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Investigation of Effects of Capacity Spectrum Method on Performance Evaluation of Multi-Story Buildings According to the IRAQI Seismic Code Requirements

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Abstract

The aim of this study is to assess the performance objectives defined in the Iraqi Seismic Code (ISC) in order to make a realistic evaluation related to Performance-Based Seismic Design (PBSD) of multi-story reinforced concrete buildings and also to compare and evaluate structural response demands obtained from nonlinear static analysis procedures according to two versions of the capacity spectrum method (CSM) which are recommended in ATC 40 and ATC 55. Two groups of three-dimensional RC buildings with different heights, designed according to Iraqi Building Code Requirements for Reinforced Concrete (IBC), are investigated. Pushover analyses are carried out to determine the nonlinear behavior of the buildings under three different seismic hazard levels, for two Iraqi seismic zones, of earthquake loads. In order to determine performance levels of the buildings, maximum inter-story drift demands and plasticizing sequence are determined and compared with the related limits using the CSM recommended in ATC 40 and ATC 55. From the results of this research, it can be concluded that RC buildings designed according to the Iraqi codes sufficiently provide the performance objectives stipulated in the ISC. Comparing structural response quantities obtained from the two versions of CSM, effects on performance evaluations of the buildings are investigated comparatively, as well.

Keywords

Pushover Analysis, Capacity Spectrum Method, Seismic Capacity, Iraq, PBSD, RC Buildings

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1. Introduction

Building damages and collapses in severe earthquakes have caused huge life and economic losses, in different parts of the world. Even smaller earthquakes have also caused the inelastic behavior in buildings. Therefore, it is necessary to examine and discuss the current country codes and develop alternative approaches to the traditional force based design [1]. Performance-based design (PBSD) is a major shift from traditional structural design concepts and represents the future of earthquake engineering. The procedure provides a method for determining acceptable levels of earthquake damage. Also, it is based on the recognition that yielding does not constitute failure and that preplanned yielding of certain members of a structure during an earthquake can actually help to save the rest of the structure. The structural engineer is interested in its concepts due to its potential benefits in assessment, design, and better understanding of structural behavior during ground motions. It also, permits the owners and designers to select personalized performance goals for the design of different structures. It seems that PBSD concepts, which allow multi-level design objectives, can provide a framework to improve the current codes; by obtaining structures that perform appropriately for all of seismic hazard levels [2].

In determination of response demands for seismic assessments of buildings within PBSD concept, nonlinear static analysis procedures (NSPs) are becoming more popular in structural engineering practice. Although nonlinear time history analysis is the most reliable analysis in determination of the seismic response demands, it requires rather sophisticated input data and provides output, which is difficult to interpret. For this reason, NSPs are frequently used in ordinary engineering applications to avoid sophisticated assumptions required by the latter. As a result, simplified NSPs recommended in ATC 40 [3], FEMA 237 [4], FEMA 356 [5], and other documents have become popular [6] [7].

The nonlinear static procedure requires development of a pushover curve, a plot of base shear versus roof displacement, by nonlinear static analysis of the structure subjected first to gravity loads, followed by monotonically increasing lateral forces with a specified invariant height wise distribution. At least two force distributions must be considered [5] [7].

Then, maximum structural response demands, (such as drifts, plastic rotations, inter-story drifts, shear strength, etc.) are obtained by using this curve. Single degree-of-freedom (SDOF) system approach is used in determination of demands in NSPs recommended in ATC 40 and FEMA 356, which is called as capacity spectrum method (CSM) and displacement coefficient method (DCM), respectively. However, these procedures have some discrepancy in determination of displacement demand for the same building model and under a specific ground motion [8] [9]. Consequently, same building performances may not be obtained due to these discrepancies in the analysis procedures.

Applied Technology Council with funding provided by FEMA conducts the ATC 55 [10] project to overcome the deficiencies and discrepancies in the NSPs using performance based engineering methods for seismic design, evaluation, and rehabilitation of buildings [11]. The ATC 55 Project has two objectives: the development of practical recommendations for improved prediction of inelastic structural response of buildings to earthquakes (*i.e.*, guidance for improved application of inelastic analysis procedures), and the identification of important issues for future research.

The capacity spectrum method (CSM) has gained considerable popularity amongst pushover users since its introduction in 1975 by Freeman and collaborators [12] [13]. Chopra and Goel [14] found some flows in CSM version of ATC 40. The ATC 55 project derives the optimal vibration period and damping ratio parameters for the equivalent linear system by minimizing the differences between its response and that of the actual inelastic system and rectifies the flows in the original version [8]. For this reason, it is of prime importance to investigate effects of the CSM versions in performance evaluations of RC buildings, having different structural characteristics, within PBD and assessment concept.

In order to obtain useful elements of comparison between the two versions of CSM, the building performance is evaluated in this work with the features proposed in ATC 40 and ATC 55 and by comparing the seismic response estimation of the analyzed buildings in terms of drift profiles, roof drift ratios, inter-story drift ratios, base shear demands and plasticizing sequence due to component rotational demands.

Performances of RC buildings designed according to the Iraqi Building Code IBC 1987 [15] and Iraqi Seismic Code ISC 1997 [16] are examined, in an attempt to investigate the behavior of RC buildings in Iraq through evaluation of the performance objectives stipulated in the ISC. As in several contemporary country codes, general principles of earthquake resistant structure design are stated in the ISC 1997, which consists of rather indistinct definitions concerning the expected seismic hazard and damage levels. Stipulated performance objectives of the ISC are as follows:

1. The structure should withstand, without any structural and non-structural damage, the effects of slight seismic motion.

2. The structure should withstand, with limited non-structural damage and limited non-linear behavior of structural members, the effects of moderate seismic motion (design earthquake).

3. The structure should not collapse under sever or maximum expected earthquake.

The code provisions attempt to provide these performance objectives with various requirements (*i.e.*, ductility and capacity requirements, displacement restrictions, etc.). These restrictions are very similar in all of the contemporary codes. However, it is not possible to check the states of the stipulated performance objectives by means of the traditional force based design. In order to determine the expected performances of the buildings, the performance based approaches including displacements rather than forces should be used in design and assessment.

