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Evaluating the Seismic Performance of High-Rise Steel Structures with Moment-Resistance Frames

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Abstract **– Nowadays, performance-based designing method has been introduced as an alternative to seismic designing of buildings due to increasing construction of high buildings and available inadequacies in related codes. The concept of performance-based designing is described as achieving one or more functional objectives indicating to a performance level on a specific seismic level. Therefore, some structures have been designed as moment-resistance frames according to 2800 code of Iran and steel codes. Nonlinear model of structure with definite specification have been created based on structural specifications and profiles designed in this stage. The nonlinear time history has been analyzed using earthquake records scaled to designing spectrum. Finally, the performance level of structure has been discussed comparing the quantities related to performance levels such as the relative displacements of the stories, plastic joint rotations, etc. considering the code limitations of every performance level.**

Keywords **– Vibration, DCR (Demand/Capacity Ratio), Performance Levels, Panel Zoon.**

I. INTRODUCTION

It should be mentioned that different codes designed according to performance-based designing method have common principles with different calculating methods. Therefore, different codes have the same responses in performance.

Performance-Based Earthquake Engineering (PBEE) indicates to designing, evaluating, constructing, and supervising over performance and installations of structures which should meet requirements of employers, applicants and society considering the ordinary and extraordinary forces imposed on these structures.

The performance-based earthquake engineering aims at designing structures whose performance is in accordance with the desired requirements. Intensely emphasizing on the objective may lead fail of the performance-based earthquake engineering. This is a fact that seismic requirements and capacities cannot be exactly predicted. However, there are several reasons to support the studies conducted in this regard and its application.

Earthquake engineering has undergone essential changes for several reasons including knowledge development about occurring of earthquake, earth movements, and reaction of structures. Unexpected financial loses seen in recent earthquakes of America and Japan are other reasons for these changes. The most important reason may be attributed to inadequacies of the present earthquake codes as follows:

1) The rules applied in these codes are not logically described to designer.
2) It is not possible for employers to judge about the costs and advantages of resisting against earthquake.
3) The society needs to know how to acquire seismic requirements and the possibly required capacities (indefinite, often) for constructing new structures are not satisfied.

Earthquake engineering proved that acceptance of ruination and collapse during earthquake is the most economical solution. However, it requires capability of designing engineers to predict damages for conscious decision making. To make such decisions, it is required to avoid conventional and experimental methods and move toward an evaluation and design method indicating to real behavior of structure while loads are imposed on it. Movement toward evolved methods of designing which emphasize more accuracy in design and prediction requires more advanced technologies. Considering that performance-based designing methods is a relatively new method in structures design, there are more unknown aspects and uncertainties in this method requiring more research.

In this research, three structures were initially loaded from seismic and gravitational perspective and analyzed in accordance with 2800 seismic code of Iran and chapter 6 of national regulations. Then, they were designed as special flexural frame according to chapter 10 of the mentioned regulation. At this stage, Etabs software was used for analyzing and designing. Then, the designed structures were used as input of Perform-3D software to create nonlinear models and evaluate their performance [1]. Some of scaled records of earth movement were selected for dynamically loading of the nonlinear model.

Using capabilities of Perform nonlinear software, effects of the above-mentioned earthquakes on determinant parameters of performance levels in any moment of applying accelerometer were studied and compared considering differences of the input earth movement parameters. Effects of different specifications of input records, how they are modeled, and behavioral curves used in structural performance have been discussed.

II. SELECT RECORDS

In this study, seven near-fault records for nonlinear time history analysis have been used. These records have been selected in a proper coherence. According to the soil shear wave velocity which is between the ranges 375 ≤Vs≤750

$\left(\frac{m/2}{s}\right)$, the kinds of soils records are chosen. This kind of soil is call as Type II in 2800 Iranian codes. Moreover, this kind of soil called Type B and C in USGS American codes. All selected records have been chosen from a fixed reference point and it can be almost ensured that there is uniformity and consistency. Data records can be seen in Table 1.

