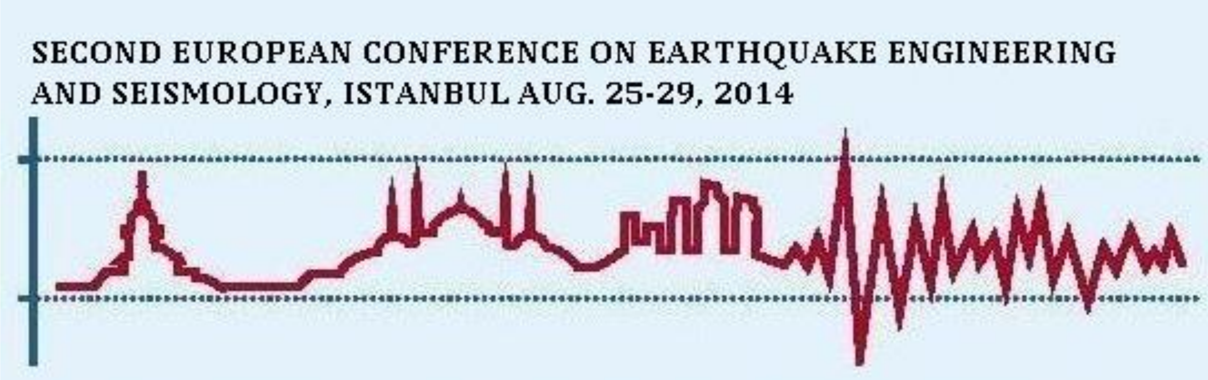

RELATIVE SAFETY MARGINS OF CODE-CONFORMING VERTICALLY IRREGULAR HIGH-RISE BUILDINGS

Aman MWAFY[1], Sayed KHALIFA[2] and Bilal EL-ARISS[3]

ABSTRACT

This study assesses the margins of safety of code-compliant vertically irregular high-rise buildings at different performance levels. The vertically irregular reinforced concrete high-rise buildings in the UAE, which is selected as a case study to represent regions of medium seismicity, are surveyed. A set of 50-story benchmark structures is selected and fully designed according to modern building codes to represent well-engineered high-rise buildings with a diversity in irregularity features. Verified fiber-based simulation models are developed and 40 earthquake records representing two seismic scenarios are selected for inelastic analysis. Incremental dynamic analyses are deployed to provide insight into the local and global response of the benchmark structures. The results indicate that the safety margins of well-designed high-rise buildings with a variation in vertical stiffness or with a geometric irregularity are not inferior to those of the regular counterparts at different performance levels. Despite the adopted overstrength factor in design as per the code recommendations, the results reflect the lower safety margins of the structure that exhibits a lateral strength/weak story irregularity and confirm the need for mitigation strategies to reduce the expected seismic losses of this class of buildings. Investigating the inelastic seismic response of a set of reference structures with diverse irregularity features at different levels of earthquake intensity renders the results of this systematic study indicative of response trends regarding the safety margins offered by modern seismic codes for irregular high-rise buildings.

INTRODUCTION

A large number of real high-rise buildings are practically irregular since the perfect structural regularity rarely exists. The architectural design of modern residential and office buildings (many of which have integrated commercial and parking spaces) have become more complex. The experience from previous earthquakes have shown that the seismic behavior of buildings with irregular distributions of stiffness, strength or mass along their height can be significantly different in comparison to the regular counterparts. The vertical irregularity is introduced due to abrupt variations in the stiffness, strength or mass of the lateral force resisting system. Therefore, simple analysis and design methods, which are often used for regular buildings, could be inefficient. Modern seismic design codes distinguish between irregularity in plan and in elevation (e.g. ASCE-7, 2010; CEN, 2004). The tendency to separate irregularity also characterizes the scientific literature related to the seismic response of this class of structures.

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The growing interest to gain insight into the seismic behavior of irregular buildings, particularly vertical irregularity, has been shown in the literature (e.g. De Stefano and Pintucchi, 2008). The seismic behavior of setback and stepped buildings was investigated in a number of studies (e.g. Duan and Chandler, 1995; Sarkar et al., 2010; Shahrooz and Moehle, 1990). It was concluded that simple analysis procedures are inadequate to predict and prevent the damage concentration near the setback levels. The effectiveness of the code provisions (ICBO, 1997) in the design of irregular structures was studies by Valmundsson and Nau (1997) using buildings with different heights, ranging from 5 to 20 stories. It was concluded that mass and stiffness irregularity caused moderate increases in response quantities. A number of modifications to the vertical irregularity design criteria were proposed based on the latter study. Das and Nau (2003) investigated different vertical irregularities such as stiffness, strength, mass. RC moment resisting frames (MRFs) with different heights (5 to 20 stories) when designed using the ELF procedure were studied. It was recommended to release the unnecessarily conservative restrictions on the applicability of ELF procedure for certain types of vertical irregularities due to their satisfactory performance. Al-Ali and Krawinkler (1998) and Chintanapakdee and Chopra (2004) investigated the seismic response of simple mid-rise single-bay frames, and almost reached to similar conclusions regarding the applicability of the code provisions. Michalis et al. (2006) studied the dynamic response of vertical irregularities using nine-story steel frames and incremental dynamic analysis (IDA). It was concluded that the effect of irregularities significantly differs depending on the irregularity type and intensity of ground motions. Le-Trung et al. (2010) investigated the vertical irregularities specified in the IBC provisions (ICC, 2012) in terms of seismic demands, capacities and confidence levels. A deformation-based design method for RC irregular frame buildings was proposed by Kappos and Stefanidou (2010). The progressive collapse-resisting capacities of 30-story tilted or twisted buildings were evaluated by Kim and Hong (2011). The results indicated that the progressive collapse potentials of the tilted structure were high when a column was removed from the tilted side, while the twisted structures had insignificant progressive collapse potentials. Wang et al. (2011) assessed the seismic behavior of transfer story connections for a high-rise building. Test results indicated that support stiffeners and mechanical connectors are needed in order to achieve more ductile and reliable seismic behavior of transfer story connections.

