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ORIGINAL ARTICLE

Seismic Response of Mass Irregular Steel Moment Resisting Frames (SMRF) According to Performance Levels from IDA Approach

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ABSTRACT

Mass irregular structures have stories with effective mass more than 150% of effective mass of adjacent storey. Seismic response of mass irregular structures are assessed by consideration of SMRF structures with 4, 6 and 8 stories, which mass irregularity is applied separately by 1.4 and 2 times mass changes in top and two intermediate stories. Seismic response is achieved by applying Incremental Dynamic Analysis. Mean annual frequency and probability of exceedance in 50 years of performance levels are evaluated by applying PBEE framework. Finally understood which mass irregular structures response is related to location and number of stories with mass changes. Also, 150% limitation of mass change for definition of mass irregularity need more study.

Keywords: *Mass Irregular, SMRF, IDA Approach, Performance Levels, Mean Frequency of Exceedance*

1. INTRODUCTION

This is an investigation about the seismic response of mass irregular steel moment resisting frames. According to ASCE/SEI 7-05 [1] and Iranian Code of Practice, Standard No. 2800–3rd Edition [2], structural irregularities are categorized into two groups, vertical (mass, strength,..) and horizontal (torsional, diaphragm discontinuity,..) irregularities. In these codes, mass irregularity affect structures while effective mass of storey is higher than 150 percent of effective mass of adjacent stories.

Mass irregularity is important especially in high seismic regions because of its ability to make much damage to buildings. Many researchers worked on response of mass irregular structures under seismic loads. Kien Le-Trung et.al found if much of mass irregularity is located in top levels of building, maximum of interstory drift occurred in top levels of structure and mass irregularity has more effects on the higher stories [3]. Valmudsson and Nau described that seismic demands of mass irregularity is more than strength irregularity [4]. Sadashiva, Macrae and Deam represented that mass irregularity has more effects on top and bottom levels of structures than intermediate levels [5].

For this purpose, response of structures is evaluated with Incremental Dynamic Analysis (IDA) method. IDA is well known dynamic structural analysis method that can improve accuracy of results which proposed by Vamvatsikos and Cornell [6, 7]. In addition, performance levels are defined in response of structures and mean annual frequency (MAF) of exceedance of these levels are assessed. By comparing of MAFs of exceedance, performance of mass irregular structures can be studied.

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1.1. Ground Motions Records and Intensity Measures

Earthquakes can cause many secondary hazards in addition to ground motion, such as liquefaction, tsunami, etc. Vamvatsikos and Cornell offered twenty ground motion records to achieve sufficient accuracy in incremental dynamic analysis for mid rise buildings [8]. Selected ground motion records have similar soil parameters to building site construction. All records are selected from Pacific Earthquake Engineering Research Center (PEER) records catalog [9]. Records are Far-Field (distance >10 km) with firm soil type D (in USGS: Vs< 180 m/s). The earthquake magnitudes are 4.5~8.0 Richter without evidence of directivity. Table 1 shows selected records.

Table 1:Set of ground motion records

No	Event	year	Station	Component
1	Kobe	1995	Shin-Osaka	0
2	Kobe	1995	Shin-Osaka	90
3	Kobe	1995	Kakogowa	0
4	Kobe	1995	Kakogowa	90
5	Kobe	1995	Nishi-Akashi	0
6	Kobe	1995	Nishi-Akashi	90
7	CHI-CHI	1999	Chi076	E
8	CHI-CHI	1999	Chi076	N
9	Loma Prieta	1989	Larkspur Ferry Terminal	270
10	Loma Prieta	1989	Larkspur Ferry Terminal	360
11	Loma Prieta	1989	Apeel2 Redwood City	43
12	Loma Prieta	1989	Apeel2 Redwood City	133
13	Loma Prieta	1989	Treasure Island	0
14	Loma Prieta	1989	Treasure Island	90
15	Northridge	1994	Montebello-Bluff	206
16	Northridge	1994	Montebello-Bluff	296
17	Superstition Hills	1987	SLT	225
18	Superstition Hills	1987	SLT	315
19	Westmorland	1981	Salton Sea	225
20	Westmorland	1981	Salton Sea	315

Hazard levels of these records can be established by Intensity Measures (IMs).Many parameters such as first mode spectral acceleration (Sa(T1)), peak ground motion acceleration (PGA) and etc. can be given as IM. Seismicity of region or hazard levels of earthquake is represented by intensity measure hazard curve, $\lambda_{(IM)}$. Usually, geologists and engineers generate IM hazard curve according to Probabilistic Seismic Hazard Analysis (PSHA).