Two groups of three-dimensional RC multi-story buildings are investigated in this study. Each group has three buildings (3, 6, and 9 stories). The buildings in the first group have a soft story, while those in the second group have none. In order to determine building performance, base shear–roof displacement relationships (capacity curves) of each building designed according to Iraqi codes are obtained by pushover analysis.

Each building is subjected to two kinds of lateral load distribution, P1**,** and P2, across its height. The first one is according to an equation of equivalent static forces as in ISC, while the second is proportional to the story masses at each story level. Two different seismic zones were chosen from the seismic zoning map of Iraq and three seismic hazard levels, derived from the ISC design spectrum, are considered in this study for each zone. Then, buildings' performances are determined using the two versions of CSM. Comparing the performances of the modeled RC buildings to the stipulated objectives in the ISC, the behavior of RC buildings in Iraq is evaluated.

2. Properties of the Buildings

In order to compare seismic demands obtained from the CSM on RC buildings, three dimensional (3D) structural systems having three (3S), six (6S), and nine (9S) stories are designed according to the Iraqi codes (IBC and ISC Codes). In order to investigate the effects of having a soft first story on performance, two groups, types, of system configurations were used T1S and T1N by taking the first story height, in the former, 50% more than the other stories, while it was kept the same in the latter. The basic structure is symmetrical in two directions and has no structural irregularity. All buildings are residential having the same square plan dimensions 20 m × 20 m with 5 m bays in both directions. All stories have the same (3 m) height, except in the first stories of the buildings in T1S group (**Figure 1**). The systems were designed to carry: Live Load of 2 kN/m^2, Flooring Load of 1.5 kN/m^2, Partitions Load of 2 kN/m^2, Mechanical and Electrical load of 0.5 kN/m^2 in addition to the slab weight of 150 mm thickness. The equivalent horizontal static seismic load was also considered according to the Iraqi seismic code. The sectional details were done for those residential buildings according to the Iraqi building code and the results are shown in **Table 1**.

3. Assumptions of the Structural Model

The next step in PBSD is the estimation of seismic demands in the structure due to imposed earthquake loads. The prediction of deformation demands is arguably the most critical step in PBD. Determining demands necessitates the development of a structural model of reasonable complexity. Errors in estimating the demand as a result of an inadequate structural model can propagate through and lead to misleading conclusions on the performance of the structure.

Nonlinear bending and axial deformations are assumed to occur at certain sections, which are defined as plastic sections, whereas the other portions of the building remain elastic. It is assumed that plastic hinges occur with pure bending moment in beams and with combined bending moment and axial force in columns.

Shear force and torsional moment capacities of beams and columns are also checked separately in the analyses. Moment-plastic rotation relationships of column and beam sections are assumed as rigid plastic with kinematic hardening, and characteristic values of them (plastic moment and maximum plastic rotation values) are taken from ATC 40. Cracked section stiffness values for columns and beams are taken as proposed in FEMA

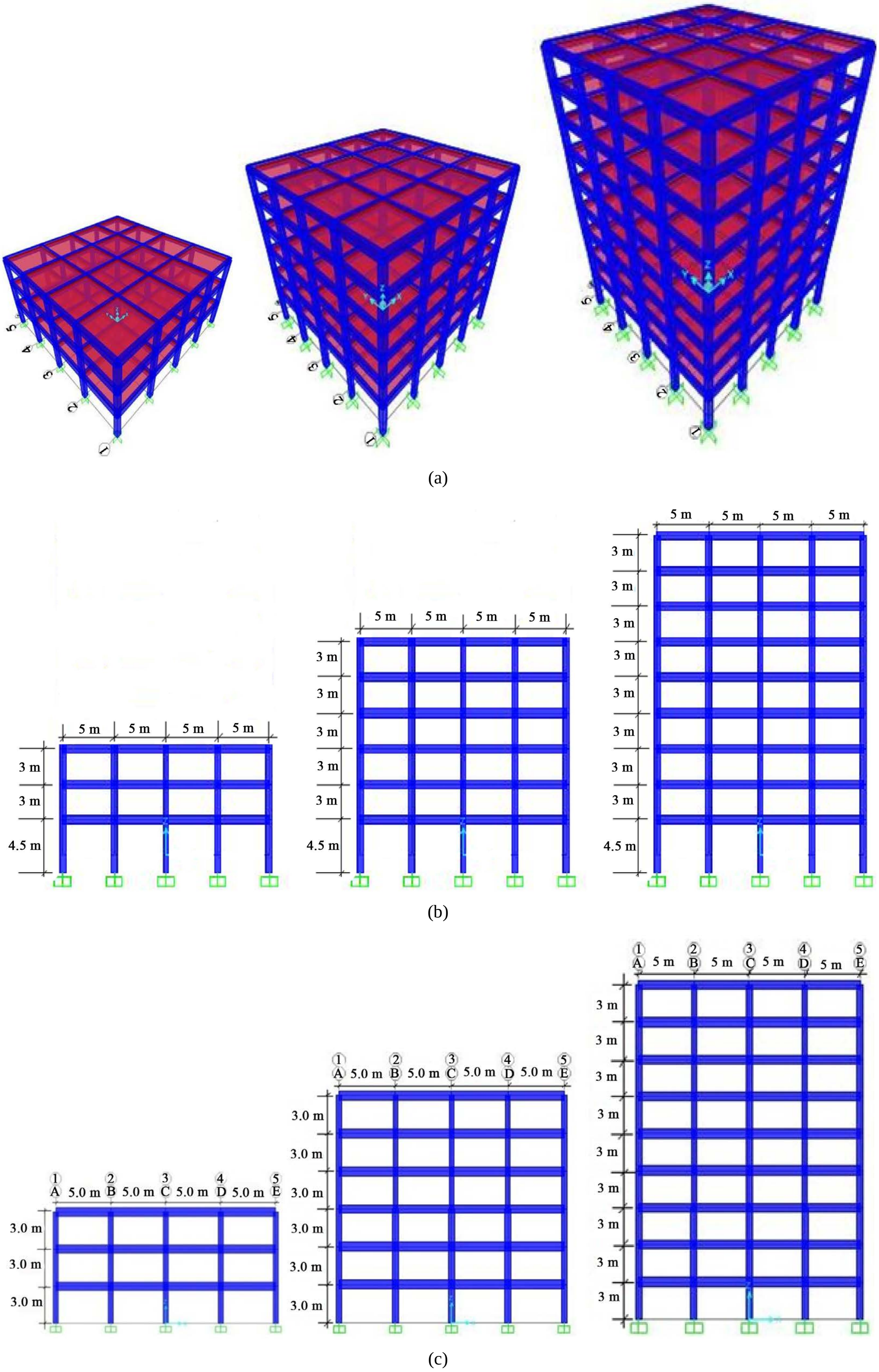


Figure 1. (a) Perspective, 3D view of the investigated buildings; (b) Buildings group T1S, with soft first story; (c) Buildings group T1N, with normal first story.

