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Probabilistic seismic assessment of concrete frame with mass irregularity

Вероятностная сейсмическая оценка бетонной конструкции с неоднородностью массы

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Ключевые слова: вероятностная оценка; специальная бетонная рамка; неоднородность массы; хрупкость

Abstract. As mass irregular structures are more influencing on the behavior of the structures, it is investigated the effect of these irregularities according to the probabilistic approach. Comparison of seismic performance of ten regular and irregular 6-story concrete special moment frame is done, based on the Mean Annual Frequency (MAF) method. The probability of collapse in all irregular models has exceeded the 1 % that is permissible value specified in the ASCE/SEI 7-16. The largest rate of increase in the probability of exceedance the collapse limit state in 50 years, is about 34.1 % in mass irregular structures. Also the results of this study have indicated that both the level of irregularity and the location of irregularity in height is effective in the probability of exceedance the collapse. It should be noted that the critical story in the mass irregular structures is the top story (fifth story).

Аннотация. Поскольку конструкции с неоднородностью массы влияют на работу сооружений, было исследовано влияние этих неоднородностей вероятностным методом. Сравнивались сейсмические характеристики десяти однородных и неоднородных бетонных рамок. Вероятность разрушения в моделях с неоднородной массой составляет более 1 %, что является допустимым значением, указанным в ASCE / SEI 7-16. Вероятность возможного превышения предельного состояния разрушения через 50 лет составляет около 34,1 %. Кроме того, результаты исследования показывают, что степень, а также положение неоднородности по высоте эффективны при вероятности превышения состояния разрушения.

1. Introduction

The uncertainties in modeling and designing of structures as well as the probabilistic nature of earthquake, cause probabilistic methods to evaluate the seismic response of the structure. The experience of past earthquakes shows that one of the major reasons of failure of a building during an earthquake is the existence of non-geometric vertical irregularity along the height. Various applications of a story with respect to the bottom or top story of it, result in changing dynamic characteristic, e.g. mass, stiffness and strength of these structures.

One common type of irregular structures which is important to investigate its seismic behavior is mass irregular structures. The most seismic provisions [1–4] have similar definitions for the mass irregularity. When the ratio of the mass of a story in the mass of upper or lower of that story is more than 150 %, the mass irregularity is occurring. The point to be considered in this definition is that there is no mention of the effect of the irregular amount and the location of irregularity in height of structures. This can be seen as a deficiency in expressing the rules of the regulations for these irregular structures. It should be noted that research on the effect of irregular structures on the seismic capacity of structures is less than the effect of irregular structures on the seismic demand of structures. In order to evaluate the collapse capacity of irregular structures, the use of a collapse behavior model of the elements with respect to the probabilistic process as well as Incremental Dynamic Analysis (IDA) can be effective. Various methods have been developed to evaluate the probabilistic response of structures. One of the important researches in this field is done by Cornell et al [5–6] over the years. A large part of these studies are compiled by

