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Systematical Approach to Evaluate Collapse Probability of Steel MRF Buildings Based on Engineering Demand and Intensity Measure

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Abstract—**The collapse probability of structures is determined through two approaches of probability of exceedance in terms of EDP-Based and IM-Based approaches. Pertaining to characteristics of structure and types of excitations, these two values may evaluate the probability of collapse in lower and upper estimation. In this study, through combining these two estimations, a precise measure of collapse probability is exhibited. To evaluate collapse capacity of structures and implementation of probabilistic scheme in structure performance assessment, incremental dynamic analysis (IDA) and fragility curves are used. The systematic view of two approaches of collapse probability consists of engineering demand (EDP-Based) and intensity measure (IM-Based) are considered in series forms. The study results show that the combination of these two aforementioned schemes exhibit comprehensive vision of collapse probability of structures which are very important in performance evaluation of structures.**

Keywords—**Collapse Probability of Structures, Incremental Dynamic Analysis (IDA), Fragility Curves, Performance Evaluation, Engineering Demand Parameter (EDP), Intensity Measure Parameter (IM), Series Combination**

I. Introduction

Insuring seismic safety of structures with special performance objectives is one of the purposes of Performance-Based earthquake engineering. These performance objectives can be stated as collapse probability in hazard level or as mean annual frequency (MAF) of occurrence of a damage level. In fact, in the framework of seismic reliability, these performance objectives are stated as the relation between damage probability and seismic intensity of ground motion (collapse fragility curves), which is influenced by the relation between seismic hazard and ground motion intensity (seismic hazard curve). Fragility curves of structures which state the probability of a damage level in different ground motion intensities are one of the most useful tools in assessing performance of structures. By combination of collapse fragility curves with site hazard curves, mean annual frequency of collapse for a hazard level can be estimated. Two common approaches are used for estimation of fragility curves, EDP-Based and IM-Based. In the first one (EDP-Based), an Engineering Demand Parameter (EDP) such as story-drift, column compressive force and etc is used for estimation of collapse. In the other approach (IM-Based), critical ground motion intensity (IM) is used as criterion for estimation of collapse. In this research, both of these approaches and the combination of them is used for estimation of fragility curves. In both of EDP-Based and IM-Based approaches, collapse probability can be calculated upon the probability of exceedance of demand to capacity. Collapse probability is sensitive to this IM or EDP parameters and because of over and under estimate of collapse probability in EDP-Based and IM-Base approaches, respectively, the series combination of these is investigated. In SAC/FEMA guidelines, methods of estimation of collapse probability are embedded; which has been studied and compared by researchers [1, 2, 3, 4].

II. Modeling

Reaching two levels of low and high ductility and consequently better description of the concepts introduced in this research, a structure with two types of connections is modeled. The analyzed 2-D frame is side-frame of a 4-story building, with special moment-resisting frames (SMRFs) as lateral resisting system, which is loaded and designed according to UBC97 and by LRFD procedure respectively.

The proposed loading consists of dead load of 6 kN/m2 on floors, 3.5 kN/m2 on roof and live load of 2 kN/m2 on floors and 1 kN/m2 on roof. It is supposed that most of gravity loads are supported by interior hinged frames and lateral loads are transferred to ground by lateral SMRFs. Considering deterioration characteristics of structural components subjected to cyclic loading and distinguishing pre- & post-Northridge earthquake connections, Ibara-Krawinkler deterioration model is implemented as lumped plasticity at the end of elements [5, 3, 6]. Plastic rotation capacity (θ_P), post-capping deformation capacity (θ_{PC}) and cyclic deterioration parameter (Λ) are parameters commonly used in the determination of collapse capacity of structures [3,7].

The OpenSees program was employed for nonlinear dynamic analysis of model. Obtaining low ductility and low level of energy absorption, Welded Unreinforced Flange-Welded Web (WUF-W) type connections pertaining to Pre-Northridge connections) and attaining high ductility and high level of energy absorption, Reduced Beam Section (RBS) type connections (pertaining to Post-Northridge connections) which act as semi-rigid connections, was employed. According to FEMA P695, additional leaning column elements capturing P-delta effects of the seismic mass on internal frames that is not tributary to the perimeter frame, are considered in modeling. Obtained periods of frames, by software and code, are listed in Table (1).

