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Optimization-based record selection approach to incremental dynamic analysis and estimation of fragility curves

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Abstract. In order to assess the seismic performance of structures, it is required to conduct incremental dynamic analysis and obtain fragility curves. Producing these curves is time consuming since it requires performing numerous nonlinear dynamic analyses; therefore, it is of significance to select appropriate earthquake ground motion records which yield reliable responses with sufficient accuracy. Due to the lack of a solid framework, selection of an appropriate ground motion record set is still a challenging problem. The main objective of this paper was to select a suitable set of records from a general set of records in order to reliably predict limit-state capacity of structures. To this end, incremental dynamic analysis was conducted for an equivalent single degree of freedom under a general set of records, and an optimization algorithm was employed to solve the problem by minimizing the error between the mean incremental dynamic analysis curves for each selected subset and mean incremental dynamic analysis curve for a general set of records. The fragility curves obtained by all records were compared with those of the selected ones, the results of which showed that the fragility curves corresponding to the selected records could appropriately estimate the target fragility curves.

1. Introduction

In recent decades, a number of researchers have turned their attention to the performance-based seismic design of structures since seismic vulnerability assessment of structures could help estimate the damage probability of buildings caused by potential earthquake hazards. Performing Incremental Dynamic Analysis (IDA) is required for obtaining fragility parameters and seismic capacity of the structures. However, selecting an appropriate set of Ground Motion Records (GMRs) is still a challenge and there is not a single consistent method in the building codes. Some studies have been conducted in this field and different methods have been proposed to select the appropriate GMRs. In most of these studies, the objective function was to select GMRs well matched with the target spectrum, i.e., the design, uniform hazard, and conditional mean spectra. For instance, Yi et al. [1] developed a method for creating a database of GMRs for the Hong Kong district, which was applicable to designing and analyzing different structural and geotechnical systems. They used the Conditional Mean Spectrum (CMS) as the target spectrum for selecting and scaling the GMRs available in the global database. Then, they selected a suite of conditional mean spectra-compatible accelerograms for rock sites and finally simulated event-specific and site-

