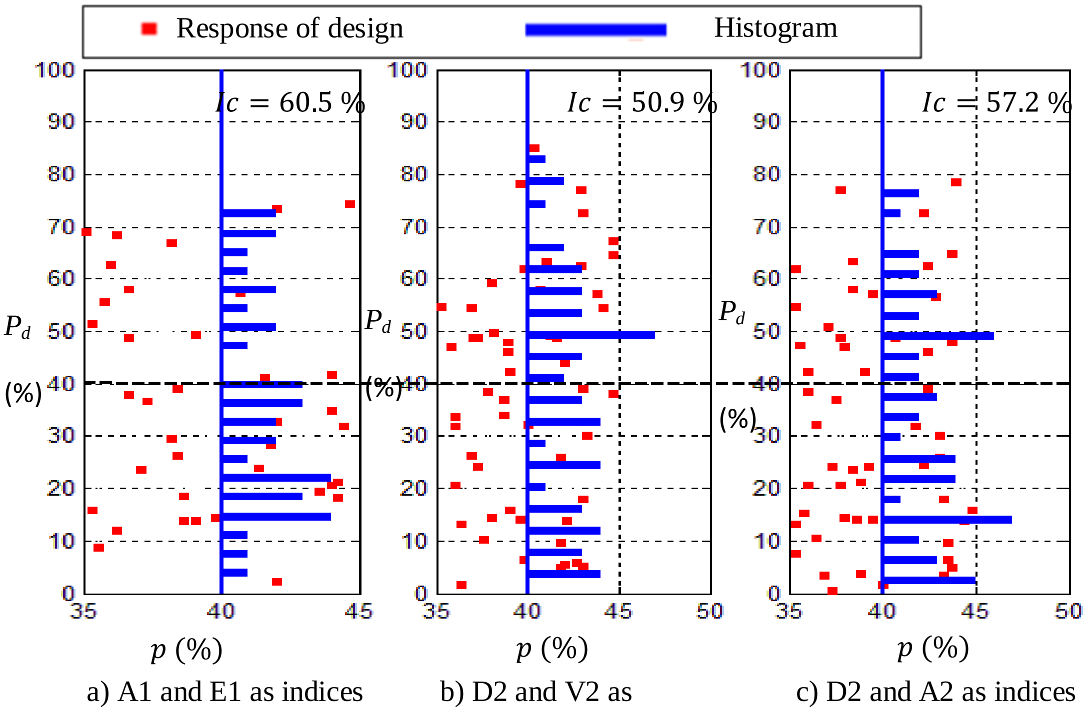


Figure 5.29 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design Ground motions selected by using indices [25]

5.7.5 Ground motion selection by indices that are less correlated with the nonlinear response

We also discuss the performance of ground motions selected based on the indices whose CoV are relatively low. Considered indices are A1, V2 and A2. Performance of design ground motions 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 5.29. The values of *Ic* for the three combinations are 60.5, 50.9, and 57.2%, respectively.

This shows that the values of *Ic* is higher than the case with indices associated with the first mode of the structure, which is shown in Figure 5. 12 and discussed in section 5.7.2. It indicates that consideration of wide variety of aspects of ground motion characteristics could help us to select an appropriate design ground motion, even if the performance of the additional index itself is not so high.

5.8 Selection of Indices for Design Ground Motions Selection

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

First, as is widely recognized, indices related with possible damage mechanisms are appropriate for the selection of design ground motions. Secondly, the probability of selection of required design ground motions is improved if wider variety of aspects of ground motion is considered in the selection of design ground motions. As the third point, it can be noticed that if you add new index to the existing indices for the selection of design ground motion, it would be effective, if that index/indices covers/cover different aspects in terms of influence of ground motion 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 performance considerably, if that aspect is already considered by existing indices.

5.9 Summary

Selection of design ground motion is a crucial stage in the design process based on nonlinear dynamic analysis of structures. Here, we presented a method to select design ground motions out of possible ground motions by using appropriate indices.

First we define the performance of the design ground motion as the probability that the probability of the intended performance is realized when design ground motion is selected based on certain conditions. We present the scheme to formulate the condition using indices that are associated with ground motion characteristics 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 ground motion 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 ground motion on nonlinear behavior of structures. We propose to use more than one index and discuss what kind of combination should be utilized for the selection of design ground motion.

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 ground motions. Firstly, index corresponding to damage mechanism is efficient for the selection of good design ground motions. Secondly, it is also shown that it is useful to use indices so that it can cover the wider variety of aspects of ground motion 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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Chapter 6

Selection of Parameters of Indices Considering Nonlinear Response

6.1 Introduction

Consideration of ground motion from various sources is necessary to enhance the seismic performance of structure. On the other side, owing to computational constraints, it is required to have a limited number of representative ground motions for design of structures. In such situations, intensity measures (indices) are commonly deployed for the selection of design ground motions. But due to simplicity, an intensity measure cannot circumscribe the uncertainty of nonlinear response. In this chapter, we discuss the consideration of affect of nonlinear response of structure in selection/synthesis of design ground motions.

For performance enhancement of proposed method of ground motion synthesis, effectiveness of indices for selection of design ground motion is enhanced by considering the effect of nonlinear response of structure. To enhance the performance of indices in context of nonlinear response of structure, it is proposed that indices should be sensitive to the stochastic nature of structural characteristics and modification of influencing parameters of nonlinear response of structure during progressive damage of the structure.

Due to variety of uncertain factors, however, it is difficult to quantitatively consider the affect of nonlinear response of structure in selection/synthesis of design ground motions. Thus, we propose to consider the fluctuation to the parameters of indices. This will be helpful to evaluate a variety of aspects of a ground motions in context of nonlinear response of structure. Thus, it will contribute to enhance the performance of proposed method of ground motion synthesis.

It is expected that the performance of proposed method of ground motion synthesis would be considerably enhanced by considering the indices which are equipped with such characteristics, which are efficient to reflect the effect of nonlinear response.

6.2 Sensitivity of Proposed Method of Ground Motion Synthesis to the Affect of Nonlinear Response

The design ground motion is synthesized based on index value and the synthesized ground motion would be used for the dynamic nonlinear analysis of structure. Therefore, it is required that the affect of nonlinear response must be considered in the synthesis of design ground motion. Second, in this study, new index/indices is/are not produced. Rather than this, out of available indices, most reliable indices are selected based on the information of nonlinear response of structure. For this purpose, the concept of damage mechanism based indices is discussed in chapter 5. For example, if response of bilinear single degree of freedom (SDOF) system is considered as reliable index based on concept of damage mechanism based indices, then parameters of SDOF system (natural time period and yield force) would be decided by considering the natural period and yield force level of target structure. Here the parameters of the structure are not known and subjected to fluctuation due to a variety of factors, such as non-homogeneity of material properties, etc. Meanwhile the properties of structure will be modified as the nonlinear response progress. In that context, even the response of SDOF is a reasonable index based on concept of damage mechanism based indices, yet the ground motion selected based on response of SDOF will not be the representative ground motion. To increase the performance of the proposed method of ground motion synthesis in this regard we need to consider the effect of nonlinear response in deciding the parameters of indices.