Table 1: Record

Acceleration (g)	Near-Fault distance (km)	Soil Type (USGS)	Magnitude (Ms)	Year	Name
0.313	8.3	C	7.2	1940	Imerial Valley
0.143	18.2	C	6.9	1979	Imerial Valley
0.132	36.1	B	7.4	1992	landers
0.274	11.6	B	7.4	1992	Landers (Joshua)
0.367	12.7	C	7.1	1989	Loma Pierta (Gilroy2)
0.215	28.2	C	7.1	1989	Loma Pierta (Hollister City Hall)
0.21	21.2	C	6.6	1971	San Fernando

III. Model of the Structures

In this research, a middle two-dimensional frame of a 25-story, 35-story, and 45-story buildings with the height of 3.2m for each storey and three openings with the lengths of 6m were selected. The structures were residential buildings (I=1) and they were supposed as very important structures (I=1.4) in an area with very high relative risk and Type II land according to 3rd edition of 2800 code. The structural system is of special steel flexural frame type figure (1).

In gravitational loading, the live and dead loads imposed on the structure equals to 200 kg/m2 and 500 kg/m2, respectively. Considering that wide of loading area of used steel materials are Fy= 2400 kg/cm2, Poisson's ratio= 0.3, and elasticity module of E=2.04×106. Lateral loading of I=1 mode on a 25-story structure was estimated as follows. Accordingly, this process was repeated for 35 and 45-story structures, too. At the second stage, the mentioned calculations will be repeated for I=1.4 mode [5, 6].

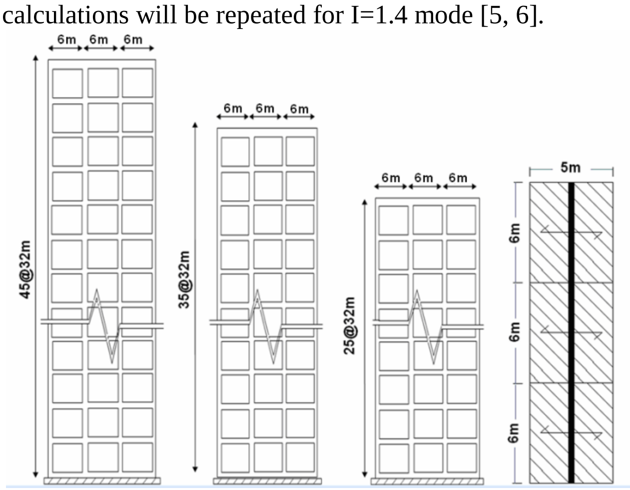

Fig.1. Dimension of understudy structures and type plan of the stories' ceilings

Frame was supposed 5m; the intensity of dead and live loads imposed on the frames' stories equals to 1000 kg/m and 2500 kg/m, respectively [2, 3, and 4]. Specifications refers to figure of the standard design spectrum of 2800 earthquake code for soil type II and area with very high relative risk (figure 2) for primary design which was acquired using spectrum dynamic analysis method, supposing linear behavior, internal forces and tensions are achieved.

Then, it was designed as special steel flexural frame according to the standards of chapter 9 of national regulations. Special standards of steel structures in seismic areas especially weak beam-strong pillar relation have been considered in designing.

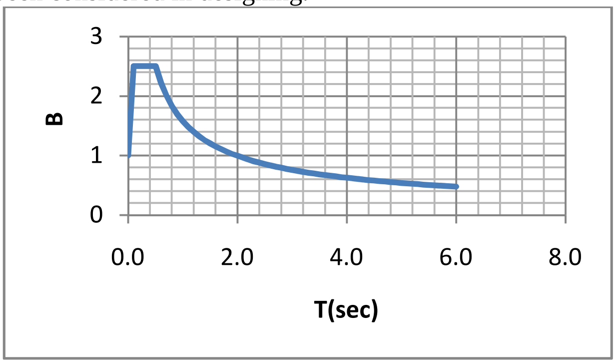

Fig.2. Standard design spectrum of 2800 earthquake code for soil type II and area with very high relative risk

IV. Displacement of Stories

The relative displacement of structures is considered as one of the qualitative parameters affecting determination of performance level and structure behavior. To evaluate the case, all relative displacement of stories were calculated as time history while applying the earthquake records. The maximum quantities of the stories' relative displacement for each story we bilaterally calculated for models during earthquake. Then, the obtained results were demonstrated the average amount of displacement figures 3 to 8.