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Jalayer [7]. Ibarra et al [8] carried out comprehensive studies on the collapse behavior of model of structures. In this regard, the studies of krawinkler et al [9–11] are of great importance. They were able to provide a systematic approach to assess collapse capacity and the collapse margin ratio using Incremental Dynamic Analysis (IDA). Various investigations carried out in the field of the seismic behavior of irregular structures. Martel [12] for the first time introduced the idea of a soft story as one of the basic methods of base isolation. Then this topic studied further by Green [13] and Jacobson [14]. In the above research, no damping did not consider for the system and the behavior of the columns of the first story (soft story) assumed to be elastic. Investigations on the vertically irregular buildings started at in the early 1970s. Fernandez [15] showed that the seismic performance of irregular structure is weaker than the regular one. Moehle [16] discussed the importance of the irregularity location in height in the seismic response in addition to the extent of structural irregularity. Valmundson and Nau [17] assessed the seismic behavior of the mass, stiffness and strength irregularities. They identified that the effect of the mass irregularity is less in comparison to the stiffness and strength irregularity on the seismic performance of the structure. Al-Ali and Krawinkler [18] carried out the elastics and inelastic dynamic analysis to study the effect of the vertical mass irregularities on the seismic response of 10-story frames. The result showed that the mass irregularities have insignificant effects on the seismic performance. The most variation in the story drift occurred in the case that the location of mass irregularity along the height, was in the top story. Magliulo et al. [19] considered the impact of mass, stiffness, strength irregularity in an RC frame. The result showed that mass irregularity did not influence the plastic demands. Chintapakdee and Chopra [20] studied the effect of the vertical irregularity on the seismic response. Combined irregularities, especially when placed in the bottom story had the maximum impact on the seismic performance. Choi [21] considered three models with mass irregularities that located in different height along the studied structures. The result stated according to the drift and the hysteric energy demands. The maximum influence of mass irregularity was in the case that the heavier story was located in the top story. Tremblay and Poncet [22] obtained the design forces and displacements using the equivalent static analysis and dynamic analysis approach that was based on Canadian design code 2005, compared for 4,8,12 and 16 story frames and considering the irregularity along the height. Mass changes of these frames were suddenly and with 200 and 300 percent ratio along the 25, 50 and 75 percent of the structure height. The story shear forces, overturning moments and story drifts obtained from the equivalent static analysis are greater than the ones of the dynamic analysis. Fragiadakis et al. [23] performed Incremental Dynamic Analysis (IDA) on the stiffness and strength irregular steel structures. They concluded that the structural capacities considerably depend on the type of irregularities, the location of irregularity along the height and the intensity of the earthquake. Ayidin [24] assessed mass irregularity using the Equivalent Lateral Force procedure, linear and nonlinear dynamic analysis. Comparison of the results that obtained from the three above mentioned, showed that the ELF method could not estimate the seismic response with reasonable accuracy. Sarkar et al. [25] determined irregularity index in setback building frames. Based on the irregularity index an equation proposed to calculate the fundamental period of a setback frame. Montazeri et al. [26] studied on dynamic properties of low and midrise of setback buildings. The result showed that existence of geometic irregularities affect considerably on the fundamental period and effective modal masses. Pirzade and Shakib [27] evaluated the seismic performance of steel MRFs with non-geometric vertical irregularities, using probabilistic-based approach. The result showed that non-geometric vertical irregularities have an effect on seismic response, particularly at the limit state around the collapse up to global dynamic instability. Habibi and Asadi [28] studied the seismic performance of concrete MRFs with irregularity in height using nonlinear time history analysis. According to their research existence of irregularity in height caused to that requirement of life safety performance was not satisfied. Also the result showed that the most damage was close to the location of irregularity. Varadharajan et al. [29] proposed an index to measure mass, stiffness and strength irregularity in terms of both extent and placement of irregularities according to the dynamic specification of the building. Manie et al. [30] focused on the collapse behavior of the low-rise plan-asymmetric buildings. The seismic behavior of these buildings investigated based on the Collapse Margin Ratio (CMR) and the probability of collapse. The result showed that the collapse behavior of the low-rise plan-asymmetric buildings was considerably differ from a regular one. Zhou et al. [31] evaluated the stiffness and strength irregularity factor, according to the Monte Carlo simulation procedure. The results showed that by decreasing the stiffness and strength irregularity factor the exceeding probability increased. It determined that the irregularity factor of 0.7 is a reasonable limit for both the strength and stiffness irregularity. Akhavan et al. [32] investigated the behavior of vertical irregular steel frame using IDA analysis. Due to the results, it observed that soft story had significant influence on fragility curve. Fanaie and Kolbadi [33] assessed the effect of mass irregularity in height on over strength, ductility, response modification factors and probabilistic seismic performance in steel MRFs. Based on the obtained results mass irregularity led to the reduction of ductility and increased the probability of damage. The major previous researches on the seismic response of the structures with vertical irregularity have been deterministic that they generally have aimed to calculate the mean values of peak responses. At present, a large number of works are devoted to studies of seismic resistance of irregular structures [34–38]. At the same time, methods for assessing the seismic safety of buildings with irregularity have not been studied sufficiently and need to be improved. The seismic behavior of the structure due to available uncertainties, is probabilistic rather than deterministic. Probabilistic point of view, is a significant issue among earthquake engineers and researches. However, although the probabilistic assessment of the collapse capacity of a structure is studied in recent researches [39], little attention is paid to evaluate of RC moment resistant frames with mass irregularity in height using this approach. The main purpose of this study is to investigate the probabilistic seismic performance of RC moment resistant frames with mass irregularity in height according to the Mean Annual Frequency (MAF) method. To do so the Incremental Dynamic Analysis (IDA) is conducted. Fragility curves are demonstrated for regular and irregular structures to identify the probability of collapse of the considered structures. According to the fragility curves, the collapse capacity of the structure is calculated for each model. Based on the MAF of collapse method, the probability of exceedance the collapse limit state in 50 years is determined. This probability is compared with the 1 % that is permissible value specified in the ASCE/SEI 7-16 [1]. Thus, the probabilistic evaluation is done by the MAF of collapse.