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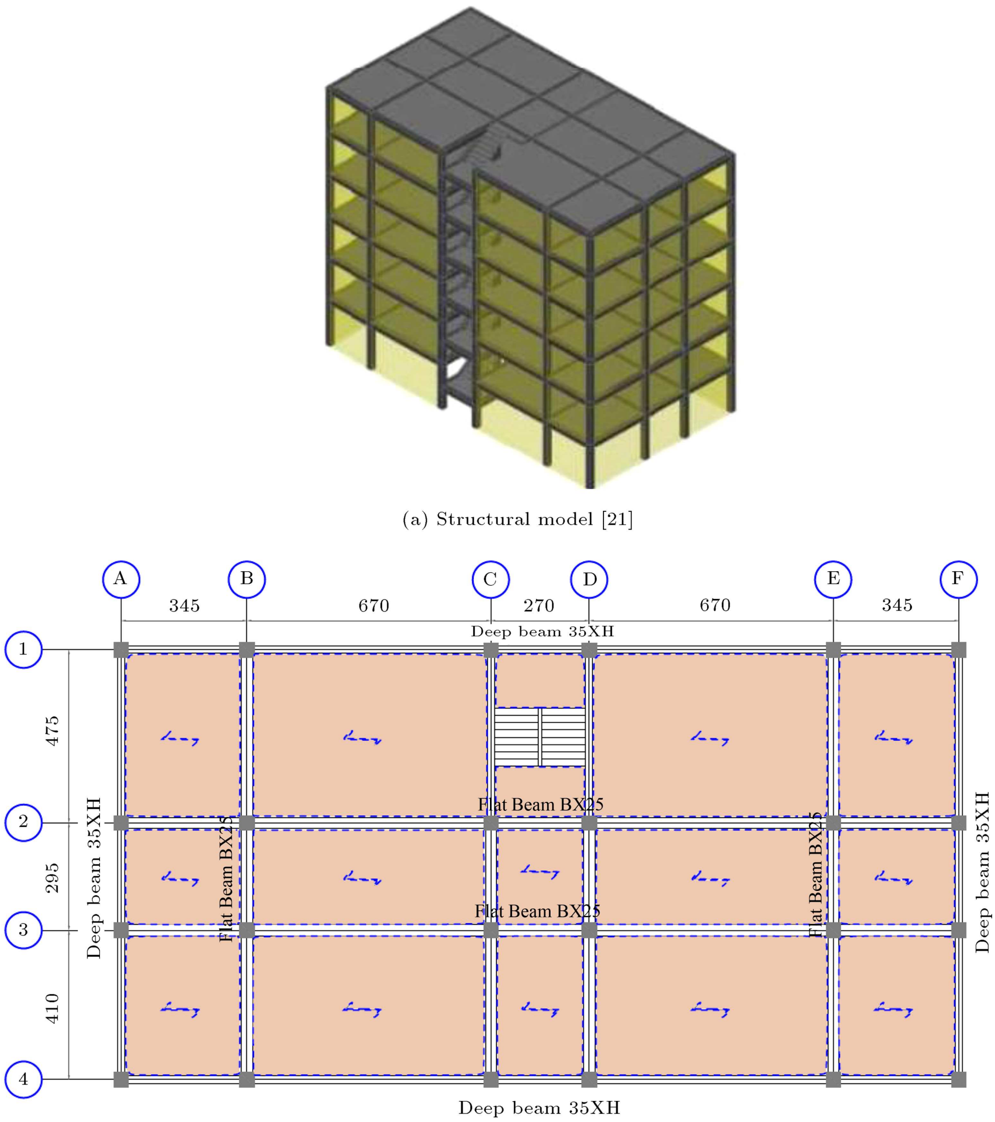
specific accelerograms through dynamic site response analysis. Perrone et al. [2] selected suitable records for their study based on spectral compatibility (matching of the geometric mean) with a CMS. Other researchers employed multi-objective algorithms to minimize the error between the mean and variance of the selected GMRs as well as the target mean and target variance spectrum [3,4]. Baker [5] introduced CMS as a tool for selecting GMRs. It provides the expected response spectrum conditioned on the occurrence of a target spectral acceleration value in a specific period. Baker and Lee [6] presented an efficient algorithm to select records that match the target mean, target variance, and correlations of the response spectrum in a given period range. Dehghani and Tremblay [7] proposed a selection method for determining a limited number of GMRs via an approach based on the damage potential characteristics of the GMRs achieved by finding the best representative Intensity Measures (IMs) for amplitude, frequency content, and duration of the data through inter-correlation analysis. Then, the records closer to the average of the representative IMs for a given dominant event were selected. Kohrangi et al. [8] extended the conditional spectrum selection to offer a method based on both scalar and vector IMs that collect information from two orthogonal horizontal components of the ground motion. A new index was introduced by Lombardi et al. [9] for linear time history analysis of ground motion selection to control the response variability corresponding to the dynamic properties of the structure in order to obtain a proper input for the design. Marasco and Cimellaro [10] offered an energy-based selection and scaling approach which could control the essential variables affecting the dynamic response of structures. They selected a group of GMRs causing an identical elastic seismic action and roughly equal plastic dissipation on the structure. Chen et al. [11] suggested a GMR selection method based on a probabilistic framework to find an optimal set of records for matching multiple target spectra, i.e., acceleration and displacement response spectra.

Performance-based Earthquake Engineering has four main analysis stages: hazard, structural, damage, and loss analyses [12]. For damage analysis, IDA should be performed in which several nonlinear dynamic analyses were performed using some GMRs scaled up and down to cover a wide range of structural behaviors. However, reaching appropriate GMRs selection is still a challenge since there is not a robust framework for this purpose. In this respect, some researchers have studied this issue and proposed several approaches. For instance, Bayati and Soltani [13] proposed a methodology for selecting a suitable set of GMRs to design concrete-reinforced frames against collapse by matching the mean and standard deviation values for the collapse fragility curve obtained based on the limited selected records with their corresponding values for the collapse fragility curve obtained based on all records in the suite. Kiani and Khanmohammadi [14] introduced a method for selecting the records that could yield minimum bias in structural response. Yaghmaei-Sabegh et al. [15] employed real- and binary-permutation genetic algorithms to select and scale the GMRs with a good agreement with the design spectrum to perform dynamic analysis. Du et al. [16] investigated the effects of amplitude scaling limits on conditional spectrum-based GMR selection. They computed target spectra for four probabilistic seismic hazard cases in the Western United States and selected 16 ground motion suites using different scaling limits. They concluded that consideration of scaling limits in the ground motion selection had a significant influence on the distribution of engineering demand parameters. The nonlinear behavior of ductile structures results in elongation of the effective period of the structure. In this regard, Fosoul et al. [17] proposed a new approach to the selection of GMRs by considering the effect of spectral shape and period elongation. Zhang et al. [18] presented an unsupervised machine learning algorithm for sequence clustering. Their proposed algorithm could evaluate the weighted distance between the sequences and clusters, minimize a regularized objective function, and assign the sequences optimally to certain clusters.