In the proposed method of ground motion synthesis, feature indices are used to describe the set of possible input ground motions. Therefore, indices are objected to quantify the damaging capabilities of ground motions. To evaluate the performance of selection/synthesis of design ground motion based on indices, following should be taken into consideration.

- Different ground motion could be regarded as effective when structural properties are changed due to fluctuation in structural characteristics.
- Indices are simple and cannot circumscribe the complex nonlinear response of structure.

Therefore, it is required that indices must be equipped with characteristics that can reflect the effect of nonlinear response in selection/synthesis of design ground motions.

6.3 Ground Motion Selection and Proposed Method of Ground Motion Synthesis

Design Ground motion synthesis procedure is explained in chapter 3 and effectiveness of the proposed method of ground motion synthesis is discussed in chapter 4. Proposed method of ground motion synthesis comprise of three steps. First, by modifying an existing ground motions, a limited number of ground motions are formulated. Second, out of formulated ground motions, a relatively efficient ground motion is selected for modification in next step. Third, the process of modification is iterated until the required ground motion is synthesized. As an essence, the ground motion synthesis procedures involve the selection of ground motion in iterative modification.

To ease the discussion and clearly see the effect of indices in proposed method of ground motion synthesis, it is preferable to discuss the affect of indices parameters in context of ground motion selection. Because in proposed method of ground motion synthesis, a ground motion is to be selected out of candidate ground motions (formulated by changing the time-frequency characteristics using wavelet transform) in each iteration.

Therefore hereafter, we are discussing about the selection of design ground motions, and the conclusions will be equally applicable for the proposed method of ground motion synthesis.

6.4 Selection of Design Ground Motion

In the selection of ground motions, a ground motion that is the “toughest” among possible ground motions should be chosen. It is difficult, however, to find such ground motion, because, due to uncertainty associated with nonlinear behavior of structure, the “toughest” ground motion 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 diversity of ground motions make the selection more difficult, because sophisticated techniques such as Nonlinear Seismic Analysis (NSA) are sensitive to change in various parameters.

Here, we use indices as condition to select the design ground motions. From design ground motion it is expected that probability $(\mathrm{P})$of occurrence of damage(D)under the condition that the structure is designed against that ground motion$(\mathrm{GM})$is smaller than a certain value $(\overline{\mathrm{P}})$.

$$\mathrm{P} = \mathrm{prob}(\mathrm{D}|\mathrm{GM}) < \overline{\mathrm{P}} \tag{6.1}$$

The value of probability(P)depends on the selected design ground motions. Since we cannot know the influence of a ground motion on the structure in advance, we need to select a ground motion which satisfies the specified condition(C).

6.4.1 Indicator of the performance of an index/indices$\boldsymbol{I_C}$

Ground motions are selected based on condition (index values), therefore it is necessary to consider the probability that Equation 6.1 is satisfied when ground motion is randomly selected based on the condition(C). As indices are used in the condition, therefore this probability is used as criteria to evaluate the goodness of index/indices, and regarded as '*indicator of the performance of an index/indices*'I_C and written as

$$I_C = prob[\{prob(D|GM) < \bar{P}\}|C] \tag{6.2}$$

> Higher value of I_C shows that index/indices are efficient to select the required design ground motion (GM)
>
> Lower value of $I_C$shows that index/indices are not efficient to select the required design ground motion (GM)

In this procedure, indices are used in the condition(C). If design ground motions are selected based on multiple indices, which consider various possible damage mechanisms, the value of $I_C$is expected to be higher than the one selected by using conventional schemes.

In this procedure, feature indices are used in the condition(C). If indices are efficient to represent the damage capabilities of ground motions, then probability of having the required design ground motion is higher. Thus, I_C(the indicator of the performance of index/indices) has a direct correlation with the efficiency of an index. In this study, we will use the value of $I_C$as criteria to evaluate the goodness of an index in context of fluctuation to the parameters of indices.

6.5 Selection of Parameters of Indices Considering Nonlinear Response of Structures

Indices for the selection of design ground motions can be categorized into two types. First types of indices are based on the properties of ground motion signal [1, 2] such as peak acceleration, duration of ground motion signal and spectral values. They do not consider the effect of structural characteristics [1, 2, and 3]

Second types of indices consider the effect of ground motions on structures [4, 5, 6, and 7]. Such as response of single degree of freedom (SDOF) system which includes dynamic characteristics similar to the structure under consideration. We use the latter types because ground motions for design should be selected based on their influence on structures.

In general, for indices which consider the effect of structural characteristics [4], the indices parameters such as yield force and natural time period of bilinear SDOF system, are decided by considering the characteristics of the structure under consideration. In such situation two points are important to mention here, first, dynamic characteristics of structure are modified in progressive damage of structure, thus the deterministic parameters of indices based on linear response of structure is not justifiable. Second, indices are simple and cannot represent the uncertainty of nonlinear response of structures.

6.5.1 Fluctuation in the parameters of indices to consider nonlinear response

Considering the background presented above, we propose to consider a fluctuation to the parameters of indices to cope with uncertainty of nonlinear response. [8]. Let us emphasize that we add fluctuation not to reproduce the complicated nonlinear response of the structure. It is assumed that consideration of fluctuation to the parameters of indices will be helpful to enhance the efficiency of indices to represent the damaging capabilities of design ground motions.

The amplitude of fluctuation added to the index parameters is not easy to specify. Comparing the simplicity of indices and complexity of nonlinear response, it is not a good option to fix the value of fluctuation. We need to specify the range of fluctuation suitable to consider the affect of nonlinear response and we try to evaluate an optimum range of fluctuation to the parameters in the following.

In the following sections, we discuss the optimal amplitude of fluctuation in index parameters, taking a reinforced concrete frame structure as an example. The indices are used to select the design ground motions out of sets of possible ground motions. The ranges of fluctuation added to the index are changed gradually. The probability of obtaining appropriate design ground motions is checked to find the optimal range of fluctuation to the index parameters.

6.6 Details of Modeling of Moment Resisting Concrete Frame

Design ground motions are selected for a two dimensional five-story moment resisting concrete frame, elevation of the frame is shown in Figure 6.1 and sectional details are shown in Table 6.1. This structure is referred to as a target structure hereafter.

