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ON REDUCTION POSSIBILITY OF GROUND MOTION RECORDS FOR THE IDA ANALYSIS

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Abstract. *The major part of the probabilistic performance assessment of structure, which is becoming popular within the performance-based earthquake engineering, represents a determination of the relation between the seismic intensity measure (IM) and the engineering demand parameter (EDP). This relation usually has to be determined for several ground motion records. A common method for achieving this goal is the Incremental Dynamic Analysis (IDA). IDA analysis is so time-consuming process especially for complicated models and hence rational methods for reduction of analysis time are necessary. Many studies have been done in the way to find a better IM with the goal to reduce the dispersion of nonlinear response and consequently reduce the number of ground motion records needed for sufficiently accurate IDA analysis. The disadvantage of such approaches is usually the unknown hazard for new IMs. Another possibility to reduce the number of ground motion records is to select only a few ground motion records within the representative set of ground motion records, which can sufficiently predict the summarized IDA curves (16%, 50% and 84% fractiles). Such an approach is proposed in the paper in order to optimize the number of selected ground motion records for sufficiently accurate prediction of summarized IDA curves. The test example is presented for a three storey building, which was tested at ELSA Laboratory, Ispra. The set of ground motion records for IDA analysis consists of thirty free-field ground motion records. It is shown that the summarized IDA curves can be predicted with an acceptable accuracy by employing only six ground motion records instead of thirty, which is the total number of ground motion records for the predefined set.*

1 INTRODUCTION

Performance-based earthquake engineering (PBEE) enables quantifying the seismic risk based on a probabilistic approach. A widely used method for PBEE was proposed at the Pacific Earthquake Engineering Research Center (PEER Center) [1]. The method decomposes the seismic risk assessment into four steps: hazard analysis, structural analysis, damage assessment and loss estimation. The structural analysis, which is important within the seismic risk assessment, is usually performed by the Incremental Dynamic Analysis (IDA) [2] which is a general parametric analysis method for the estimation of the seismic demand and capacity for the different levels of seismic intensity measure (IM), based on the ground motion records within a set defining the earthquake scenario. Such an approach requires a huge computational effort, especially due to the many ground motion records involved in the analysis. In order to reduce the computational effort, a number of different approximate methods have recently emerged. Most practical, i.e. approximate methods for IDA analysis involved the replacement of nonlinear dynamic analysis by a combination of pushover analysis of a multi-degree-of-freedom (MDOF) model, and nonlinear dynamic analysis of a single-degree-of-freedom (SDOF) model [3,4,5, 6].

On the other hand the methodology for prediction of a median IDA curve, based on a small number of ground motion records, has been proposed [7]. In this paper an attempt has been made in order to extend the proposed methodology to be applicable for prediction of the summarized IDA curves (16%, 50% and 84% fractiles). For this purpose a precedence list of ground motion records has been introduced, which can be determined by utilizing a simple model (e.g. SDOF model) in combination with an optimization procedure. The methodology is illustrated by an example of a three-storey reinforced concrete building for which the summarized IDA curves are predicted with only six ground motion records selected from a set of thirty free-field ground motion records.

2 METHODOLOGY

The aim of the methodology is to decrease the number of ground motion records needed for the prediction of the summarized IDA curves (16%, 50% and 84% fractiles). In addition to the MDOF model, which is employed in the IDA analysis [2], the advantages of the simple model (e.g. the SDOF model), which is not computationally demanding, are taken into account. Such an approach has been employed also in other approximate methods (e.g. [4, 6]). These methods use the response of the simple model, in combination with the pushover analysis, to predict the seismic response of the MDOF model. However, the methodology described here employs the simple model only to predict the precedence list of ground motion records. Single-record IDA curves are then calculated step-by-step, using the MDOF model and the ground motion records from the precedence list of ground motion records, however, only until the acceptable tolerance for the summarized IDA curves is reached. The main steps of the methodology are presented in Figure 1, and can be described as follows:

1. Select a set of ground motion records based on the earthquake scenario. This is the same step as in an IDA analysis. The number of records within the given set can, if so desired, be high, since, when using the methodology, there is no need to compute the seismic response of the MDOF model for all records in order to obtain a good prediction of the summarized IDA curves.
2. Create a MDOF mathematical model which can be used for the simulation of the realistic seismic response of the structure under investigation.
3. Define a simple mathematical model, e.g. a SDOF model. This model should be a good representative of the linear and nonlinear characteristics of the MDOF mathe-

matical model, yet simple enough for it to be possible to perform a large number of non-linear time history analyses, without the need for very time-consuming calculations.