Hazard curve of intensity measure (λ_{IM}) describes mean annual frequency of exceedance of IMs from each special IM and can be approximated by power function as equation 1 in interest region [10, 11]:

(1)

In equation1, k_0 is constant of prediction of site seismicity and k is the logarithmic slope of hazard curve. This equation is valid in interest region which probability of exceedance of spectral acceleration in 50 years is between 2% and 10% [10, 12].

In this study, Sa(T1) is assumed for assessment of ground motion hazard intensity measure. Figure 1 shows Sa hazard curve for Los Angeles in log-log space which is taken from USGS website [13].

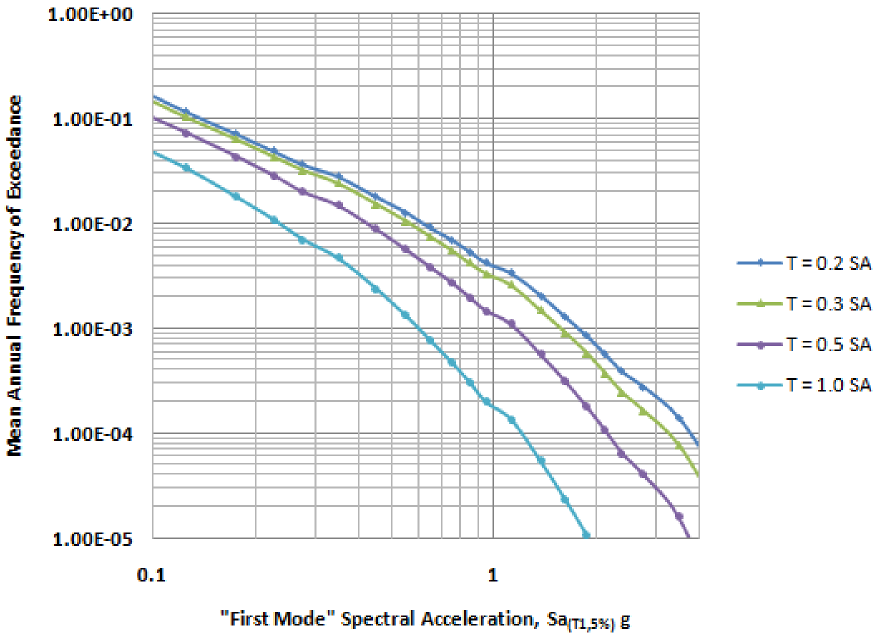

Figure 1: hazard curve for spectral acceleration of Los Angeles

2. STRUCTURAL MODELLING

Figure 2 shows eight, six and four stories 3-dimensional steel moment resisting frames for assessment of response of mass irregular structures. Structures have 2 x 3 bays with distribution of 20kN/m of dead load on beams and they are symmetric to avoid Torsional effects. Structures are designed according to ANSI/AISC 360-05 [14] and IBC 2006 [15].