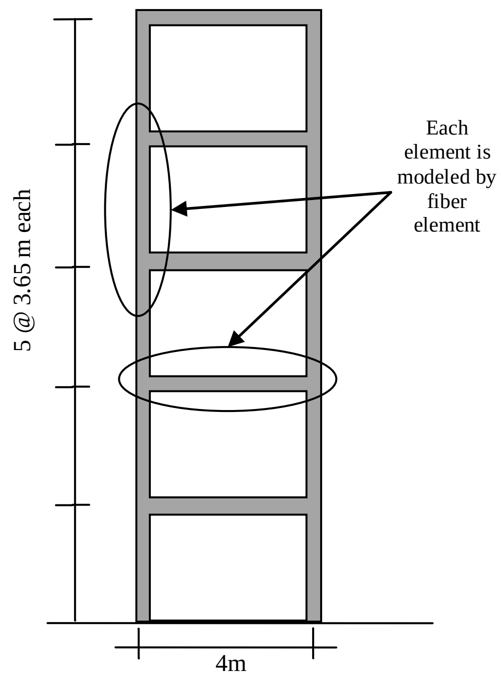

Figure 6.1Elevation of concrete frame [8]

Table 6.1Detail of beam and column sections [8]

	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

The dead load for the nonlinear analysis is contributed by the self weight of members such as beam, columns, concrete slab and weight of floor finishes. Nonlinear dynamic analysis is conducted by using OpenSees [9].

Beams and columns of moment resisting concrete frame are modeled by using 12,600 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` [9, 10] is used to model confined and unconfined concrete and material model `Steel02` [9] is used to characterize the stress strain behavior of steel fibers. Nonlinear dynamic analysis is conducted by using OpenSees. As an example, the stress

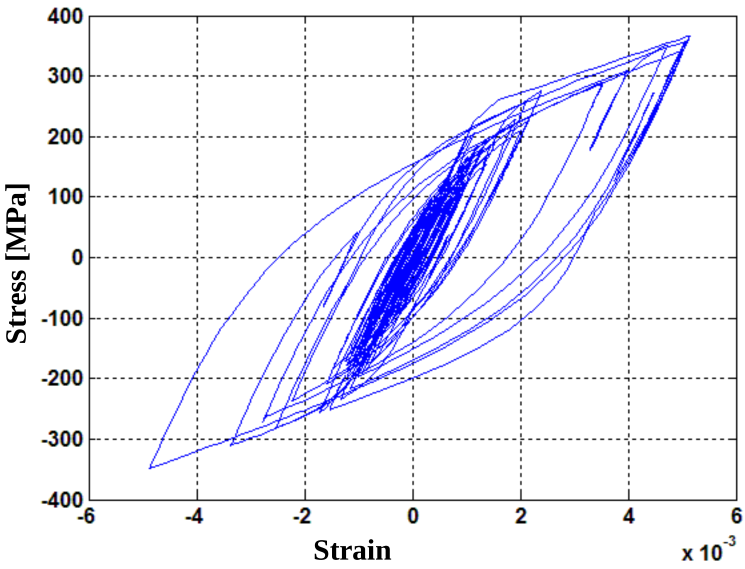

Figure 6.2Stress strain distribution of longitudinal steel bar of maximum stressed section of first-story column [8].

strain distribution of longitudinal steel bar at the maximum stressed section of first-story column is plotted in Figure 6.2.

In order to consider the effect of uncertain material properties on structure response, we consider material properties of elements as independent stochastic variables. We consider a uniform distribution of material properties to give an equal importance to possible values of material properties. Yield strength of steel, modulus of elasticity of steel and compressive strength of concrete are considered as stochastic variables.

The details of`Concrete02` model, `Steel02` model, consideration of fluctuation to material properties, fiber model, etc have been discussed in chapter 4 and chapter 5.

6.7 Set of Possible Input Ground Motions

Set of possible ground motions is considered for the design of structures to enhance the reliability of structural performance. To check the stability of the proposed method, we consider two sets of possible ground motions: Set A and Set B. Different ground motions records are used to formulate the sets of possible ground motions.

Two sets of possible ground motions are used to verify the stability of the proposed approach. Each set is comprises of 500 ground motions. The ground motions records of past earthquake events are obtained from K-NET [11]. It would be possible to generate such ground motions using numerical techniques, but actual ground motion records are used in order to discuss the applicability of the presented scheme for real ground motions. The ground motion records are factored so that their peak ground acceleration values are ranging between 600cm/sec^2 to 800cm/sec^2.

Selection of set of possible ground motions is important. Magnitude of event, source to site distance, site characteristics, etc are considered as criteria to formulate the possible ground motions which are required to be consider for the design of important structures. In the presented work, intentionally, we randomly selected the set of possible input ground motion to incorporate a variety of ground motions in set of possible ground motions.

6.8 Damage Mechanism Based Indices and Selection of Parameters of Indices

Concept of damage mechanism based indices [5, 12] to select appropriate indices has been elaborated in chapter 5. According to that concept, influential damaging mechanisms are accessed and accordingly indices are selected. The details of indices selection for the structure under consideration by using concept of damage mechanism based indices is in the following.

6.8.1 Indices selection

It is proposed to use indices which are related with expected damage mechanisms of the structure under consideration, because ground motions effective in terms of such indices would be effective to excite possible damage mechanism and therefore should be used as a design ground motion. In this simulation, indices are determined as follows.

First, the stress strain distribution of columns of all floors at maximum stressed section presented in Figure6.3 is analyzed. It is observed that columns of first and second floor are most stressed and stress in columns of each floor decreases as the floor number increases. It indicates that oscillation in the first mode is the most prominent mechanism to damage this structure. Second, size and reinforcement of all columns are same therefore due to higher bending moment in first and second floor columns, damage will be concentrated at lower floors.

Based on these results, first mode is dominant in structural behavior and damage of the structure will be mainly due to oscillation of the structure in first mode. Therefore, displacement response of bilinear single-degree-of-freedom (SDOF) system is an appropriate index for the structure under consideration.

