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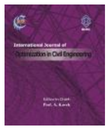

A SENSITIVITY ANALYSIS FOR ENHANCING IDA EFFICIENCY IN FRAGILITY ANALYSIS OF 3D REINFORCED CONCRETE FRAMES

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ABSTRACT

Due to several uncertainties which affect structural responses of Reinforced concrete (RC) frames, it is sensibly required to apply a vulnerability analysis tool such as fragility curve. To construct an analytical fragility curve, the incremental dynamic analysis (IDA) method has been extensively used as an applicable seismic analysis tool. To employ the IDA method for constructing fragility curves of RC frames, it is important to know how many records will be adequate to assess seismic risk analysis properly? Another issue is to know how many IDA steps are required for developing an accurate fitted fragility function? For this purpose, two 3D RC frames called 3STRCF and 5STRCF have been nonlinearly modeled and 200 2-componets actual records have been considered for the IDA. The results reveal that at least 15 IDA steps are required to reduce fragility function error to less than 5% and 10 IDA steps are required to yield less than 10% error. In addition, it is revealed that a selection of 100 records is completely adequate to be certain to have an accurate fragility curve. It is concluded that at least 25 records are required to decrease fragility curve error to less than 5% and 15 records to have less than 10%. The closeness of fragility curve error variation for two models and in all limit states show that these results can be generalized to other RC frames.

Keywords: Analytical fragility curve, Incremental dynamic analysis, Error estimation, Reinforced concrete frames.

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1. INTRODUCTION

All structures including reinforced concrete (RC) frames that are affected by the earthquake events may experience different damage levels. Consequently, structural responses have different probability for exceeding a specified damage level or limit state. Therefore, to determine the exceeding probability from a particular damage level, the structural engineers need a strong statistical computational tool. According to this comprehensive and increasing necessity, fragility curves are developed to predict structural seismic performance regarding various uncertainties. These uncertainties are associated with both seismic demand and capacity. In fact, to develop fragility curve deterministically, the level of intensity measurement (IM) necessary to achieve a pre-specified level of damage state will be predicted [1].

In probabilistic seismic risk assessment of structures, to effectively consider the inherent randomness of ground shakings and decreasing dependency of structural responses to seismic excitation inputs, structural engineers need to use a wide-range analysis (WRA) [2]. In the WRA, a vast domain of intensity measurements will be applied to structures and structural outputs will be proportionally extracted. There are several methods for wide range analysis of structures including: multiple strip analysis (MSA), incremental dynamic analysis (IDA) and endurance time method (ET). In the ET method, structures will be analyzed using a dynamic time history increasing function and the desired responses will be picked through time while loading intensity is enhanced. The ET acceleration functions can continuously monitor a wide range of excitation level from low intensity to a maximum intensity which causes structural collapse. By applying this method, structural responses can be monitored through uninterrupted range of increasing seismic input intensities [3].

Multiple stripe analysis (MSA) is a sufficient set of single stripe which analyzes and evaluates structural seismic responses in different IM levels [4]. Using this method, different excitation intensities will be presented in different strips. At each strip, median and dispersion of engineering demand parameters (EDP) can be calculated. The difference between IDA and MSA lies in the record selection mechanism. In the IDA method, a set of earthquake records will be picked neglecting record excitation level. Subsequently, theses records, will be primarily scaled to a response spectrum and by changing the obtained scale factor, different IMs will be considered [5]. However in the MSA, earthquake records will be selected such that in all pre-defined IM levels, sufficient number of records will be available. Figure 1 illustrates the schematic IDA and MSA curves.

To employ the IDA method for constructing fragility curve and probabilistic analysis of RC frames, an important point is to know how many records will be adequate to assess seismic risk analysis properly? Other questions that may be arised are as follows: How many IDA steps are necessary to reach an accurate fragility curve? And is the convergence rate dependent on the selected damage states? In this research, these questions will be discussed.

2. INCREMENTAL DYNAMIC ANALYSIS (IDA)

To consider a seismic risk assessment of structures, an increasing analysis must be used. Several methods of Static pushover analysis are available. However by development of computational tools and computer processors, gradually, static analysis will be replaced with dynamic time history analysis. Due to loss of accuracy while using static methods, incremental dynamic analysis (IDA) can be used in such cases which requires proper precision. A large number of researchers concentrated on the IDA methodology. For example, Yun et al. used the IDA method to assess seismic performance of steel frames [5]. In addition, Luco et al. investigated the effect of near-source and ordinary earthquake record on IDA procedure [6]. Zarfam and mofid used modal incremental dynamic analysis (MIDA) to investigate the performances of RC frames and compared the results obtained through the MIDA against those obtained from exact IDA [7]. Dimitrios and Vamvatsikos studied using parallel processing in the IDA [8]. Zacharenak et al. worked on bias which involved the IDA procedure due to different record scaling methods [9].