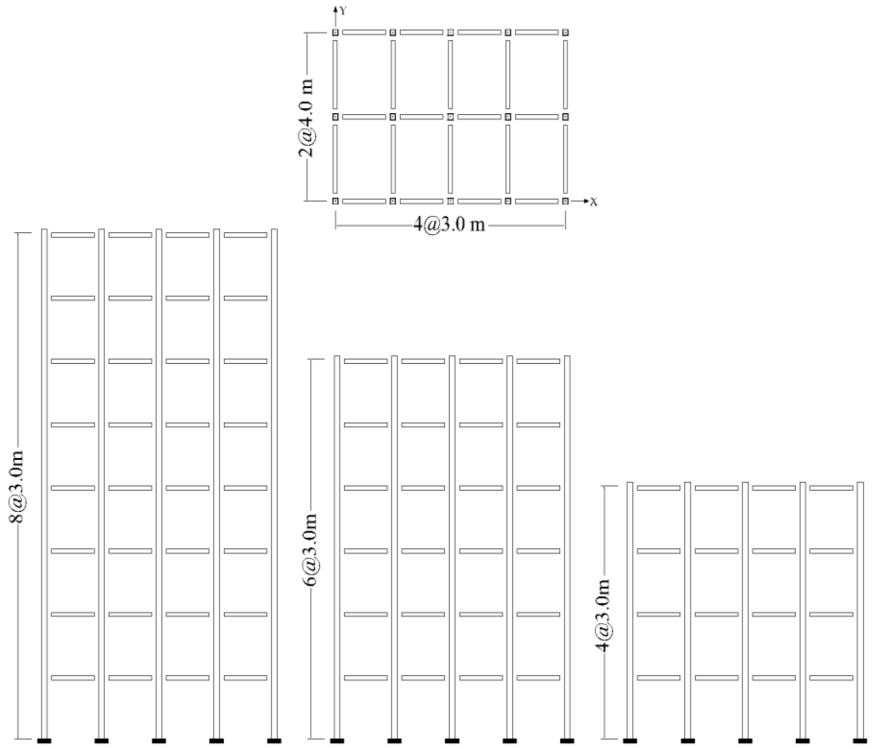

Figure 2.Configuration of plan and elevation of 8, 6 and 4 stories structures

Elastic Perfectly Plastic (EPP) hysteretic behavior is used for structural material behavior according to FEMA 440 [16]. It is a reasonable hysteretic model for steel beams without lateral or local buckling and connection failure. Figure 3 displays the considered EPP behavior in this study.

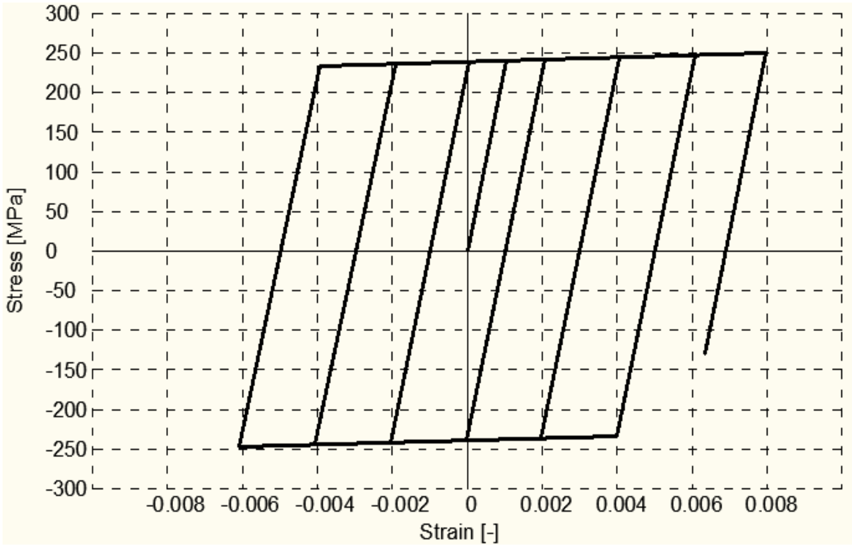

Figure 3: Elastic Perfectly Plastic (EPP) hysteretic

Mass irregularity is applied separately on two levels of structure; at top and two intermediate storey levels with 1.4 and 2 times multiplier to same mass M of other stories. Table 2 shows all of considered regular and irregular structural models. 8St, 6St and 4St are original regular structures. Irregular structures are referenced by three parts; original regular structure, percent of irregularity and finally mass irregular storey. For example 8St-140-4&5 means the model with 8 stories and 140% mass changes at storey levels of 4 and 5. Structural models are performed in SeismoStruct-V5 software [17] which able to perform IDA.

Table 2: Regular and mass irregular structure

No.	Model Name	No.	Model Name	No.	Model Name
1	8St	6	6St	11	4St
2	8St-200-8	7	6St-200-6	12	4St-200-4
3	8St-140-8	8	6St-140-6	13	4St-140-4
4	8St-200-4&5	9	6St-200-3&4	14	4St-200-2&3
5	8St-140-4&5	10	6St-140-3&4	15	4St-140-2&3

3. INCREMENTAL DYNAMIC ANALYSIS (IDA) AND PERFORMANCE LEVELS

The IDA is a promising parametric method for description response of structures to seismic loads. IDA is series of nonlinear dynamic analysis from scaled records of ground motion time histories. Each record is scaled to several levels of intensity so as to cover a full range of the model's behavior from elastic and nonlinear inelastic to overall dynamic instability.