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TABLE I. CALCULATED PERIODS OF FRAMES.

	Special Moment-Resisting Frame with High-Ductility	Special Moment-Resisting Frame with Low-Ductility
$T_{1,Software}$	1.0049	0.7501
$T_{1,Code}$	0.0853H^(3/4)=0.577	0.0853H^(3/4)=0.577

III. Records Selection for Time History Analysis

Incremental dynamic analysis (IDA) is used widely for assessing structural performance under earthquake excitations through implementing a selected set of records that are more likely to occur in the region, where structure is located. In fact, if sufficient number of earthquakes records for understudied region is available, they will be used; otherwise, similar earthquake records from the view points of magnitude, closest distance to rupture plane, average shear wave velocity within 30-meter depth of soil of the site, types of fault mechanism will be selected [8]. Here 22 records have been selected from PEER ground motion database (BETA version), according to guidelines of FEMA-P695, as be compatible to regional seismic hazard level incorporated in Iranian national codes.

IV. Incremental Dynamic Analysis (IDA)

The frames were analyzed by IDA method [9] in OpenSees, using selected records. In IDA method, the structure is analyzed by a series of time history analysis, in which intensity of applied records are increased incrementally; indeed, records are scaled from a low value of peak ground acceleration (PGA), where structural response is elastic, to a limit value that dynamic instability of structure occurs. IDA curves are plotted by spline curve fitting of obtained Intensity measure (IM) versus engineering demand parameter (EDP) [9]. It is necessary to investigate nonlinear behavior of buildings that are to be retrofitted by new seismic retrofitting techniques and also damaged buildings which have significant changes in dynamic characteristics after earthquake [10]. Researchers have shown that spectral acceleration associated with 5% damping at the first mode period of the structure, is a good criterion for intensity measure (IM); and because of study of global behavior of structure in this research, maximum interstory drift ratio (the maximum over time and over all stories of the interstory drift ratios recorded during the time history analysis) is known to relate well to global dynamic instability and is chosen as damage measure (DM) [11]. Although each single-record IDA curve is developed definitely for a specified structural model and a specified seismic record, but because of lack of complete knowledge about probable future earthquakes, probabilistic characteristics are considered in analysis. Derivation of 16th, 50th, and 84th percentiles are suggested as simplest method for generalizing the results of IDA curves [9]. The resulted IDA curves with 16th, 50th and 84th percentiles are shown in Fig. 1 & Fig. 2, for both of frames with low & high levels of ductility. Also the median IDA curves for both frames are shown in Fig. 3.

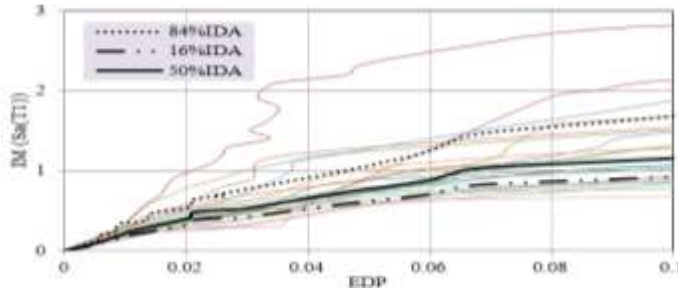

Figure 1. Obtained IDA curves for high-ductile frame

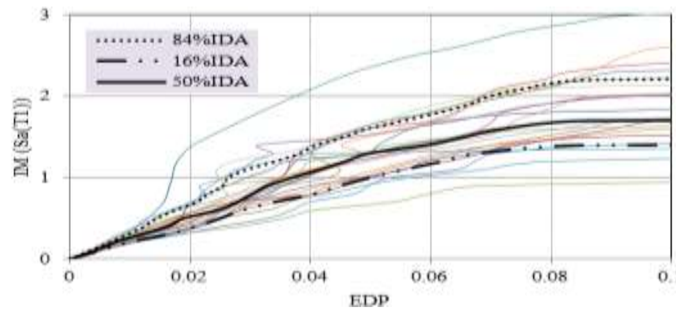

Figure 2. Obtained IDA curves for low-ductile frame.