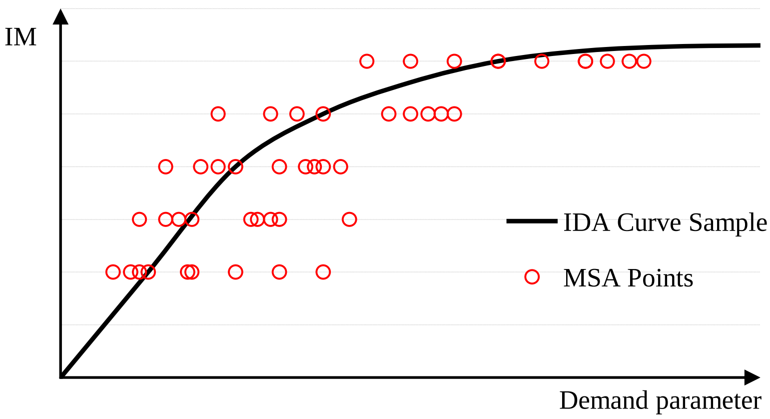


Figure 1. IDA and MSA in IM-EDP diagram

2.1 IDA procedure

According to previous studies for incremental dynamic analysis and constructing an IDA curve, in this study, the steps below are performed respectively:

(i) Record selection: the first step for a time history analysis is to select suitable records. For this purpose, peer database provides a great collection of earthquake events [10]. The greater number of selected record increases IDA accuracy and covers ground-shaking uncertainties.

(ii) Scaling of records on a pre-defined design response spectrum is done according to code requirements. If a large number of records have been selected, it is recommended that record scaling is done for the maximum of each 7 records [11]. For each scaled record, a suitable scale factor (Ci) will be resulted.

(iii) To consider more and less intensity earthquakes, the resulted Ci will be factored in a scalar coefficient such that γj (j varies from 1 to n (j)). The number of selected γj, depends on necessary precision level. For each one of the records, all domains will be factored by γj Ci. Thus for (i=I)-th record and for all j-steps:

$$\gamma_j = \frac{1}{\frac{2}{3}\times n(j)} \times j \tag{1}$$

$$\text{for all } \omega \text{ in Ith} - \text{record and for j from 1 to n(j):}$$
$$A(I,j,T)_{Scaled\ \ record} = \gamma \text{j}\ C_I\ A(I,T)_{natural\ \ record}$$

where:

$\text{n(j)} = \text{Maximum nember of selected j} - \text{steps}$

*it is should be mentioned that 2/3 factor in equation 1 is for considering the maximum probable earthquake (MPE) that is 1.5 times of 475 years-return period basis earthquake (DBE).

(iv) In I-th record and for all j-steps, a record with new $\mathrm{A(I,j,T)}$ domain will be applied to structural model and the maximum wanted EDP will be extracted. By changing j and analyzing structures in all j-steps, the IDA curve for I-th record will be constructed (Fig. 2).

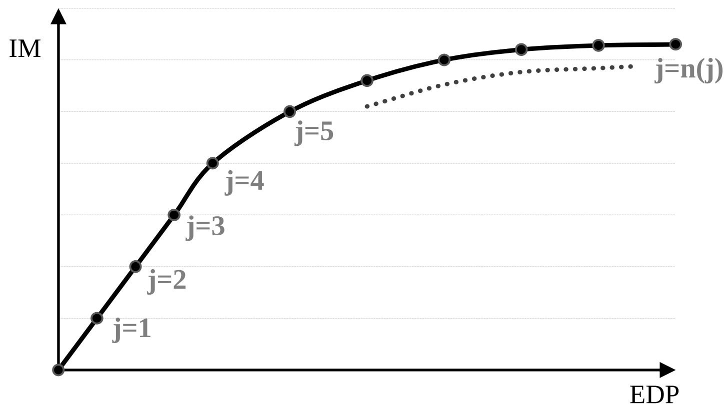


Figure 2. constructing IDA curve for I-th record

(v) Going to step 3 and performing steps 3 and 4 for all the selected records will be done. Hence for each record, a unique IDA curve will be earned. Afterwards depending on the problems, median, 84% or 16% fractile of all IDA curves will be estimated [5] (Fig. 3).

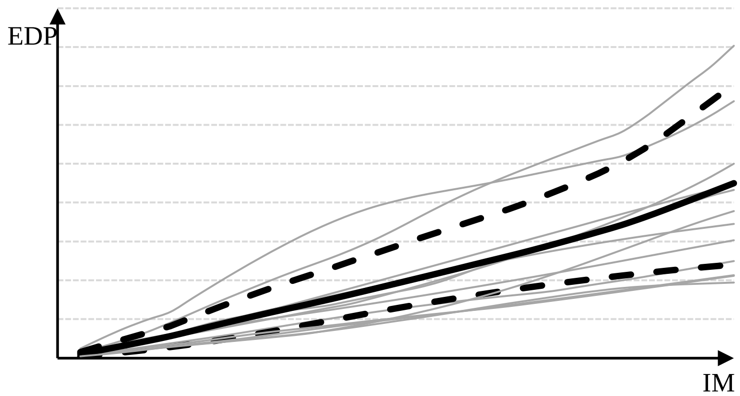


Figure 3. IDA curves and their summaries (median, 16% and 84% fractile) for fourteen records

3. ANALYTICAL FRAGILITY CURVES:

The relative vulnerability of structures can be represented by their fragility curves. Generally, fragility curves show probability which a structure will reach a predefined damage level versus an excitation parameter representing ground shaking intensity. The fragility curve can be developed in both empirical and analytical forms [12,13]. In analytical form, each fragility curve can be developed by a median value of excitation parameter and an associated lognormal standard deviation as follows [14]:

$$F_{ds} = P\,\{D > ds|IM\} = 1 - \Phi\left(\frac{\ln(ds)-\alpha}{\beta}\right) \tag{2}$$

where:

P{a|b} is probability that 'a' is true given that 'b' is true
Φ(.) is standard normal cumulative distribution function.
D is uncertain damage state of observed structure.
ds is a particular value of D.
β is referred to logarithmic standard deviation and is given by :

$$\beta = \sqrt{Ln(1 + (\frac{SD}{\mu})^2)} \tag{3}$$

where SD is responses of standard deviation and μ is responses mean from different records in each IM level.

