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Performance Verification of Seismic Design Codes for RC Frames

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Abstract**—**In this study, a frame work for verification of famous seismic codes is utilized. To verify the seismic codes performance, damage quantity of RC frames is compared with the target performance. Due to the randomness property of seismic design and earthquake loads excitation, in this paper, fragility curves are developed. These diagrams are utilized to evaluate performance level of structures which are designed by the seismic codes. These diagrams further illustrate the effect of load combination and reduction factors of codes on probability of damage exceedance. Two types of structures; very high important structures with high ductility and medium important structures with intermediate ductility are designed by different seismic codes. The Results reveal that usually lower damage ratio generate lower probability of exceedance. In addition, the findings indicate that there are buildings with higher quantity of bars which they have higher probability of damage exceedance. Life-cycle cost analysis utilized for comparison and final decision making process.

Keywords**—**RC Frame; Fragility Curve; Performance-base Design; Life-Cycle Cost Analyses; Seismic Design Codes

I. INTRODUCTION

THERE are many seismic codes for seismic design of structures which are valid in different countries. The purpose of these codes is always to establish the minimum requirements in order to safeguard the public health, safety and general welfare. Only performance view in seismic design of buildings is in risk category of buildings. However this performance view is in design loads standard such as ASCE/SEI 7-10[1].

To design RC frames, codes have several provisions to detail elements such as stirrup configuration which should be considered in order to obtain target ductility. These provisions frequently are similar in codes. However the main difference parameters among codes include load combination and reduction factors of bending, torsion and shear capacity relations. Frequently in the RC frames, element sections are designed by drift control parameter. Difference codes parameters usually make a difference in bars quantity and distribution. In this study, a frame work for verification is utilized in order to make a decision for famous codes. The RC frames are designed by EURO048 [2] for three different ductility levels in of Yong Lu et al study [3]. These frames are subjected to earthquake simulation tests and the results are observed and compared. In that experiment, it is observed that the framed design for high ductility (thus large reduction of design seismic force) are likely to attract more extensive damage compared to those which are designed for lower ductility.

For verification performance of seismic codes, comparison of damage ratio can be utilized. Moreover, this factor can be used to access more efficient seismic codes. Due the main essence of designing structures under seismic excitation is probabilistic; the evaluation of structures cannot be concluded if all the uncertainties are neglected. In this study, to survey codes efficiency, fragility curves are developed. In this procedure, the fragility curve is investigated in order to assess the efficiency of these codes on the probability of damage limit levels exceedance.

Many studies have employed fragility curves to evaluate structures under seismic excitation with random parameters. Generally, these studies have been carried out in three categories: based on observation data, experimental data and analytical based procedure. Hwang and Huo (1994) [4] displayed an analytical method to show fragility curves based on numerical simulations of the dynamic behavior of specific structures. One of the specific studies is presented by Barron et al. (2000) [5]. They applied fragility curves to evaluate various structural retrofitting techniques. By comparing damage exceedance of each technique, the appropriate one is selected. Furthermore by this method, one can see the influence of retrofitting on decreasing the probability of damage exceedance.

The main point of all categories and studies is to employ fragility curves for evaluation of existing structures under earthquake excitation. In this research, a new approach is developed. In this method, fragility curves are applied to evaluate structures while designing. To accomplish this goal, several structures are designed by various famous and usual codes.

To make final decision among codes, life-cycle cost analysis (LCCA) is utilized. This is a useful tool in economic analysis that exploits damage ratios and fragility curves tools together in order to make final decision for a proper code selection. To strike a balance between the initial cost and potential large losses over the buildings' lifetime, the lifecycle cost needs to be carefully considered. In Lagaros and fragiadakis (2011) [6] research to evaluate ASCE-41, ATC-40 and N2 static pushover methods based on optimally designed buildings. In this research, this process is used for comparison and evolution optimization algorithm. They concluded that depending on the design method employed, the increase in construction cost does not always mean that seismic safety is further increases.

In the current procedure, first of all, with respect to the actual behavior of elements in earthquake and by applying

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seismic code provisions, two squads of structures have been designed. In the next step, for nonlinear dynamic analysis of structures, sufficient group of records are selected. Next, by nonlinear dynamic analysis of structures, fragility curve of structures are developed. By these consequences LCCA are performed to make a proper decision. Finally, the results of all analyses and the fragility curves are concluded and discussed.