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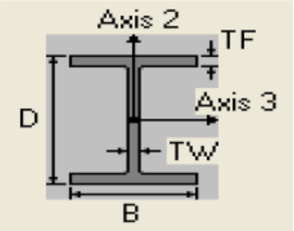
Table 2: Profiles of elements used in designing



		B (cm)	D (cm)	TF (cm)	TW (cm)	Axial Area (cm^2)	Bending Inerti about Axis 2 (cm^4)	Bending Inertia about Axis 3 (cm^4)
Profiles of columns	HD400x900	44.2	53.1	10.6	6.59	1149.2	153300	450200
	HD400x818	43.7	51.4	9.7	6.05	1043.3	135500	392200
	HD400x744	43.2	49.8	8.89	5.56	948.06	119900	342100
	HD400x677	42.8	48.3	8.15	5.12	863.41	106900	299500
	HD400x634	42.4	47.4	7.71	4.76	807.96	98250	274200
	HD400x551	41.8	45.5	6.76	4.2	701.38	82490	226100
	HD400x421	40.9	42.5	5.26	3.28	537.09	60080	159600
	HD400x237	39.5	38	3.02	1.89	300.92	31040	78780
Profiles of beams	IPEO600	22.4	61	2.4	1.5	196.76	4520.7	118300
	IPE600	22	60	1.9	1.2	155.98	3387.3	92080
	IPEO550	21.2	55.6	2.02	1.27	156.07	3224.4	79160
	IPE550	21	55	1.72	1.11	134.42	2667.6	67120
	IPEO500	20.2	50.6	1.9	1.2	136.71	2621.7	57780
	IPE500	20	50	1.6	1.02	115.52	2141.7	48200
	IPE450	19	45	1.46	0.94	98.82	1675.9	33740
	IPE360	17	36	1.27	0.8	72.73	1043.4	16270
	IPE330	16	33	1.15	0.75	62.61	788.14	11770

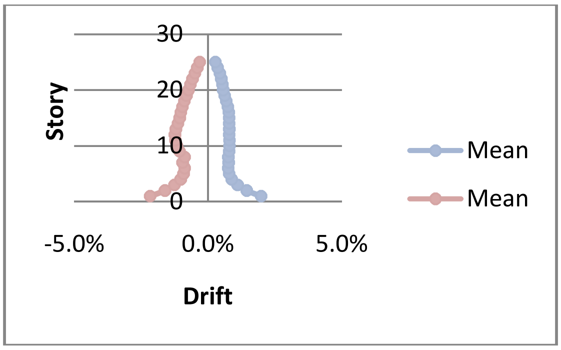


Fig.3. Mean of maximum relative displacement of stories in all seven earthquakes, 25-story structure with moderate importance

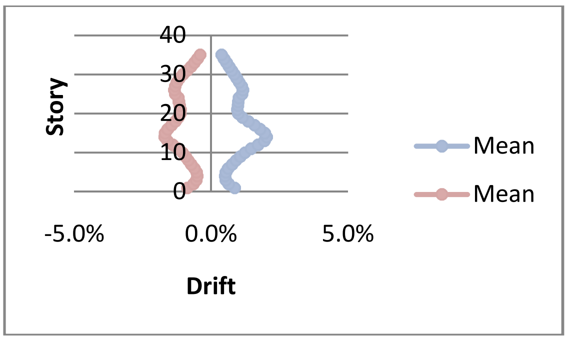


Fig.4. Mean of maximum relative displacement of stories in all seven earthquakes, the 35-story structure with moderate importance