4. Compute single-record IDA curves for the simple model, for all the ground motion records within the given set. Because of the simplicity of the chosen simple model, this should not be a time-consuming task.
5. Based on the results obtained in step 4, arrange the ground motion records within the given set in order to obtain a good precedence list. This is an optimization problem, which is explained in the next Section. The objective of the optimization is to minimize the differences between the "original" and the "selected" summarized IDA curves. The "original" summarized IDA curves are obtained from all the single-record IDA curves (step 4), whereas the "selected" summarized IDA curves are obtained only for the first *s* ground motion records from the precedence list, where *s* is the number of "selected" ground motion records.
6. Compute a single-record IDA curve for the MDOF model, starting with the first record from the precedence list. After computation of single-record IDA curves for the s^{th} record from the precedence list (where *s* is a number greater than or equal to three), compute the "selected" summarized IDA curves and compare it with the "selected" summarized IDA curves obtained from the $(s\text{-}1)^{th}$ records.
7. Repeat step 6 until the difference between the "selected" summarized IDA curves, determined for the s^{th} and $(s\text{-}1)^{th}$ records, is less than the acceptable tolerance, and then stop performing the IDA analysis on the MDOF model.
8. The "selected" summarized IDA curves, calculated from the *s* single-record IDA curves can be used for further seismic performance assessment.

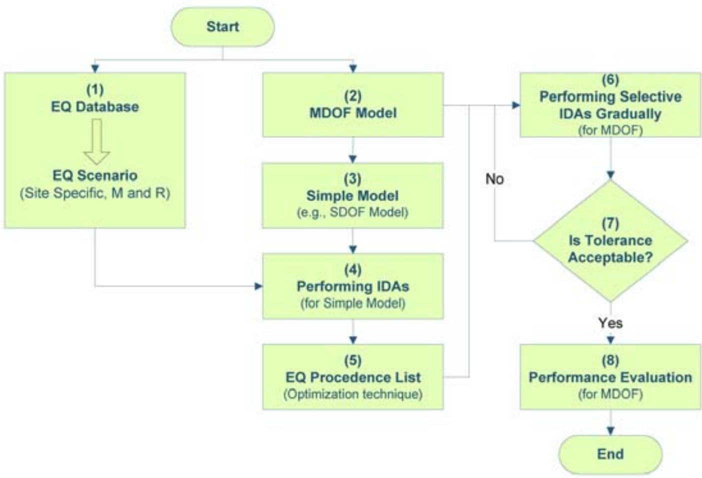

Figure 1. The main steps in the proposed methodology.

The described procedure can significantly reduce the number of nonlinear time history analyses needed to predict the summarized IDA curves with sufficient accuracy. However, the efficiency of the procedure depends on the ability of the simple model to predict the damage measure of the MDOF model, as well as on the ability of the optimization algorithm to find the best precedence list of ground motion records. The summarized IDA curves, obtained from the described procedure by employing a limited number of ground motion records, is usually a good approximation to the "original" summarized IDA curves for the MDOF model, which is calculated from all the single-record IDA curves.

Note that the procedure can be easily applied to other problems, and not just to the problem of minimizing the number of records for the sufficiently accurate prediction of the summarized IDA curves. For example, the procedure can be applied for the selection of a certain number of records for a particular design purpose, since many codes recommend using a certain number of records for the prediction of the most critical actions and/or a different number of records (usually more) for the prediction of the mean or summarized response. In this case the described approach can significantly reduce bias in the seismic response which is present because of the limited number of ground motion records prescribed for nonlinear dynamic analyses.

Steps 1 to 7 of the methodology are illustrated in this paper, whereas step 8 is not in the scope of this paper.

3 PRECEDENCE LIST OF GROUND MOTION RECORDS

The precedence list of ground motion records was determined for the selected set of ground motion records by employing the Genetic Algorithm (GA) technique [8]. The input data for determining the precedence list are "original" summarized IDA curves (16%, 50% and 84% fractile), single-record IDA curves, both determined on the basis of IDA analysis for the simple model (e.g. SDOF model), and the corresponding ID numbers of the ground motion records (Table 1). The precedence list of the ground motion records is obtained by rearranging the ID numbers of the ground motion records (Table 1) in order to minimize the fitness function Z

$$Z = \frac{1}{n-2}\sum_{s=3}^{n} V(s) = \frac{1}{n-2}\sum_{s=3}^{n}[\sum_{f=1}^{3} Error(s,f)] \tag{1}$$