II. Fundamental Theoryes Procedure for Paper

A. Fundamental of Fragility Curve Formulation

To achieve fragility curves, damage distribution of structures should be assumed by calculating mean and variance; furthermore, for each level of damage criteria, the probability of damage exceedance should be produced. Hwang HHM, Huo JR, 1994(1994) [4], used cumulative absolute velocity, CAV and described probability(PF_{ij}) of damage exceedance from i^{th} damage level, for an earthquake with equal CAV v_j as follows:

$$PF_{ij} = prob\left(DT \geq DT_i \middle| CAV = v_j\right) = F_{DT}(DT_i|CAV = v_j) \quad (1)$$

Where DT is damage index and F is the function of the probability distribution. By considering normal distribution PF_{ij} derivate as:

$$PF_{ij} = 1 - \Phi\left(\frac{Ln(DI_i) - \overline{Ln(DI)}}{\sigma_{Ln(DI)}} \middle| CAV = v_j\right) \quad (2)$$

It is important to know that the PGA can be utilized instead of CAV as seismic parameter.

B. Life-cycle Cost analysis

Total cost expressed as a function of time and the design vector by Wen at al (2001) [7] as follows:

$$C_{TOT}(t,s) = C_{IN}(s) + C_{LS}(t,s) \quad (3)$$

Where C_{IN} is the initial cost of a new or a retrofitted structure, C_{LS} is the present value of the expected limit-state cost; s is the design vector corresponding to the design loads, resistance and material properties and t is the time period.

Based on the Poisson model of earthquake occurrence and the assumption that after a major damage-inducing seismic event, the building is immediately retrofitted to its original intact conditions, Wen and Kang [7,8] proposed the following formula for the expected life-cycle cost considering N damage states:

$$C_{LS}(t,s) = (\nu/\lambda)(1 - e^{-\lambda t}) \sum_{i=1}^{N} C_{LS}^{i} P^{i} \quad (4)$$

$$P(\theta_{max} > \theta_{max}^{i}) = (-1/t)\ln\left[1 - \bar{P}(\theta_{max} > \theta_{max}^{i})\right] \quad (5)$$

$$P^{i} = P(\theta_{max} > \theta_{max}^{i}) - P(\theta_{max} > \theta_{max}^{i+1})$$

Where P^i is the probability of the ith damage state of building subjected the occurrence of an earthquake. Assumed the maximum inter storey drift θ_{max} as the characteristic demand. Finally, ν is the annual occurrence rate of earthquakes modeled as a Poisson variable. In this research, life time obtained 100 years for hospitals and 50 years for office buildings and λ assumed 5%.

III. Structural Models

To prepare structural models, two squad of structure were designed. These buildings have 3and 7 storey which they have 4 bays. The first squad is hospital buildings which have very high important factor with high ductility. The second squad is ordinary office buildings with medium importance and intermediate ductility. Weight loads are extracted from usual details for office and hospital buildings.

Earthquake design loads and control parameters are taken from earthquake code provision of IRAN (2800 standard [9]). Hazard level is assumed as the highest earthquake hazard, (PGA=0.35g). The probability of occurrence of an earthquake with this PGA is 10% in 50 years. The purpose of designing in this standard for very high important buildings such as hospital buildings is similar to IO performance level in FEMA356. For intermediate important buildings such as office buildings, the purpose of designing is similar to LS performance level defined in the FEMA356.

Each squad of buildings is designed by ACI318-89 [10], ACI318-08/IBC2009 [11], British code (BS97) [12], Iranian national institute chapter nine (INI9) [13] and EURO042004 [2]. For nonlinear dynamic analysis, 23 scaled earthquake records are chosen by considering the type of soil division adapted to design properties. To scale these records, power spectra response is applied as shown in figure 1.

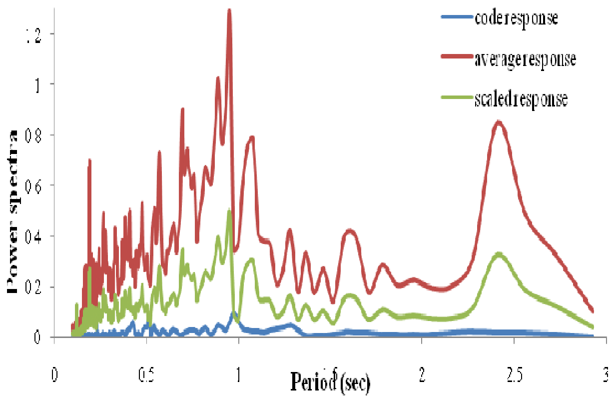


Fig. 1 Diagram of scaling procedure with power spectra

To design the structures, a general finite element program is employed and for nonlinear dynamic analysis of structures under earthquake excitation, open source software, IDARCV7.0 [14] is utilized. Section dimension of elements are calculated based on drift limitation, and bar quantities and distributions are designed based on codes relations. Bars quantity and distributions of designed buildings are shown in table I and II.