And **α** is referred to median and is given by:

$$\alpha = \ln(\mu) - 0.5\beta^2 \tag{4}$$

Fig. 4 illustrates a fragility curve sample.

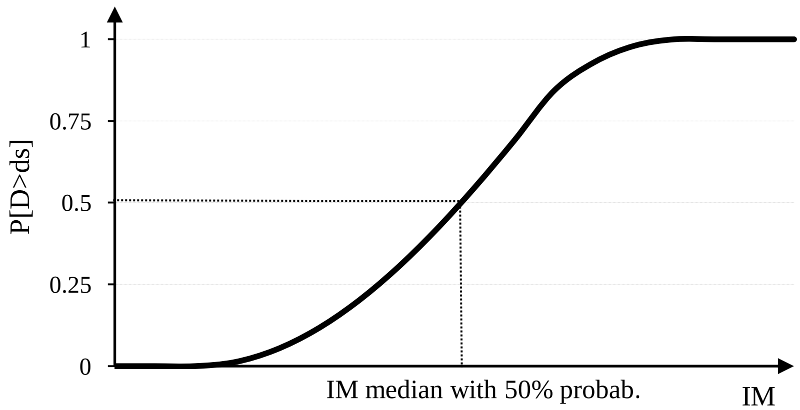


Figure 4. A typical fragility curve

Different excitation parameters or IMs have been used in previous studies such that pga [15], Sa(T1) [16], Sd(T1) [17] and etc. In this research, Sa (T1) is used as the IM for constructing the fragility curves. In addition, to assess seismic responses for all selected records associated with any supposed IM levels, a 3D 2-directional non-linear time history analysis with P-Δ effects is considered and all above-mentioned parameters have been achieved for developing fragility curves.

4. RECORDS SELECTION

In this research, 200 actual ground motion records with 2 horizontal components have been picked from peer database on soil condition C [10]. To select earthquake records, code requirements of FEMA-P-58 have been satisfied [18]. In addition, to have records scaling, an ASCE/SE7-10 target design response spectrum with coefficients according to Table 1 has been selected [19]. Record scaling has been done according to the procedure as follows: At first, for each record, the SRSS of the 5%-damped response spectra of the two not-scaled components must be calculated. Subsequently, for each set of 7 records, mean value of previously SRSS calculated spectrums have been scaled such that they are more than design response spectrum over the period range from 0.2T1 to 1.5T1. Figure 5 illustrates the design response spectrum and the average of scaled record spectrum for T1=0.53sec.

Table 1: ASCE/SEI 7 selected coefficients for developing design response spectrum

Soil Condition	SDS	SD1	T0	Ts	S1	Ss	Fv	Fa
C	1.1	0.65	0.12	0.59	0.75	1.65	1.3	1

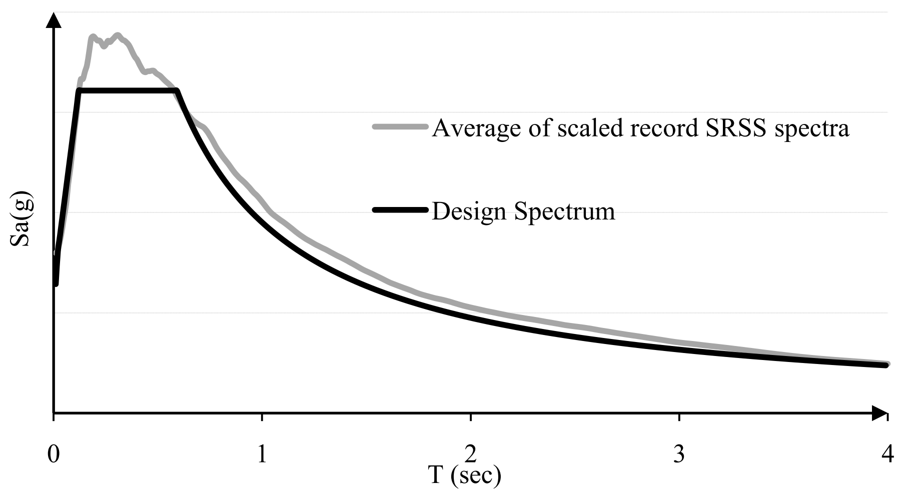


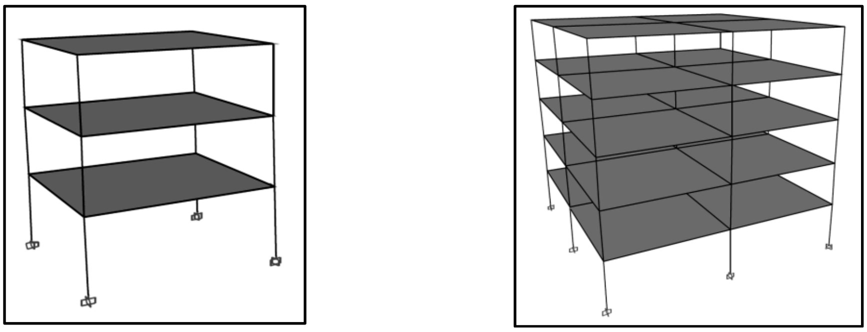
Figure 5. Scaling of two horizontal components SRSS combination of 200 selected records on response spectrum