Table 1. Section details of reinforced concrete frames type T1S and T1N.

Building	Level	Exterior Columns		Interior Columns		Beams		
		Size (mm × mm)	Steel (mm^2)	Size (mm × mm)	Steel (mm^2)	Size (mm × mm)	Top Steel (mm^2)	Bottom Steel (mm^2)
Three Stories	1	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
	2	450 × 450	5130	450 × 450	5130	30 × 700	1000	1000
	3	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
Six Stories	1	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	2	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	3	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	4	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
	5	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
	6	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
Nine Stories	1	550 × 550	7660	550 × 550	7660	300 × 700	1500	1500
	2	550 × 550	7660	550 × 550	7660	300 × 700	1500	1500
	3	550 × 550	7660	550 × 550	7660	300 × 700	1500	1500
	4	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	5	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	6	500 × 500	6330	500 × 500	6330	300 × 700	1250	1250
	7	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
	8	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000
	9	450 × 450	5130	450 × 450	5130	300 × 700	1000	1000

356. For the cases where members lose all or a significant portion of their lateral load carrying ability, but could continue to deflect with no other unacceptable effects, ATC 40 and FEMA 356 purpose a procedure in order to determine the capacity curves and the performance points for these types of buildings.

The SAP 2000 structural analysis program was used in the pushover analyses of the RC buildings [17]. **Table 2** shows the weight, the fundamental period, and the legend for each building.

4. Performance Objectives

A performance objective may be regarded as the main element in PBSD and is composed of two parts: a performance level and a seismic hazard level which describes the expected seismic load at the site. Terms such as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) are examples of performance levels, as defined in FEMA 356 [5] and ATC 40 [3].

Seismic hazard levels are typically prescribed in terms of response spectra and are controlled by site characteristics. As the performance objectives in the ISC are not clearly defined as to seismic hazard levels and performance levels, it is not possible to fully validate or interpret building performance. For this purpose, based on the performance and substitute damage levels defined in ATC40, performance objectives of the ISC are defined in the study. In the seismic design of the buildings two different seismic zoning areas, Baghdad and Dehok (**Figure 2**), were chosen from the seismic zoning map of Iraq (**Figure 2**). The corresponding seismic coefficients **Ca** and **Cv** are 0.11, and 0.21 for Baghdad zone and 0.20, and 0.25 for Dehok zone. According to this, three different seismic hazard levels for each zone, with a seismic importance factor of 1, are considered in determination of the structural and nonstructural response demands of the RC buildings. These seismic hazard levels are expressed as:

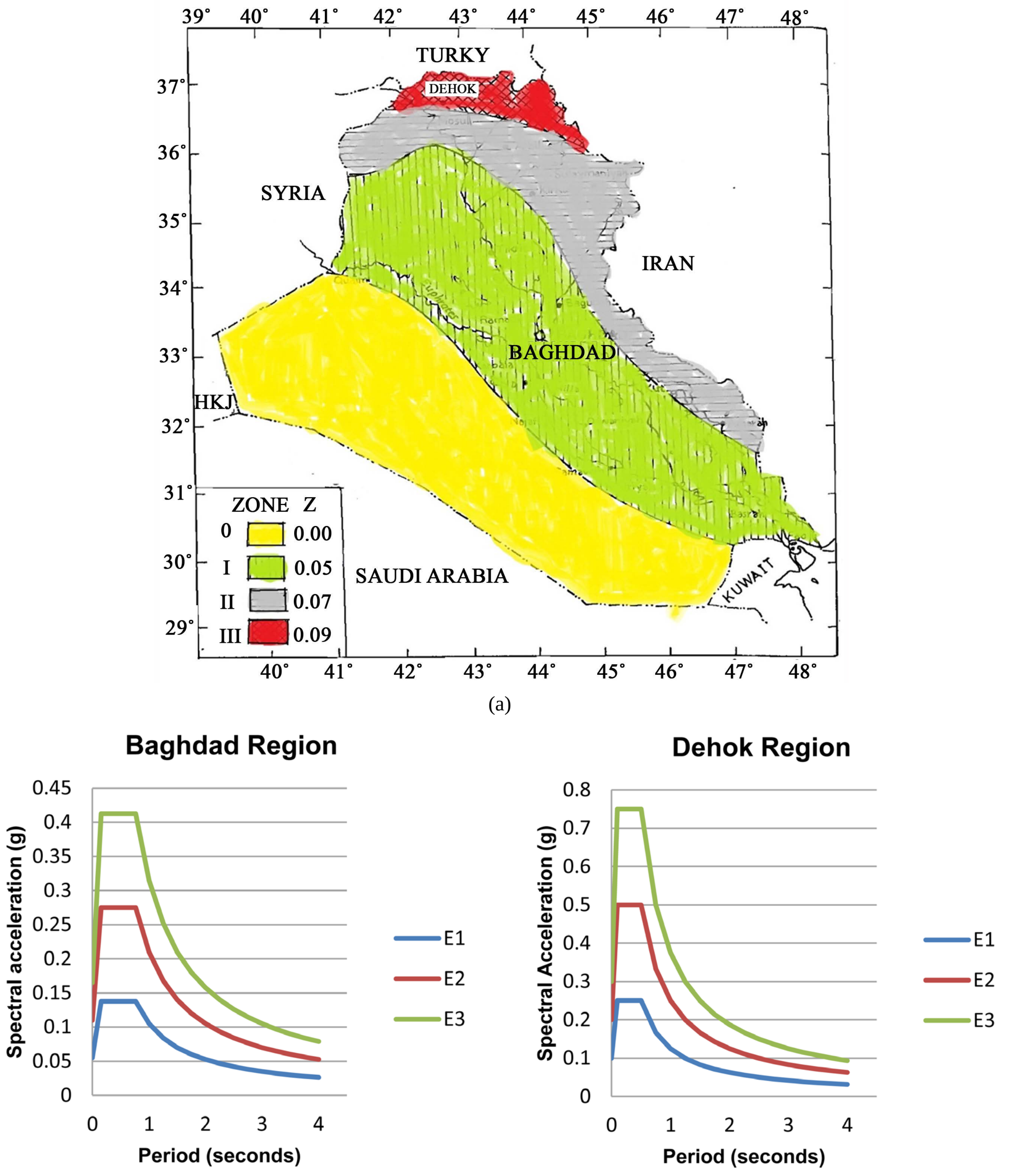


Figure 2. (a) Seismic zoning map of Iraq; (b) Response spectrum, Baghdad Zone; (c) Response spectrum, Dehok Zone.

Table 2. Building type, weight, modal mass, fundamental period, and legend.

Frame Geometry	Number of Stories	Building Type	Weight (kN) L + D	α_1 Modal Mass Coefficient	T_1 Fundamental Period (s)	Building Legend
3D Three Dimensional	3S Three Stories	T1S	15820	0.967	0.785	3D-3S-T1S
		T1N	15640	0.876	0.561	3D-3S-T1N
	6S Six Stories	T1S	31760	0.904	1.208	3D-6S-T1S
		T1N	31530	0.812	1.019	3D-6S-T1N
	9S Nine Stories	T1S	47980	0.847	1.606	3D-9S-T1S
		T1N	47710	0.785	1.450	3D-9S-T1N

1. Seismic Hazard Level I—(E1): In low-intensity earthquakes with 50% probability of being exceeded in 50 years, it is assumed that the buildings remain at immediate occupancy (IO) performance level or better.
2. Seismic Hazard Level II—(E2): In moderate earthquakes with 10% probability of being exceeded in 50 years, it is assumed that the buildings remain between immediate occupancy (IO); performance level and life safety performance level (LS).
3. Seismic Hazard Level III—(E3): In the maximum earthquake with 2% probability of being exceeded in 50 years, it is assumed that the buildings remain at (LS) performance level of the building or very close to it and should never reach collapse prevention (CP) performance level.

There are two criteria for determining performance levels in order to make performance evaluations of the buildings. These criteria are the maximum plastic rotation values in the members of the structural system (beams and columns) and maximum inter-story drift values of the building, which is pushed statically until the maximum displacement demand is reached.

5. Distribution of Seismic Forces

To represent the earthquake effects, the buildings are subjected to a lateral load distribution across its height according to two patterns; the equivalent static ISC [16] triangular load pattern P1, and the uniform load pattern P2. In the first pattern, the total horizontal seismic design force *V* should be distributed over the height of the building in accordance with the following formula [16]:

$$V_i = \frac{W_i h_i}{\sum_{j=1}^{N} W_j h_j} V \tag{1}$$

In the above expression, V_i is the seismic design force in the *i*-th level, W_i and W_j are the *i*-th and *j*-th floor weights, h_i and h_j are the heights of the *i*-th and *j*-th floors from the top of the foundation, and *N* is the total number of levels. The lateral loads were increased monotonically in the pushover analyses. **Figure 3** shows the equivalent Horizontal Static Design Seismic Loading in kN, applied on a typical Interior Frame according to the ISC in Baghdad Zone for the investigated Buildings. For buildings with more than five levels, **0.15 *V*** shall be considered to be concentrated at the top level while the remaining **0.85 *V*** shall be distributed in accordance with the above formula.

6. Determination of Capacity Curves

In the pushover analyses, combinations of vertical and lateral loads were based on the rules of the Iraqi Seismic code (ISC) and the design was based on the Iraqi Building Code (IBC1987). According to this, capacity curves

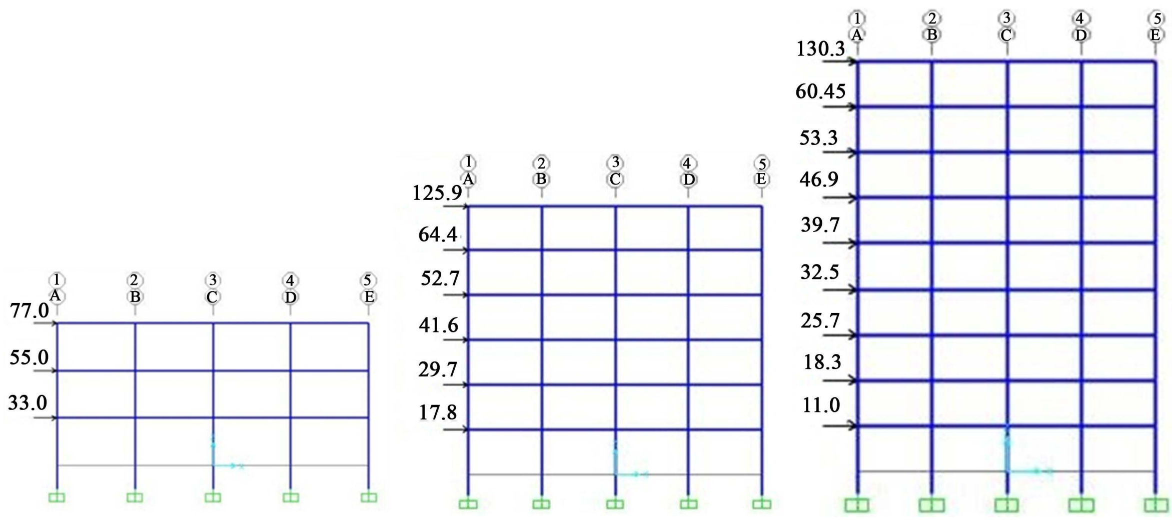


Figure 3. Equivalent horizontal static design seismic loading (kN), applied on a typical interior frame according to the ISC in Baghdad Zone for the investigated buildings.

including the load combinations (D + L + E with e = 0, and D + L + E with e = 0.05) were determined for the investigated buildings. In these formulas, D, L, E, and e denote dead load, live load, earthquake load, and eccentricity (5% additional eccentricity in buildings without plan irregularities), respectively. The lateral loads were increased monotonically in the pushover analyses to produce the capacity curves.