Several previous studies focused on the impact of irregularities on seismic demands, typically at certain limit states. Several findings were drawn based on the response in the elastic and early inelastic ranges. Such conclusions may not be valid as inelasticity increases, especially when approaching collapse. Most previous studies also focused on low to medium-rise MRFs or on limited case studies of high-rise buildings. A systematic study that involves a group of well-designed high-rise buildings representing different irregularity features is therefore needed. The objective of the present study is to assess the seismic safety margins of vertically irregular high-rise buildings considering geometric nonlinearity and the inelastic behavior of structural material at different limit states. Various vertical irregularities are systematically introduced in a group of high-rise buildings. The benchmark structures are designed as per modern design codes and then effectively idealized to assess their seismic response using advanced assessment methodologies under the effect of a wide range of input ground motions.

DESCRIPTION OF BENCHMARK STRUCTURES

Four 50-story RC shear wall buildings are considered in this study to represent the regular and vertically irregular high-rise buildings. Each building consists of three basements, a ground story and 46 typical stories. The reference buildings (denoted as B1-REG, B2-SST, B3-GEO and B5-WST) represent: (i) regular structures, (ii) stiffness/soft story irregularity, (iii) geometric irregularity, and (iv) discontinuity in lateral strength/weak story irregularity, respectively, as shown in Table 1. All reference buildings have the same layout at the ground and typical stories, as shown in Fig. 1. To effectively represent the irregularity, B3-GEO and B5-WST have different layouts at the three basements, as shown in Fig. 2. According to the design codes (ASCE-7, 2010; ICC, 2012), a building exhibits stiffness-extreme soft story irregularity when a story lateral stiffness (S1) is less than 60% of the stiffness of the story above (S), as explained in Fig. 3(a). The vertical geometric irregularity exists where the horizontal dimension of the seismic force-resisting system in any story (Li) is more than 130% of that in an adjacent story (L), as shown in Fig. 3(b). The extreme weak story irregularity is introduced when a story lateral strength (St1) is less than 65% of the lateral strength (St) for the story above, as depicted in Fig. 3(c). The three irregularities discussed above and in Fig. 3 are represented in the reference structures B2-SST, B3-GEO and B4-WST, respectively. The shear wall structural system is employed in all reference buildings. This system is efficient in resisting the lateral loads from wind and earthquakes. Table 1 summarizes the main structural characteristics of the selected reference structures, while Fig. 4 depicts their configurations.

Table 1. Characteristics of reference structures

Building Reference	Building Irregularity type	Typical Story Height (m)	Ground Story Height (m)	Total Height (m)
B1-REG	Regular building	3.2	3.2	160
B2-SST	Stiffness/soft story irregularity	3.2	6.4	163.2
B3-GEO	Geometric irregularity	3.2	3.2	160
B4-WST	discontinuity in lateral strength/weak story irregularity	3.2	3.2	160

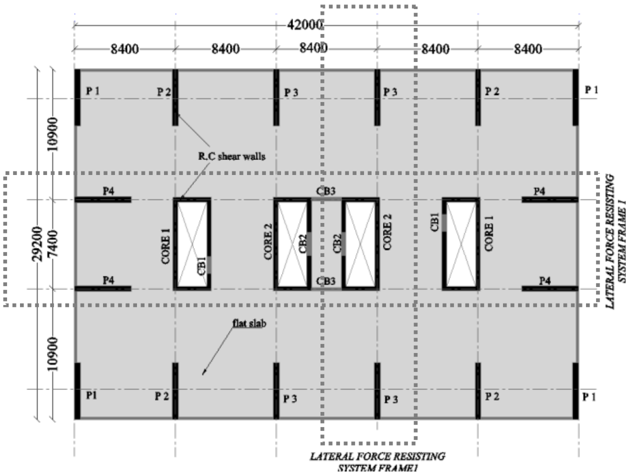


Figure 1. Layout and lateral force resisting systems at the ground and typical floors of all reference buildings

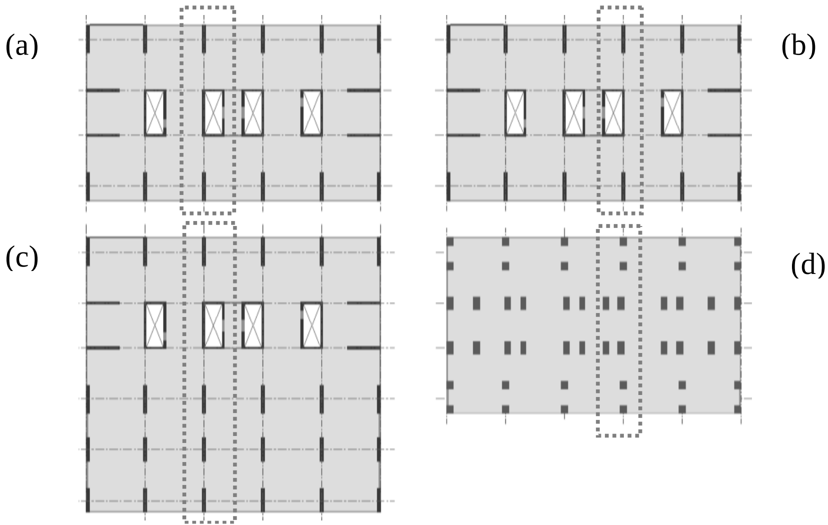


Figure 2. Layouts and lateral force resisting systems of reference structures at the basements:
(a) B1-REG, (b) B2-SST, (c) B3-GEO, and (d) B4-WST

DESIGN OF BENCHMARK BUILDINGS

Three-dimensional (3D) finite element (FE) models are developed for the design of the benchmark structures using the extended three-dimensional analysis of building system ETABS (CSI, 2011). All gravity, wind and seismic loads are considered as per ASCE 7 (2010). The modal response spectrum analysis (MRSA) is used to calculate the seismic force using the design code spectrum. The MRSA analysis includes a sufficient number of modes to account for a combined modal mass participation of more than 90% of the actual mass in each of the two orthogonal horizontal directions. The code requirements related to different types of irregularities, such as the overstrength factor, are fully considered during the design process. A concrete compressive strength ($f_c^`$), ranging from 32 to 48 MPa, is used with a reinforcement yield strength of 460 MPa. The benchmark buildings are designed and detailed according to the design provisions and construction practices adopted in the study area to represent well-engineered buildings with diversity in irregularity. Table 2 shows sample of the design results for B2-SST.