In recent years, optimization methods have been extensively studied in the field of civil engineering [19,20]. In this paper, an optimization-based GMR selection method was proposed for reliable estimation of demand parameters and seismic performance levels of structures. First, a general set of GMRs was selected based on preselection criteria and then, IDA was performed for Equivalent Single Degree of Freedom (ESDF) of the structure to produce the mean IDA curve. At the next step, the optimization problem was solved in order to select a limited number of GMRs well matched with the mean IDA curve. Finally, fragility curves were plotted based on IM values corresponding to that for the considered earthquake demand parameter.

2. The structural model

In this study, a six-story Reinforced Concrete (RC) building, selected from [21], was considered to evaluate the viability of the proposed approach. This residential building is located in L'Aquila (soil type C) and characterized by a regular plan of approximately 240 square meters and 6 stories above the ground. The height of the stories is equal to 3.05 m and the bottom story height is 3.4 m. The building is designed based on the current Italian code. Figure 1 shows the schematic of the structure and its plan view.



(a) Structural model [21]

(b) Plan view

Figure 1. The selected structure.

Since conducting IDA is time consuming, ESDF of the structure was used to perform IDA analysis. In order to achieve the Single Degree Of Freedom (SDOF) system, dynamic characteristics such as time period and viscous damping ratio, backbone curve, and hysteretic role should be considered. The backbone curve corresponds to the response of the system to monotonic loading and is defined by four parameters in the case of a quadrilinear backbone curve. As shown in Figure 2, these parameters include (a) hardening slope (α_h) which is defined as a positive ratio of post-yield stiffness to elastic stiffness, (b) the capping-point ductility (α_c) in which loss of strength begins with increasing deformation, (c) post-capping slope (α_c) corresponding to the ratio of the negative post-capping stiffness divided by the initial elastic stiffness, (d) height of the residual strength plateau (r_p), and (e) fracture ductility (μ_f) in which sudden complete loss of strength happens. In order to obtain a backbone curve, pushover analysis corresponding to the two principal directions of the structure was utilized, and

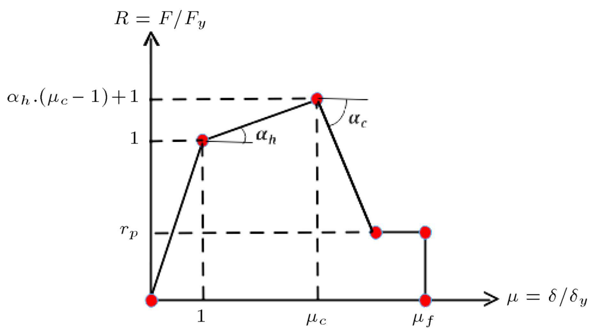
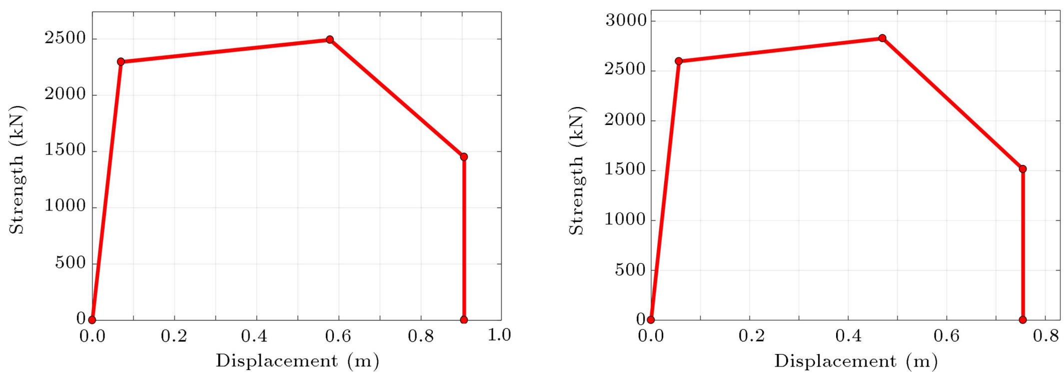


Figure 2. Quadrilinear backbone curve and its parameters.