The fitness function is defined as summation of the so-called "partial" fitness function $V(s)$ normalized with the $n-2$ where n is the number of ground motion records in the set. Z can be therefore interpreted as the average "partial" fitness function $V(s)$. The "partial" fitness function, $V(s)$, is defined as the cumulative error for three fractile curves (f = 16%, 50%, 84%), which are the subject of the optimization. However, minimization of the "partial" fitness function means the selection of these s ground motion records, which are the best representatives of the "original" summarized IDA curves (16%, 50% and 84% fractiles) determined on the basis of IDA analysis for the simple model (e.g. SDOF model). The $Error(s,f)$, which is called error function, is defined as the normalized area, which is determined based on the difference between the "original" and "selected" fractile IDA curve, which can be 16%, 50% or 84% fractile. The error function is a function of a particular fractile curve f and of the s selected ground motion records for which the "selected" fractile IDA curve is determined. Note, as explained in the methodology, that the "original" summarized IDA curves (16%, 50% and 84% fractiles) are obtained from all the single-record IDA curves, whereas the "selected" summarized IDA curves are obtained for just the first s ground motion records from the precedence list, where s is equal to or greater than 3, since three fractile curves (16%, 50% and 84%) can be predicted at least with three ground motion records.

The normalized area, expressed in percentage, between the "original" and the "selected" summarized IDA curves, can be calculated as:

$$Error(s,f) = 100 \times \frac{\int_0^{DM_{max}(s,f)} \left| \Delta IM(s,f) \right| dDM}{\int_0^{DM_{max,or}(f)} IM_{or}(f)\, dDM} \tag{2}$$

where DM is the damage measure, IM is an intensity measure for the IDA analysis, $\Delta IM(s,f)$ is the difference in the IM corresponding to the "original" and "selected" *f* fractile IDA curve, and $DM_{max}(s,f)$ is the maximum DM, as presented in Figure 2. The parameter $\Delta IM(s,f)$ depends on the *s* ground motion records which are employed to determine the "selected" *f* fractile IDA curve, and also depends on the DM, as schematically shown in Figure 2. The maximum damage measure $DM_{max}(s,f)$ is usually defined by the capacity point on the "original" or "selected" summarized IDA curves. This measure also depends on the number of selected ground motion records *s*. The original maximum damage measure $DM_{max,or}(f)$ is usually defined by the capacity point on the "original" summarized IDA curves and $IM_{or}(f)$ is intensity measure of the "original" *f* fractile IDA curves. Different possibilities of the relationship between the "original" and "selected" fractile IDA curves and the explained parameters of Eq. (2), are presented in Figure 2.

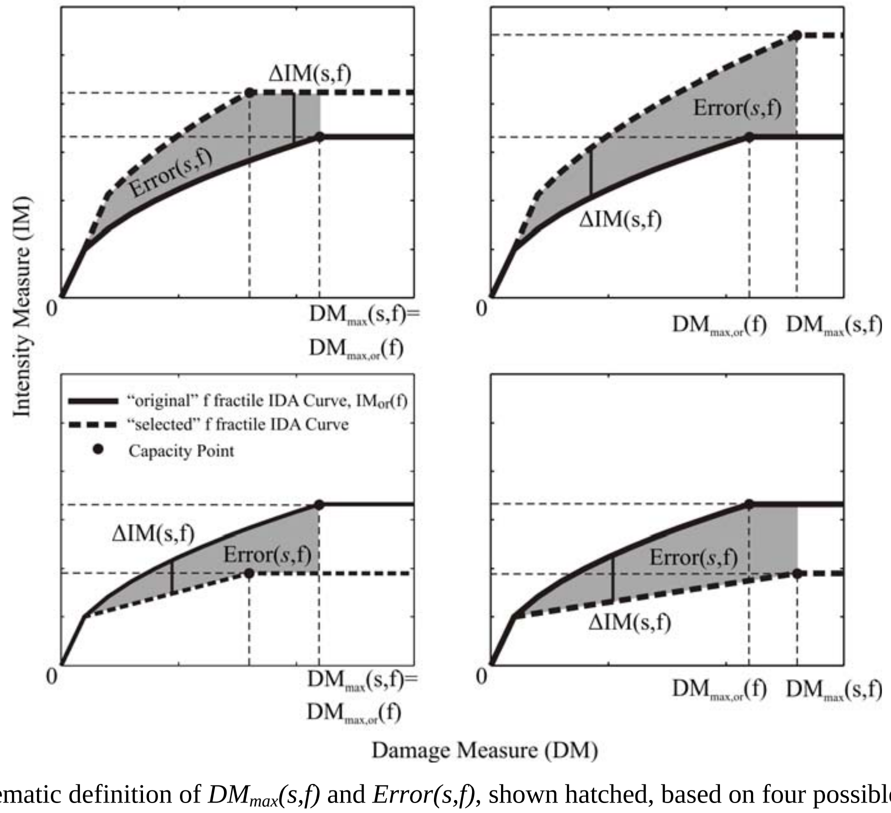

Figure 2. Schematic definition of *DMmax(s,f)* and *Error(s,f)*, shown hatched, based on four possible conditions of the "original" summarized IDA curves and the "selected" fractile IDA curve, which is determined based on *s* selected ground motion records.