For each analysis scale of IMs is increased and Engineering Demand Parameters (EDPs) are gathered and finally results are summarized in IDA curves which describe IMs versus EDPs. In this study, maximum interstorey drift ratio (θmax) is used as EDP.
According to FEMA 350 [12] for structural components, three performance limit state can be defined as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) as with increasing on EDPs and damages on building. Vamvatsikos and Cornell described IO limit state occurred where θmax is 2% and CP limit state depend on damages that generally can be considered as θmax is 10% or slope of curve decrease to 20% of elastic slope, whichever occurs first in IM terms [8, 12]. Finally Global Dynamic Instability (GI) is defined as curve change to flatline.

4. ANALYSIS AND RESULTS

Results of mass irregular structures analysis are gathered in IDA curves in format of maximum interstorey drift ratios versus first mode spectral acceleration. Figure 4 shows IDA curves for all models.

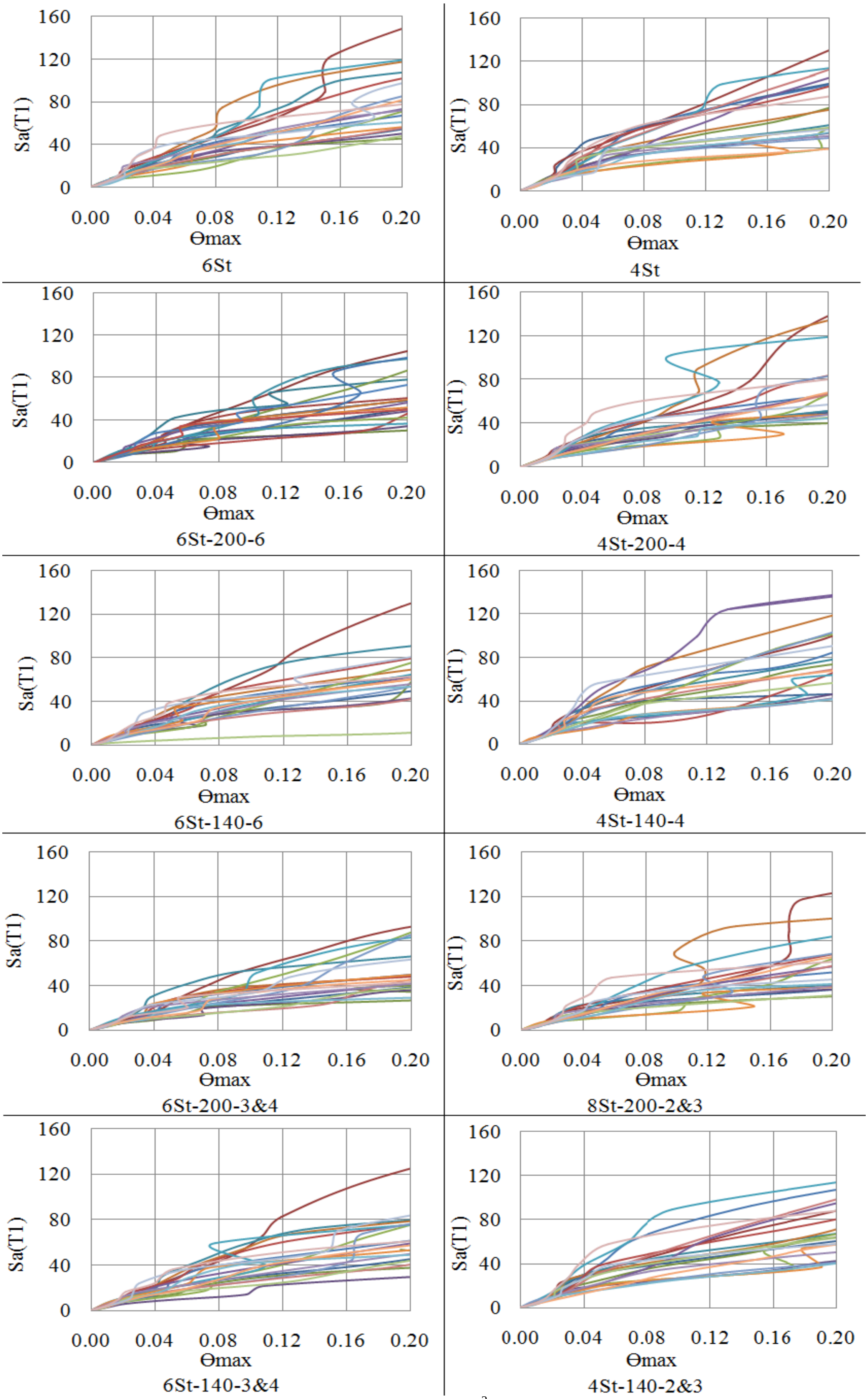

Figure 4. IDA Curves in format of $S_{a(T1)}$ (cm/s^2)~ θmax (continue in next page)

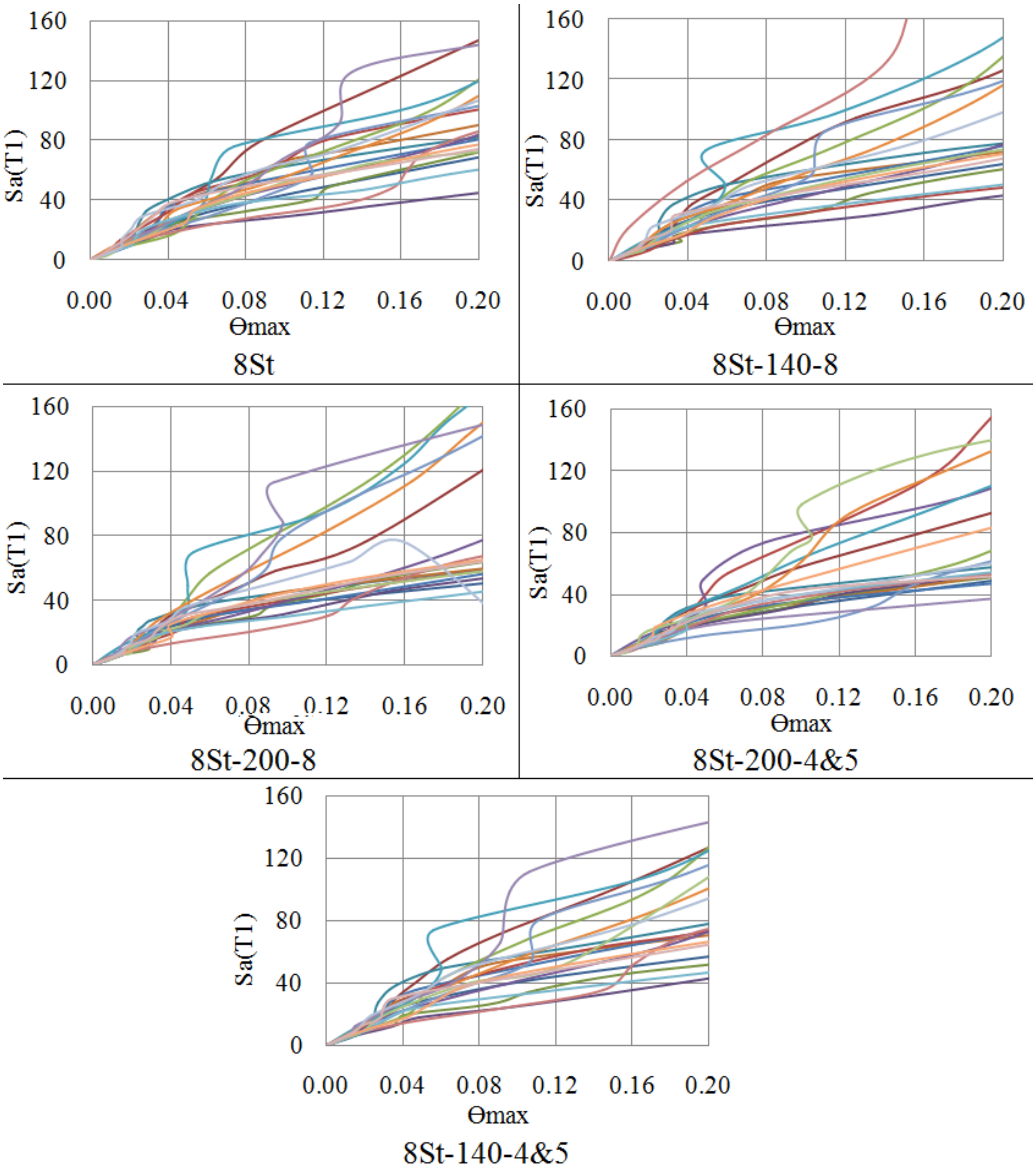

Figure 4: IDA Curves in format of $S_{a(T1)}$ (cm/s^2) ~ θmax

Maximum interstorey drift ratios (θmax) and Sa(T1)of 16%, 50% and 84% probability of occurrence for each performance levels can be evaluated according to gathered response of structures [8]. Table 3 display θmax and Sa(T1) of IO, CP and GI performance levels.