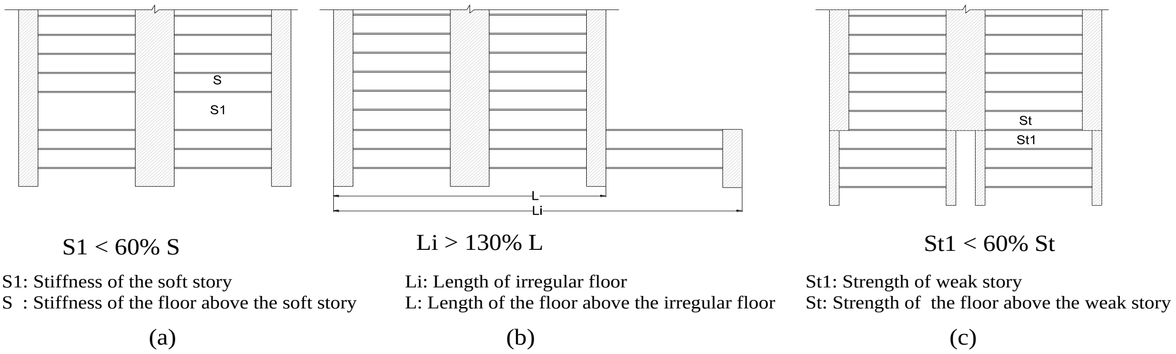


Figure 3. Definition of irregularities: (a) extreme soft story irregularity, (b) vertical geometric irregularity, and (c) extreme weak story irregularity

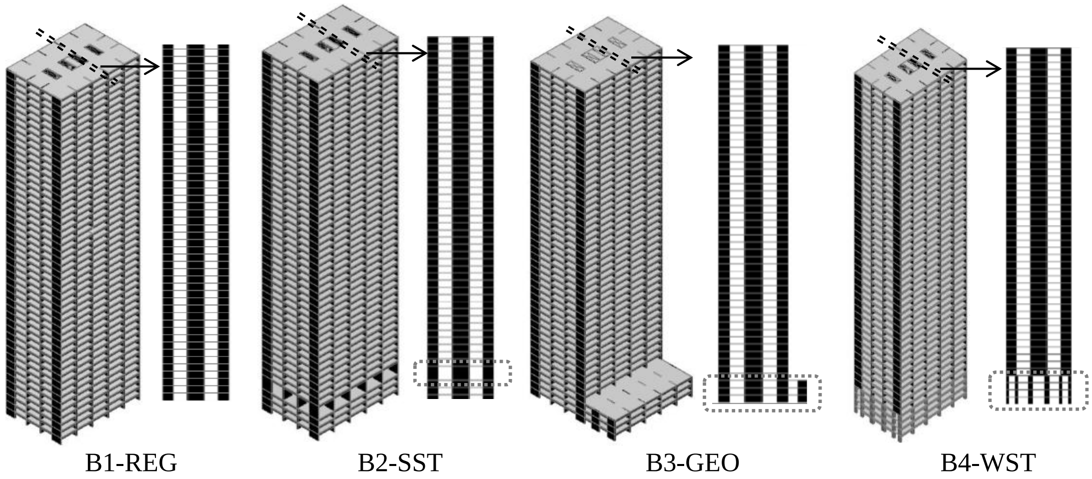


Figure 4. Configurations of reference structures

Table 2. Sample design results for the vertical structural members of building B2-SST

Location of section	base	Floor no.1	Floor no.6	Floor no.11	Floor no.16	Floor no.21	Floor no.26	Floor no.31	Floor no.36	Floor no.41
Shear Wall P3										
VL. reinforcement	80T40	80T40	380T40	68T40	68T40	32T40+ 36T32	32T32+ 36T14	32T20+ 36T14	50T16	50T14
HL. reinforcement	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm
Pier section (mm x mm)	500x4750	450x4750	450x4750	400x4750	400x4750	350x4750	350x4750	300x4750	300x4750	200x4750
Concrete strength (fc') MPa	48	48	40	40	32	32	32	32	32	32
CORE 2										
VL. Reinforcement	146T12+ 96T40	146T12+ 96T40	146T12+9 6T40	146T16+9 6T32	146T16+ 96T32	146T16+ 96T20	196T12			
HL. reinforcement	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm	T12-200mm			
Core thickness (mm)	300	250	250	200	200	200	200			
Core width (mm)	3200	3200	3200	3200	3200	3200	3200			
Core length (mm)	7700	7700	7700	7700	7700	7700	7700			
Concrete strength (fc') MPa	48	48	40	40	32	32	32			

MODELLING APPROACH FOR INELASTIC SIMULATION

Fiber-based (FB) numerical models are developed to predict the seismic response of the reference structures (Fig. 5). In this modeling approach, each structural member is assembled using three cubic elasto-plastic frame elements capable of representing the spread of inelasticity within the member cross-section and along the member length (Elnashai et al., 2012). Sections are discretized to steel, confined and unconfined concrete fibers. The stress-strain response at each fiber is monitored during the entire multi-step analyses. The developed FB assessment models are verified by comparisons with the dynamic characteristic and elastic response of the FE design models. Table 3 summarizes the elastic periods of the reference structures form both the FE and FB models. It is shown that the periods from the detailed FB models are slightly lower than those from the FE design models. The differences result from the effective modeling of reinforcing steel in the concrete sections of the FB models unlike the case of the FE models. IPAs and IDAs are carried out using the FB models to assess the relative damage states and safety margins of the reference structures at different performance levels.