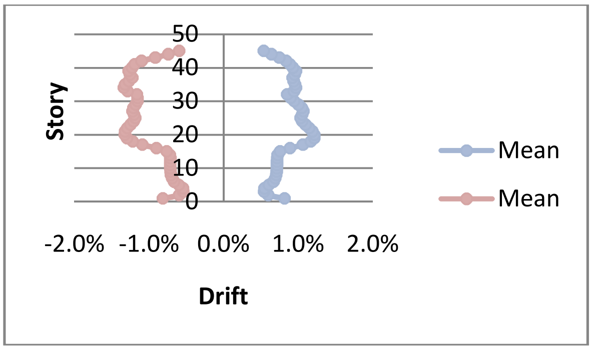


Fig.5. Mean of maximum relative displacement of stories in all seven earthquakes, the 45-story structure with moderate importance

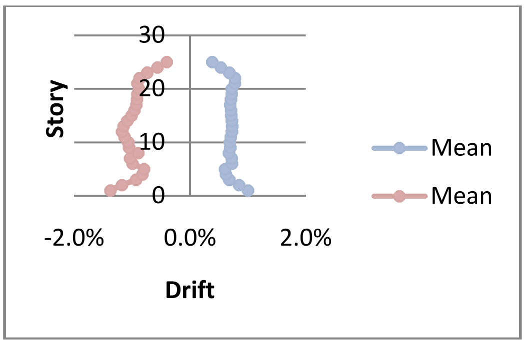


Fig.6. Mean of maximum relative displacement of stories in all seven earthquakes, the 25-story structure with very high importance

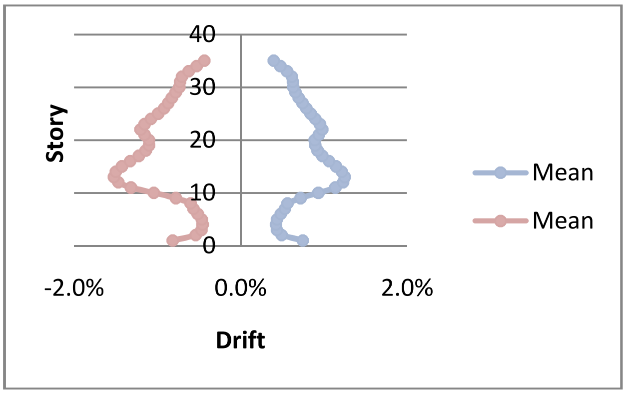


Fig.7. Mean of maximum relative displacement of stories in all seven earthquakes, the 35-story structure with very high importance

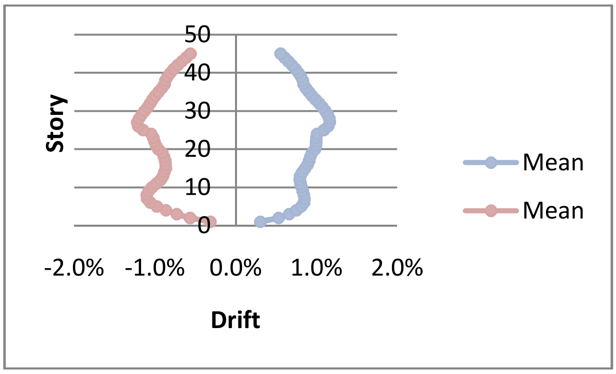


Fig.8. Mean of maximum relative displacement of stories in all seven earthquakes, the 45-story structure with very high importance

3.2 Performance Levels

The most distinguished aim of this research is studying the parameters of performance level and evaluation of performance level of designed structures. The main reason for selecting the PERFORM software for this research may be attributed to its extended capabilities in evaluation of the mentioned parameters. For this purpose, the values of plastic joint rotation in beams and columns, the shearing strain value of connection spring, and relative displacement values are calculated at any moment of earthquake. DCR (demand/capacity ratio) obtained through dividing these values by defined limit values of the software (Using table 5-4 from FEMA 273) are called application ratios. Evidently, the limited level is not exceeded, if the value is less than one. Therefore, if all ratios of the defined four parameters are less than one during earthquake, the performance level is acquired in correspondence with input limit modes.