(a) X-direction (b) Y-direction

Figure 3. The linear idealization of the static pushover of the frame.

two quadri-linear backbones were obtained from these static pushover curves. To obtain pushover curves, the structure was modeled in OpenSees. In the two ESDF oscillators, time periods for X and Y directions were 1.11 s and 1.25 s, respectively. The linear idealization of the static pushovers of the frame is shown in Figure 3.

3. The ground motion pre-selection

In order to select ground motions that are compatible with the site of the structures in the global database, some specific data should be taken into account. The ranges of magnitude, shear velocity, focal distance, and damping ratio are among the required information to select the suitable records. In addition, the ranges of these criteria for preselection of records for the selected model were considered based on [dyanas]. In this paper, 114 two-component GMRs were selected from PEER Ground Motion Database [22] and Itaca [23]. The following criteria are considered in the preselection of records:

- Moment magnitude ranging from 6.1 to 7.6;
- Shear velocity for soil type C based on Eurocode 8 [24]: $180 \leq vs \leq 360$;
- The focal distance of 43 km or less (the records that do not exhibit impulsive characteristics due to directivity are selected);
- Damping ratio of 5%.

4. Optimization problem

The main objective of this study is to select a limited number of GMRs in which the mean IDA curve of the selected GMRs can be in good agreement with the mean of the general set of records. In order to solve the optimization problem, a Chaotic Optimization Algorithm (COA) was employed. The optimization problem aims to minimize the error between the mean IDA values for the selected GMRs and those for the GMRs selected in the preselection phase.

$$f_{obj} = Minimize\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(mean_{i_{selectedGMRs}} - mean_{i_{target}}\right)^2}. \quad (1)$$

In the above equation, m is the number of Earthquake Demand Parameters (EDPs) where the values for the IDA curve are given; $mean_{i_{target}}$ is the mean value for the primary selected GMRs based on preselection criteria at the i-th EDP, and $mean_{i_{selectedGMRs}}$ is the mean value for the selected GMRs at i-th EDP.

4.1. Chaotic Optimization Algorithm (COA)

This algorithm features some properties of chaotic maps such as ergodicity, randomness, and sensibility. Ergodicity and randomness of chaos can prevent the searching process from trapping into local minima and resolve the drawbacks of traditional optimization algorithm [25]. In this algorithm, Chebyshev map is used as a powerful chaotic number generator with a relatively high Lyapunov exponent. The formulation of the selected map is provided in Table 1.

The visualization of the selected chaotic map and its Probability Density Function (PDF) are shown in Figure 4. The COA algorithm has three main steps which are described in the following:

Step 1: *Initialization.* Scattering and evaluation: Initialize an array of particles with random positions. An arbitrary array of the velocity vector should be created in accordance with the number and type of groups that belong to particle positions. In the current position, function evaluation should be done

Table 1. The properties of Chebyshev chaotic map.

Name	Chaotic map	Range
Chebyshev	$x_{i+1} = \cos(i\cos^{-1}(x_i))$	(0,1)

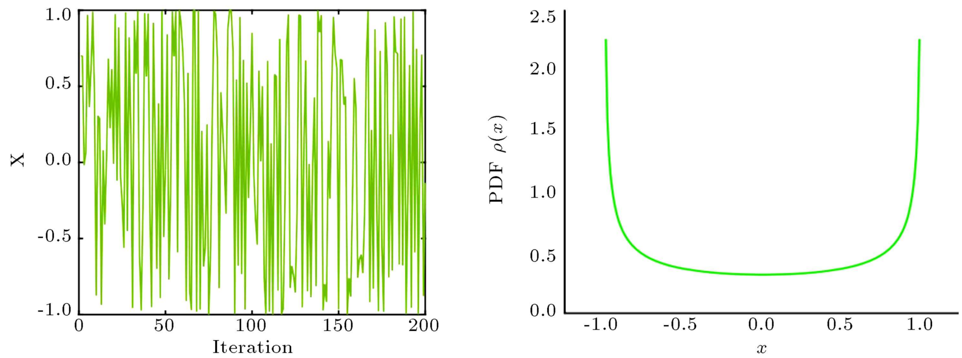


Figure 4. Visualization of Chebyshev map and its Probability Density Function (PDF).

for each particle. The position of the best particle and that of each particle should be saved as the global best and local best for each particle, respectively.