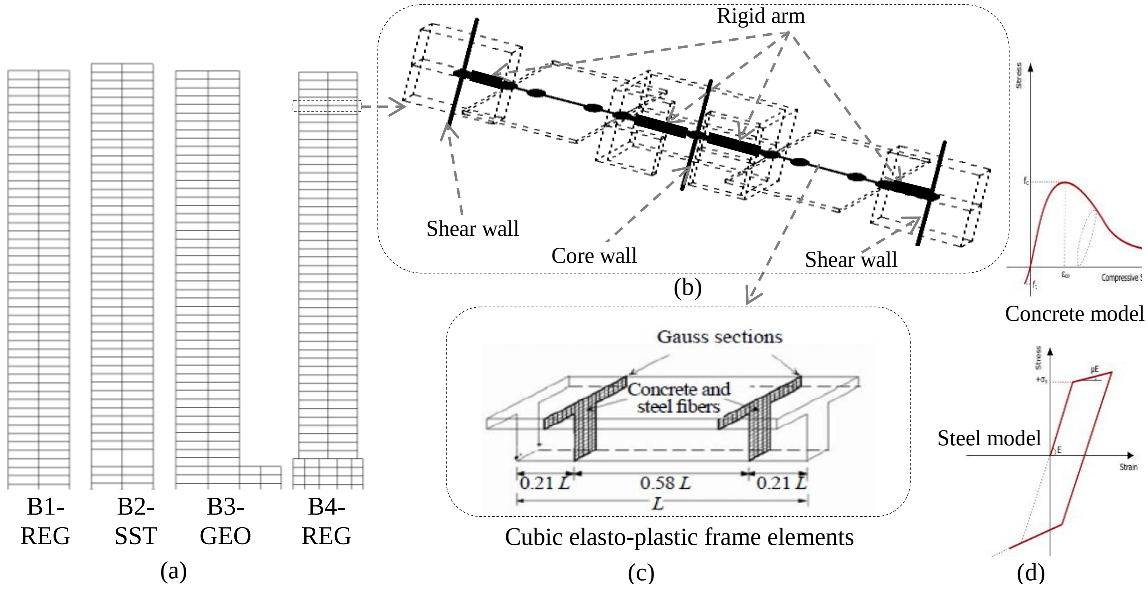


Figure 5. Modelling approach of reference structures (a) Zeus-NL models (b) geometrical modeling of horizontal and vertical members (c) fiber based modeling (d) martial modeling

Table 3. First five periods of the reference buildings from finite element (FE) and fiber base (FB) models

Period, T	Reference Structure							
	B1-REG		B2-SST		B3-GEO		B4-WST	
	FE	FB	FE	FB	FE	FB	FE	FB
T1	4.688	4.540	4.822	4.673	4.603	4.280	5.021	4.978
T2	1.326	1.220	1.368	1.240	1.300	1.204	1.430	1.309
T3	0.629	0.554	0.649	0.531	0.616	0.560	0.708	0.598
T4	0.376	0.359	0.387	0.360	0.444	0.385	0.441	0.399
T5	0.327	0.315	0.335	0.315	0.352	0.346	0.367	0.340

FE: Finite element design models
FB: Fiber-base assessment models

EARTHQUAKE GROUND MOTIONS

This phase of the study involves the selection of a diverse set of input ground motions for the dynamic response simulations. The natural earthquake records are selected to represent the study area. The PEER and the European strong-motion databases are searched to select 40 natural records that represent two earthquake scenarios recommended for the study area (Ambraseys et al., 2004; Chiou and Youngs, 2008). The two scenarios represent far-field earthquakes and near-source events (e.g.

Khan et al., 2013; Mwafy et al., 2006). The adopted criteria for selecting input ground motions are: (i) epicentral distance, (ii) magnitude, (iii) soil class, (iv) peak acceleration to velocity ratio a/v, and (v) peak ground acceleration PGA. Fig. 6 compares the response spectra of the 40 input ground motions that represent the two seismic scenarios with the design spectra of the study area for soil classes C and D. The characteristics of a sample record from each of the selected two sets of input ground motions are depicted in Fig. 6.

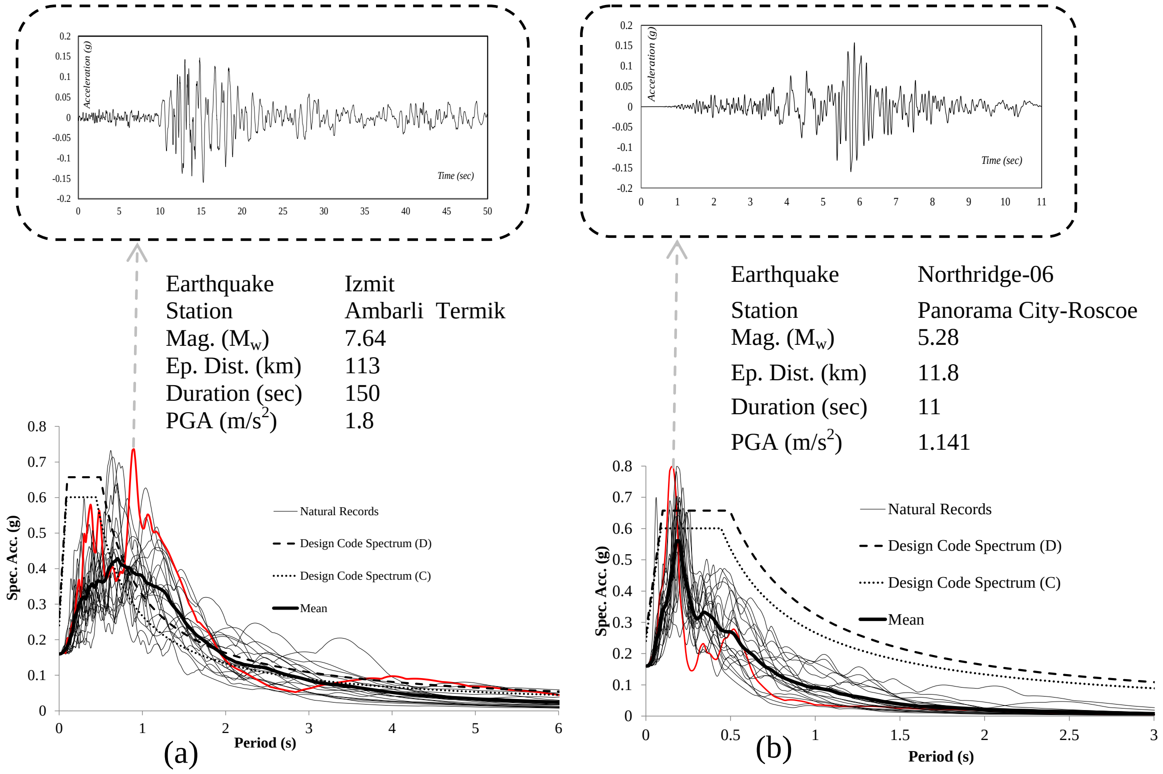


Figure 6. Response spectra of 40 earthquake records representing two seismic scenarios: (a) Far field and (b) Near field