2. Methods

2.1. Introduction of regular and irregular models

In order to quantify the mass irregularity effect on the seismic performance of concrete SMFs, ten concrete special moment-resisting frames involved one regular and nine irregular frames were considered as discussed below.

The regular building is assumed to be a 6-story which was designed according to Iranian national building code (part 9) [40]. As shown in Figure 1, the concrete building models have rectangular plan and perimeter three-bay special concrete moment frames in x and y direction. The width of each span is 5.0 m. The height of the stories is 3.2 m. The regular building is designed for a seismic zone 1 (Tehran, Iran) which is related to the high seismic zone and is constructed on the soil type II, based on the Iranian earthquake code provisions [4], that is equivalent to type C of the IBC code division [41]. Distributed dead and live loads are 7.0 $KN/m^2$and 3.0 KN/m^2, respectively, on floors. Earthquake design loads and control parameters are taken from the Iranian seismic code [4]. Compressive strength of concrete at 28 days and rebar tensile strength are assumed to be 30 MPa and 400 MPa, respectively. The fundamental period of the reference model is T_1= 0.86 s. As illustrated in Figure 1, the perimeter frame is designed to withstand lateral load. The modelling of the structure is done two-dimensionally in OpenSees [42] which has been developed by the Pacific Earthquake Engineering Research (PEER) Center for nonlinear analyses. The inelastic behavior of elements, beam-column joints, and large deformation (P-Δ) effects is considered in the collapse analysis of structures. The concentrated springs at the Beam and column ends and the beam-column joint zone are considered that are kinematically constrained to show finite joint size effects and are connected to a joint shear spring [43]. In this method, the inelastic deformations are lumped at the ends of the element that requires assembling of three elements of the 2D model. The structure is modeled with elastic beam column elements linked with Zero Length element and the elastic section of all beams and columns that is subjected to uniformly distributed gravity loads. As shown in Figure 2, inelastic response is idealized by a tri-linear monotonic backbone curve. The hysteretic cyclic models are developed by Ibarra et al. [8].

The modelling parameters are obtained according to the modified Ibarra-Medina-Krawinkler (IMK) deterioration model [8]. Several parameters of concentrated hinges including (i) yield rotation θ_y; (ii) yield moment M_y ; (iii) the ratio of maximum to yield moment M_c/M_y; (iv) plastic hinge rotation capacity θ_{cap}^p; (v) post-capping rotation capacity θ_{pc}; and (vi) energy dissipation and capacity per cycle of inelastic response λ, are determined based on the presented equations by Panagiotakos and Fardis [44] and in the FEMA P695 [45]. A leaning column accounts for the additional seismic mass on the gravity system (P-Δ effects), but not the contribution of the gravity system to the lateral resistance of the frame. The soil–structure interaction is not considered. Rayleigh damping equal to 5% of critical damping in the first and third modes is used.