TABLE I
Bars Quantity and Distribution in Hospital Buildings (KG)

STOREY		ACI318-89	ACI318-08	INI9	EURO04	BS97
3	Beam	2183	2306	2289	2081	2357

	Col.	3995	3993	3328	3993	3993
	Sum.	6178	6299	5617	6074	6350
	Beam	5864	6323	5830	5601	6062
7	Col.	8344	9054	7143	7143	7704
	Sum.	14208	15377	12973	12744	13766

TABLE II
BARS QUANTITY AND DISTRIBUTION IN OFFICE BUILDINGS (KG)

STOREY		ACI318-89	ACI318-08	INI9	EURO04	BS97
	Beam	2162	2238	2204	1967	2264
3	Col.	3140	3140	2588	2588	3140
	Sum.	5302	5379	4792	4555	5404
	Beam	6138	6144	5950	5734	6415
7	Col.	7489	9446	6273	6273	8696
	Sum.	13636	15590	12223	12006	15111

Based on the world normalized payments, total cost of construction new buildings are showed as table 3 & 4:

TABLE III
TOTAL COST OF CONSTRUCTION OF HOSPITAL BUILDINGS ($)

STOREY	ACI318-89	ACI318-08	INI9	EURO04	BS97
3	12650	12820	11870	12510	12890
7	31390	33030	29670	29359	30780

TABLE IV
TOTAL COST OF CONSTRUCTION OF OFFICE BUILDINGS ($)

STOREY	ACI318-89	ACI318-08	INI9	EURO04	BS97
3	8770	8860	8150	7870	8890
7	22770	25110	21070	20810	24540

To consider the effect of special and intermediate ductility of structures in models, hysteresis behavior model and degradation parameters have been applied. There are some types of hysteresis behavior model in IDARC program [14]. The RC frames can have several degradations in hysteresis diagrams. In general cases, these degradations included stiffness, strength and pinching. In this research, three parameter Park model (1987) for beams and column is employed. According to intermediate and special details and provisions, two hysteresis diagrams are selected from Washington site [15].

IV. RESULTS

A. Hospital Buildings

Nonlinear dynamic analyzes of hospital buildings displayed that they approximately have target performance adapted to IO damage level. In accordance with the defined damage levels in FEMA356 [16] for the RC frames, the levels of drift ratios are displayed as table 5.

TABLE V
DRIFT RATIO OF DAMAGE LEVEL OF RC FRAMES IN FEMA356

	Immediate Occupancy (IO)	Life Safety (LS)	Collapse Prevention
Drift ratio	1%	2%	4%

This performance level is expected from the design purpose. Limit-state parameters for cost evaluation based on Ghobarah [17] categories are expressed in FEMA227 [18]. Table 6, based on FEMA 356 and FEMA 227 parameters, expressed cost evaluation for each damage level:

TABLE VI
COST EVALUATION OF EACH DAMAGE LEVEL BASED ON FEMA356 AND FEMA227

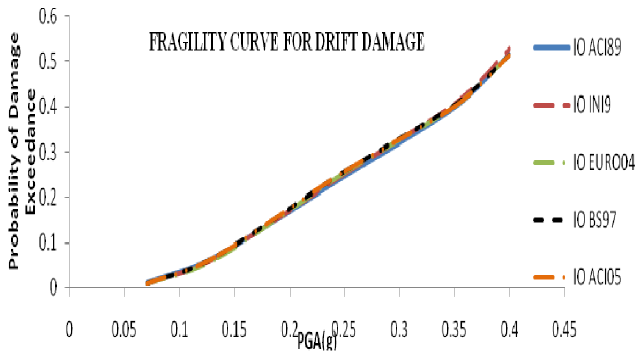
	Immediate Occupancy (IO)	Life Safety (LS)	Collapse Prevention
Drift ratio	1%	2%	4%
Mean damage index (%)	20	45	80

Average of maximum drift ratio of hospital buildings under earthquake excitation are displayed in table 7.