4 EXAMPLE

In order to demonstrate the applicability of the proposed methodology, a precedence list of ground motion records has been determined in order to predict the summarized IDA curves (16%, 50% and 84% fractiles) for a three-storey reinforced concrete frame building by employing only a limited number of ground motion records. Precedence list of ground motion records was determined for a set which includes thirty free-field ground motion records. The intensity measure selected in the example was the spectral acceleration at the period of the equivalent SDOF model, which was introduced as a good representative of the simple model. The maximum interstory drift ratio of the building was chosen as the damage measure. The results are presented in terms of "selected" summarized IDA curves, and compared with the "original" summarized IDA curves.

4.1 Ground motion records

A set of thirty ground motion records, as used by other researchers [e.g. 2, 3 and 6], has selected from the PEER Strong Ground Motion Database [9]. The earthquake moment magnitudes M_w for the selected records, which are relatively large, ranged from 6.5 to 6.9. The selected ground motion records were recorded on firm soil [10], with no marks of directivity effects. The list of records and the corresponding precedence list are presented in Table 1.

Table 1. The free-field set of ground motion records.

Event, Year, M_W *	ID	Precedence List (th priority)	Station	$\phi^{\circ\dagger}$	*Soil* ±	$R^{\hbar}$	PGA
Loma Prieta, 1989, 6.9	1	17	Agnews State Hospital	090	C,D	28.2	0.159
	2	1	Hollister Diff. Array	255	-,D	25.8	0.279
	3	16	Anderson dam Downstrm	270	B,D	21.4	0.244
	4	4	Coyote Lake Dam Downstrm	289	B,D	22.3	0.179
	5	11	Sunnyvale Colton Ave	270	C,D	28.8	0.207
	6	20	Anderson dam Downstrm	360	B,D	21.4	0.24
	7	10	Hollister South & Pine	000	-,D	28.8	0.371
	8	18	Sunnyvale Colton Ave	360	C,D	28.8	0.209
	9	19	Halls Valley	090	C,C	31.6	0.103
	10	22	WAHO	000	-,D	16.9	0.37
	11	26	Hollister Diff. Array	165	-,D	25.8	0.269
	12	28	WAHO	090	-,D	16.9	0.638
Northridge, 1994, 6.7	13	5	LA, Baldwin Hills	090	B,B	31.3	0.239
	14	14	LA, Hollywood Storage FF	360	C,D	25.5	0.358
Imperial Valley, 1979, 6.5	15	25	Computertas	285	C,D	32.6	0.147
	16	24	Plaster City	135	C,D	31.7	0.057
	17	13	El Centro Array # 12	140	C,D	18.2	0.143
	18	23	Cucapah	085	C,D	23.6	0.309
	19	30	Chihuahua	012	C,D	28.7	0.27
	20	6	El Centro Array # 13	140	C,D	21.9	0.117
	21	8	Westmoreland Fire Station	090	C,D	15.1	0.074
	22	9	Chihuahua	282	C,D	28.7	0.254
	23	3	El Centro Array # 13	230	C,D	21.9	0.139
	24	29	Westmoreland Fire Station	180	C,D	15.1	0.11
	25	7	Computertas	015	C,D	32.6	0.186
	26	21	Plaster City	045	C,D	31.7	0.042
San Fernando, 1971, 6.6	27	2	LA, Hollywood Stor. Lot	180	C,D	21.2	0.174
	28	12	LA, Hollywood Stor. Lot	090	C,D	21.2	0.21
Superstition Hills, 1987, 6.7	29	15	Wildlife Liquefaction Array	090	C,D	24.4	0.18
	30	27	Wildlife Liquefaction Array	360	C,D	24.4	0.2

* Moment magnitude, † Component, ± USGS, Geomatrix soil class, $\hbar$ Closest distance to fault rupture expressed in kilimeter.