V. The Results of Performance Levels in Structures with Moderate Importance

In 9, 10, 11, 12, 13, and 14 charts, push curve application ratios of four application ratios, plastic joint rotation of beams and columns, shearing strain of panel zone, and relative displacement of stories, during earthquake has been designed for performance level of life safety. Studying the mentioned charts initially indicates to the performance level of structures and then the changing time of each application ratio during earthquake and type of changes in content of the records which resulted in the mentioned changes. Mean values should be used in final judgment of performance level of structure.

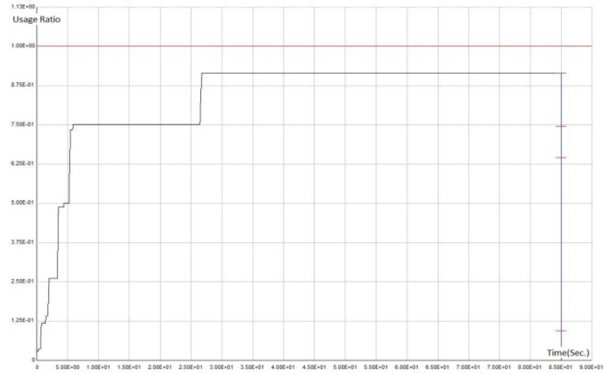


Fig.9. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the Imperial Valley earthquake (1940), for a 25-story building with moderate importance

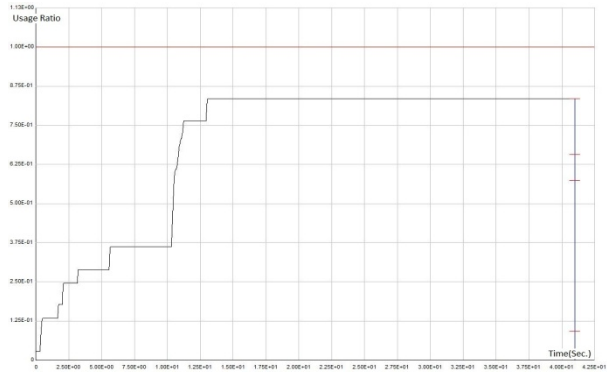


Fig.10. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the San Fernando earthquake, a 25-story building with moderate importance

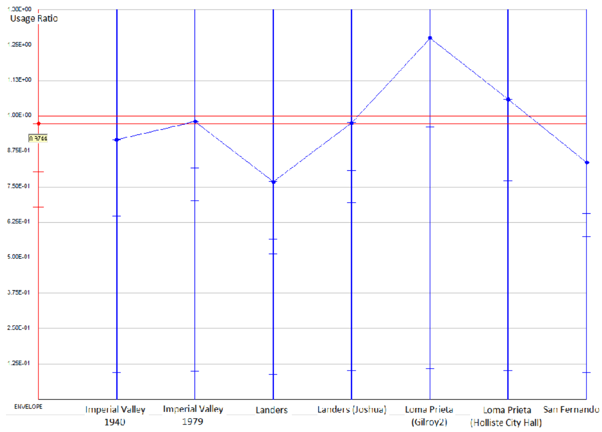


Fig.11. Mean Push of application ratios of seven earthquakes at performance level of life safety, for a 25-story building with moderate importance

International Journal of Engineering Innovation & Research
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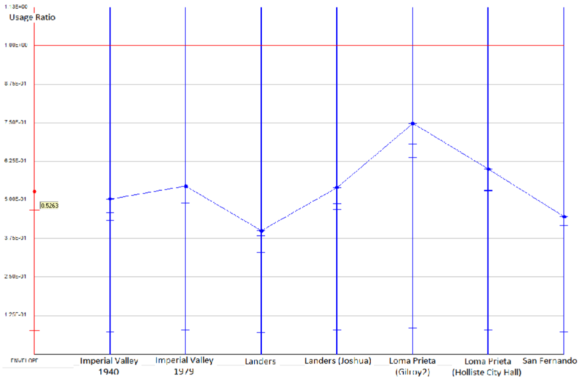

Fig.12. Mean Push of application ratios of seven earthquakes at performance level of collapse prevention, for a 25-story building with moderate importance