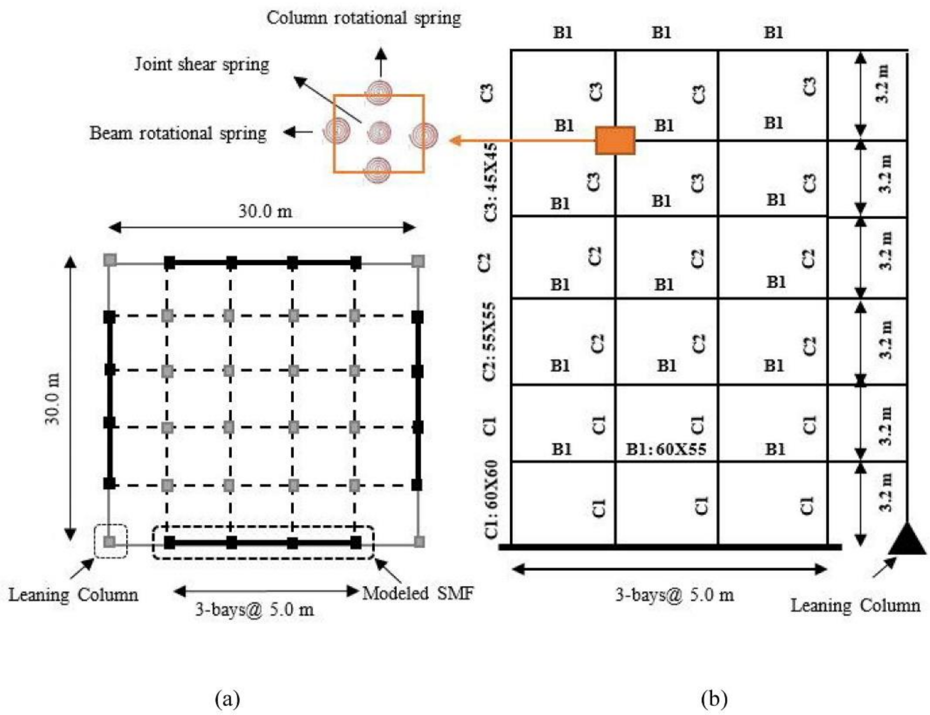

Figure 1 (a) Typical plan view of the concrete structure model and (b) Elevation of the six-story SMF

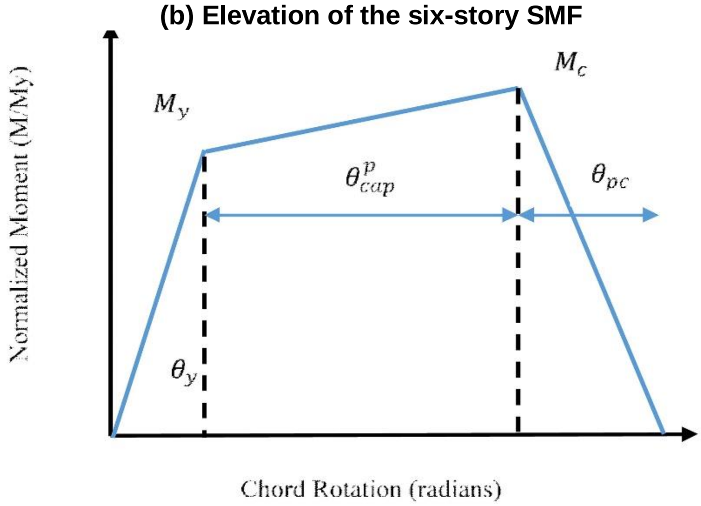

Figure 2 Monotonic behavior of component model used to model reinforced concrete beam-column elements [8]

In order to evaluate the irregularity effect, one type of irregularity considering mass (M) is assumed. Mass irregular structures studied in this paper are created by changing the distribution of mass along the regular structure height. Importance of irregularity location is considered with three different height levels, including, the first bottom story, the middle story (third story) and the top story (five story) of the structure. Three extents of mass irregularities (150 %, 200 %, and 300 %) were investigated. Irregular frames are identified so that the first letters show the type of the frame, IF show irregular and R represent regular frame. The first number represents the extent of irregularity and the letter after that show the kind of irregularity, M shows mass irregularity. The last letter shows the location of irregularity that occur in elevation. B show Bottom, M related to Middle and T show the top of height of buildings that respectively correspond to the first, third and fifth story. For example the model IF.1.5M.B implies, the irregular frame which has mass irregularity with the level of irregularity equal to 1.5 in the first story.

2.2. The Mean Annual Frequency of collapse method

The MAF of limit state exceedance, λ_{PL} is estimated using the forming Equation (1) that is adopted by the Pacific Earthquake Engineering Research Center [5]:

$$\lambda_{PL} = \int F\left((IM^c|IM)\right)\left|\frac{d\lambda(IM)}{dIM}\right|\mathrm{dIM} \quad (1)$$