5. STRUCTURAL MODELING

Reinforced concrete frames are one of the frequently used systems for constructing residential and commercial buildings. In this study, two 3D RC structural models have been considered. Model 1 is a 3-stories 1-span building called as 3STRCF and model 2 is a 5-storires 4-spans called as 5STRCF. All two structures are designed according to INBC 2800 for soil type III and the maximum ground acceleration (Sa (T=0)) equal to 0.3g (475-years return period) [20]. Both structures are supposed to be in residential category; therefore, they have an importance factor (I) equal to one. The fundamental periods of the RC frames are 0.56s and 0.36s for 3STRCF and 5STRCF, respectively. Opensees software [21] has been employed to analyze frames and processing structural responses.

For cover concrete modeling concrete02 [21], material of opensees database has been used having these coefficients: concrete compressive strength at 28 days (f'_C) =25MPa, concrete strain at the maximum strength (ε_c)=0.0027, concrete crushing strength (f'_{cu})= 6.6MPa, tensile strength (f_t)= 3.11MPa. Moreover for core concrete, Mander model with the maximum effective lateral pressure (f_l)=1.3MPa has been used to modify cover concrete stress-strain relationship [22]. Reinforcements have been modeled according to opensees steel02 material having yield stress (Fy) =400MPa and elastic modulus (Es) = 200GPa. To model failure in steel, a min-max material has been added in $\in = \pm 0.012$. Beam and column elements have been considered as opensees dispBeamColumn having uniform plasticity. To have appropriate geometry of nonlinearity effects in columns, a P-Δ transformation is used [21]. The two considered models are shown in Fig. 6.

As explained previously, 200 2-horizontal-components earthquake records have been considered in the present research. Theses 200 2-components accelerograms have been applied to models in an IDA loop with 30 IDA-steps considering from 0-intensity to 1.5 times of design earthquake intensity. In addition, alpha and beta Rayleigh damping coefficients have been considered for ζ=5% [23].



(a) (b)

Figure 6. Structural models: a) 3STRCF, b) 5STRCF

6. DETERMINATION OF LIMIT STATES:

Determination of limit states has an important role in the fragility curves development. If limit states definition is wrong, it significantly reduces the advantages of fragility curves.

Quantification of limit states is clearly dependent on the seismic characteristics of the structures. In this study, according to previous researches, limit states have been defined in terms of the ratio of story drift to story height [24]. Four limit states such as slight, moderate, extensive and complete have been considered on the basis of HAZUS-MH [25]. According to HAZUS definitions, 3STRCF and 5STRCF have been categorized in low-rise (C1L) and mid-rise (C1M) respectively. For these classifications, threshold of damage states have been selected according to Table 2 based on the HAZUS studies.

Table 2: Maximum story drift limit states for 3STRCF and 5STRCF

Modeled Structure	HAZUS Category	Limit states	Maximum interstory drift ratio (%)
3STRCF	C1L*	Slight	0.5
		Moderate	1
		Extensive	3
		Complete	8
5STRCF	C1M**	Slight	0.33
		Moderate	0.67
		Extensive	2
		Complete	5.33

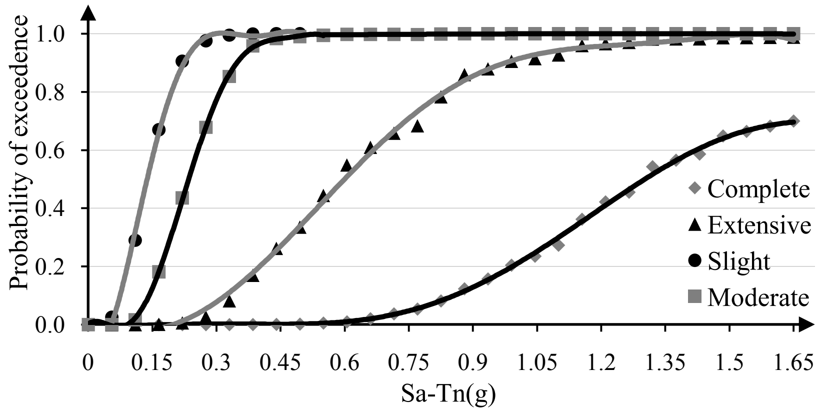
*C1L: Low-rise moment resisting reinforced concrete frames [25]
**C1M: Mid-rise moment resisting reinforced concrete frames [25]

7. RESULTS AND DISCUSSION

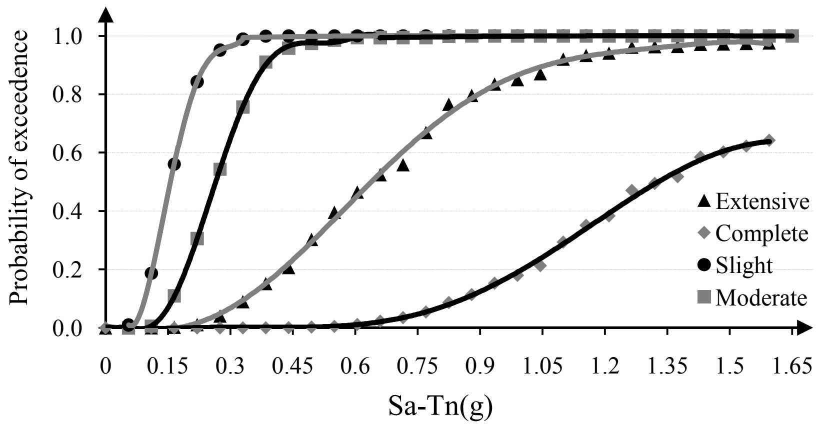
7.1 Fragility curve of modeled structures from 200 actual earthquake records