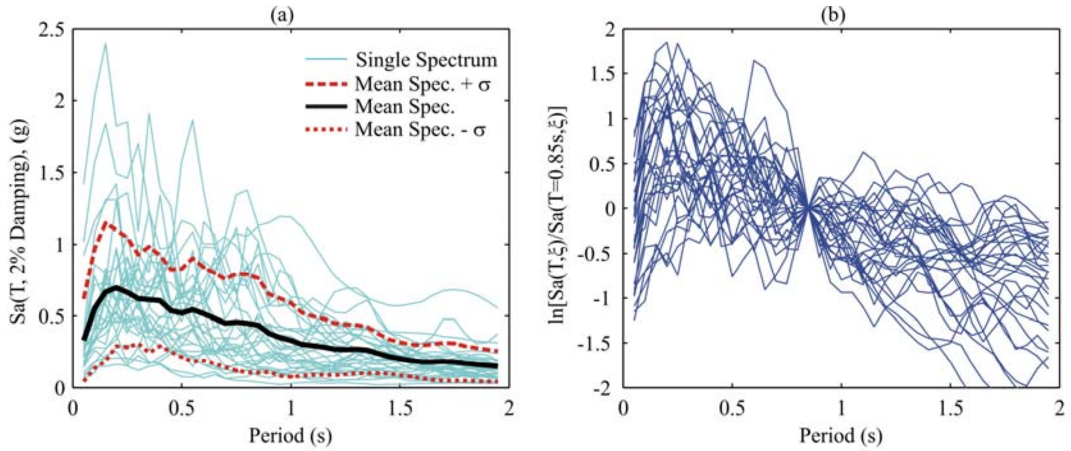

Figure 3. (a) The 2%-damped elastic acceleration spectra for thirty ground motion records, (b) The 2%-damped elastic acceleration spectra normalized to the spectral acceleration at the period of 0.85 second.

The 2%-damped acceleration elastic response spectra of the set of ground motion records are presented in Figure 3a. The large dispersion is observed although the ground motion records were selected within fairly limited interval of magnitude and fault distance (Table 1). The natural logarithm of the spectral acceleration (Figure 3a) normalized to the spectral acceleration at the period of 0.85 s is shown in Figure 3b. Clearly the dispersion for a SDOF model with the period of 0.85 s is equal to zero. However, the dispersion is still high for the periods beyond the period of the SDOF system as shown in Figure 3b.

4.2 The test structure and mathematical model

The test structure (referred in the following as the SPEAR building) is a three-storey asymmetric reinforced concrete frame building, for which a pseudo-dynamic experiment was performed at a full scale model at the ELSA Laboratory, within the European research project SPEAR ("Seismic performance assessment and rehabilitation of existing buildings") [11]. The elevation and the plan view as well as the typical reinforcement in beam and columns of the "SPEAR" building are presented in Figure 4. This building was designed for gravity loads only.

So called post-test mathematical model [12] created in the OpenSees program [13] was employed for analyses performed in this study. The mathematical model consists of beam and column elements for which the flexural behaviour was modeled by one-component lumped plasticity elements, composed of an elastic beam and two inelastic rotational hinges (defined by the moment-rotation relationship). The element formulation was based on the assumption of an inflexion point at the midpoint of the element. For beams, the plastic hinge was used for major axis bending only. For columns, two independent plastic hinges for bending about the two principal axes were used. The moment-rotation envelope for inelastic rotational hinges was determined based on axial force from vertical load and zero axial force for hinges in columns and beams, respectively. The maximum storey drift time histories observed in the experiment are presented in Figure 5 and compared to the calculated results. A more detailed explanation of the model and comparison with experimental results can be found in [12]. The input files of the mathematical model of the SPEAR building are available at www.ikpir.com\projects\spear.

For reasons of simplicity, the nonlinear dynamic analyses were performed by subjecting the structure to loads in the weak direction only. For this direction the ratio between the base shear and the weight of the building amounted to only about 0.1.