6.8.2 Properties of indices for selection of design ground motion

Response of SDOF system is apparently a good index for the first mode dominant structure. Values of parameters of SDOF system (yield force and

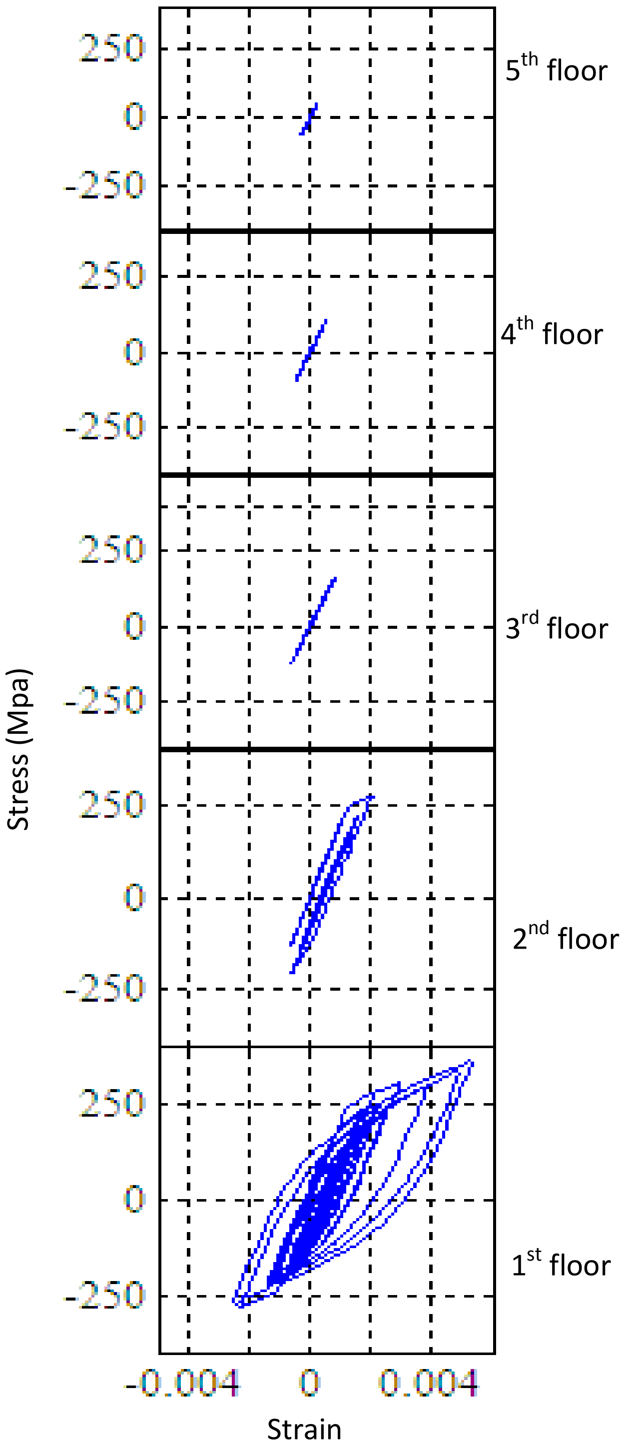

Figure 6.3Stress strain responses of steel fibers of left side columns of all floors at maximum stressed section [8]

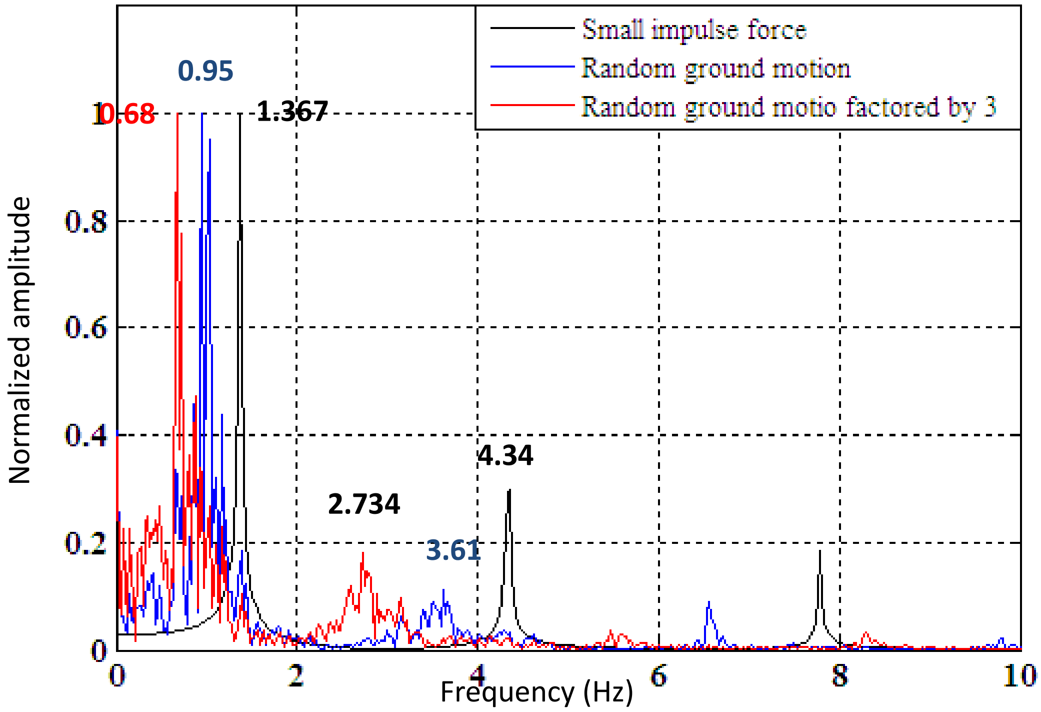

Figure 6.4 Fourier amplitude of displacement response of the target structure [8].

natural time period) are difficult to determine, because stiffness of structure reduces with progressive damage progresses. Thus, it results with longer natural period. Therefore there is no theoretically correct value of stiffness of structure, nor for yield force of structure.

Natural time period of the structure is difficult to determine, because it is a function of number of uncertain factors, such as material properties, sectional properties, bond between steel and concrete, etc. It is more difficult to determine the time period of damaged structure. Therefore, to access the time period of the structure, we use an indirect approach. In that approach, we evaluate the variation of frequencies due to damage of the structure by analyzing the response of the structure against three different excitation forces. Figure 6.4 shows the distributions of frequency component of displacement response of the damaged structure. Vertical axis is normalized by the corresponding maximum values to ease the comparison and visualization. Three input motions such as following was investigated.

- Impulse force: Structure is exposed to a small impulse force. The distribution of frequency content of displacement response shown in Figure 6.4. Figure 6.4 shows that frequency contents of displacement response has three peaks, which corresponds to three fundamental modes of the structure.