Step 2: *Search.* The update moves a particle by adding a changing velocity V_i^{k+1} to the current position X_i^k, as shown in the following:

$$V_i^{k+1} = \omega V_i^k + C_1 . \frac{(MaxIt+k).GB+(MaxIt-k).LB_i}{2.MaxIt}, \quad (2)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}, \quad (3)$$

where ω is the inertia weight regarded as a decreasing function of time which gradually reduces to 1 through each iteration, and C_1 is the generated number based on the chaotic maps. $MaxIt$ is the total number of iterations of the optimization process, and GB and LB_i are the global best and local best of the ith particle, respectively.

In this paper, to enhance the exploitation, a Pitch-Adjusting Rate (PAR) was used which was taken from harmony search algorithm (Eq. (4)) [26]. To decrease the convergence rate of the algorithm, a PAR with a narrow bandwidth should be used. However, a quite high PAR with a wide bandwidth may cause the solution to scatter around some potential optima as in a random search [27].

$$X_i^{k+1} \leftarrow \begin{cases} X_i^{k+1} = X_i^{k+1} + bw \times C_2(-1,1) \\ \quad \text{with probability PAR} \\ X_i^{k+1} = X_i^{k+1} \\ \quad \text{with probability } (1-PAR) \end{cases} \quad (4)$$

where bw is an arbitrary distance bandwidth for variables and C_2 is a normalized chaotic generated number between -1 and 1.

Step 3: *Controlling the terminating criterion.* The computations are repeated until the terminating criterion is satisfied. The flowchart of the algorithm is shown in Figure 5.

5. Incremental Dynamic Analysis (IDA)

In order to solve the problem, for all of the GMRs selected in the preselection phase, IDAs are conducted using DYANAS [28]. DYANAS is a MATHWORKS-MATLAB-based graphical user interface that uses OpenSees to conduct nonlinear dynamic analysis of SDF systems. The space work of the DYANAS interface is shown in Figure 6. This software allows choosing different EDPs including maximum displacement, residual displacement, and demand-capacity ratio. In this study, the demand/capacity ratio (D/C) is chosen (Eq. (5)) as it reveals how close the response of the structure is to the threshold EDP.

$$\frac{D}{C} = \frac{\delta}{\delta_f}, \quad (5)$$

in which δ is the displacement in the corresponding direction and δ_f is the failure displacement.

In order to present the seismic collapse fragility curves of the structure in terms of a common IM, the geometric mean of the spectral acceleration of two components in one second period, Sa_{gm} ($T = 1.0$ s), is selected and all IDA curves are converted to that IM. As stated in [8], Sa_{gm} is a good representative of IM in general use. The IDAs are obtained in two X and Y directions and are plotted for max (X, Y). The IDA curves are presented in Figure 7.

After performing IDAs and obtaining the mean IDA values in each direction, COA optimization algorithm is employed to select GMRs that best fit with the mean IDA curve as a target curve. Seven GMRs were selected from the preselected GMRs pool using the optimization algorithm. The IDA of selected GMRs, mean IDA, and target IDA curve are depicted in Figure 8. As observed in Figure 8, the mean IDA of the seven selected GMRs is in good agreement with the target in all three cases. The selected GMRs are appropriate options for performing dynamic time history analysis. As a result, a limited number of records are selected through this approach that can be used for time history dynamic analysis of the structure with a minimum response bias.