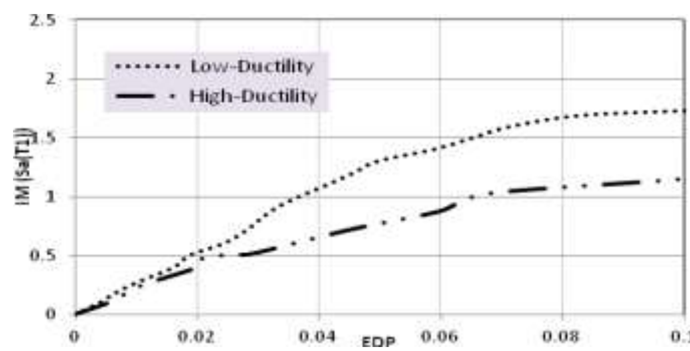

Figure 3. Comparison of median IDA curves for low & high ductile frames.

The structural fragility for a limit state which is defined as probability of exceeding damage from specified damage limit-state can be expressed as (1), where DS is damage limit-state and ds is the damage value in structure and IM is the parameter for measurement of ground motion magnitude or intensity [12].

$$f = P(DS \geq ds | IM = im) \tag{1}$$

Estimation of damage probability can be stated according to EDP or IM approaches. In this research, with the application of concept of systematic approach to damage, collapse fragility curves for understudied frame are derived and compared with each other [13,14,15,16].

A. *IM-Based approach for derivation of fragility curves*

In IM-Based approach for derivation of fragility curves, IM variable (usually selected as spectral acceleration) is selected as the variable for determination of limit-state; thus probability of collapse can be stated as:

$$P(C|IM = im_i) = P(im_i > IM_c) = 1 - F_{IM_c}(im_i) \quad (2)$$

Where $F_{IM_c}(im_i)$ is cumulative distribution function of IM (spectral acceleration) capacity. IM can be a parametric variable from PGA, return period, modified Mercalli intensity, etc; which are known as random variables. Because of intrinsic randomness of earthquakes, IM varies from one record to another record. Since the study of combination of collapse probability in both of IM & EDB-Based approaches is one of the purpose of this research and because of simplicity, only record-to-record variability effects is considered. The IM corresponding to collapse occurs when IDA curve resulting from nonlinear response history analysis has converged (i.e., dynamic instability is attained) within a certain tolerance; which is due to P-Δ effects and deterioration of strength and stiffness in structural components [17]. Considering systematic concept of collapse, the IMs collected from mentioned IDA method, constitute event A; which for each IM, the corresponding collapse probability (i.e., P(A)) can be gained. Equation (3) describes this statement in mathematical notation.

$$P(A) = P(C|IM = im_i) = P(IM_c < IM = im_i) \qquad (3)$$

In this equation, IM_C is 'collapse capacity' (the ground motion intensity at which the building experiences dynamic instability) and $P(C|IM = im_i)$ is the cumulative collapse probability for ground motion intensity of im_i .

B. *EDP-Based approach for derivation of fragility curves*

In EDP-Based approach for estimating fragility curves, an engineering demand parameter (EDP) is used as the parameter for determination of collapse limit-state. The SAC/FEMA definition for estimating EDP_C is used (i.e. the EDP value at which the slope of the IDA curve lessens 20% of the initial (elastic) slope of IDA curve or the EDP value which drift exceeds 10%) [2]. Thus IMs resulted according to this criterion, for derived IDA curves, constitute event B; which for each IM, the corresponding collapse probability (i.e., P(B)) can be gained. The mathematical notation is shown in (4). It should be noted that in this research, EDP_C corresponds to drift where the slope of the IDA curve lessens 20% of the initial (elastic) slope of IDA curve.

$$P(B) = P(C|IM = im_i) = P(EDP_d > EDP_c|IM = im_i) = \sum_{all\ edp_c} P(EDP_d > EDP_c|EDP_c = edp_{ci}, IM = im_i) \times P(EDP_c = edp_{ci}) \qquad (4)$$