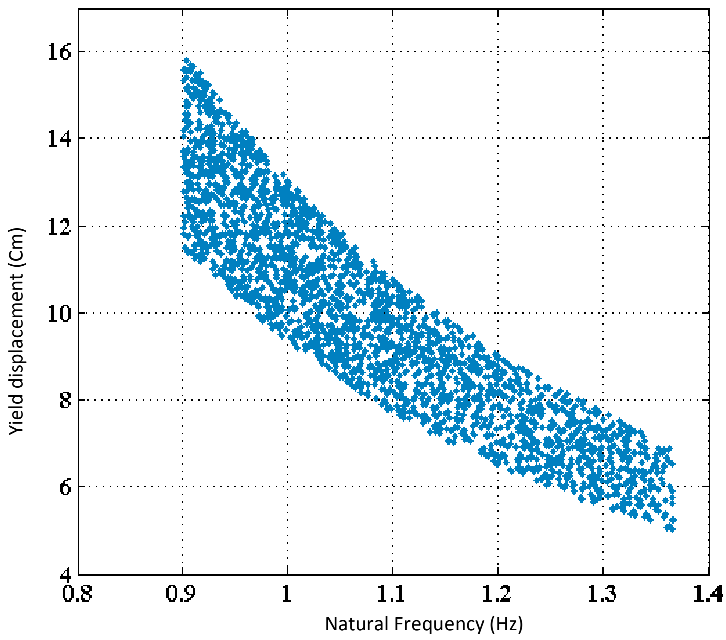

Figure 6.5Distributions of frequencies and yield displacement for SDOF realizations [8]

- Randomly selected ground motion (X): Structure is exposed to a random ground motion X. The distribution of frequency content of displacement response shown in Figure 6.4has three peaks. Corresponding frequencies of these peaks are lower than those by impulse case.
- Randomly selected ground motion factored by three (3X): To explore the elongation of natural frequencies due to damage, structure is exposed to ground motion X which is three times amplified. Further decrease in fundamental frequencies is clear from Figure 6.4.

The reduction of frequency of first mode from 1.36 Hz to 0.95 Hz helps us to formulate the properties of SDOF system. Figure 6.5 shows the distribution of natural frequencies and yield displacement of the SDOF realization.

In this simulation same strength columns are used for all the floors (columns have the same size and reinforcement), the damage will be contributed at lower part of structure due to peak bending moments. In that context, utilizing the concept of damage mechanism based indices, response of a bilinear SDOF is adopted as an appropriate index for the concrete moment resisting frame under consideration.

This index is a response of a spring mass system, and it cannot circumscribe the uncertainty of nonlinear response of concert structure. Meanwhile, we cannot *quantitatively* consider the aforementioned uncertainties of nonlinear response in selection/synthesis of design ground motion. Thus, we consider fluctuation to the parameters of indices to consider various aspects of influence of ground motion on the structure under consideration, which we cannot know if we use a single spring mass system.

6.9 Quantification of Structural Damage

OpenSees calculated the strain of each fiber against the deformation of member. This is used to quantify the effect of ground motion on the structure.

The structural damage is judged by comparing the strain of steel bars of all columns and beams. Damage level caused by ground motions is assessed by comparing maximum strain experienced by steel rebar of each member of the structure. Letε_m^i denote the strain of the rebar of the m-th structural member when the structure is exposed to the i-th ground motion. Suppose that the d-th ground motion is the design ground motion, 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 the members exceeds the value given for each member by the design ground motion.

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

$$P_d = \mathrm{prob}\left[\frac{\sum_{m=1}^{M} \mathrm{Ind}\{\varepsilon_m^n > \varepsilon_m^d\}}{M} > \frac{1}{2}\right] \tag{6.3}$$

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

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

6.10 Conditions to be Design Ground Motion

Displacement response of bilinear SDOF system (D1) is used as index to select the ground motion representing the set of possible ground motions. We compare two conditions as examples:

Case-I: *Critically damaging ground motions out of set of possible ground motions*: A ground motion with 10% exceedance probability is selected as the condition to be design ground motions. It is important to note that any ground motion which would satisfy the condition, will be the design ground motion. As mentioned earlier, indices are used in conditions, thus a ground motion which shows 10 % exceedance probability in terms of feature indices would be design ground motion. 10% of exceedance probability means that at most 10% of ground motions out of set of possible ground motions may exceed beyond the required design ground motion. In general, in this case we are looking for tough ground motions out of set of possible ground motions. And accordingly it is required that indices must equip with properties which reflect the uncertainty of nonlinear response.

Case-II: Least damaging ground motions out of set of possible ground motions: In this case, we are interested to have least damaging ground motions out of set of possible ground motions. In this case, a ground motion for which exceedance probability is 90 to 100% are required ground motions. 90% of exceedance probability means that 90% of ground motions out of set of possible ground motions may exceed beyond the required ground motion. Thus, the required ground motions in this case are expected to be least damaging for the structure under consideration, hence it is expected that we need to consider less fluctuation to the parameters of indices.

6.11 Simulations Results and Discussion

Based on the natural time period and yield force of concrete moment resisting frame, the properties of the bilinear SDOF system are formulated. Displacement response of the bilinear SDOF system is used an index. We consider fluctuation in the parameters of bilinear SDOF system.

First, let us explain how we consider the fluctuation (say x % of original value) to the parameters of indices. We consider x % fluctuation to the parameters of indices and 50 realizations of bilinear SDOF systems are formulated. The average of displacement responses of aforementioned 50 bilinear SDOF realizations is used as index to show the effectiveness of a ground motion. This is used to formulate exceedance probability in terms of feature indices for the set of possible ground motions. Thus the ground motions which show the required exceedance probabilities are selected as required design ground motions.