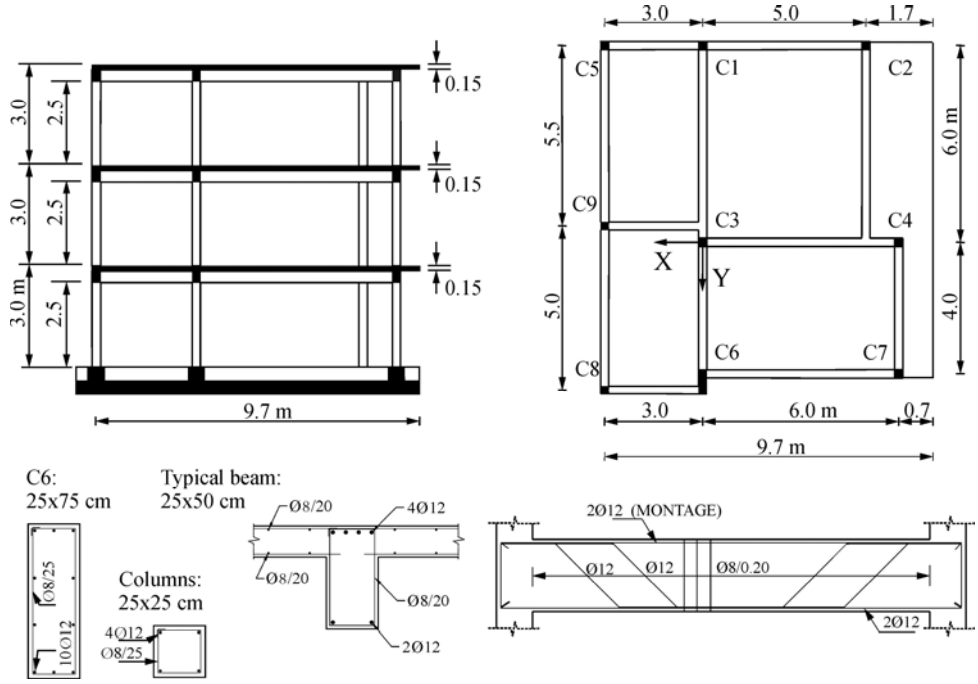

Figure 4. The elevation and the plan view of the SPEAR building, showing typical reinforcement details.

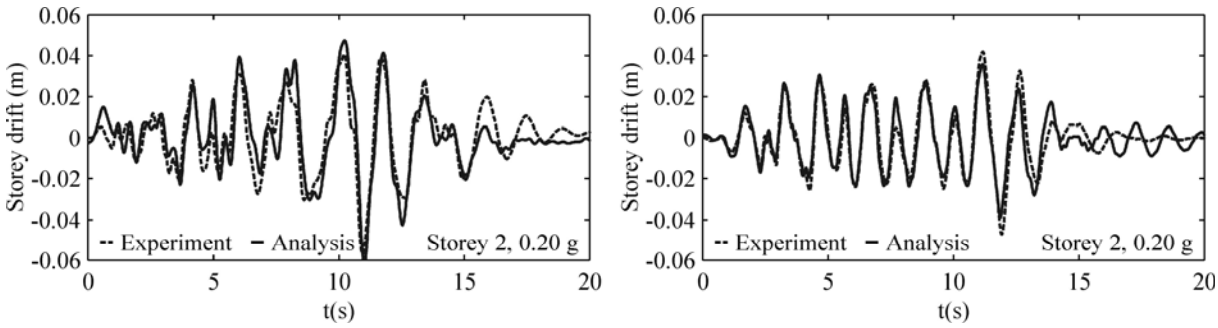

Figure 5. The comparison between calculated and test results for a second storey drift at mass center and for a ground motion with PGA = 0.2 g.

4.3 The IDA analysis for a simple mathematical model

The simple mathematical model is introduced by a SDOF model, which is based on the results of pushover analysis. Pushover analysis of the MDOF model was performed for the weak direction only, since the mathematical model of the test structure, too, was subjected only to ground motion records in the weak direction. The load pattern employed in the pushover analysis corresponded to the dominant mode shape in the weak direction. The pushover curve and the idealized base shear – top displacement relationship is presented in Figure 6a.

The SDOF model was then defined based on the approach presented in [14]. The force-displacement envelope of the SDOF model was obtained by dividing the forces and displacements of the idealized pushover curve (Figure 6a) by a transformation factor Γ, which in this example, is equal to 1.26. The period of the SDOF model is 0.85 second. Hysteretic behavior of the SDOF model, as presented in Figure 6b, has been selected in order to properly simulate the hysteretic behaviour of the MDOF model.

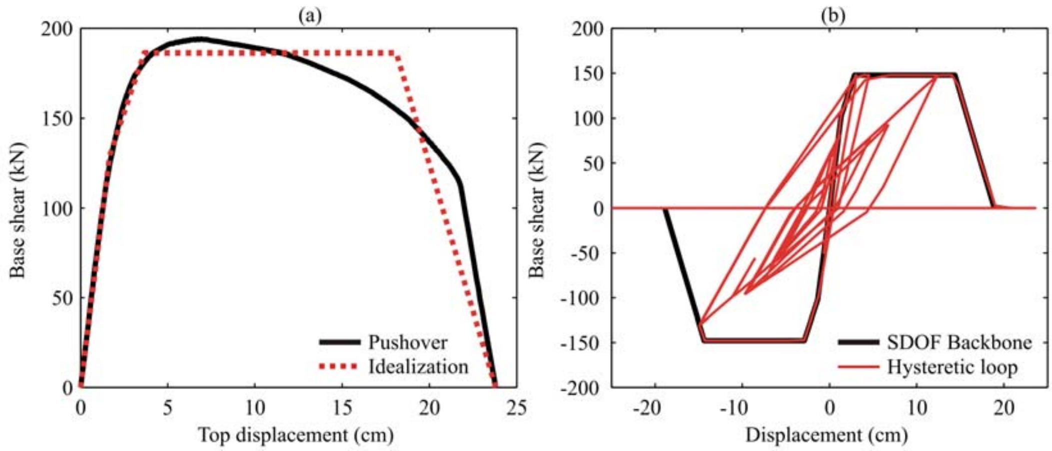

Figure 6. (a) The pushover curve, the idealized base shear – top displacement relationship, and (b) the force-displacement relationship for the SDOF model, with typical hysteretic behaviour.