Thus for any EDP_C, $P(EDP_d > EDP_c|EDP_c = edp_{ci})$ and $P(EDP_c = edp_{ci})$ can be calculated for any level of im_i s; and with taking sum of derived probabilities for all of EDP_C, at any level of im_i, P(B) will be found. Fig. 4 shows the scheme of EDP-Based approach for IDA curves in Fig. 2, in which solid black circles are EDP capacity points (EDP_C) and the projection of these points on the horizontal axis and the

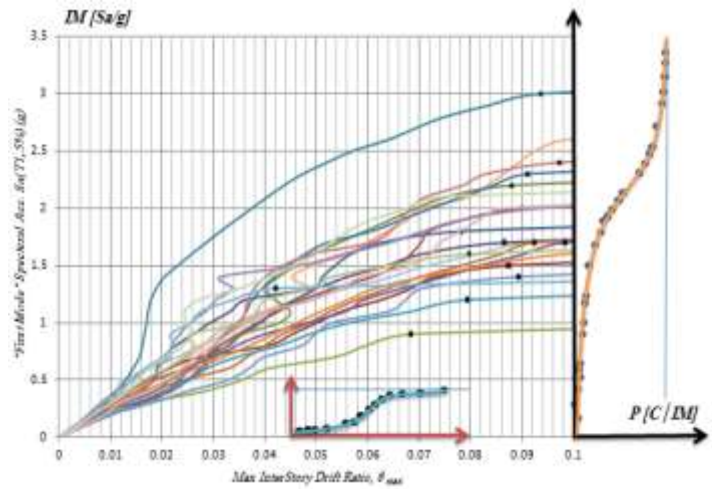

Figure 4. EDP-Based approach for derivation of fragility curves; for IDA curves in Fig. 2.

$P(EDP_C < edp_c|IM = im_i)$. Using (4) to evaluate numerically probability of collapse given IM at various IM levels and plotting the resulting data points with blue solid circles on the right-hand side of Fig. 4; the collapse fragility curve is obtained by fitting a log-normal distribution to the probability of collapse given IM data points.

C. *Considering systematic concept of collapse (combination of IM-Based and EDP-Based approaches)*

According to systematic concept of collapse of structures, the union of the aforementioned approaches can be used and it is assumed that the approaches act as series systems (Fig. 5). As (5) shows, the union of event A and B can be calculated from P(A), P(B) and the joint probability of them. It is assumed that the two events A and B are independent; then the joint probability is obtained by product of probability of approaches (6). Also for events with negative correlation, the margins of joint probability is in the range mentioned in (7); and finally, the union of approaches can be calculated by (5) [18,19]. Fig. 6 and Fig. 7 show derived fragility curves according to IM-Based approach (P(A)) and EDP-Based approach (P(B)) and combination of them at two levels of IO & CP damage states, for frames with low & high-ductility respectively. In Fig. 8 and Fig. 9 derived IM-Based and EDP-Based fragility curves at two levels of IO & CP damage states, for frames with low & high-ductility, are compared with each other. As trends of this figures show, collapse rate is faster in frames with low-ductility than frames with high-ductility.

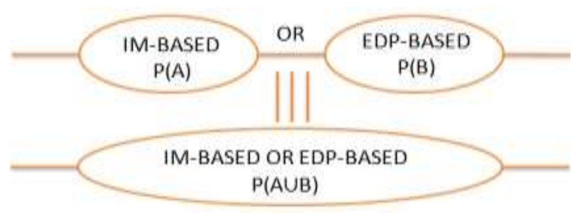

Figure 5. Schematic scheme of systematic approach to estimation of fragility curves.

$$P(A \cup B) == P(A) + P(B) - P(A \cap B) \quad (5)$$

$$P(A \cap B) = P(A) \times P(B) \quad (6)$$

$$0 \leq P(A \cap B) \leq \min(P(A), P(B)) \quad (7)$$

Derived fragility curves from combination of the two approaches gives better and more conservative results for collapse probability. As is shown, both of IM-Based and EDP-Based approaches try to state a common purpose for collapse of structures and the combination of them also follows the same trend; the difference is that there will be one fragility curve instead of two criterion fragility curves.