TABLE VII
AVERAGE OF MAXIMUM DRIFT RATIO OF HOSPITAL BUILDINGS

STOREY	ACI89	ACI05	BS97	INI9	EURO04
3	1.01	1.01	1.02	1.03	1.02
7	1.14	1.22	1.24	1.24	1.21

Results displayed that in general cases, they have drift ratio near 1%, which is IO level. The IO damage level is precisely the level of target design of hospital buildings. The comparison between standard codes reveals that ACI318-89 has approximately the best results in drift ratio. All the other results are nearly similar. For verification of these results, the fragility curves are investigated for each building. Figure 2 and 3, displayed the fragility curves of these buildings.



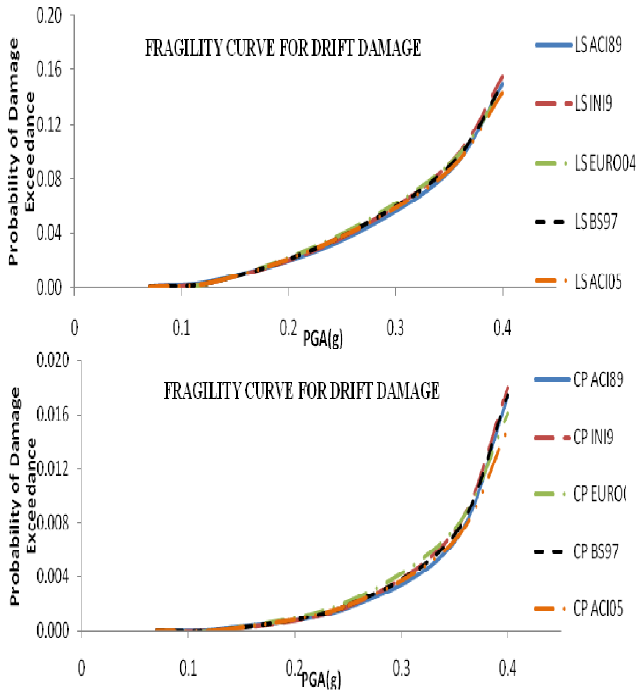
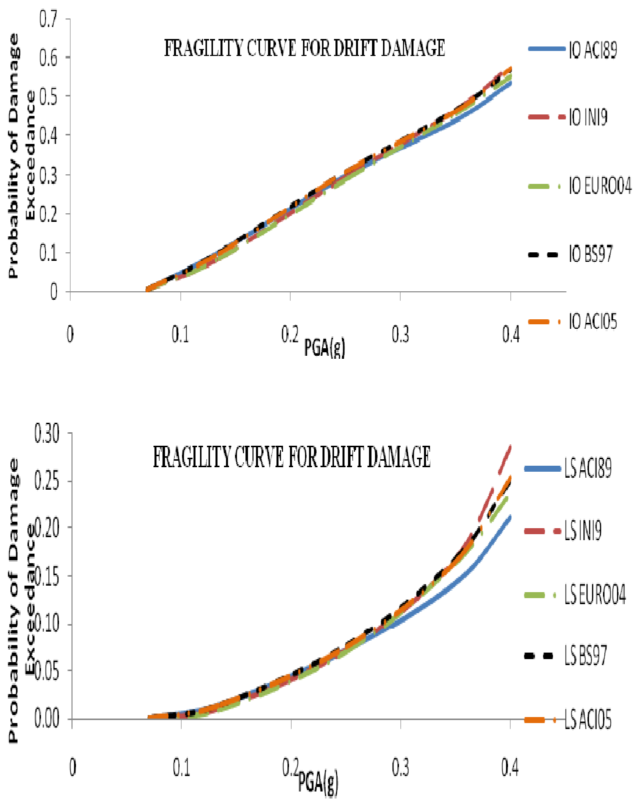