PERFORMANCE CRITERIA

Studying the structural performance at both the global and local response levels would provide a clear understanding about the seismic behavior of the structure. The local and global seismic response of the benchmark structures are therefore assessed using inelastic pushover analysis (IPA) and IDA to provide insights into the performance criteria. The results of these analyses are presented hereafter. The following definitions of limit states are considered in this study (ASCE-41, 2007): (i) immediate occupancy (IO) where a minor damage may occur while the lateral force resisting elements retain their initial strength and much of their original ductility, (ii) life safety (LS) which reflects a significant damage to the lateral force resisting system but it maintains a large margin against collapse, and (iii) collapse prevention (CP) which allows for a small margin of safety against collapse during a severe earthquake. The interstory drift ration (IDR) is adopted in seismic provisions and in several previous studies as the main building damage indicator. For RC wall structure, ASCE-41 (2007) adopts three IDR limits (0.5%, 1% and 2%) for the IO, LS and CP performance levels, respectively. Less conservative IDR limits were recommended in previous experimental and analytical studies, as shown in Table 4 (Beyer et al., 2008; Ghobarah, 2004; Lehman et al., 2013; Panagiotou et al., 2010).

The IDRs corresponding to the first indication of reinforcing steel yielding and confined concrete crushing are presented in Table 4. These results are obtained from the IPAs and time history analyses (THAs) of the reference structures. The IDRs corresponding to the first indication of yield and collapse, which are estimated from IDAs of the reference structures, are also presented in Table 4.

Based on the IDA results, IDRs of 0.49%, 0.48%, 0.51% and 0.44% are adopted as the IO limit state of B1-REG, B2-SST, B3-GEO and B4-WST, respectively. These limit states are consistent with the values recommended in ASCE 41 (2007) and the study of Lehman et al. (2013). As a result of the significantly high limit states obtained from IDAs at the CP limit state, the IDR observed in the experimental study of Lehman et al. (2013) is adopted for the regular structure, B1-REG. This CP limit state is slightly higher than that adopted by ASCE 41 (2007), while it is slightly conservative compared with other previous studies. As a results of the lack of previous experimental studies and code provisions related to the performance limit states of irregular structures, and due to the differences in the CP limit state obtained from IPA and THA for the four reference structures, it was decided to scale the selected CP limit state for the regular building using the CP thresholds observed from THA. This process results in IDRs of 2.27%, 2.26%, 2.39% and 1.38% as the CP limit state of B1-REG, B2-SST, B3-GEO and B4-WST, respectively. Finally, the LS limit state, which falls between the IO and CP, represents a significant damage sustained by the structure, while it accounts for a reasonable margin of safety against collapse. This margin is considered 50% of the CP limit state as per ASCE 41 (2007). Table 4 summarizes the selected limit states of the benchmark structures based on the results of the present study, previous experimental and analytical studies, and the code-recommended values.

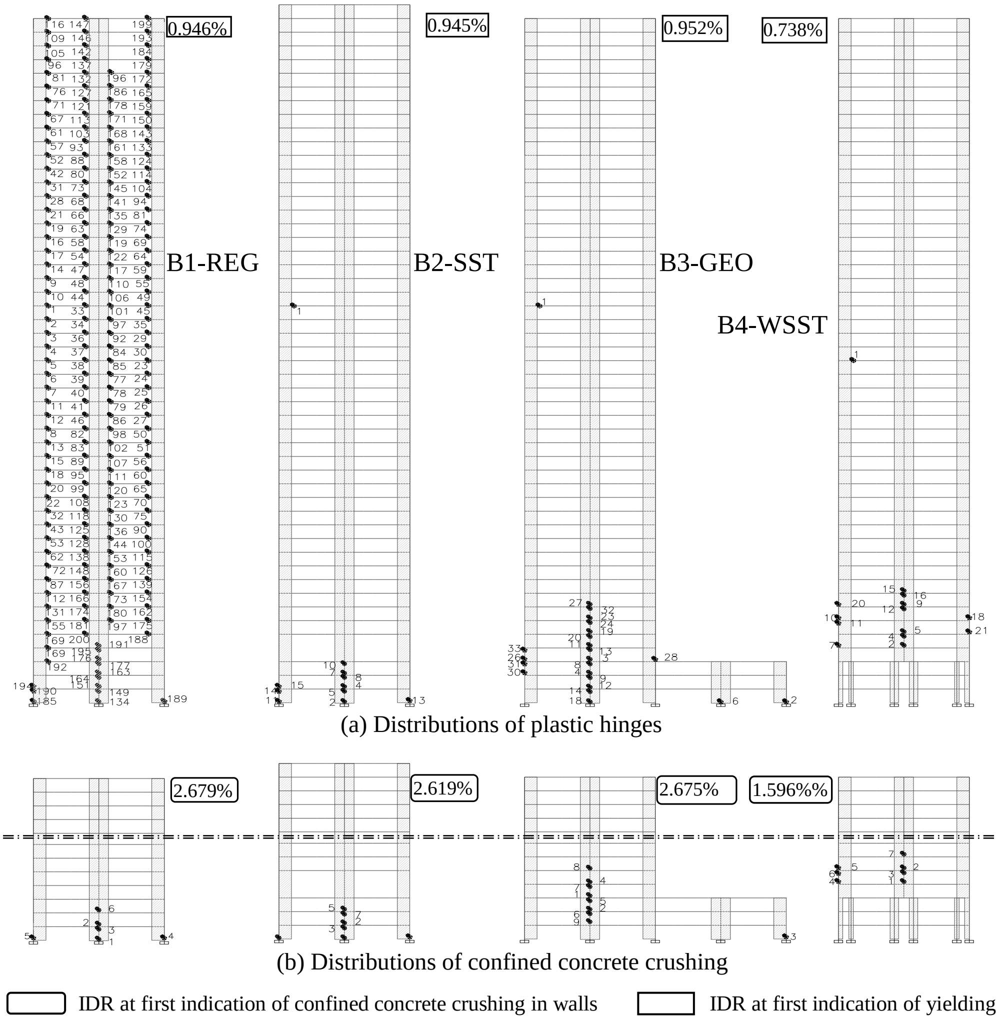
Table 4. Limit states for reference building