Here, $F\left((IM^c|IM)\right)$ is the cumulative probability function of the intensity measure value of the limit-state capacity (IM^c) and $\frac{d\lambda(IM)}{dIM}$ is the slope of seismic hazard curve given this IM – value of limit-state capacity. Assuming power-low form of equation for seismic hazard curve ($\lambda(\mathrm{IM}) = k_0 IM^{-k}$) and log normally distributed for the IM-capacity values, Equation (1) is simplified to Equation (2) in the following way:

$$\lambda_{PL} = \lambda(IM^C)EXP\left(\frac{1}{2}k^2\beta_{IM^C}^2\right) \quad (2)$$

where $\lambda(IM^C)$ is the MAF of IM^C, k is a logarithmic slope of the approximated hazard curve and β_{IM^C} is the standard deviation of the natural logarithm of the IM -value of limit-state capacity. The seismic hazard curve of the site where the structure is located (Tehran city) is assumed according to Figure 3. Assuming the Poisson distribution for earthquake occurrence, the MAFs can be converted to the probabilities. The probability of exceedance the collapse limit state in n years, (50years) is obtained from the Equation (3).

$$P_c(n\ years) = 1 - EXP(-\lambda_{PL}n) \quad (3)$$

This probability is compared with the 1 % that is permissible value specified in the ASCE/SEI 7-16 [1]. Thus, the probabilistic evaluation is done by the MAF of collapse.

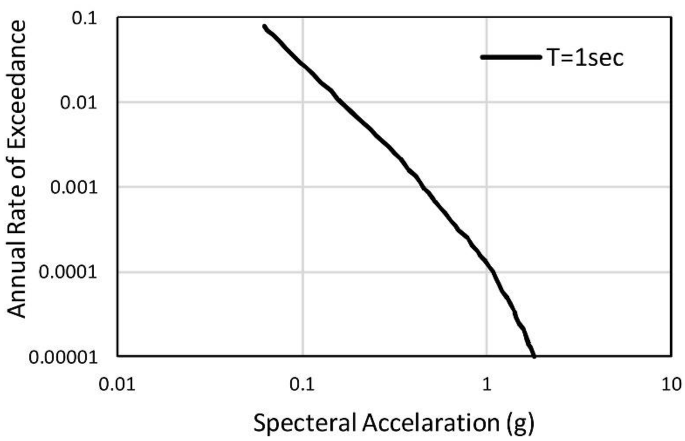

Figure 3 Seismic hazard curve [46]

3. Results and Discussion

Incremental dynamic analysis is one of the best analysis procedure available, as it can provide a precise estimate of the behavior of structure from linear elastic to collapse state. IDA includes providing a series of nonlinear dynamic analysis for each record. In this study, a set of 22 Far-Field ground motion record (i.e. a total of 44 records) specified in FEMA P695 is selected. In order to perform IDA curve, Intensity Measure (IM) and Engineering Demand Parameter (EDP) should be selected. For the purpose of this research, the IDA curves plotted using maximum inter-story drift ratio (θ_{max}) as EDP versus the first mode, 5 % damped, spectral acceleration $S_a(T_1, 5\%)$ as IM. The analyses are performed until the slope of the IDA curve became less than 20 % of its elastic slope, or until the maximum of story drift exceeds the story drift value of 0.1. In the current research, Hunt & Fill algorithm is used to optimize the number of scaling for each record. Figure 4 shows that the IDA curves along with the median, for each of the regular and irregular structures. In all mass, irregular models the median intensity measure capacities of structures are decreased for all values of θ_{max} compared with the regular structure, depending on the location of irregularity.