Fig. 2 Fragility curves for drift damage for 3 storey hospital building



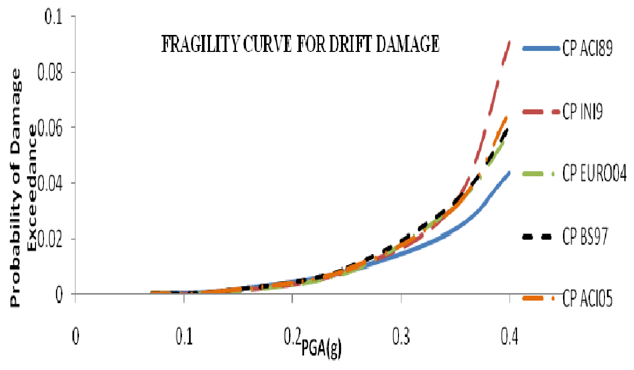


Fig. 3 Fragility curves for drift damage for 7 storey hospital building

Such as table of maximum drift ratios, buildings which are designed by ACI318-89 have the lowest probability of damage exceedance Results further displayed that ACI318-08 and EURO042004 codes have usually higher probability of damage exceedance compared to other codes

The comparison between bar weighs of designed building indicated that BS97 and ACI codes frequently have heavier bars compared to other codes. However it did not assure that they have lower probability of damage exceedance. Hospitals that are designed by BS97 always have low probability of damage exccedance, however buildings that are designed by ACI code have occasionally higher probability of damage exceedance.

The comparison between the bar distributions shows that in fixed total quantity of bars, the hospitals with higher quantity of beam bars have lower probability of damage exccedance which is expected. Due to the high ductility of buildings under earthquake excitation, beams work in high range and the maximum crack and plastic rotations lie in beams. In addition, in philosophy of hospital design, the RC frames should be designed in such conditions that in frame joints the total strength of columns should be higher than the total strength of beams.

The results which utilized fragility curves in life-cycle cost analysis are displayed in table VIII:

TABLE VIII
LIFE-CYCLE COST ANALYSIS OF HOSPITALS ($)

STOREY	ACI318-89	ACI318-08	BS97	INI9	EURO04
3	17900	18190	18370	16950	17830
7	48400	52910	49590	47740	46860

For final justification between codes, it can be stated that INI9 code is the proper code to design hospital buildings. Since the designed buildings have always performance index such as other codes, the probability of damage exceedance is always in low range. Moreover in comparison among all codes, quantities of their designed bars always are confined in the minimum ranges. By comparison between life-cycle cost analyses, it is evident that INI9 and EURO04 have the lowest total cost compared to others. However, with respect to life cycle cost performance point and fragility curves together, hospitals are designed by INI9 which are in a proper situation.
In the comparison between INI9 and ACI codes, buildings designed by the ACI codes have lower drift ratio and probability of damage exceedance; however, this advantage is

neglected because this advantage changes between ACI318-89 and ACI318-08 codes and the bars quantity of each building is designed by preference ACI code which is much higher than buildings designed by the INI9 code. To transform this quality comparison to quantity comparison, the life cycle analysis is utilized. These analyses are clarified so that the total cost of hospitals designed by INI9 is lower than hospitals designed by ACI codes.

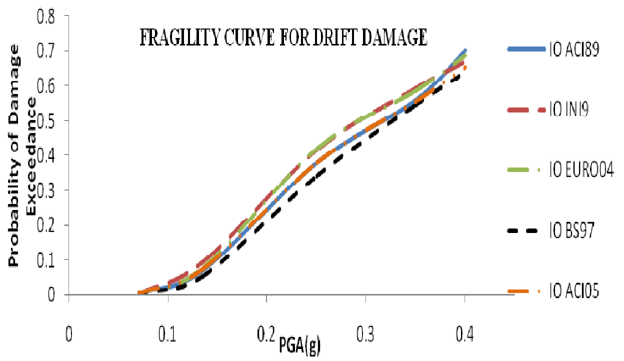
B. Office Buildings

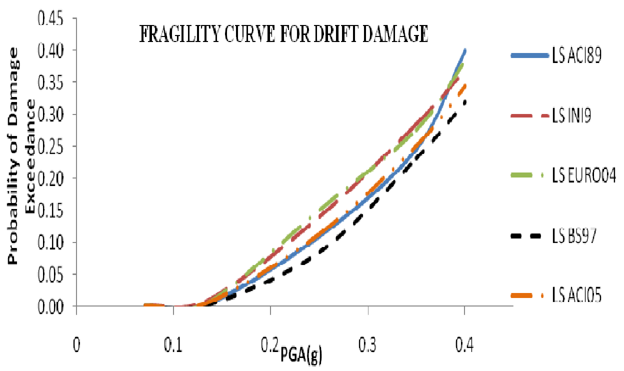
Nonlinear dynamic analyzes of office buildings displayed that they approximately have target performance adapted to LS damage level. The average of the maximum drift ratio of office buildings under earthquake excitation are displayed in table 9.