Selection Approach		Reference Structure											
		B1-REG			B2-SST			B3-GEO			B4-WST		
		Limit State – Interstory Drift (%)											
		IO	LS*	CP	IO	LS*	CP	IO	LS*	CP	IO	LS*	CP
ASCE 41-07		0.50	1.00	2.00									
Previous studies	Ghobarah, 2004	0.40	1.50	2.50									
	Beyer et al. (2008)	0.30		2.40									
	Panagiotou et al. (2010)	0.35	0.89	2.36									
	Lehman et al. (2013)	0.50	1.00	**2.27**									
Current study	IPA	0.95		2.68	0.95		2.62	0.95		2.75	0.74		1.60
	THA - 16%	0.61		**3.07**	0.61		**3.06**	0.79		**3.23**	0.55		**1.86**
	THA - 50%	0.70		3.46	0.71		3.44	0.92		3.66	0.64		2.23
	THA - 84%	0.81		3.89	0.82		3.86	1.08		4.16	0.74		2.69
	IDA - 16%	**0.49**		4.97	**0.48**		4.56	**0.51**		6.08	**0.44**		3.61
	IDA - 50%	0.60		6.31	0.56		5.93	0.66		7.61	0.56		4.90
	IDA - 84%	0.74		8.02	0.65		7.71	0.86		9.52	0.72		6.67
Selected Limit State		**0.49**	**1.14**	**2.27**	**0.48**	**1.13**	**2.26**	**0.51**	**1.20**	**2.39**	**0.44**	**0.69**	**1.38**

IO: Immediate Occupancy, LS: Life Safety, CP: Collapse Prevention,
IPA: Inelastic Pushover Analysis at first indication of yield and confined concrete crushing,
THA: Time History Analysis at first indication of yield and confined concrete crushing,
IDA: Incremental Dynamic Analysis at first indication of yield and collapse (Vamvatsikos and Cornell, 2002),
*: LS limit state is considered 50% of the CP counterpart

ASSESSMENT OF LOCAL RESPONSE

Local and global performance criteria of the reference structures are monitored during the multi-step IPA and THA analyses using post-processors. The following two categories of local damage are considered in the current study: (i) formation of a plastic hinge, which is considered when the strain of the main reinforcing steel bars reaches the yield stain of steel, and (ii) crushing of the confinement concrete, which is defined when the strain of confined concrete reaches its ultimate value. The sequences of member yielding and crushing along with the corresponding IDRs of the benchmark structures are traced in Fig. 7. The plastic hinge distributions and the IDR corresponding to the formation of first plastic hinge for each building are presented in Fig. 7(a). For the regular structure, B1-REG, the results are presented for all structural members, while the plastic hinge distributions in vertical structural members are only shown in other buildings due to the significant contribution of shear walls and core walls to the lateral-force resisting systems. Fig. 8(b) depicts the distributions of concrete crunching in vertical structural elements and the IDR corresponding to the first detection of crushing for each of the reference building. It is shown that the IDRs corresponding to the first indication of hinging and crushing are comparable for B1-REG, B2-SST and B3-GEO, while much lower IDRs are observed in B4-WSST compared with other structures. It is clear that the undesirable effects of decreasing stiffness by increasing story height on local seismic response of well-designed structures are marginal. It is also observed that the geometric irregularity, although increases the number of plastic hinges and crushing points at the irregularity levels, it has minor effects on the seismic response of code-conforming structures. This conclusions are consistent with those reported in the literature (e.g. Sarkar et al., 2010). On the other hand, the discontinuity in lateral strength/weak story irregularity (B4-WSST) has significant impacts on the local response. This is clearly shown form the decreased IDRs corresponding to the first indications of hinging and crushing.



(a) Distributions of plastic hinges

(b) Distributions of confined concrete crushing

IDR at first indication of confined concrete crushing in walls   IDR at first indication of yielding

Figure 7. Local response of the reference buildings and the corresponding interstory drift

ASSESSMENT OF GLOBAL RESPONSE

IPA and IDA are performed using the fiber-based models of the reference structures. The IPAs are carried out for the transversal direction of the reference structures, as shown in Fig. 8. Two lateral load patterns are applied incrementally in a step-wise manner, namely a uniform load distribution, resembling the lateral forces that are proportional with mass, and an inverted triangular load distribution, representing the fundamental mode shape. Since higher modes significantly contribute to the response of high rise buildings, Mwafy et al. (2006) studied the load pattern representing the effect of the second mode. The study concluded that the uniform load pattern can be used for multi-story and high rise buildings as it provides a conservative estimate of the initial stiffness and the lateral capacity. The uniform lateral load pattern is therefore adopted to estimate the relative lateral capacity of the reference structures (Mwafy and Elnashai, 2001). It is worth mentioning that IPA was not employed in the present study to estimate seismic demands. These demands are mainly predicted using THA and IDA, as discussed below. Fig. 8 shows the ultimate capacity, the first indication of yielding and crushing in both the vertical and horizontal members, global yielding, and the corresponding IDRs. The capacity curves of the irregular structures are compared in Fig. 8 with the regular building.

It is shown in Fig. 8(b) that the extreme soft story structure (B2-SST) has a minor influence on the local and global response relative to the regular one (B1-REG). It slightly reduces the initial stiffness, ultimate lateral capacity, building ductility and the IDRs corresponding to local and global response parameters such as member yielding and crushing. Fig. 7(c) shows that the building that exhibit the geometric irregularity (B3-GEO) is slightly improved in terms of the initial stiffness, lateral capacity and ductility. The IDRs corresponding to local and global response parameters also slightly increased. In Fig. 7(d), the capacity curve of B4-WSST indicates higher initial stiffness and lateral capacity yet much lower ductility and IDRs corresponding to local damage compared to B1-REG. This is attributed to the assigned overstrength factor to the weak stories during the design process, as per the code recommendations. The shortcomings of the lateral strength/weak story irregularity are clearly shown from the results presented in Fig. 8.