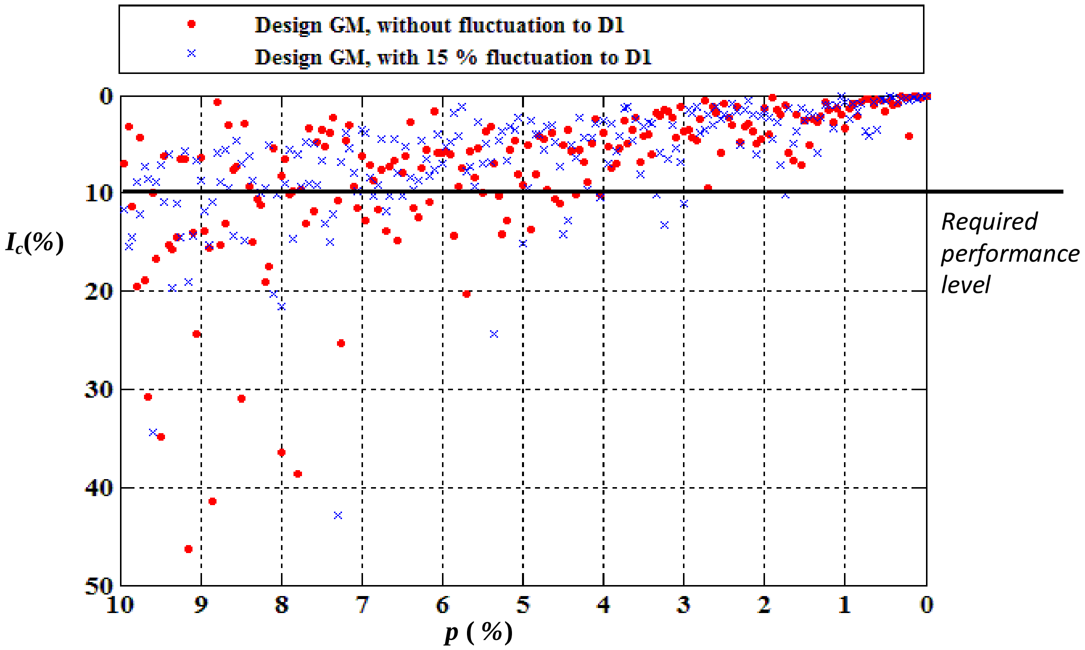

Figure 6.6Distribution of exceedance probability of structural damage (Pd) against exceedance probability in terms of indices (p) for design ground motions for two different values of fluctuation to the parameters of indices.

Secondly, the responses of all ground motions, which conform the condition, to be design ground motions are plotted in Figure 6.6. Exceedance probability in terms of feature indices (p) is plotted in the horizontal axis and exceedance probability of structural damage (P_d, formulated by Equation6.3) is plotted on vertical axis. According to Equation6.1, the probability of structural damage should be less than a certain value $(\bar{P})$. This required performance level is marked by horizontal solid line in Figure 6.6. Selected design ground motions are expected to be above the required performance level. But some ground motions lie below the target level.

To show the goodness of indices, the percentage of ground motions showing the required performance for five floor moment resisting concrete structure model to the ground motions conforming the condition to be the design ground motion are calculated. This corresponds to the I_C(the indicator of the performance of index/indices), defined in Equation6.2.

For the specific results presented in Figure 6.6, the fluctuations to the parameters of indices are 0% and 15%. For the 0% case, the value of I_C is 76.1%. It means if we randomly select a ground motion which conform the required condition, there is 25% chance that the selected design ground motion do not cause the expected response of structure. For 15% case, the

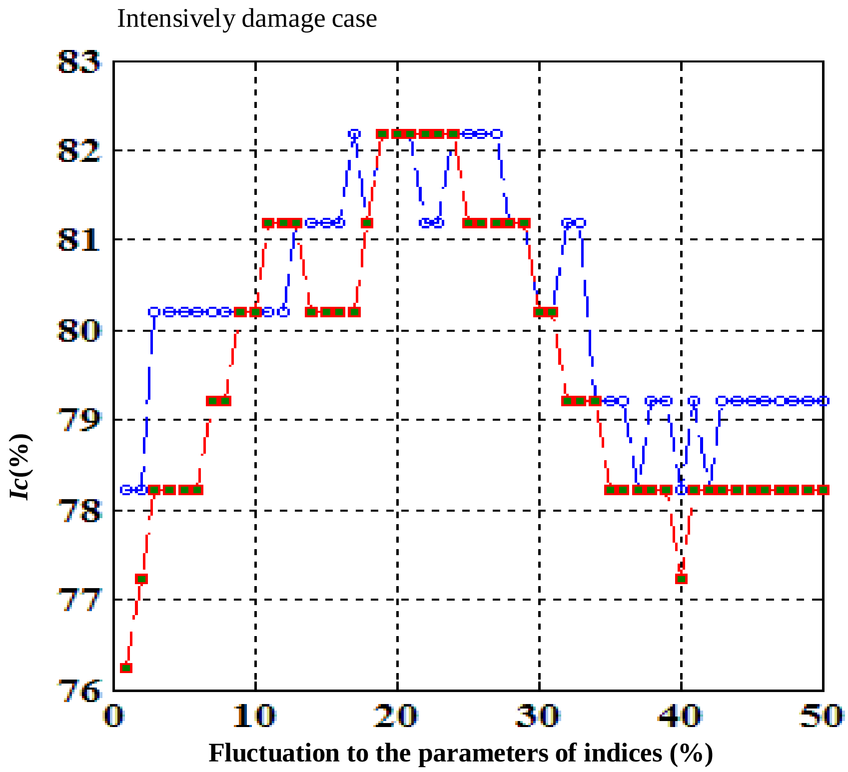

Figure 6.7Effect of fluctuation to the parameters of indices on of I_C(probability of having required design ground motion) for two sets of possible ground motions for intensively damage case

value of I_C is 81.0%. This shows that probability of having the required design ground motions is increased as compared to 0% case, for which I_C was 76.1%.

It is important to know the optimal range of fluctuation to the parameters of indices. This aspect is discussed in the followings.

6.11.1 Case-I: Critically Damaging Ground Motions

The ground motions with 10% exceedance probability are expected to be most damaging for the structure under consideration. We use D1 as index to select the design ground motions and we consider the fluctuation to the parameters of bilinear SDOF.

We considered a fluctuation up to 50 % in the parameters of indices. Similar to the 0 % and 15 % fluctuation cases discussed in the previous section, we fluctuated the parameters by a step of 1%, and check the variation of value of I_C (i.e. probability of having required design ground motion) for both Set A and Set B of possible ground motions. The results are presented in Figure 6.7. In Figure 6.7, the fluctuations to the parameters of indices are

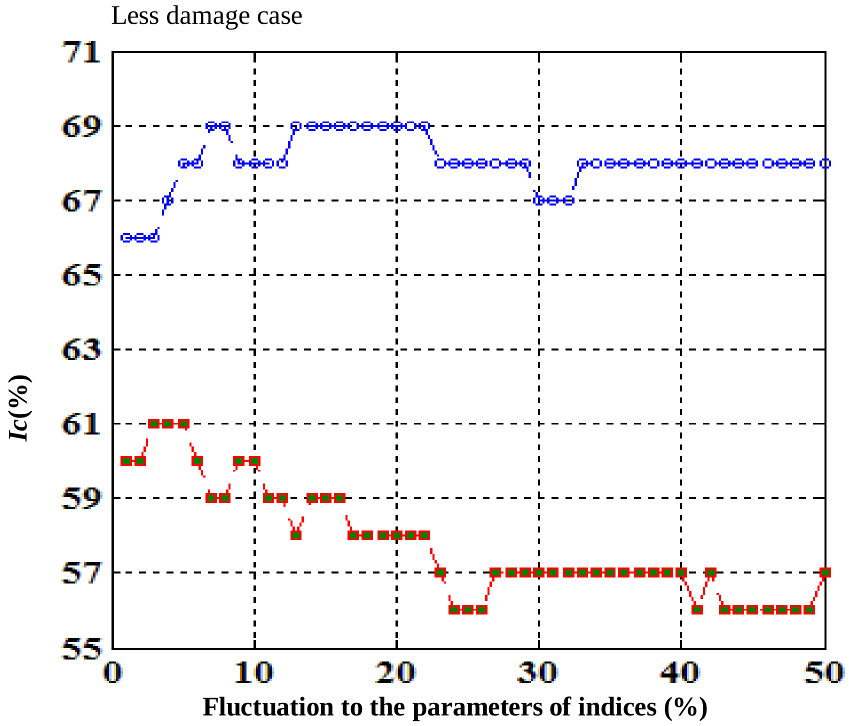

Figure 6.8Effect of fluctuation to the parameters of indices on value of I_C(probability of having required design ground motion) for two sets of possible ground motions for less damage case.