Table 3: Capacity of models for each limit state

	8St					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.11	0.25	0.6	0.02	0.05	∞
50%	0.14	0.36	0.82	0.02	0.06	∞
84%	0.16	0.53	1.06	0.02	0.08	∞

	8St-200-8					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.1	0.25	0.55	0.02	0.05	∞
50%	0.12	0.32	0.63	0.02	0.06	∞
84%	0.15	0.55	0.92	0.02	0.09	∞

	8St-140-8					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.25	0.6	0.02	0.04	∞
50%	0.11	0.36	0.71	0.02	0.05	∞
84%	0.13	0.5	0.99	0.02	0.07	∞

	8St-200-4&5					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.22	0.48	0.02	0.05	∞
50%	0.11	0.31	0.55	0.02	0.06	∞
84%	0.14	0.4	0.98	0.02	0.07	∞

	8St-140-4&5					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.22	0.55	0.02	0.05	∞
50%	0.1	0.33	0.72	0.02	0.06	∞
84%	0.13	0.43	0.95	0.02	0.07	∞

	6St					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.09	0.18	0.53	0.02	0.045	∞
50%	0.1	0.23	0.75	0.02	0.062	∞
84%	0.12	0.35	1.02	0.02	0.1	∞

	6St-200-6					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.07	0.13	0.41	0.02	0.035	∞
50%	0.08	0.15	0.52	0.02	0.04	∞
84%	0.1	0.27	0.73	0.02	0.05	∞

	6St-140-6					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.07	0.15	0.49	0.02	0.038	∞
50%	0.09	0.21	0.6	0.02	0.045	∞
84%	0.11	0.33	0.78	0.02	0.055	∞

	6St-200-3&4					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.065	0.095	0.23	0.02	0.03	∞
50%	0.09	0.15	0.41	0.02	0.04	∞
84%	0.1	0.23	0.62	0.02	0.045	∞

	6St-140-3&4					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.07	0.1	0.44	0.02	0.03	∞
50%	0.095	0.16	0.6	0.02	0.04	∞
84%	0.11	0.27	0.76	0.02	0.05	∞

	4St					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.09	0.14	0.5	0.02	0.03	∞
50%	0.1	0.21	0.7	0.02	0.04	∞
84%	0.12	0.37	0.98	0.02	0.055	∞

	4St-200-4					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.11	0.47	0.02	0.03	∞
50%	0.09	0.17	0.51	0.02	0.035	∞
84%	0.11	0.28	0.8	0.02	0.045	∞

	4St-140-4					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.14	0.45	0.02	0.03	∞
50%	0.09	0.22	0.68	0.02	0.04	∞
84%	0.11	0.3	0.98	0.02	0.045	∞

	4St-200-2&3					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.06	0.12	0.38	0.02	0.03	∞
50%	0.08	0.15	0.56	0.02	0.035	∞
84%	0.09	0.2	0.68	0.02	0.04	∞

	4St-140-2&3					
	Sa(T1)			Θmax		
NO	IO	CP	GI	IO	CP	GI
16%	0.08	0.13	0.5	0.02	0.035	∞
50%	0.09	0.21	0.68	0.02	0.04	∞
84%	0.11	0.36	0.9	0.02	0.05	∞

Mean annual frequency (MAFs) of exceedance of EDPs or hazard curve of EDPs can be calculated according to PBEE framework from equation 2 [18, 19 and 20]:

(2)

In this equation, G(X) is complementary cumulative distribution function of EDP that calculated as equation 3 [18]:

(3)

By consideration of EDPs of performance limit states, mean annual frequency of exceedance of each limit state can be calculated from equation 2. Vamvatsikos in his thesis [21] summarized equation 2 for performance limit states as equation 4 for 50% probability of occurrence:

(4)

By applying equation 4 to IDA results of mass irregular systems, mean annual frequency of exceedance for each limit state can be calculated. Also probability of exceedance in 50 years (50 years PE) of performance levels can be calculated from MAFs. Table 4 show MAFs and return period for assumed mass irregular models.