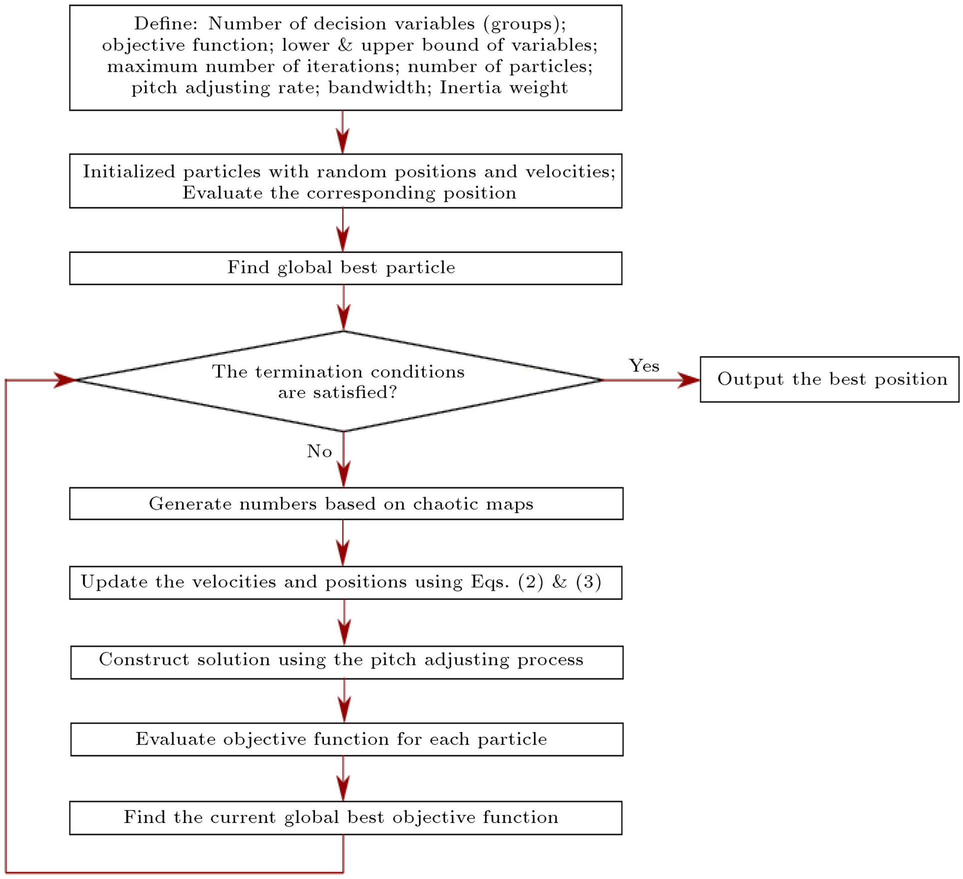


Figure 5. Flowchart of the Chaotic Optimization Algorithm (COA).