TABLE IX
AVERAGE OF MAXIMUM DRIFT RATIO OF OFFICE BUILDINGS

STOREY	ACI318-89	ACI318-08	BS97	INI9	EURO04
3	1.58	1.62	1.50	1.76	1.71
7	1.31	1.26	1.30	1.79	1.40

Results revealed that in general cases, they have drift ratio near 1.5%, which is the LS level. The LS damage level exactly is the level of target design of office buildings for design purpose. The comparison among standard codes shows that ACI318-08 and BS97 approximately have the best results in drift ratio. Other results of designed buildings are nearly similar. For verification of these results, the fragility curves are investigated for each building. Figure 4 and 5 displayed the fragility curves of these buildings.





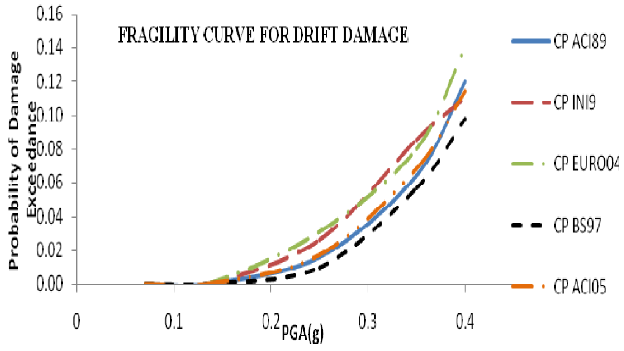
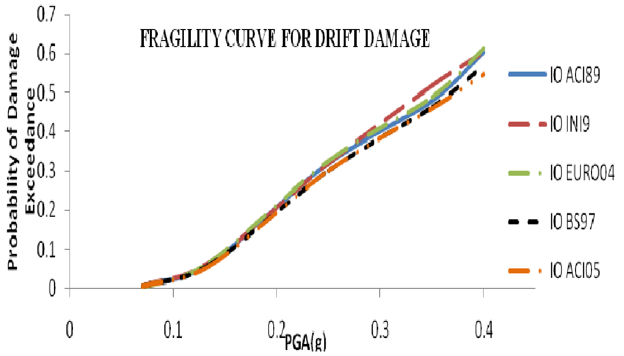
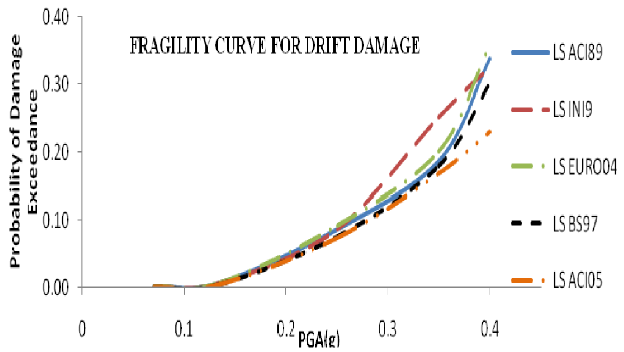


Fig. 4 Fragility curves for drift damage for 3 storey office buildings





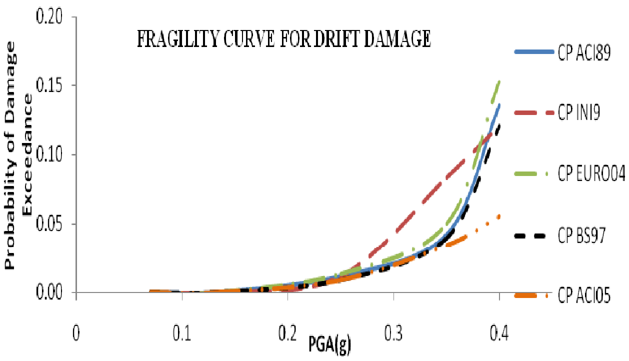


Fig. 5 Fragility curves for drift damage for 7 storey office buildings

Similar as the table of the maximum drift ratios, buildings which are designed by the ACI318-08 and BS97 have the lowest probability of damage exceedance. The comparison among bar quantities in designed office buildings reveals that the fix sequence ACI08>BS97> ACI89>INI9> EURO04 exist. In addition, the comparison among bar distributions shows that significant difference between total quantities of bars lies in column bars. The results displayed that the office buildings which have more quantity of bars further have lower probability of damage exceedance. Consequently, it can be resulted that by increasing the column bars in intermediate ductility buildings, one can reduce the damage index and probability of damage exceedance of such buildings. This building has beam bar quantity equal to other designed buildings; however the quantity of column bar is very lower compared to the others. This distribution makes the damage index approximately similar to the damage index of other designed buildings but the probability of damage exceedance of this building especially under high hazard of earthquake occurrence is much higher compared to the others.