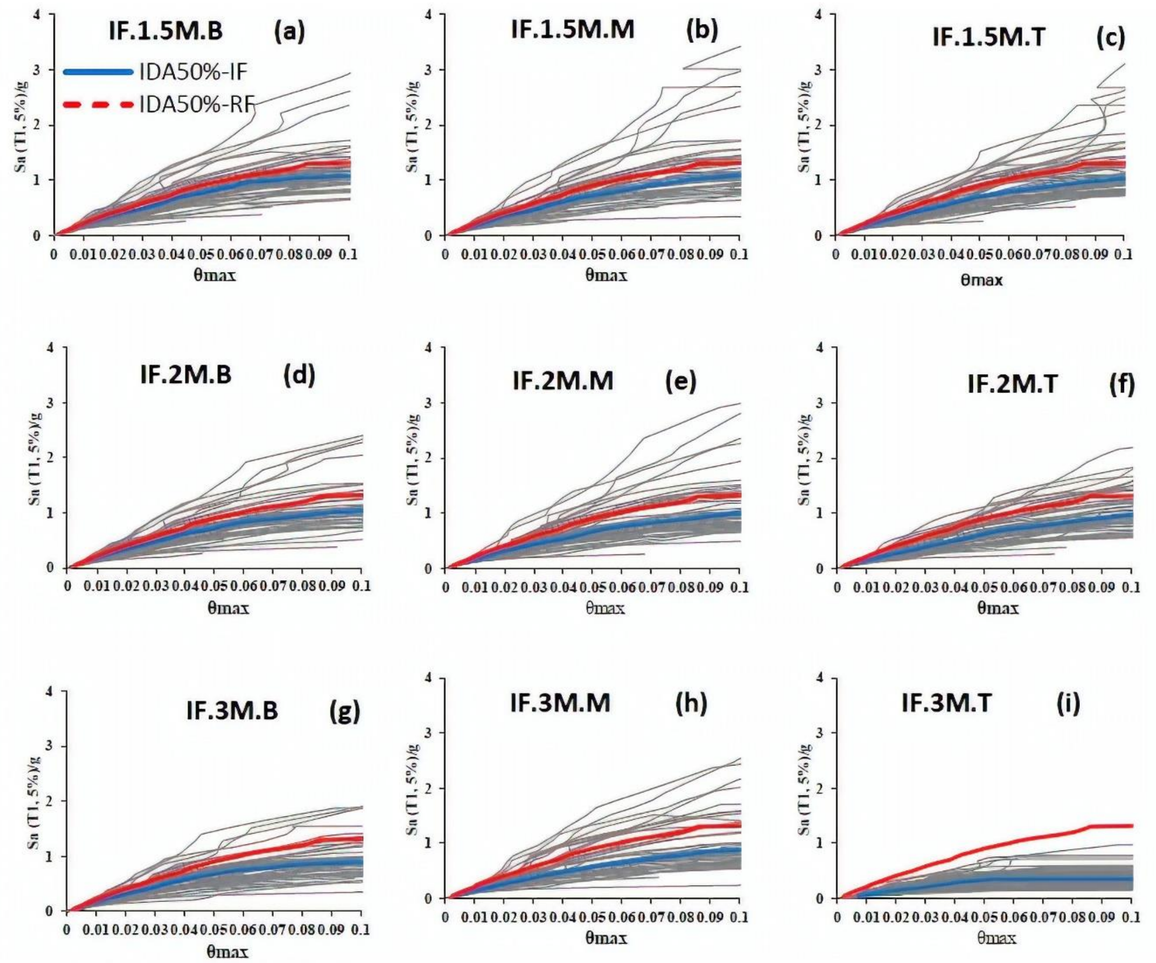

Figure 4 IDA curves along with the median, for each of the regular and irregular structures

To assess the effect of irregularity in various levels and the location of irregularity, the median of IDA curves, have been brought up in Figure 5. According to this figure, the presence of mass irregularity caused to reduce capacity of structures. For the mass irregularity models, when an irregularity occurs in the top story (five story), the reduction in capacity is more intense. When the collapse data are obtained from IDA outcomes, collapse fragility curve can be determined. Fragility curve is a statistical tool that demonstrates the relation between the ground motion intensities and the probability of a specific damage level. The most usual type of the seismic fragility function is a lognormal Cumulative Distribution Function (CDF). Fragility curves for different placement of irregularity in height of structures and for different level of irregularity are shown in Figure 6.