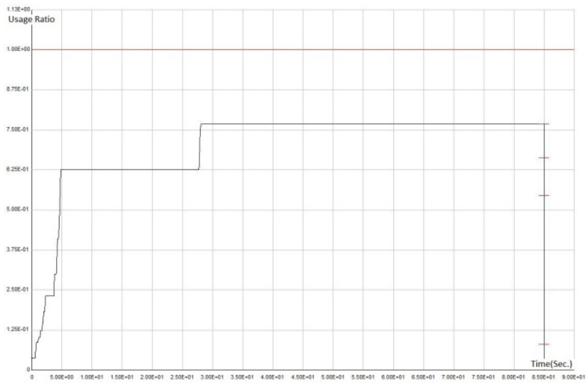

Fig.13. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the Imperial Valley earthquake (1940), for a 35-story building with moderate importance

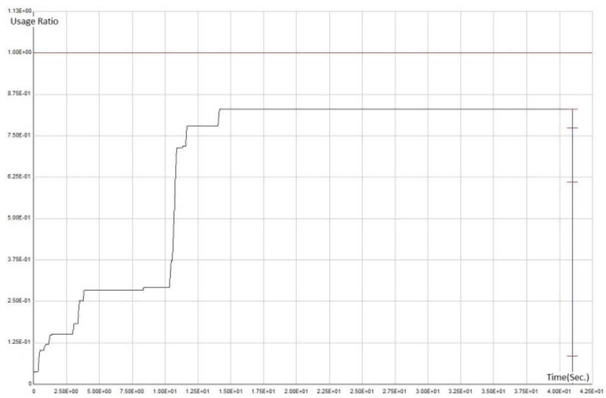

Fig.14. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the San Fernando earthquake, for a 35-story building with moderate importance

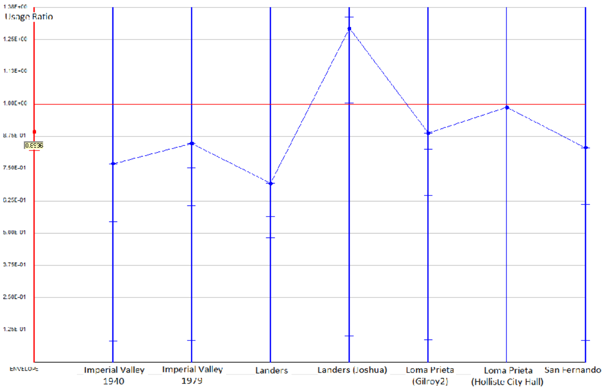

Fig.15. Mean Push of application ratios of seven earthquakes at performance level of life safety, for a 35-story building with moderate importance

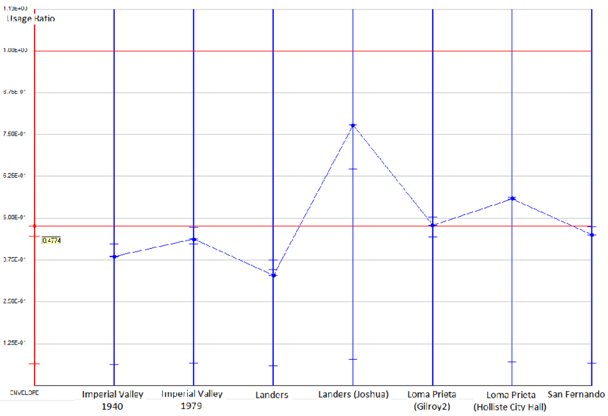

Fig.16. Mean Push of application ratios of seven earthquakes at performance level of collapse prevention, for a 35-story building with moderate importance

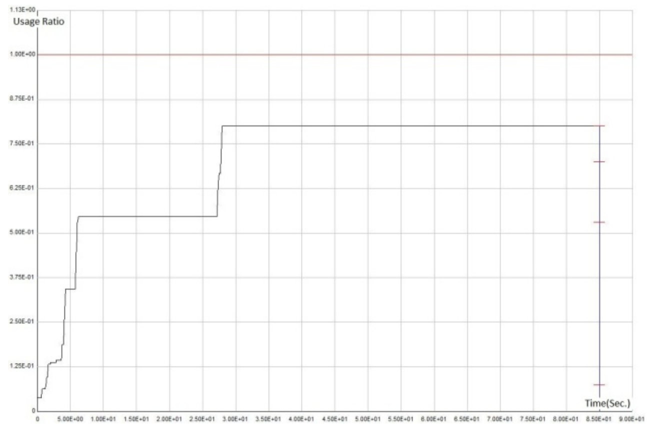

Fig.17. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the Imperial Valley 1940 earthquake, for a 45-story building with moderate importance