Due to considering ground shaking uncertainty, whenever the number of applied records increases, the accuracy of developed fragility curve will be enhanced. In this study, it has been assumed that 200 2-components real earthquake records are sufficient regarding ground shaking uncertainties in order to develop an acceptable fragility curve. To construct a parametric fragility curve, if the number of IDA steps is such that it represents a continuous IM-EDP curve, it can be fitted with a polynomial function with r-square parameter nearly to 1. The more IDA steps increase, the reality of fitted function significantly will be enhanced and an appropriate polynomial will be fitted to IM-Probability points. Fitting polynomial for developing fragility function clearly reduces computational efforts in integration process. Figure 7 illustrates fragility points (IM-Probability pairs) and the best fitted polynomial for 200 2-components actual records. As illustrated in Fig. 7, by considering 30 IDA steps, a very good 6-order polynomial will be fitted to all IM-Probability pairs. Also in Table 3, equation of polynomials that is fitted to fragility points in all limit states and 3STRCF and 5STRCF have been presented. As shown in Table 3, R-square of fitted polynomial function for all limit states and in two models is sufficiently close to 1.

Another major benefit of polynomial fitting is to reduce computation efforts in order to calculate median value of IM in all limit states. For all the produced polynomials by calculating x in y=0.5, the median values will be earned (x & y refers to Sa(Tn) and probability respectively). Figure 8 shows the median values of two considered models in all limit states based on the aforementioned trend.



(a)



(b)

Figure 7. Fragility curves and their fitted polynomial for 200 records and 30 IDA steps: (a) 3STRCF & (b) 5STRCF

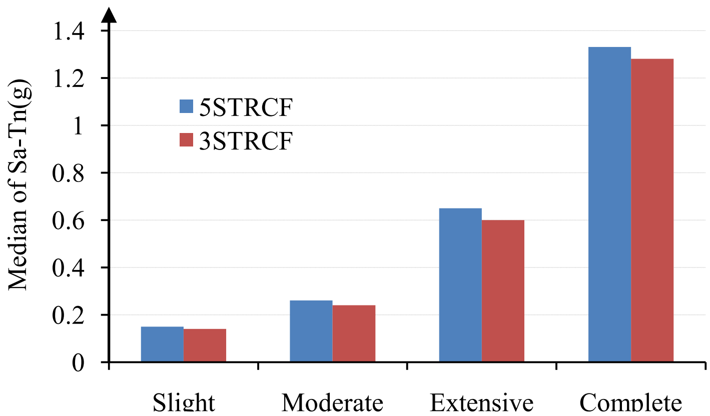


Figure 8. median values of fundamental period Sa (g) for all limit states resulted from polynomial fitted functions

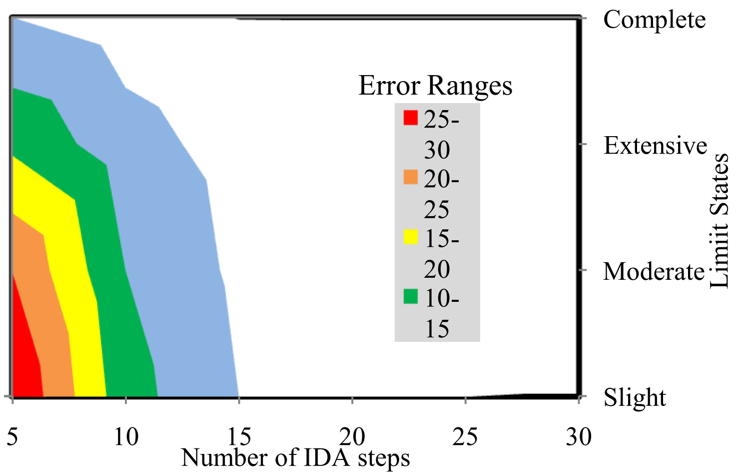
Table 3: Best fitted polynomials for constructing fragility curve and their R-square considering 30 IDA steps

Model	Limit State		Best fitted polynomial*	R-square
3STRCF	Slight	$x \leq 0.495$	$y = -14810x^6 + 17030x^5 - 6913.4x^4 + 1078.2x^3 - 29.593x^2 - 0.1893x$	1
		$x>0.495$	$y=1$	
	Moderate	$x \leq 0.55$	$y = -1535.1x^6 + 2806.2x^5 - 1874.8x^4 + 527.77x^3 - 48.573x^2 + 1.2655x + 0.001$	0.9999
		$x>0.55$	$y=1$	
	Extensive		$y = -2.9828x^6 + 14.523x^5 - 25.693x^4 + 18.718x^3 - 3.8876x^2 + 0.2048x$	0.9989
	Complete		$y = 0.6861x^6 - 3.5923x^5 + 6.4152x^4 - 4.4673x^3 + 1.2872x^2 - 0.1221x$	0.9988
5STRCF	Slight	$x \leq 0.44$	$y = -8834.7x^6 + 11562x^5 - 5384.1x^4 + 995.16x^3 - 44.783x^2 + 0.3085x + 0.0009$	0.9995
		$x>0.44$	$y=1$	
	Moderate	$x \leq 0.66$	$y = -761.26x^6 + 1606.1x^5 - 1235.4x^4 + 401.52x^3 - 44.076x^2 + 1.4447x$	0.9999
		$x>0.66$	$y=1$	
	Extensive		$y= -1.6224x^6 + 7.8362x^5 - 13.147x^4 + 7.7799x^3 + 0.2653x^2 - 0.2297x$	0.9987
	Complete		$y = 0.6227x^6 - 3.3191x^5 + 5.994x^4 - 4.2117x^3 + 1.2322x^2 - 0.1192x$	0.9985