Dividing the values of the base shear by the weight and the top drift by the height of the building, the normalized capacity curves were obtained. Those curves are shown for the three story buildings, 3S-T1S and 3S-T1N, using the two load patterns P1 and P2 in **Figure 4(a)**. The first yield points FYP are also indicated on the curves. It is found that the curves ordinates are greater for P2 than P1 and T1N than T1S. The same conclusion could be obtained for the six story buildings, 6S-T1S and 6S-T1N, and the nine story buildings, 9S-T1S and 9S-T1N, (**Figure 4(b)**, **Figure 4(c)**). **Figure 4(d)** demonstrates that the normalized capacity curves values for the three story buildings are the highest while those of the nine story buildings are the lowest.

The performance points for the three hazard levels, E1, E2, and E3, along with the first yield points FYP, were done on the Capacity Curves for both seismic zones, Baghdad and Dehok. As a sample, **Figure 5** represents the curves for the nine story buildings. The horizontal shear design forces HSDF, according to the ISC, are also drawn on the same graphs. It is found that: 1—The performance points for E1 are lower than FYP, which means that the structures will remain elastic. The spacing is much more obvious for the T1N buildings and even more for the higher ones. 2—The curves ordinates due to P2 are always higher than P1. 3—The performance points for Dehok Zone are higher than Baghdad and the ATC 55 values are higher than those of ATC 40, everywhere.

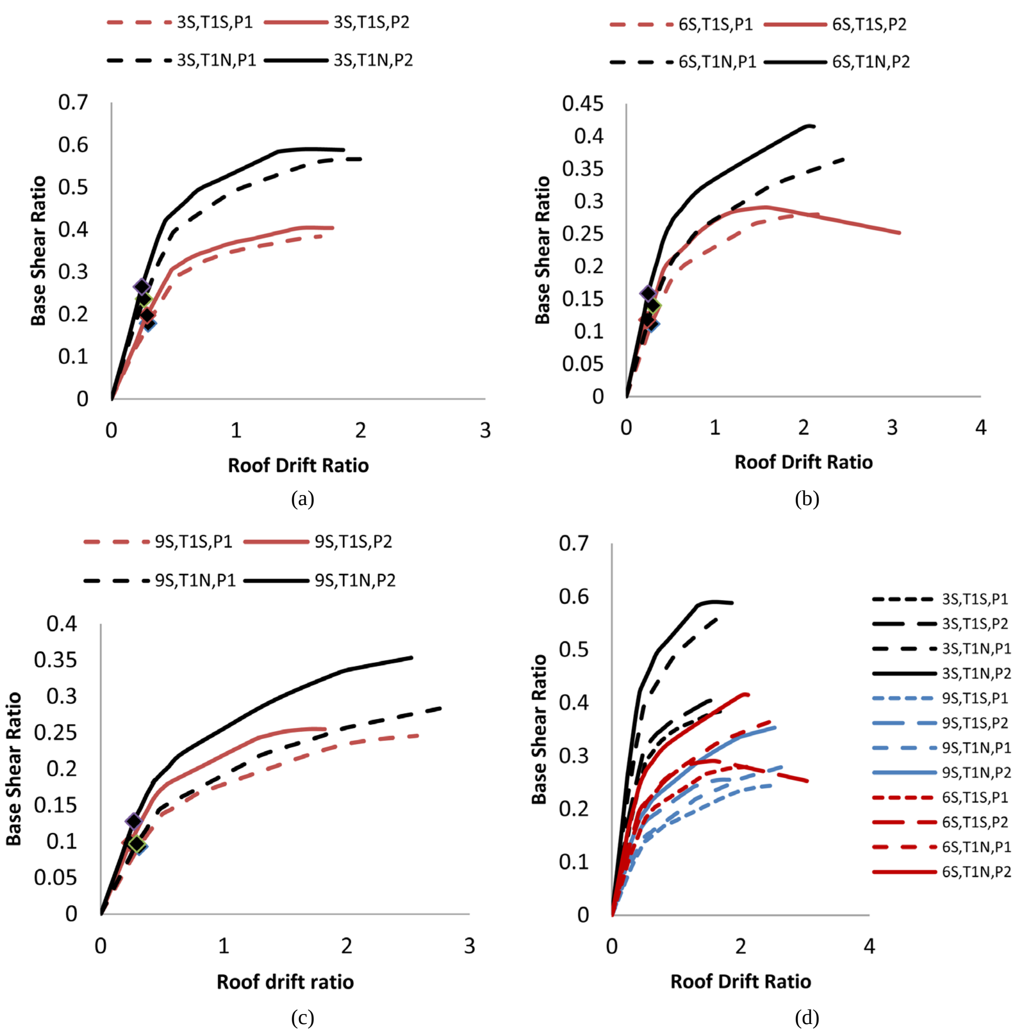


Figure 4. (a) Capacity curves for 3S; (b) Capacity curves for 6S; (c) Capacity curves for 9S; (d) Capacity curves for all buildings.