The IDA analysis for the selected set of ground motion records (Table 1) was then performed on the SDOF model. The results are presented in terms of single-record IDA curves (Figure 7a). In addition to the single-record IDA curves, based on the response of the SDOF model, the corresponding ID numbers of the ground motion records (Table 1), and the summarized IDA curves (Figure 7a) are needed in order to determine the precedence list of the ground motion records.

4.4 The precedence list of ground motion records, results and discussion

The precedence list of ground motion records were determined by employing the GA based optimization technique, which has been described in [7]. The time for determining the precedence list of ground motion records, together with the IDA analysis performed for SDOF model, is less than 30 minutes. This is even much less than the time needed for determination of one single-record IDA curve of the MDOF model.

The precedence list of the ground motion records is basically obtained by rearranging the ID numbers of the ground motion records (Table 1) in order to minimize the fitness function defined in Section 3 (Eq. (1)). The ID numbers and the precedence list of ground motion records are presented in Table 1. For example, the “selected” summarized IDA curves determined for first six ground motion records from the precedence list are presented in Figure 7, and compared to the original summarized IDA curves. In Figure 7a, the comparison is made on the basis of IDA analysis for the SDOF model, while on the Figure 7b, the results are shown for the MDOF model. Good agreement between the summarized IDA curves is observed, although a few number of ground motion records, six in this case, are used. Even better agreement has been also observed for the predictions of summarized IDA curves with more than six ground motion records, which were gradually selected from the precedence list of ground motion records. This observation is illustrated by the error function (Eq. (2)) versus the number of selected ground motion records (Figure 8). The error function is clearly equal to zero if the number of selected records is the same as number of all the records from the given set of ground motion records (thirty records in this case). Although the minimization procedure is done for SDOF model and the corresponding error function has small values (Figure 8), still the error function based on MDOF model is in the acceptable range.

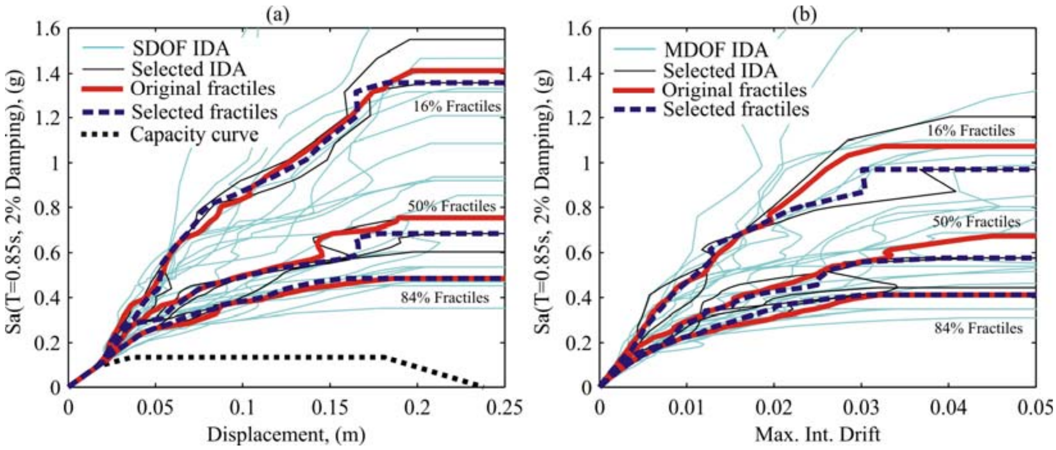

Figure 7. The comparison of "selected" summarized IDA curves using first six ground motion records from the precedence list (Table 1) with the "original" summarized IDA curves: (a) for the SDOF model; and (b) for the MDOF model.