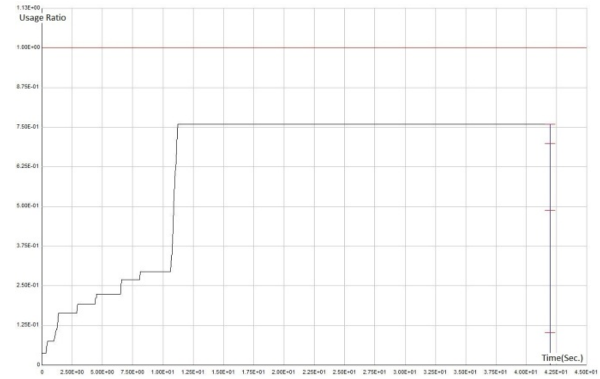

Fig.18. Push changes to capacity demand (application) parameters that determine performance levels for life safety performance level during the San Fernando earthquake, for a 45-story building with moderate importance

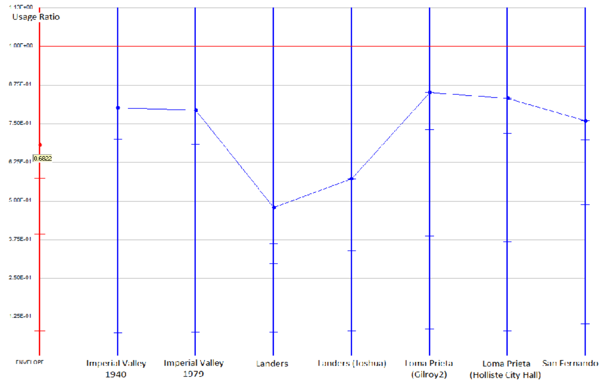

Fig.19. Mean Push of application ratios of seven earthquakes at performance level of life safety, for a 45-story building with moderate importance

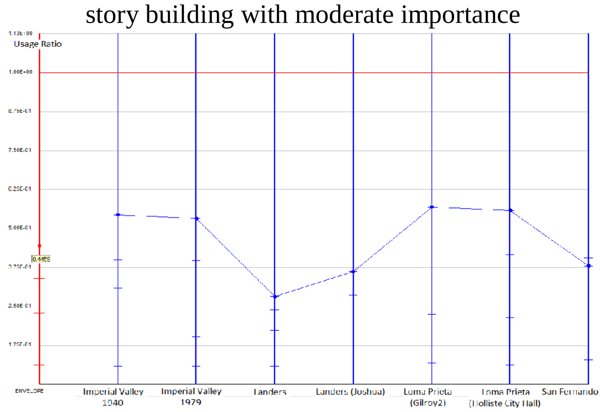

Fig.20. Mean Push of application ratios of seven earthquakes at performance level of life safety, for a 45-story building with moderate importance

The expected mean application ratios for performance level of life safety considered for designing aim. The mean demand for 25, 35 and 45-story structures with moderate importance is 0.97, 0.89 and 0.68 times of the capacity, respectively. So, life safety is introduced as performance level of structures. Therefore, our goal has been realized and the structure satisfies performance level of life safety, as expected. The important point to be considered is that if limitations of relative displacement of stories were not included in design, the much smaller profiles would have strength sufficiency and performance level would fall. The limit values of relative displacement are more crucial in high buildings with flexural frame system. The approaches have been highlighted in newer codes of performance / displacement-based designing.

The performance level of collapse prevention has also been proved. To study values, where the mean demand is 0.53, 0.48 and 0.45 times of capacity.