The results obtained from the fragility curves of office buildings employed in life-cycle cost analysis are displayed in table 10:

TABLE X
LIFE-CYCLE COST ANALYSIS OF OFFICE BUILDINGS ($)

STOREY	ACI318-89	ACI318-08	BS97	INI9	EURO04
3	12120	12310	12130	11700	11200
7	29690	32170	31730	29270	27510

To make the final decision, EURO04 code can be selected as the optimum code to design office buildings. Since the designed buildings have always performance level and probability of damage exceedance, they always lie in medium range. However, in comparison among all codes, quantities of their bars always are in minimum quantity. It is evident that with life cycle analysis the higher damage in performance points and the higher probability of damage index exceedances can be neglected because of the lightweight bar designed by this code. In the comparison among codes displayed that there is an invert sequence for life cycle cost versus the sequence of damage point and the probability of damage exceedance. This means that occasionally the cost of increasing in initial construction of buildings is much higher than the repair costs and it does not mean that the increase in initial cost will lead to high redundancy in damage point and probability of damage exceedance

V. CONCLUSION

To design RC frames, codes have several similar provisions to detail elements. The main difference parameter among codes includes load combination and reduction factors of bending, torsion and shear capacity relations.

For performance verification of seismic codes, the damage quantity of the RC frames is compared with the target performance. Due the main innate of designing structures under seismic excitation is probabilistic; the evaluation of structures cannot be concluded if all these uncertainties are neglected. In this paper, a new approach is developed to verify the performance of seismic codes by utilization of fragility curves. For making final decision the life-cycle cost analysis is performed. Two squad of structure were designed by ACI318-89, ACI318-08, British code (BS97), Iranian national institute chapter nine (INI9) and EURO042004. Afterwards, each squad of buildings is nonlinear dynamic analyzed. A brief conclusion of hospital buildings are described as:

1) Hospital buildings have drift ratio near 1%, which is IO level which is exactly the level of target design of hospital buildings.
2) Such as the table of the maximum drift ratios, buildings which are designed by ACI318-89 have the lowest probability of damage exceedance. Furthermore, the results displayed that ACI318-08 and EURO042004 codes have usually higher probability of damage exceedance compared to the other codes.
3) The comparisons indicated that heavier bars designed by a code compared to other codes did not assure that have lower probability of damage exceedance.
4) The comparison among bar distributions shows that in the fixed total quantity of bars, hospitals with higher quantity of beam bars have lower probability of damage exccedance.
5) For final justification among codes one can say that INI9 code is the proper code to design hospital buildings. Since the designed buildings have usually low drift ratio with probability of damage exceedance, they normally lie in low range that includes quantities of their designed bars which are restricted in minimum ranges. With respect to the life cycle cost analysis with performance point together, the fragility curves displayed that the advantage of the low cost of the initial cost of construction of hospital buildings in INI9 code is higher than little increases in damages and probabilities.

The conclusion of office buildings described as:

1) Approximate 1.5% drift ration which is extracted from nonlinear dynamic analysis of office buildings showed LS performance level for these designed buildings which is exactly what is expected in design of office buildings.
2) The same as the table of the maximum drift ratios, buildings which are designed by ACI318-08 and BS97 have the lowest probability of damage exceedance.
3) The comparison among bar quantities in designed office buildings shows that there is a fix sequence ACI08>BS97> ACI89>INI9> EURO04; the same as in comparison between probability of damage exceedance of designed buildings.
4) The results indicated that by an increase in column bars in intermediate ductility buildings one can reduce the damage index and probability of damage exceedance of such buildings.

5) To make the final decision, EURO04 code can be selected as optimum code. However buildings designed by this code have damage in performance point and probability of damage exceedance in medium range; however, the advantage of the low cost of the initial construction of these office buildings is highly significant compared to the total cost of construction and repair of these buildings. Consequently, the office buildings designed by EURO04 have the lowest total cost compared to the other designed office buildings.

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