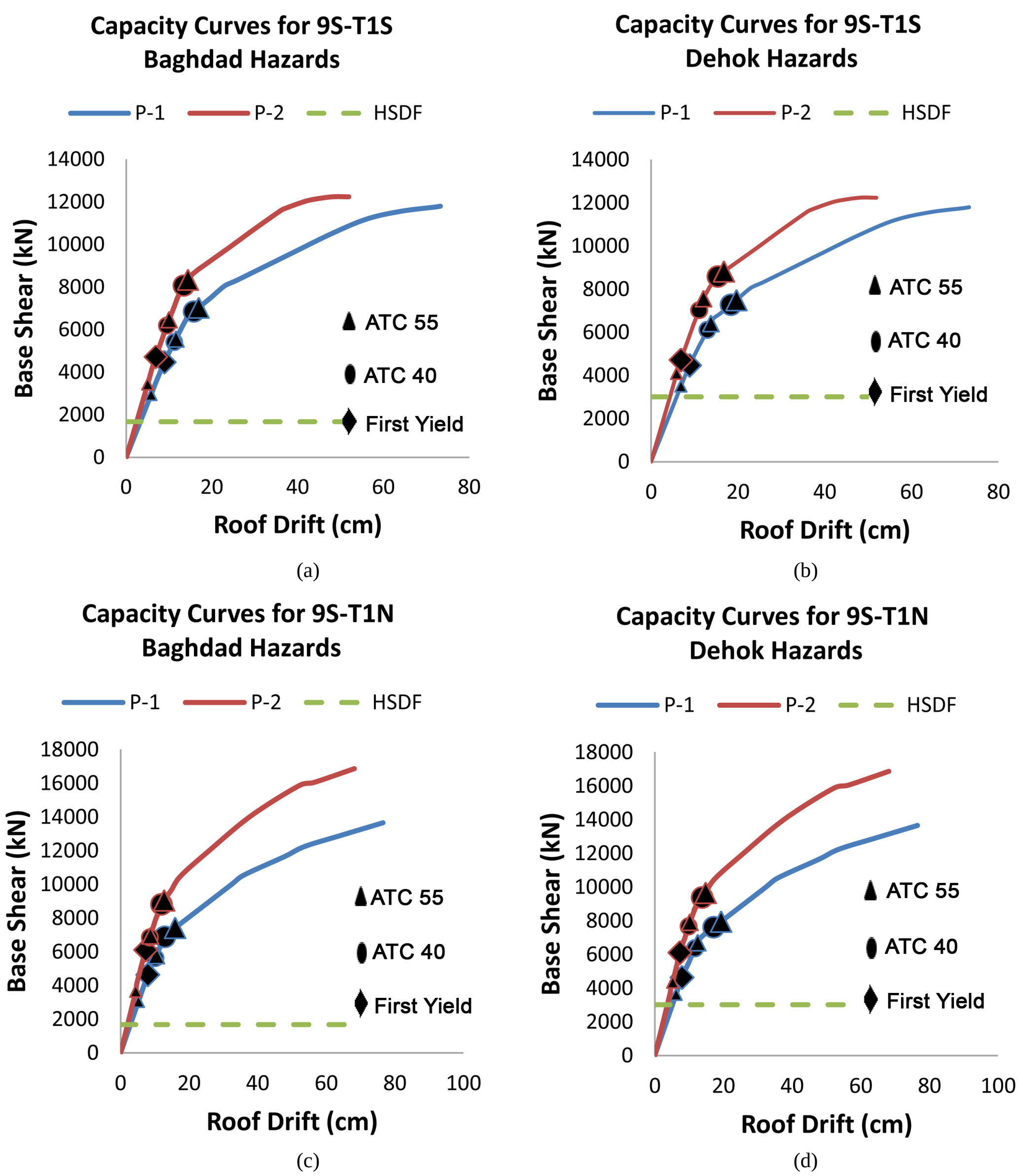


Figure 5. (a) Capacity curves for 9S-T1S-bag; (b) Capacity curves for 9S-T1S-Dehok; (c) Capacity curves for 9S-T1N-bag; (d) Capacity curves for 9S-T1N-Dehok.

7. Prediction of Seismic Response Demands

Displacement and strength demands for the various building configurations were determined according to the investigated versions of CSM for both lateral load patterns using the three seismic hazard levels of each seismic zone. The maximum displacement and strength demand values with certain characteristic parameters obtained from the CSM (δ_{max}, V_b, S_a, S_d, β_{eff}) are shown in Table 3. The displacement profiles of the nine story buildings pushed to maximum displacement demands are shown in Figure 6 for seismic hazard level E3. It was clear that both displacement and strength demands are higher for ATC 55 than ATC 40.

8. Performance Assessment

In this final phase of the procedure the seismic demands, at both global and local levels, computed in the previous steps are compared with acceptable levels of damage for various performance states. Ultimately, the objective of a seismic evaluation is to identify deformation demands in structural components during an earthquake

Table 3. (a) Analysis results for T1S-P1, in Baghdad and Dehok due to ATC40; (b) Analysis results for T1S-P1, in Baghdad and Dehok due to ATC55; (c) Analysis results for T1S-P2, in Baghdad and Dehok due to ATC40; (d) Analysis results for T1S-P2, in Baghdad and Dehok due to ATC55; (e) Analysis results for T1N-P1, in Baghdad and Dehok due to ATC40; (f) Analysis results for T1N-P1, in Baghdad and Dehok due to ATC55; (g) Analysis results for T1N-P2, in Baghdad and Dehok due to ATC40; (h) Analysis results for T1N-P2, in Baghdad and Dehok due to ATC55.

(a)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	2.5	2.9	2256	2686	0.132	0.157	2.1	2.5	5.0	5.0
	E_2	4.7	5.5	4018	4580	0.235	0.268	4.0	4.7	6.7	7.6
	E_3	6.6	7.5	4853	5093	0.283	0.296	5.6	6.5	11.2	14.4
6S	E_1	4.2	5.0	2717	3234	0.084	0.100	3.2	3.9	5.0	5.0
	E_2	8.1	9.4	4820	5480	0.149	0.169	6.3	7.3	6.8	7.7
	E_3	11.3	13.1	6090	6477	0.187	0.199	8.9	10.3	10.3	12.8
9S	E_1	5.8	6.9	2947	3509	0.063	0.076	4.3	5.1	5.0	5.0
	E_2	11.2	13.0	5417	6114	0.116	0.131	8.4	9.7	6.3	7.3
	E_3	15.8	18.4	6848	7286	0.146	0.155	11.9	14.0	9.4	11.7