VI. Results of Performance Level in Structures with Very High Importance

Figures 21 and 22 demonstrate life safety and mean application ratios for performance level of immediate occupancy expected for structures with very high importance considering their designing goal. The figures indicate that mean demand for 25, 35 and 45-story structures with very high importance were 2.14, 3.58 and 1.84 times of the capacity. It was 0.60, 0.68 and 0.52 times of the capacity in life safety performance level. Thus, life safety is introduced as performance level of structures. So, our goal has not been realized since it was expected that the structure would reach to performance level of immediate occupancy due to increasing of importance factor.

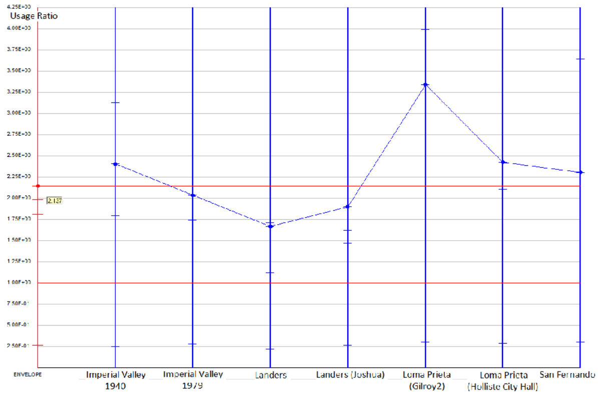

Fig.21. Mean Push of application ratios of seven earthquakes at performance level of immediate occupancy, for a 25-story building with very high importance

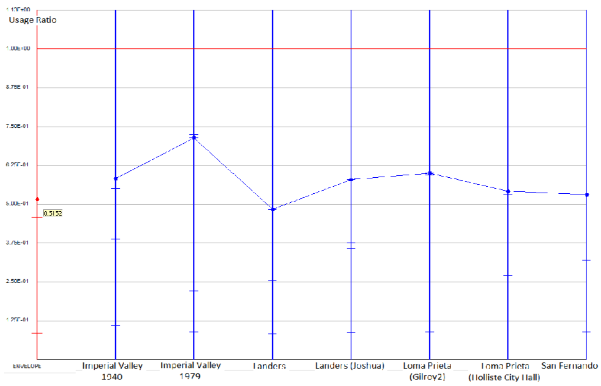

Fig.22. Mean Push of application ratios of seven earthquakes at performance level of life safety, for a 45-story building with very high importance

VII. Conclusion

The present study modeled six structures in two moderate and very high importance groups and different heights in order to evaluate the seismic performance of steel flexural frames. The standards of 2800 seismic code of Iran and steel structures' code were considered in primary design. The research follows two main goals through calculating four main parameters in determining performance levels of steel flexural frames (relative displacement of stories, plastic joints rotation of beams and columns, and shearing strain of panel zoon) with accelerometer scaled with designing spectrum in nonlinear dynamic analysis and comparing these quantities with the permitted values at every performance level. First, whether high structures with moderate importance and mentioned specifications have performance level of life safety in accordance with 2800 seismic code. Second, whether increase of importance factor of building as well as increase of base shears of designing (40% in this case) results in promoting performance level of structure from life safety to immediate occupancy.

Studying results of performance levels indicate that the structures of the first group with DCR of 0.97, 0.89, and 0.68 satisfied the performance level of life safety as expected. Although increase of performance level was expected, structures of the second group with DCR of 2.14, 3.58, and 1.84 did not reach the expected performance level of immediate occupancy. In these structures, the DCR only decreased at performance level of life safety. It indicates that the structures studied as counter examples in this research refer to impossibility of promotion of performance level of structures only through increasing a percentage of base shears.

Since limit values exceed parameters of performance level and stable relative displacements in some records even about performance level of life safety, it seems necessary to consider dispersion of mean limits and not to content mean values especially in important buildings.

Inelastic dynamic response indicates that the structures with main period greater than pulse period have different response in comparison with structures with short period. In these structures, the first yielding occurs in upper stories and the plasticity demand is transferred to lower stories when earth motions become stronger. But, the maximum demands occur in lower stories in structures with short period. The same behavior was observed in relative displacement of stories as well as the structures since the main period was greater than pulse period.

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