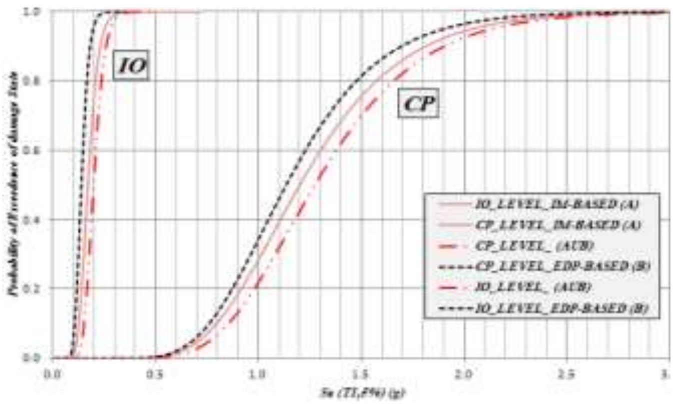

Figure 6. Derived fragility curves for IM-Based approach (P(A)) And EDP-Based approach (P(B)) and combination of them; at two levels of IO & CP damage states, for frames with low-ductility.

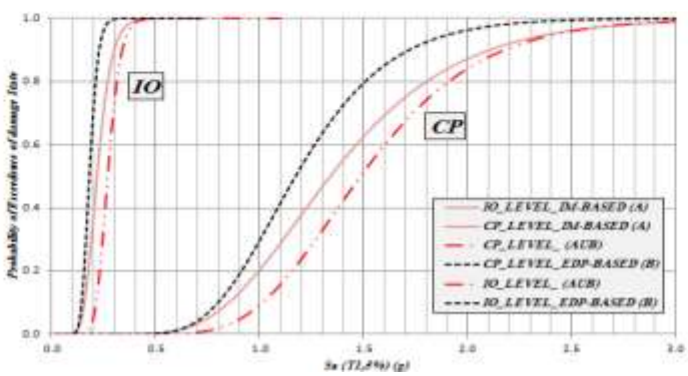

Figure 7. Derived fragility curves for IM-Based approach (P(A)) And EDP-Based approach (P(B)) and combination of them; at two levels of IO & CP damage states, for frames with high-ductil.

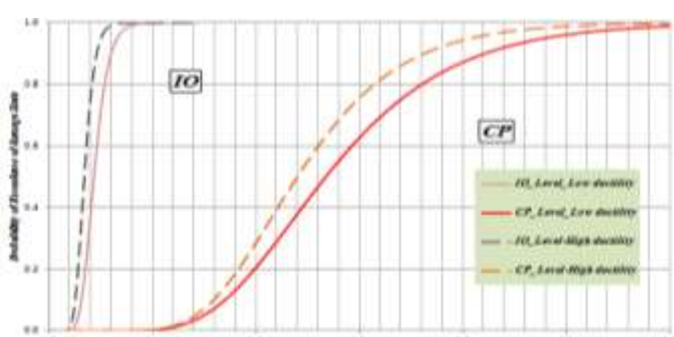

Figure 8. IM-Based fragility curves at two levels of IO & CP damage states; for frames with low & high-ductility.

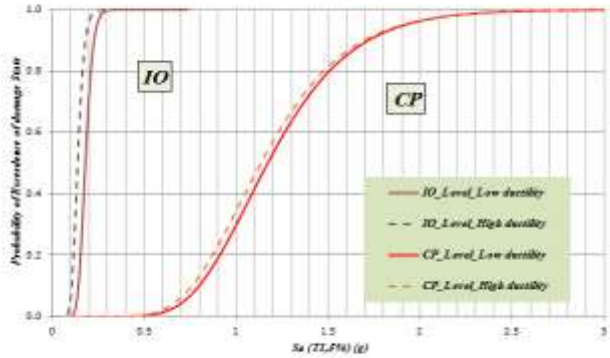

Figure 9. EDP-Based fragility curves at two levels of IO & CP damage states; for frames with low & high-ductility.