(b)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	2.5	2.9	2256	2686	0.132	0.157	2.1	2.5	5.0	5.0
	E_2	5.1	5.9	4280	4685	0.250	0.274	4.3	5.0	7.0	7.4
	E_3	7.0	7.9	4951	5165	0.288	0.300	6.0	6.8	7.4	7.7
6S	E_1	4.2	5.0	2717	3234	0.084	0.100	3.2	3.9	5.0	5.0
	E_2	8.6	10.2	5091	5820	0.157	0.179	6.7	8.0	6.9	7.7
	E_3	12.1	14.4	6285	6646	0.193	0.208	9.5	11.4	7.6	8.7
9S	E_1	5.8	6.9	2948	3509	0.063	0.076	4.3	5.1	5.0	5.0
	E_2	11.6	13.8	5558	6411	0.119	0.137	8.6	10.3	5.8	6.5
	E_3	16.9	19.7	7029	7495	0.150	0.160	12.8	15.0	7.4	8.2

(c)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	2.3	2.7	2375	2837	0.138	0.164	2.0	2.4	5.0	5.0
	E_2	4.4	5.1	4297	4843	0.249	0.281	3.8	4.5	6.5	7.6
	E_3	6.1	7.0	5131	5347	0.296	0.308	5.3	6.1	11.4	14.5
6S	E_1	3.7	4.4	3064	3648	0.092	0.109	3.0	3.6	5.0	5.0
	E_2	7.1	8.2	5424	6190	0.162	0.184	5.7	6.7	6.8	7.7
	E_3	10.1	11.7	6726	7100	0.199	0.209	8.4	9.9	9.9	12.1
9S	E_1	5.0	5.9	3440	4095	0.071	0.084	3.9	4.6	5.0	5.0
	E_2	9.5	11.1	6193	7030	0.126	0.143	7.5	8.8	6.6	7.5
	E_3	13.4	15.4	8068	8593	0.163	0.173	10.7	12.4	9.5	12.0

(d)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	2.3	2.7	2375	2837	0.138	0.164	2.0	2.4	5.0	5.0
	E_2	4.7	5.4	4524	4934	0.262	0.286	4.1	4.7	6.5	6.8
	E_3	6.4	7.3	5220	5409	0.301	0.311	5.6	6.5	6.6	7.4
6S	E_1	3.7	4.4	3064	3648	0.092	0.109	3.0	3.6	5.0	5.0
	E_2	7.6	9.1	5802	6510	0.173	0.193	6.2	7.5	7.3	8.3
	E_3	11.3	13.3	6975	7401	0.206	0.217	9.4	11.2	9.7	10.9
9S	E_1	5.0	5.9	3440	4095	0.071	0.084	3.9	4.6	5.0	5.0
	E_2	10.0	12.1	6470	7564	0.132	0.153	7.9	9.6	6.6	7.6
	E_3	14.4	16.8	8343	8824	0.168	0.177	11.6	13.6	7.7	8.3

(e)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	1.3	2.2	2122	3455	0.138	0.224	1.1	1.7	5.0	5.0
	E_2	2.7	4.1	4091	5784	0.265	0.374	2.1	3.3	5.5	7.8
	E_3	3.9	5.9	5516	6700	0.357	0.427	3.1	4.8	7.4	12.6
6S	E_1	3.6	4.3	2940	3499	0.102	0.121	2.7	3.2	5.0	5.0
	E_2	6.9	8.0	5302	5932	0.183	0.205	5.2	6.1	6.6	7.7
	E_3	9.7	11.4	6715	7155	0.231	0.246	7.4	8.7	9.7	12.8
9S	E_1	5.2	6.2	3048	3628	0.071	0.085	3.8	4.6	5.0	5.0
	E_2	10.1	11.7	5615	6360	0.131	0.149	7.5	8.7	6.2	7.1
	E_3	14.4	17.1	7182	7604	0.168	0.177	10.8	12.9	8.5	9.9

(f)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok	Bag.	Dehok
3S	E_1	1.3	2.2	2122	3455	0.138	0.224	1.1	1.7	5.0	5.0
	E_2	2.7	4.6	4151	6226	0.269	0.402	2.2	3.6	5.5	8.2
	E_3	4.3	6.5	6006	6906	0.388	0.438	3.4	5.3	7.9	10.2
6S	E_1	3.6	4.3	2940	3499	0.102	0.121	2.7	3.2	5.0	5.0
	E_2	7.1	8.5	5434	6205	0.188	0.214	5.4	6.4	5.9	6.6
	E_3	10.5	12.4	6925	7415	0.238	0.255	8.1	9.5	7.7	8.8
9S	E_1	5.2	6.2	3048	3628	0.071	0.085	3.8	4.6	5.0	5.0
	E_2	10.4	12.5	5775	6695	0.135	0.157	7.7	9.3	5.9	6.6
	E_3	15.9	19.3	7415	7947	0.173	0.185	12.0	14.6	8.2	9.8

(g)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**
	E_1	1.2	2,0	2176	3778	0.138	0.239	1.0	1.6	5.0	5.0
3S	**E_2**	2.3	3.8	4300	6485	0.272	0.409	1.9	3.1	5.2	7.5
	E_3	3.3	5.3	5848	7261	0.369	0.450	2.7	4.4	6.8	13.8
	E_1	3.1	3.7	3453	4110	0.114	0.136	2.4	2.9	5.0	5.0
6S	**E_2**	5.9	6.9	6254	7072	0.205	0.231	4.7	5.4	6.5	7.5
	E_3	8.3	9.5	8056	8599	0.262	0.279	6.6	7.7	9.6	12.1
	E_1	4.4	5.2	3651	4347	0.081	0.097	3.4	4.0	5.0	5.0
9S	E_2	8.5	9.8	6843	7657	0.151	0.169	6.6	7.7	6.0	7.1
	E_3	11.9	13.8	8809	9375	0.193	0.205	9.3	10.9	8.9	11.1

(h)