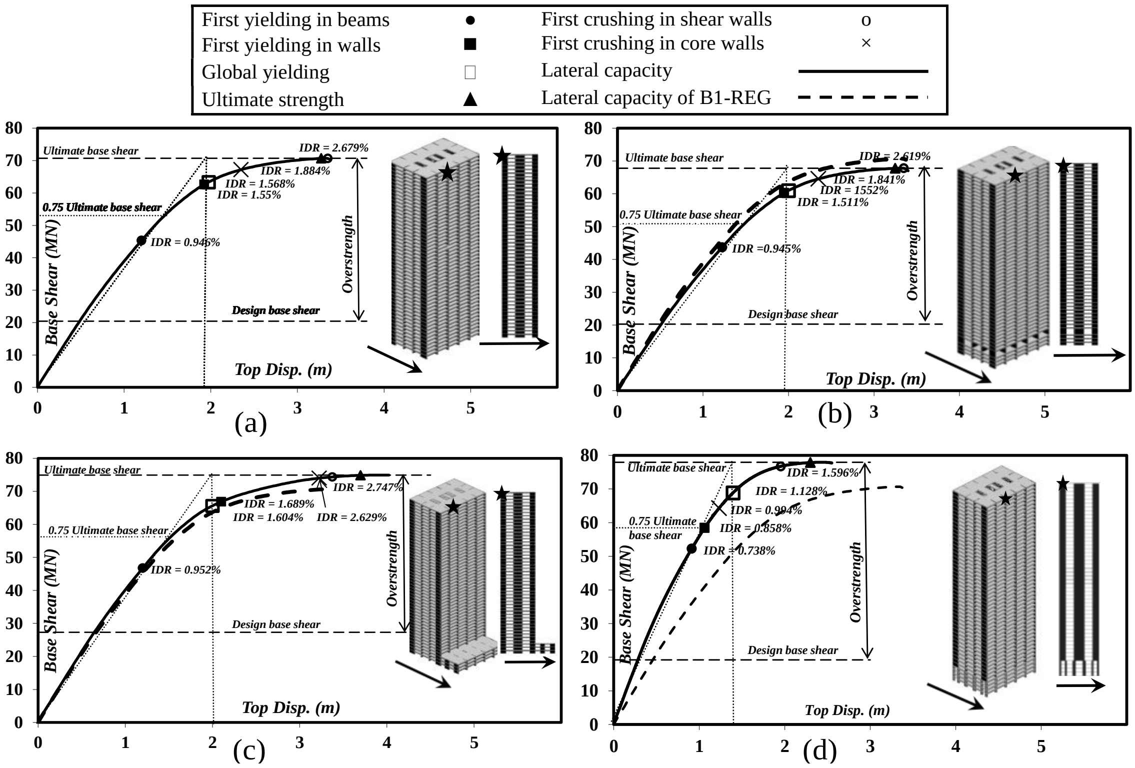


Figure 8. Lateral capacity of reference buildings in the transverse direction along with IDRs at the first indication of member yielding and crushing, (a) B1-REG, (b) B2-SST, (c) B3-GEO, (d) B4-WST

A large number of IDAs are carried out using the 40 input ground motions described above to derive reliable vulnerability relationships for the reference structures. Fig. 9 depicts the IDA results obtained from twenty natural records representing the far-field earthquake scenario along with the power law equations and limit states of the reference buildings. Fig. 10 compares between the vulnerability functions of the reference structures under the effect of the far-field earthquake scenario. The IO, LS and CP limit states are presented separately to allow effective comparisons between different buildings. To provide a more informative presentation of the results, Fig. 10 also depicts the limit state probabilities of the reference buildings under the long-distance earthquake scenario at the design and twice design ground motion intensity levels.

The results of the probabilistic vulnerability assessment shown in Figs. 9 and 10 confirm the satisfactory performance of well-designed regular and irregular buildings under the design earthquake. With the exception of B4-WST, the probabilities of exceeding different limit states at twice the design intensity are also acceptable, particularly for the LS and CP limit states. These observations are consistent with the seismic design philosophy of modern building codes. In contrast, the developed LS and CP fragility curves as well as the probabilities of exceeding different limit states at twice the design intensity confirm the higher vulnerability of B4-WST compared with other structures. Despite the assigned overstrength factor to the weak stories during the design process of B4-WST, as per the code recommendations, the deficiencies of the lateral strength/weak story irregularity are clearly shown from the results presented at different performance levels. These observations shed the light on the expected higher earthquake losses in certain classes of irregular structures and the need for mitigation strategies to reduce these losses for new and existing irregular buildings.

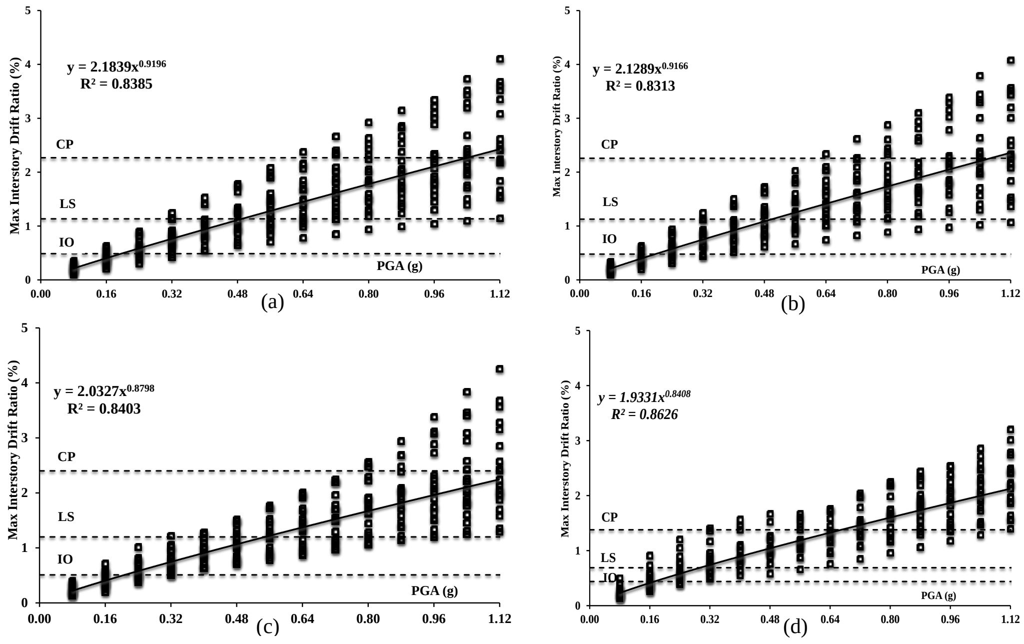


Figure 9. IDA results obtained from the far-field earthquake scenario along with the power law equations and limit states of the reference buildings: (a) B1-REG, (b) B2-SST, (c) B3-GEO, and (d) B4-WST