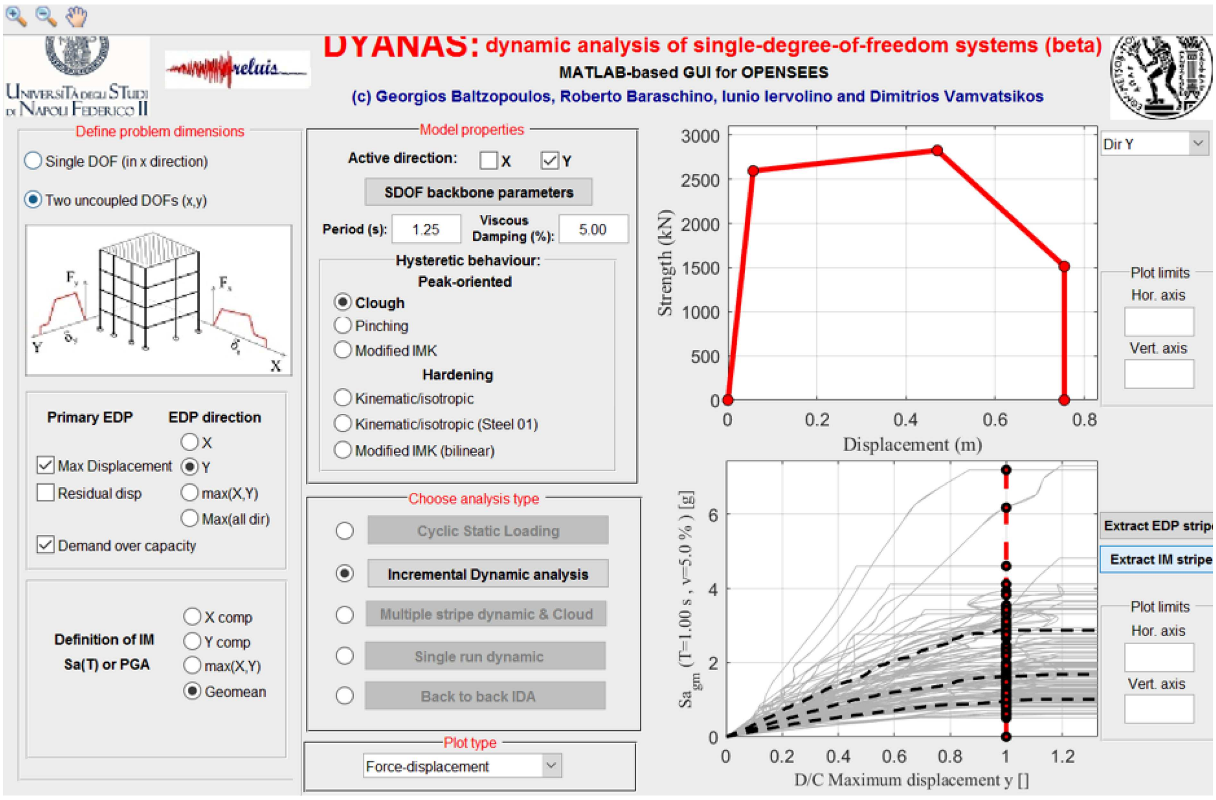


Figure 6. The workspace of the DYANAS interface.

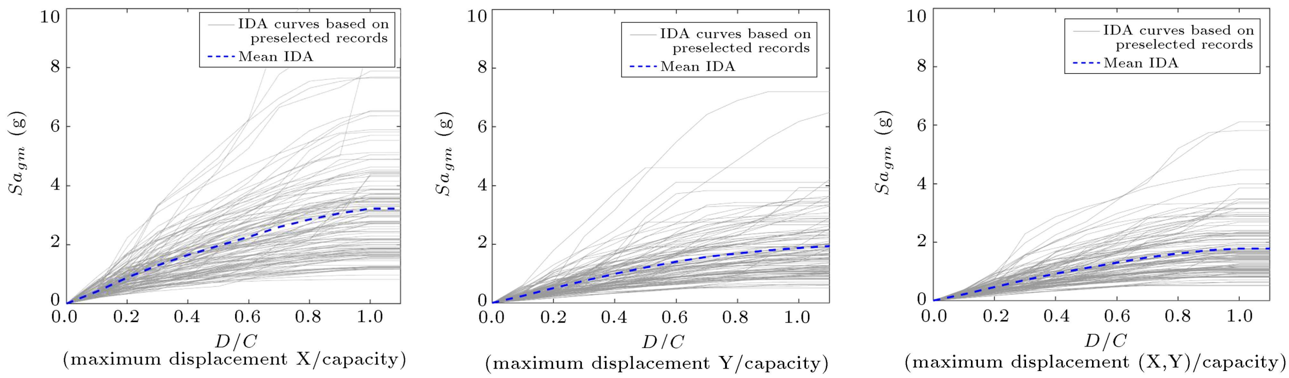


Figure 7. Incremental Dynamic Analysis (IDA) curves obtained by Ground Motion Records (GMRs) in the preselection phase.

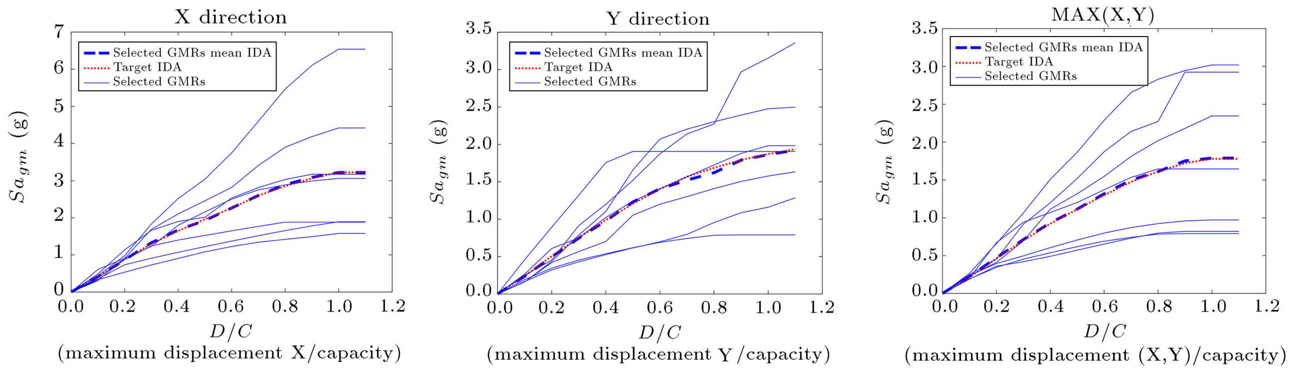


Figure 8. Incremental Dynamic Analysis (IDA) curves and their mean values obtained by the selected Ground Motion Records (GMRs).