shown on horizontal axis, and the values of I_C(based on Equation6.2) are plotted on vertical axis.

Figure 6.7 clearly shows that if we do not consider the fluctuation the parameters of indices (this is a common practice) then the probability of having the required design ground motion is lower. Also, the value of I_C(probability of having required design ground motion) is keep on increasing with increase in fluctuation to the parameters of indices and attain a maximum value between 20 and 30 % fluctuation to index parameters, and then decreases. This bell shape trend is common for both set of possible ground motions, which indicates the stability of the proposed approach

The reason to increase in the value of I_C(probability of having required design ground motion) is that, due to consideration of fluctuation to the parameters of indices, we can evaluate diverse aspects of ground motions which are influential in nonlinear analysis. While if we consider deterministic parameters of bilinear SDOF (0% fluctuation) then we may not effectively evaluate the ground motions in the aforementioned context. This approach fairly works for the structure under consideration. For the structure under consideration the optimum range of fluctuation to the parameters of indices is 20% to 30%

6.11.2 Case-II: Less Damaging Ground Motions

In case-II, we look for the ground motions which are least damaging to the structure. In this case, the ground motions with exceedance probability 90 to 100% are required ground motions. As with the Case-I, we investigated the fluctuation up to 50% in the parameters of indices with a step size of 1%. The value of I_C(from Equation6.2) is formulated for 50 cases. The results are presented in Figure 6.8

The results presented in Figure 6.8 shows that initially the value of $I_C$increases with increase in fluctuation to the parameters of indices. Value of I_C attains a maximum value corresponding to a fluctuation of 4 to 8%.

The reason is that the required ground motions are not damaging to the structure, thus the structure remains in linear range, and we do not need to consider a wider fluctuation to the parameters of indices. While in case-I, the required ground motions were expected to be damaging for the structure, thus it was required to select a wider range of fluctuation to the parameters of indices for having the required design ground motions.

For the structure under consideration, the proposed approach shows that the probability of selection of required design ground motion is considerable enhanced if the indices are equipped with the characteristics, which are required to reflect the uncertainty of nonlinear response.

6.12 Summary

Simulation techniques to generate the ground motions from fault parameters and facilities to record the seismic events are considerably enhanced in past two decades. This resulted into large number of ground motions. Consideration of such ground motions is essential to enhance the seismic performance of the structure. But, due to time and computational constraints, a limited number of ground motions representing the possible ground motions are requested for the design.

Available method of ground motion selection incorporates the intensity measures (indices) to evaluate the relative performance of ground motions. In comparison with uncertainty of nonlinear response, the indices are simple. Indices may not represent the possible ground motions in context of nonlinear response of structure. To improve the performance of index based design ground motion selection approaches, the effect of nonlinear response must be reflected in the ground motion selection.

We propose to consider a fluctuation to the parameters of indices to improve the performance of indices to represent the possible ground motion. Because, it is not possible to quantitatively consider the effect of nonlinear response of structure in selection of design ground motions. It is assumed that consideration of fluctuation to the parameters of indices will be helpful to evaluate a variety of aspects of ground motions, hence, it will increase the probability of selection of required design ground motions.

Results of numerical simulations show that selecting the parameters of indices by considering the influence of nonlinear response of structure, the probability of having the required design ground motion is considerably enhanced.

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Chapter 7

Conclusions and Future Work

7.1 Summary

Selection of design ground motion is an important aspect of seismic design. The ground motions to be considered for the design of structures are available from design ground motions simulation techniques and from record of previous earthquakes. The data bank of ground motion is increasing due to wide spread of seismic instrumentation, and also the availability of more powerful computational machines stipulate the acceptability of ground motion simulation from the fault parameters. Development of sophisticated numerical and empirical methods give helping hand to promote such computation based ground motions. Meanwhile, the uncertainties of various seismic parameters undermine the reliability of simulated ground motion. Consideration of seismic uncertainties results with bundles of possible ground motions and all are requested to be considered for the reliable design of structures. In practice, however, a limited number of ground motions can be used in the nonlinear analysis. Therefore, we need to have a ground motion which is as effective as a set of possible ground motions, in such situation designing a structure against the synthesize ground motion will be equivalent to the structural design using the set of possible input ground motions.

An effective ground motion out of possible ground motions can be used to consider the effect of possible input ground motions. Selection of ground motion is a difficult task, especially when the nonlinear dynamic analysis has to be conducted. The complexity of ground motion selection is increased when the stochastic nature of structural characteristic are considered. Therefore, it is required to set a procedure for synthesis of design ground motion considering the uncertainty of seismic activity and complexity and unpredictability of nonlinear response.

This study is intended to propose a mean to have a reliable ground motion in context of uncertainty of seismic event and unpredictability of nonlinear response. In that regards, this work is completed in following three stages.

- To propose a method for synthesis of design ground motion using feature indices.

- Selection of feature indices and selection of parameters of feature indices considering nonlinear response is discussed in stage two and three.
- To propose a mean for selection of appropriate indices out of available indices.
- To set guidelines for selection of parameters of indices considering the uncertainty of nonlinear response.

7.1.1 Design ground motion synthesis considering uncertainty of seismic event and unpredictability of nonlinear response:

Owing to uncertainty of seismic event, a large number of ground motions are possible (termed as set of possible ground motions), and are equally important to be considered for reliable design of structure. But practically we need a limited number of ground motions. Therefore in this study, we propose a method to synthesize the design ground motion that can represent the set of ground motions, which are generated by considering the uncertainty of seismic event, we propose to generate a ground motion that represents the set of possible ground motions by feature indices which are related to important aspect of nonlinear behavior of structure. The ground motion tough in terms of feature indices will represent the set of possible ground motions and hence would be suitable for the design of structure. Such ground motion cannot be obtained analytically. Therefore, design ground motion is synthesized by modifying the time frequency characteristics of a ground motion record using wavelet functions.