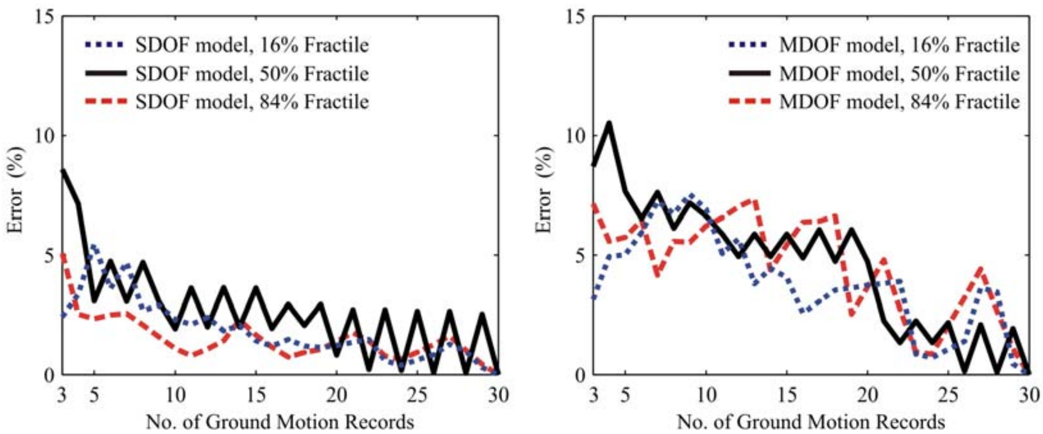

Figure 8. The error (Eq. (2)) versus number of ground motion records employed to predict the summarized IDA curve.

The decision for prediction of summarized IDA curves based on only six ground motion records is obtained through the tolerance (Section 2). Based on the previous studies it was decided that the acceptable tolerance is about 10%. Firstly, the single-record IDA curves for the MDOF model were calculated gradually, starting from the first ground motion record in the predefined precedence list (Table 1).After single-record IDA curves are obtained, the tolerance can be determined as the sum of tolerances, which are determined for each predicted summarized IDA curve (16%, 50% and 84 % fractile). The tolerance for each summarized IDA curve is determined as the area, which is defined as the difference between the summarized IDA curves calculated based on the *s* and *s-1* ground motion records, and normalized by the area under the summarized IDA curve, determined based on the *s-1* selected ground motion records. The tolerance as the function of number of the ground motion records is presented in Figure 9. For example, if only six ground motion records are used to predict the summarized IDA curves, the observed tolerance is about 11% (Figure 9) which is in the range of the predefined acceptable tolerance. In addition also the error, calculated for the SDOF model, (Figure 8) is not reduced significantly if more than six ground motion records are employed for determination of summarized IDA curves. It has therefore been concluded that the first six ground motion records from the precedence list are sufficient to predict the median IDA curve. However, in the example the single record IDA curves for MDOF model were calculated for all the ground motion records within the set of ground motion records although there was no need to do so. These calculations were done only for presenting the influence of the *s* selected ground motion records on the error function (Eq. (2), Figure 8) and on the tolerance (Figure 9).

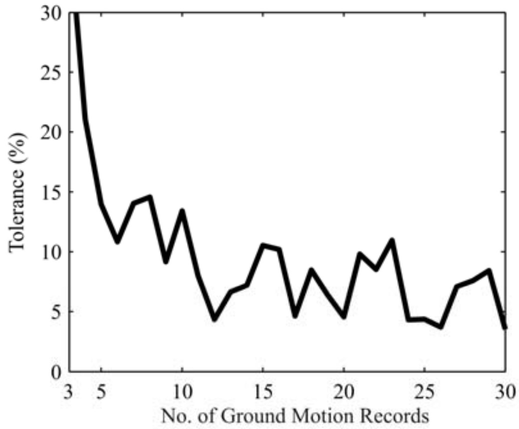

Figure 9. The tolerance function versus number of ground motion records.

In the example it was proved that the SDOF model was sufficiently representative for the simple model. For different structures, especially for special buildings or bridges, which are not first mode dominant, the SDOF model may not be sufficiently representative for the simple model. Additional studies are therefore needed in order to define sufficient simple models for different types of structures.

5 CONCLUSIONS

A methodology has been proposed in order to predict the summarized IDA curves with only a limited number of ground motion records from a given set of records. For this purpose the concept of a precedence list of ground motion records has been introduced. Determination of the precedence list of ground motion records is an optimization problem, which is solved in the paper by a simple genetic algorithm technique. In the proposed methodology, as in other simplified methods, the response of a simple (e.g. SDOF) model is taken into account. Such an approach is not computationally demanding, and can substantially decrease the number of nonlinear dynamic analyses needed for sufficiently accurate prediction of the summarized IDA curves.

The methodology was applied to a three-storey reinforced concrete frame building, using a set of thirty ground motion records. It was proved that, for this particular example, the 16%, 50% and 84% fractile IDA curves can be predicted with acceptable accuracy by employing only six ground motion records instead of thirty, which is the number of all ground motion records in the set of records.

6 ACKNOWLEDGMENTS

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