Table 4.Calculated MAFs and 50 years probability of exceedance

8St	IO	CP	GI
MAF	0.01489	0.00031	0.00007
50 years PE	0.744	0.016	0.004

8St-200-8	IO	CP	GI
MAF	0.01635	0.00036	0.00016
50 years PE	0.818	0.018	0.008

8St-140-8	IO	CP	GI
MAF	0.01539	0.00032	0.00015
50 years PE	0.77	0.016	0.007

8St-200-4&5	IO	CP	GI
MAF	0.02118	0.00045	0.00017
50 years PE	1.059	0.022	0.0085

8St-140-4&5	IO	CP	GI
MAF	0.02003	0.00043	0.00015
50 years PE	1.002	0.022	0.008

6St	IO	CP	GI
MAF	0.0181	0.00036	0.00014
50 years PE	0.905	0.018	0.007

6St-200-6	IO	CP	GI
MAF	0.0216	0.00042	0.00032
50 years PE	1.08	0.021	0.016

6St-140-6	IO	CP	GI
MAF	0.02147	0.00038	0.00029
50 years PE	1.073	0.019	0.015

6St-200-3&4	IO	CP	GI
MAF	0.02513	0.0005	0.0036
50 years PE	1.257	0.025	0.018

6St-140-3&4	IO	CP	GI
MAF	0.02336	0.00049	0.0003
50 years PE	1.168	0.025	0.015

4St	IO	CP	GI
MAF	0.0181	0.00011	0.00007
50 years PE	0.905	0.006	0.004

4St-200-4	IO	CP	GI
MAF	0.01974	0.00017	0.00013
50 years PE	0.987	0.008	0.0065

4St-140-4	IO	CP	GI
MAF	0.01974	0.00012	0.00009
50 years PE	0.987	0.006	0.0045

4St-200-2&3	IO	CP	GI
MAF	0.02562	0.00021	0.00017
50 years PE	1.281	0.011	0.0085

4St-140-2&3	IO	CP	GI
MAF	0.0219	0.00015	0.00012
50 years PE	1.095	0.008	0.006

According to table 4,in structures with 140% mass changes probability of exceedance for limit states in 50 years is almost similar to structures with 200% mass changes. It is considerable which limitation of mass changes for definition of mass irregularity is 150% in codes.

Also duo to table 4, Location and number of stories with mass changes in structures are important.

Probability of exceedance of limit states in 50 years for structures with mass changes in two intermediate stories are more than mass changes in top storey. For example structures with 140% mass changes in two intermediate stories have more effect in response than 200% mass changes in top storey.

Also in some cases, especially for mass changes in two intermediate stories of eight and six stories structure probability of exceedance of collapse is more than 2%. It causes not to overcome our expectation for life safety of occupants according to codes.

5. CONCLUSIONS

In this article, the effects of mass irregularity in 4, 6 and 8 stories steel moment resisting frame systems are evaluated. The well known IDA approach is applied for structural analysis to evaluate the nonlinear seismic response of structures. For this purpose, responses of mass irregular structures are assessed in the form of the first mode spectral acceleration as IM versus to maximum interstorey drift ratios as EDPs. By applying PBEE framework, performance limit states are assessed in IDA curves. Finally, by calculating of mean annual probability of exceedance for each performance level land comparing of probability of exceedance in 50 years, following results can be noted:

1. Percent of mass changes of storey for occurrence of mass irregularity need more studies. 150% mass changes limitation between regular and irregular structures according to codes may involve undesirable response of structure under seismic loads.

2. Location and number of stories with mass changes are important and need more analytical and experimental studies.

3. Analysis and design criteria in codes for mass irregular structures need high consideration of accuracy, because probability of exceedance for performance levels may be more than interest probability for each performance level. Specially, it is so important for collapse prevention performance level which probability of exceedance in 50 years must be lower than 2%.Safety of occupants has direct relationships with probability of exceedance of collapse prevention limit state in 50 years.

6. ACKNOWLEDGEMENT

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