The effectiveness of the proposed method of ground motion synthesis is evaluated in context of different type of structures and for different sets of possible ground motions. Here, Different set of possible ground motions means, for some cases, the set of possible ground motions is formulated by simulation of fault models, while records of previous earthquake records are used to formulate the set of possible ground motion for other cases. The results validate that the design ground motion synthesized by the proposed method represents the ground motions generated due to uncertainty of seismic event in terms of nonlinear response values and the also validate the stability and applicability of the proposed method of ground motion synthesis for a variety of situation.

7.1.2 Selection of appropriate indices out of available indices

In the proposed method of ground motion, it is important to know that what indices are appropriately related with important features of nonlinear response of structure. For this aspect we need to propose a method for the selection of appropriate indices.

We proposed and verified the concept of damage mechanism based indices for selection of relatively influential index/indices out of available indices. 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.

7.1.3 Selection of parameters of indices

Selection of parameters of indices is important and influential on performance of index. For example, if response of SDOF is set as an index, then we need to decide about the stiffness and yield force of SDOF in context of structure under consideration. But, in comparison with complexity and unpredictability of nonlinear response, the indices are simple. Indices may not represent the possible ground motions in context of nonlinear response of structure. To improve the performance, the effect of nonlinear response must be reflected in the ground motion selection.

In this study, we propose to consider a fluctuation to the parameters of indices to improve the performance of indices to represent the possible ground motion. Because, it is not possible to quantitatively consider the effect of complicated nonlinear response of structure in selection of design ground motions. It is assumed that consideration of fluctuation to the parameters of indices will be helpful to evaluate a variety of aspects of ground motions, hence, it will increase the reliability of selection of required design ground motions.

7.2 Conclusions

Feature indices based design ground motion synthesis method is proposed to consider the effect of nonlinear response of structure in synthesis of design ground motions. In step by step modification process, Wavelet is used to generate limited number of ground motions, an efficient ground motion is selected to modify in next step. This process is iterated to get the design ground motion.

Characteristics of the presented method are summarized in the followings:

- In this proposed method a randomly selected ground motion is iteratively modified, the proposed method of ground motion synthesis is not sensitive to initial selected ground motions.
- Proposed iterative method generate the ground motion which is robust to represent the set of possible input ground motion
- In iterative modification process, a limited number of realizations of indices are used to represent evaluate the candidate ground motions (formulated by Wavelet transform). The proposed method is not sensitive the number of realization of indices used to evaluate the effectiveness of candidate ground motions.

- Theoretically, infinite number of ground motions is possible, but a sample of limited number of ground motions can be used in synthesis process. It is verified that the proposed method of ground motion synthesis is not sensitive to the sampling of set of possible ground motions
- The structural properties are uncertain and may vary due to a number of factors, such as aging of structure. In synthesis of ground motion we also assume a fluctuation to the parameters of indices for which design ground motion is to be efficient. But in reality the fluctuation to the parameters may differ. When the structure with modified properties is exposed to set of possible ground motions and synthesized ground motion, the response of structure against synthesized ground motion is among maximum responses which are due to set of possible ground motions. This shows that the proposed method is robust in context of fluctuation to the structural parameters.
- Performance of synthesized ground motion is verified against possible ground motions and in comparison to a similarly safe ground motion which is formulated by using amplification factor. .
- Selections of index/indices which are influential in context of important feature of nonlinear response are important for having reliable design ground motion. We propose and verified the concept of damage mechanism based indices for selection of indices out of available indices.
- For selections of indices, first important mechanisms which are expected to primarily contribute in the total damage of the structure are selected. The indices which are related with expected damage mechanism are to be used, and here name as damage mechanism based indices.
- Damage mechanism based indices are related with expected damage mechanisms. Therefore the ground motion tough in terms of damage mechanism based indices is expected to trigger the expected damage mechanism and hence used as design GM.
- It is verified that, reliability of design GM selection is considerably enhanced due to inclusion of damage mechanism based indices in ground motion selection.
- Selection of parameters of indices is important and influential in performance of indices. The indices must be sensitive to the effect of nonlinear response. Due to simplicity of indices, it is not possible to quantitatively consider the effect of nonlinear response in selection of design ground motion. Therefore, we propose to consider fluctuation to the indices parameters.
- Consideration of fluctuation to the parameters of indices is necessary to enhance the reliability of design GM selection, because it helps to evaluate the ground motions from a variety of aspects

- It is verified that fluctuation to the parameters of indices is efficient to cope with nonlinear response of structure

7.3 Future Works

This work is different from the state of the art procedure for the selection of design ground motions, such as matching a target response spectrum etc. The idea is to accept the uncertainty of seismic event and unpredictability of nonlinear response. The uncertainty of seismic event leads to a large number of ground motions, we tried to use the information from such large number of ground motions to synthesize the design ground motion, and it helps us to improve the reliability of seismic design.

For application of the proposed concept of ground motion synthesis for design of structures, we need to complete following three steps.

First in this study, it was not intended to propose an index for selection or synthesis of design ground motion. Rather than that we propose a method for selection of appropriate index/indices out of list of large number of indices proposed in the literature. The process of selection of indices involves the identification of expected damage mechanism of structure. The design engineers may not take the responsibility of selection of expected damage mechanism of structure. So it is required to specify the suitability of indices for different categorize of structures as recipes. For example, ASCE-07 describes more than twenty categories of structural configuration under the heading of concrete structures. We can use such information to formulate different categories of structures to prepare a list of suitability of indices for different types of structures. In this work we introduce an 'Indicator of performance of an index/indices' (Ic). It is required to use *Ic* in conjunction with the 'concept of damage mechanism based indices' to propose the indices for a variety of structures. And such indices would be more appropriate to use for selection/synthesis of design ground motion for practical purposes.

Second, to set the parameters of indices, we propose to consider the fluctuation to the parameters of indices. It is required to further explore the suitable range of parameters of indices for different types of structure under different conditions.

Third, in the work, the concept of damage mechanism based indices and effect of fluctuation to the parameters of indices are evaluated in context of selection of ground motions out of a number of ground motions. The conclusions are extrapolated for the case of synthesis of design ground motion. Because, we need to select a relatively improved ground motion in each modification step of synthesis of design ground motion procedure. After completing the first and second step it is required to plan an extensive computation for synthesis of design ground motion for different type of structures in different conditions. This is required to import the confidence to use the proposed method of ground motions for solution of practical purposes by the design engineers.