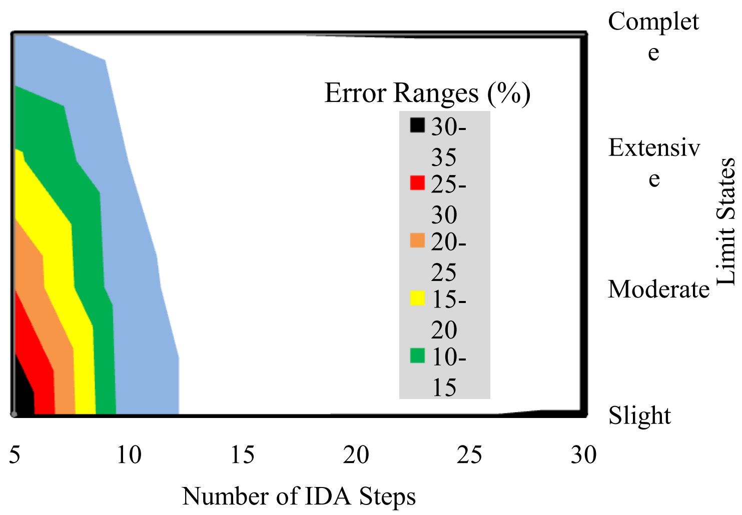
* x & y refers to Sa(Tn) and probability respectively.

7.2 How increasing of IDA steps effect on accuracy of fragility curves

A question which may be arised is to know how many IDA steps are required to develop an acceptable fragility function? Undoubtedly, the more is the IDA steps, the accuracy of fitted polynomial function will be increased. However, there is a decreasing trend which is related to the maximum fragility polynomial function error versus the selected IDA steps. This trend has been illustrated in Fig. 9 for two considered models. As seen in Fig. 9, in all limit states, by increasing IDA steps, the maximum error developed in polynomial fitting will be significantly decreased. It can be concluded from Fig. 9 that if 15 or more IDA steps have been chosen, the developed error will be less than 5% in all limit states. In addition, it is shown that if 10% error is passable, by choosing 10 IDA steps, an acceptable fragility function will be resulted for the two considered models.



(a)



(b)

Figure 9. Fitted fragility function error changes versus increasing IDA steps and considering 200 earthquake records for: a) 3STRCF, b) 5STRCF

It is noteworthy to consider the assumption made that polynomial function fitted to 30 IM-Probability pairs is adequately correct and can be the basis of error calculation. Another point can be observed in Fig. 9 which if insufficient IDA steps are employed, the maximum error developed in 3STRCF is less than 5STRCf that may be due to higher degree of freedom for 5STRCF. In addition, it is clear in low limit states due to using less IDA steps, the fragility curve errors will be higher. Since numerical values of error is relatively close to each other as presented in Fig. 9 for the two considered models, it is concluded that the results can be generalized to other RC structures.

7.3 How increasing of earthquake records effect on accuracy of fragility curves

To apply the IDA method in fragility curve development, an important problem that may be occurred is to figure out how many records are necessary to be sure considering ground shaking uncertainties? It is clear that taking more actual earthquake records result in more realistic fragility curves. However in cases of considering nonlinear inelastic models, adding even 1 record to IDA method may lead to major computational efforts. Moreover, due to massive usefulness of fragility curves in vulnerability analysis of RC structures, there is no way to the maximum simplification of fragility curve development process with negligible loss of accuracy.

To investigate how increasing earthquake records affect the accuracy of the fragility curves, for all the 200 records, the IDA curves considering 30 IDA steps have been primarily calculated. Figures 10(a) and 10(b) illustrate the summary of the obtained IDA curves applying 200 actual records for the 3STRCF and 5STRCF, respectively. Next for constructing error changes diagram, the flowchart provided in Fig. 11 is employed.