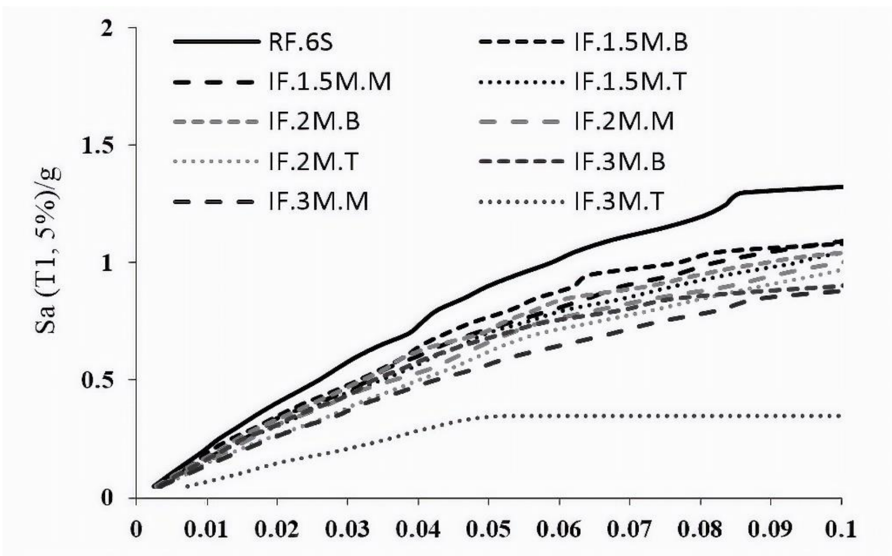

Figure 5 the median of IDA curves for each of the regular and irregular structures

Figures 6a–6c demonstrate the effect of different level of irregularity and Figures 6d–8f show the effect of different placement of irregularity in height of structures. Based on the fragility curves the median collapse intensity ($\hat{S}_{CT}$) at the 50 % level of probability on these curves, are calculated [45]. According to Figure 6 the probability of collapse of irregular structures is more than regular one. With an irregular increase in the structure, the probability of its collapse increases. The highest rate of increase in the probability of collapse of mass irregular structures occurs in the case that the irregular story located at the top story (five story).