V. Hazard Analysis

In fact, hazard analysis represents the potential of ground-motion hazard and effective parameters in response of structure, such as soil type. Seismic hazard curves used in this research are extracted from previous studies; in which seismic hazard for different locations of Tehran are estimated using different attenuation relations. With averaging of obtained seismic hazard values, hazard map of Tehran is presented [1, 20,21]. Seismic hazard curves which represent annual frequency of exceeding a given seismic intensity are derived using Uniform Seismic Hazard curves and for different structural periods. The mean annual frequency of exceeding a given spectral acceleration, λ_{s_a} , was estimated by a power-law expression (linear relation in log-log space) as in (8) [1, 21].

$$\lambda_{s_a} = k(s_a)^t \quad (8)$$

Where t & k are constant parameters correlated to first mode period of structure. Selected values of t & k for understudied structures are shown in Table (2) [1, 21]. Fig. 10 shows seismic hazard curve for understudied structures in high hazard region.

VI. Mean annual frequency of exceeding limit-states

Mean annual frequency (MAF) of exceeding limit-states as quantities which reflect probabilistic capacity of structures, in correlation with site hazard, are noticeable. These quantities can be used in reliability of structures or in building design codes [22]. Mean annual frequency of exceeding limit-states is calculated using (9).

$$\lambda(Collapse) = \int_0^{\infty} P[Collapse|IM = im_i] \left| \frac{d\lambda(IM > im_i)}{d_{im}} \right| d(im) \quad (9)$$

Where $\lambda(Collapse)$ is mean annual frequency of exceeding limit-states for IM, the term inside absolute is gradient of hazard IM and $P[Collapse|IM = im_i]$ is collapse probability or fragility curve value. MAF of the frames for CP limit-state are shown in Table (3); by numerical integration of

TABLE II. PARAMETERS OF SEISMIC HAZARD CURVES FOR UNDERSTUDIED STRUCTURES

	High Hazard Level		
	T_1	*k*	*t*
Special Moment Frame With High-Ductility	1.0049	1.42E-04	-2.011
Special Moment Frame With Low-Ductility	0.7501	3.72E-04	-2.068

TABLE III. MEAN ANNUAL FREQUENCIES OF UNDERSTUDIED FRAMES FOR CP LIMIT-STATE

	High-ductility Frame	**Low-ductility Frame**
IM-Based, P(A)	0.0000297	0.0000712
EDP-Based, P(B)	0.0000457	0.0001252
Systematic, P(AUB)	0.00002183	0.00005233

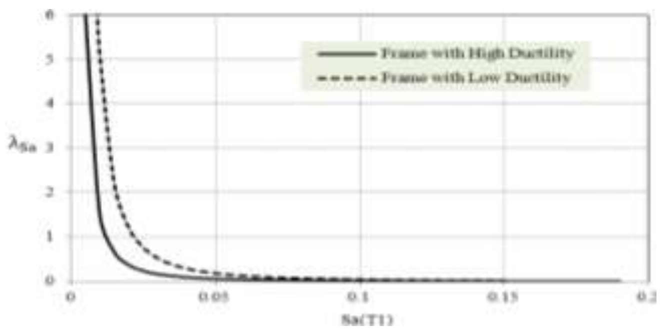

Figure 10. Seismic hazard curve for understudied structures; in high hazard region.

(9) using seismic hazard curve in high hazard region and fragility curves values.

It can be seen from Table (3) that the MAF values is higher in low-ductility frames than high-ductility ones, for all three approaches. Also MAF values for IM-Based is lower than EDP-Based and values of both of them are lower than combined systematic approach. It should be noted that the difference between MAF values of IM-Based and EDP-Based originates from estimations and intrinsic uncertainties in the two approaches

VII. Conclusion

In this study, methods for quantification of collapse performance of structures was presented and IM-Based and EDP-Based approaches and the series combination of them was used to analyze structures with low & high levels of ductility in Iran. The combined systematic approach resulted in more conservative outcomes. Also mean annual frequency of exceeding limit-state (MAF) was lower for combined approach than the other ones.

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