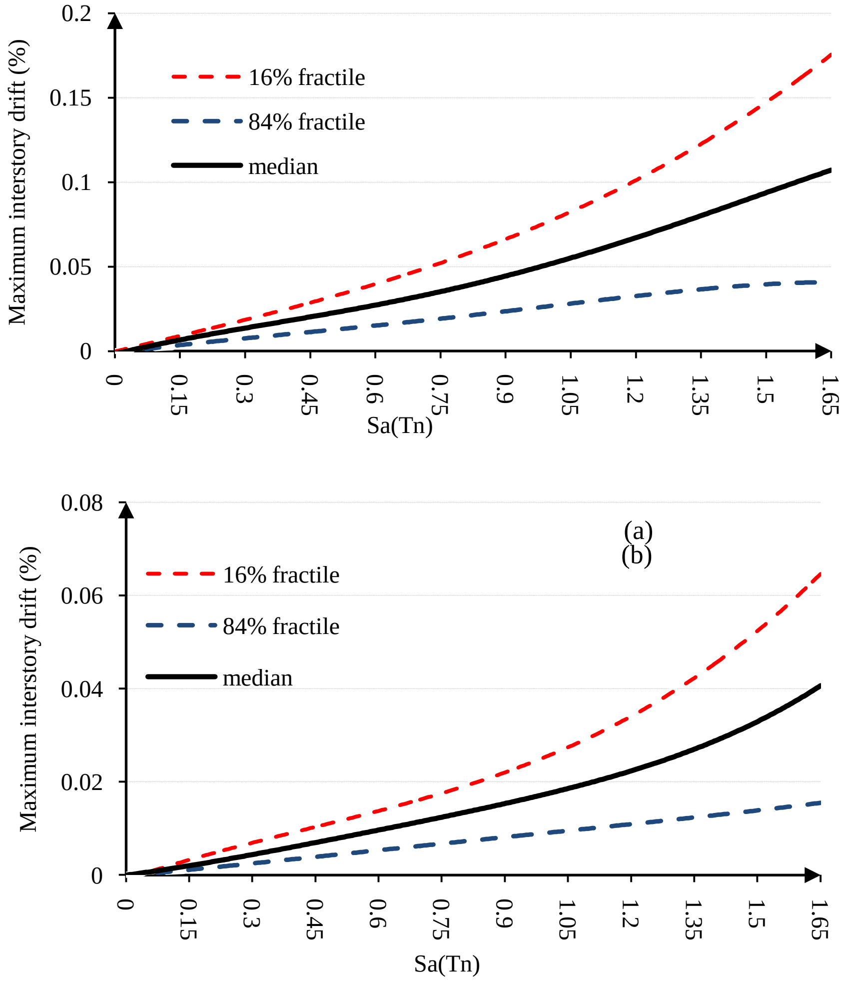


Figure 10. IDA curves produced from applying 200 EQ records for a) 3STRCF & b) 5STRCF

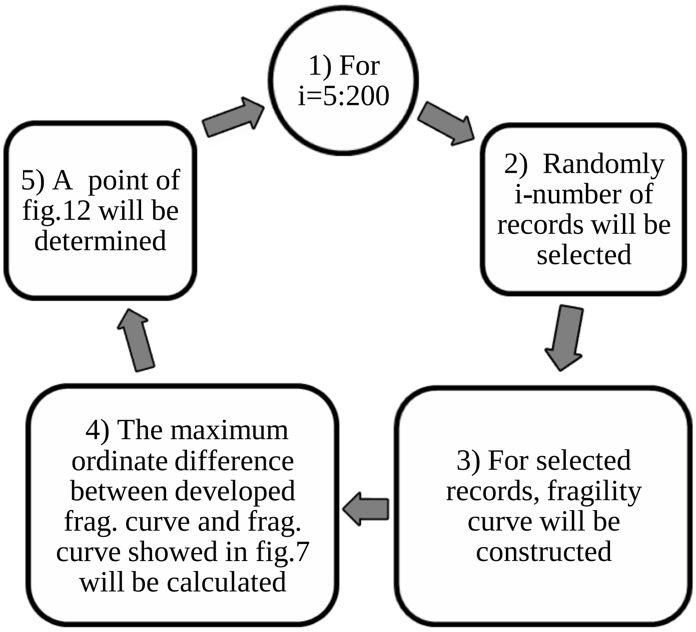


Figure 11. Employed flowchart for knowing fragility curve error changes according to number of selected records variation.

An important point should be emphasized: To calculate error in each step and for all 30 IDA points, the maximum absolute difference between the developed fragility curve and the base fragility curve (for 200 records, see Fig.7) is attained and the relative error is not employed. Based on the flowchart of Fig. 11, in the *i*th step, a pair (the number of selected records, maximum fragility curve error) is achieved and consequently for the two considered models, the maximum error change trend versus the number of selected records have been developed as seen in Fig. 12.

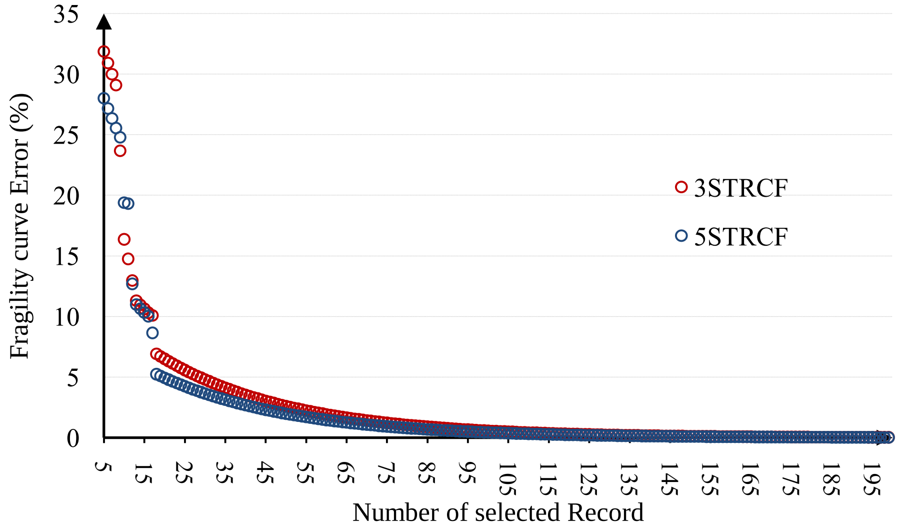


Figure 12. Fragility curve error decreasing trend according to increasing applied records