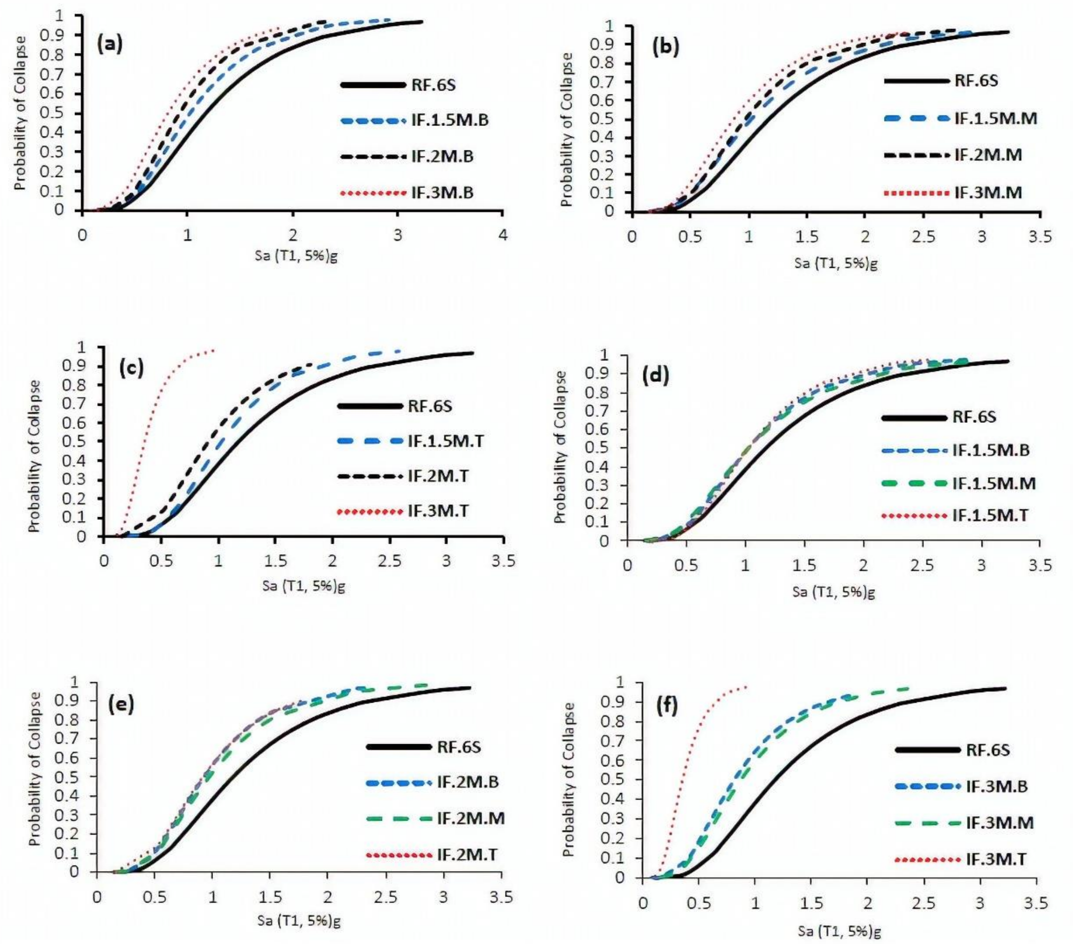

Figure 6 Comparison the effect of level of mass irregularity and also different placement of irregularity in height on the fragility curves: (a) mass irregularity located at the first bottom story, (b) mass irregularity located at the middle story, (c) mass irregularity located at the top story, (d) level of mass irregularity equal to 1.5, (e) level of mass irregularity equal to 2, (f) level of mass irregularity equal to 3

The effect of mass irregularity is compared to the MAF and the probability of exceedance the collapse limit state in 50 years. So, according to the explanation given in Section 2.2, based on the median collapse intensity and seismic hazard curve the MAF of collapse and the probability of exceedance the collapse limit state in 50 years is estimated (see Table 1). The irregular presence in the structure is caused the probability of exceedance the collapse limit state in 50 years to exceed its limit (1 %). As can be seen the probability of exceedance the collapse limit state in 50 years, for three extents of mass irregularities and different location of irregularity that is considered in this study, is different. In average, for three extent of mass irregularities that is considered in this research, the ratio of the probability of exceedance the collapse limit state in 50 years for irregular models to regular one is 2.2, 2.81 and 13.9 for irregularity located in the first bottom story, the middle story (third story) and the top story (five story) of the structure, respectively.

Table 1. The required parameters for calculating Mean Annual Frequency of collapse and the corresponding probability of collapse in 50 years for regular and irregular models

Frame	$\hat{S}_{CT}$	k	β_{IM^c}	$\lambda(IM^C)$	$e^{1/2k^2\beta^2}$	λ_{PL}	$P_{50,years}\%$
RF.6S	1.3	2.656	0.52	0.0000489	2.595414	0.000127	0.63257
IF.1.5M.B	1.10	2.656	0.52	0.0001128	2.595414	0.000293	1.453152
IF.2M.B	0.97	2.656	0.52	0.0001065	2.595414	0.000276	1.372552
IF.3M.B	0.87	2.656	0.52	0.0001088	2.595414	0.000282	1.401985
IF.1.5M.M	1.11	2.656	0.52	0.000142	2.595414	0.000369	1.82587
IF.2M.M	1.05	2.656	0.52	0.000133	2.595414	0.000345	1.711141
IF.3M.M	0.93	2.656	0.52	0.000141	2.595414	0.000366	1.813129
IF.1.5M.T	1.04	2.656	0.52	0.000214	2.595414	0.000555	2.738887
IF.2M.T	0.97	2.656	0.52	0.000176	2.595414	0.000457	2.25808
IF.3M.T	0.35	2.656	0.52	0.00187	2.595414	0.004853	21.54706

4. Conclusions

This study focused on the probabilistic seismic assessment of mass irregularity using tri-linear monotonic backbone curve for reinforced concrete beam-column elements. The results of the present study indicate that collapse behavior of such structures is more complicated and much more different in comparison with their regular one. Probabilistic seismic assessment is done using the MAF of collapse method. For this purpose, Incremental Dynamic Analysis was carried out with respect to collapse behavior. According to the main finding, the following conclusions can be drawn:

1. Based on the IDA results, the most influence of mass irregularity in reducing the capacity of structures is when an irregularity occurs in the top story (five story).

2. The collapse probability rises when the level of irregularity increase. Investigation of the probability of collapse reveals the role of location of irregularity. The probability of collapse is higher in the cases the heavier floor at the top story (five story), considering the fragility curves.

3. According to the MAF of collapse, the probability of collapse in all irregular cases has exceeded the 1% that is permissible value specified in the ASCE/SEI 7-16. It should be noted that the maximum probability of exceedance the collapse limit state in 50 years occurs when the mass irregularity located at the top story (five story).

The result show that both the level of irregularity and the location of irregularity in height affect the seismic responses of these structures. It seems that, the reconsideration of seismic code requirements for mass irregularities needs to be necessary to provide more accurate for structures with mass irregularities especially for them with an irregularity in the critical stories.

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