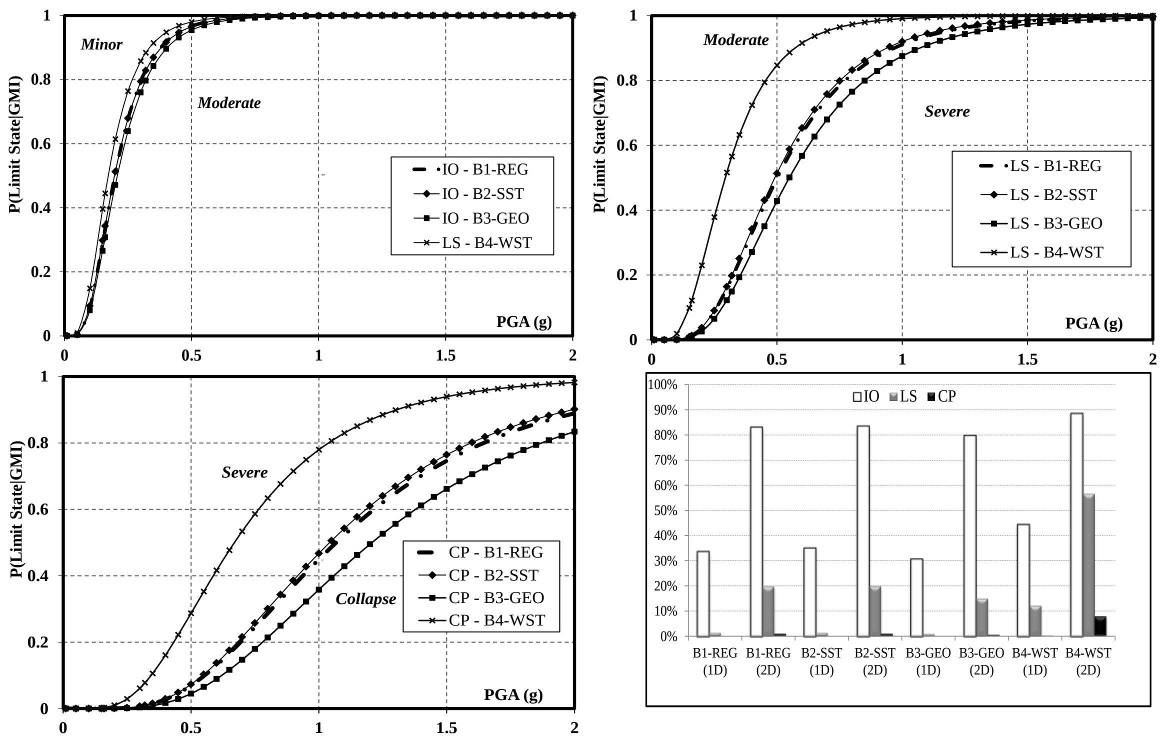


Figure 10. Comparisons of the fragility relationships and damage state probabilities for the reference structures

CONCLUSIONS

Several previous studies related to the seismic behavior of irregular buildings focused on the impact of irregularity on seismic demands in the elastic and early inelastic ranges. The findings from such studies may not be valid with increasing inelasticity. Most previous studies also focused on low to medium-rise MRFs or on limited case studies of high-rise buildings. The relative margins of safety offered by modern design codes for vertically irregular high-rise buildings at different performance levels were thus investigated in the present study. A set of 50-story benchmark structures were selected and fully designed according to modern provisions for the design of irregular structures to represent code-conforming high-rise buildings. A number of important vertical irregularities highlighted by building codes were systematically introduced in the selected group of reference structures. The local and global seismic response of the benchmark structures were assess using verified fiber-based simulation models and advanced assessment methodologies under the effect of 40 input ground motions representing two seismic scenarios. The limit states were selected based on the results of the present study, previous experimental studies, and the code-recommended values.

The local and global seismic response obtained from a large number of IPAs and IDAs were compared for the benchmark structures to provide insights into their seismic performance and relative safety margins. It was concluded that the undesirable effects of decreasing the vertical stiffness due to increasing the story height of well-designed structures were marginal. Introducing a soft story slightly reduced the initial stiffness, ultimate lateral capacity, building ductility and the IDRs corresponding to local and global response parameters. The geometric irregularity, although increased plasticity and damage at the irregularity levels, it had also minor positive influence on the seismic response of code-conforming structures. The discontinuity in lateral strength/weak story irregularity had significant impacts on the local and global response parameters, particularly at high ground motion intensity levels. Although the initial stiffness and lateral capacity increased due to the assigned overstrength factor to the weak stories as per the code recommendations, much lower ductility and IDRs corresponding to local damage were observed in the reference structure with the latter irregularity compared with other reference structures. With the exception of the lateral strength/weak story irregularity, the probabilities of exceeding different limit states at the design and at twice the design intensity levels were acceptable. In contrast, the probabilistic vulnerability assessment confirmed the vulnerability of well-designed high-rise buildings with the lateral strength/weak story irregularity, particularly at twice the design intensity. The penalty assigned by the design code in the form of an overstrength factor did not effectively overcome the apparent deficiencies of the lateral strength/weak story irregularity at high intensity levels. These observations shed the light on the expected high earthquake losses in certain classes of irregular structures, and the need for expanding the study to cover other structural irregularities and effective mitigation strategies to reduce earthquake losses for new and existing irregular high-rise buildings.

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