6. Collapse fragility of the ESDF

To investigate the collapse probability of the structure,the dispersion and median responses obtained by IDAs are quantified for each direction. In all cases, EDP is regarded as the D/C ratio and the corresponding IM values at $D/C = 1$ are obtained. Lognormal fragility functions are estimated using Eq. (6):

$$P[f|IM = im] = \Phi\left[\frac{\ln(im) - \ln(\mu)}{\beta}\right],$$

$$\mu = \frac{1}{n}\sum_{i=1}^{n}\ln(im_i^f),$$

$$\beta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[\ln(im_i^f) - \mu\right]^2}, \qquad (6)$$

where $\Phi(.)$ is the standard Gaussian distribution function, and μ and σ are the mean and standard deviation of the logs of $im^f s$, respectively. Here, im_i^f represents the ith record IM value causing collapse (threshold exceedance).

Figure 9 presents the fragility curves that are defined as the probability of reaching or exceeding a specific damage state under earthquake excitation. According to this figure, these curves show the probability of failure (P_f) in a specific spectral acceleration (S_a) range. The results showed that there was a good correlation between the two curves in each direction. In addition, the fragility curves obtained from the IMs corresponding to the selected GMRs had a reasonable estimate of fragility. According to the results, collapse capacity could be accurately estimated by substituting all the ground motions of a suite by seven GMRs selected using the proposed optimization-based approach. After selecting appropriate ground motions, time-consuming time history analysis could be performed for the structure.

7. Conclusions

The fragility parameters of structures should be investigated since it is one of the main steps of the PBEE. Performing Incremantal Dynamic Analysis (IDAs) under different records is also necessary in determining the fragility values for the structure. In this paper, an optimization-based approach was proposed to efficiently select the limited Ground Motion Records (GMRs). Some records were selected based on preselection criteria, and the Equivalent Single Degree

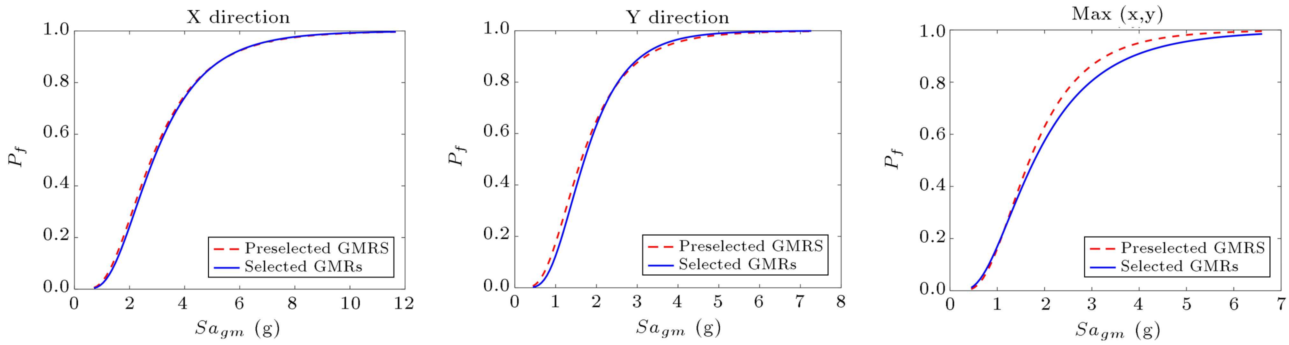


Figure 9. Fragility curves plotted using preselected Ground Motion Records (GMRs) and selected GMRs by COA.

of Freedom (ESDF) of the structure was analyzed. To this end, DYANAS software was utilized to conduct IDAs which would allow a user to get results in all directions with different Earthquake Demand Parameter (EDP) and Intensity Measure (IM) forms. Then, Chaotic optimization algorithm was employed to select a limited number of records where their mean IDA curve agreed well with the mean of the IDA curve obtained in the previous step. Finally, fragility curves were plotted according to *im* values corresponding to IM stripe for $D/C = 1$. Based on the obtained results from selected GMRs, it is concluded that through the proposed approach, the results obtained by all the preselected records could be appropriately estimated. Consequently, seven selected ground motions could be substituted by all seismic records selected by preselection criteria via applying this computationally efficient time-saving method.

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Biographies

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