As illustrated in Fig. 12, with increasing the number of applied records, the maximum fragility curve error rapidly is vanished. In addition, if 100 actual records are considered, the error of produced fragility curve is nearly 0% and if 5% error is acceptable, the minimum 25 records must be considered in fragility curve development. Similarely, if almost 15 records are applied, the developed error is less than 10%. Another point that will be concluded from Fig. 12 is the proximity of error changes trend for the two considered models. This proximity guided us to the fact that error changes is approximately independent of the considered models and is relevant to ground shaking uncertainties. Also as shown in Fig. 13, in all limit states, the errors changes are completely similar that verify independency of error changes to anything except ground shaking uncertainties. Figure 13 illustrates the correlation between the maximum developed error and error in each limit state for 3STRCF. For the 5STRCF, there is similar correlation as well.

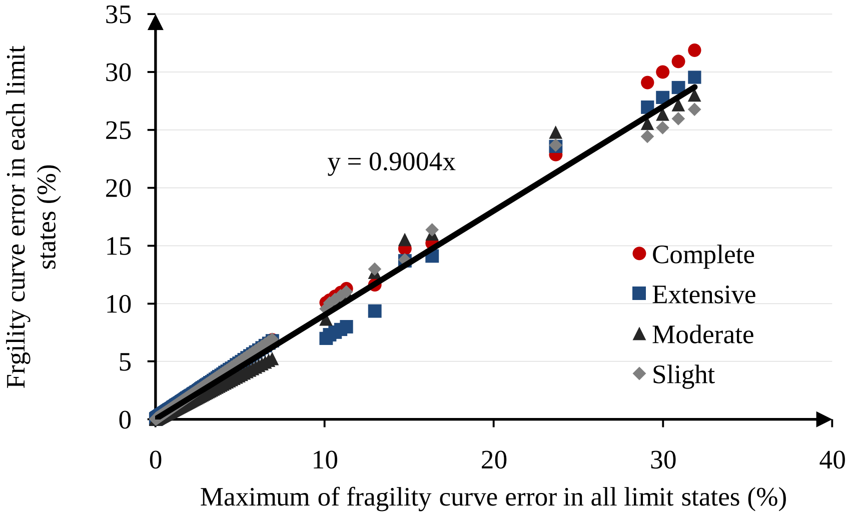


Figure 13. Correlation between the maximum of fragility curves error in all limit states and fragility curve error in each limit states due to variation of the number of applied records

As seen in Fig. 13, proximity of error change trends for 2 models and in all limit states can lead us to define a general relation that relates fragility curve error to variation of the considered actual earthquake records. This equation can be resulted from fitting an appropriate power function to points as illustrated in Fig. 12. This relationship can be expressed in equation 5 as follows:

$$\text{Frag Err. function} = 550 \times (\text{No. AEQR})^{-1.5} \tag{5}$$

where:

No.AEQR: number of applied earthquake records (greater than 5)

Frag. Err. function: Maximum of fragility points errors due to considering insufficient records.

The usefulness of equation 5 will be evident when, due to high computational efforts, inadequate number of records is considered. In these situations, conservatively, error resulted from equation 5 can be added to the ordinate of produced fragility points. This idea may be an upper hand; however, it is better than underestimating the probabilities due to applying insufficient records.

8. CONCLUSION

The objective of this investigation is a sensitivity analysis that shows how "number of selected records" and "IDA steps" parameters can affect the developed analytical fragility curve precision for RC frames. For this purpose, 2 3D RC frames called as 3STRCF and 5STRCF have been considered and for these models, the fragility curve error variations have been investigated. In all stages, an analytical fragility curve is developed from 200 2-components actual EQ records and 30 IDA steps have been considered adequately accurate and is the basis of error calculations. This assumption has been approved by reviewing other studies. However the following conclusions have been extracted from this study:

(i) Considering sufficient IDA steps in the development process of the fragility curve can lead to fitting an appropriate polynomial function with R-square close to 1. It is clear that availability of a polynomial function that properly represents fragility curves significantly reduces computational efforts in the integration process of the fragility functions.

(ii) As the IDA steps increase the accuracy of fragility function will be enhanced. But due to time-consuming of IDA process, a sensitivity study should be available knowing that how increasing IDA steps enhances the developed fragility function accuracy. For this purpose, it is shown that at least 15 IDA steps is required to be certain that fragility function error is less than 5%. The closeness of results for the two considered models indicate that this outcome can be generalized to other RC structures.

(iii) Similar to the IDA steps, when the number of applied records increases, the accuracy of the fragility points will be enhanced. It is shown that selection of 100 records is completely adequate to be certain of an accurate fragility curve. In addition, it is concluded that at least 25 records are required to decrease fragility curve error to less than 5% and 15 records to less than 10%.

(iv) The closeness of fragility curve error variations versus number of selected records in all limit states and for the 2 considered models indicates the dependency of error changes on nothing except ground shaking uncertainties. Thus a power function that is fitted to the error changes trend can represent error rate when using insufficient number of records.

This power function ($\mathrm{Frag\,Err.function} = 550\ \times (\mathrm{No.AEQR})^{-1.5}$) can be used in reliable RC frames fragility curve development process in the future.

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