Buildg.	Seismic Hazard Level	δ_{max} (cm)		V_b (kN)		S_a (g)		S_d (cm)		β_{eff} (%)	
		Bag.	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**	**Bag.**	**Dehok**
	E_1	1.2	2.0	2176	3778	0.138	0.239	1.0	1.6	5.0	5.0
3S	**E_2**	2.3	4.0	4321	6655	0.273	0.418	1.9	3.3	5.1	7.4
	E_3	3.6	5.6	6240	7411	0.393	0.458	2.9	4.6	6.9	8.5
	E_1	3.1	3.7	3454	4110	0.114	0.136	2.4	2.9	5.0	5.0
6S	**E_2**	6.2	7.4	6470	7502	0.212	0.245	4.9	5.8	6.2	7.0
	E_3	8.9	10.3	8313	8840	0.270	0.286	7.1	8.3	7.4	7.8
	E_1	4.4	5.2	3651	4347	0.081	0.097	3.4	4.0	5.0	5.0
9S	E_2	8.7	10.2	6944	7910	0.154	0.174	6.7	8.0	5.5	6.1
	E_3	12.7	14.8	9042	9655	0.198	0.211	10	11.7	7.0	7.8

and whether these demands will exceed the capacity of the element. The drifts are the key elements to build on for performance assessment. The inter-story drift ratio is determined from the drifts and the maximum Inter-story drift ratio is concluded then from them. The latter is compared with the deformation limits mentioned in ATC and FEMA documents for assessment. **Figure 6** and **Figure 7** show the drifts and the inter-story drift ratio for the Nine Story buildings, respectively.

It is clear from **Figure 6** and **Figure 7** that the drifts and the inter-story drift ratios (IDR) are higher for ATC55 compared with ATC40. The same could be said about Dehok Zone compared with Baghdad zone. Although P1 pattern yields higher values for the global roof drift ratio (GDR or RDR), P2 pattern accentuates IDR of the soft story in the first level. For this reason P2 is more suitable for exploring T1S group of buildings.

9. Relationship between Inter-Story Drift Ratio and Roof Drift Ratio

The inter-story drift ratio of story *i* of the building is calculated as:

$$\mathrm{IDR}_i = \frac{\Delta_i - \Delta_{i-1}}{h_i} \tag{2}$$

The global, roof drift ratio for the building is:

$$\mathrm{RDR}_i = \frac{\Delta_{\mathrm{roof}}}{H} \tag{3}$$

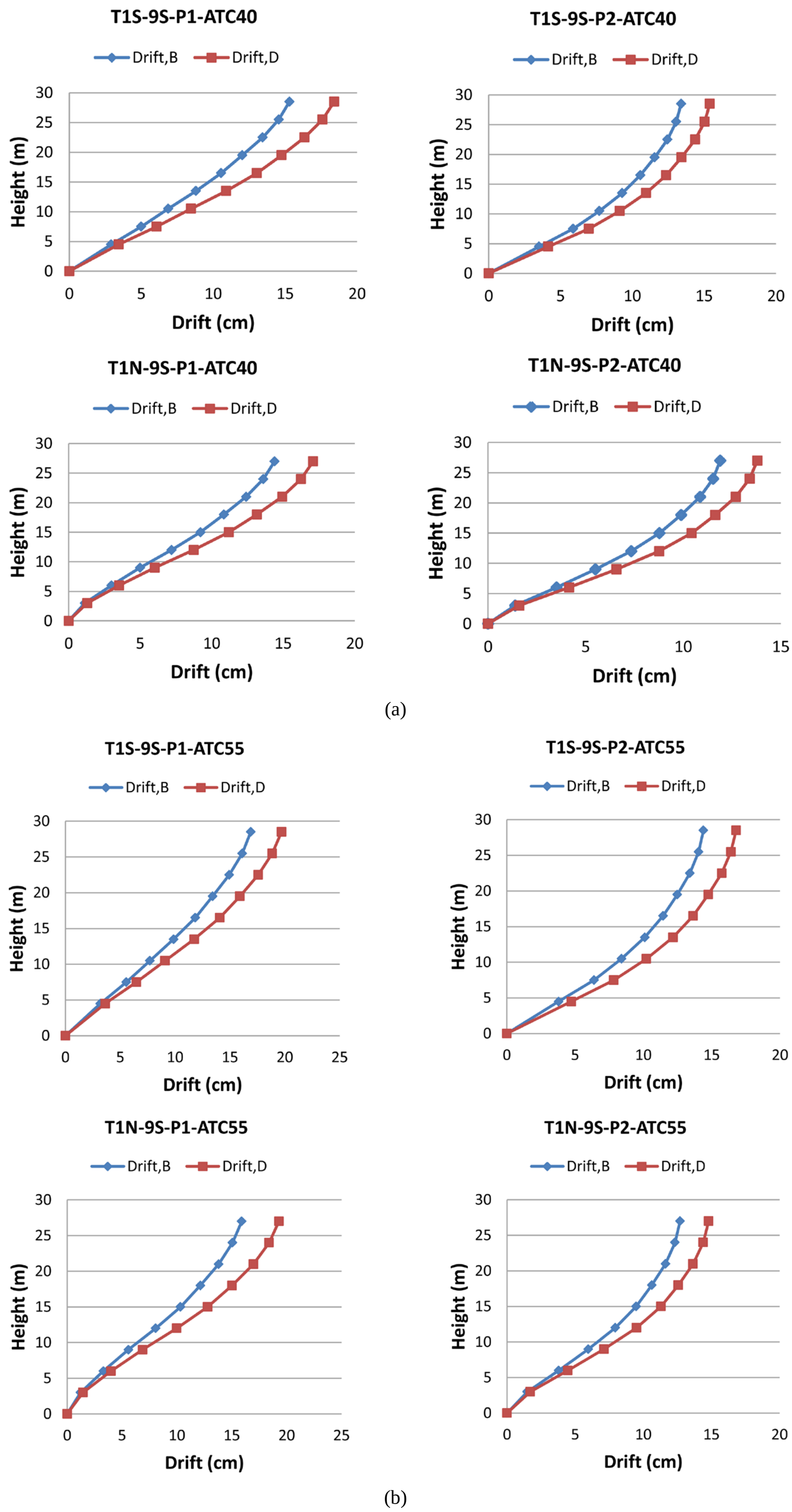
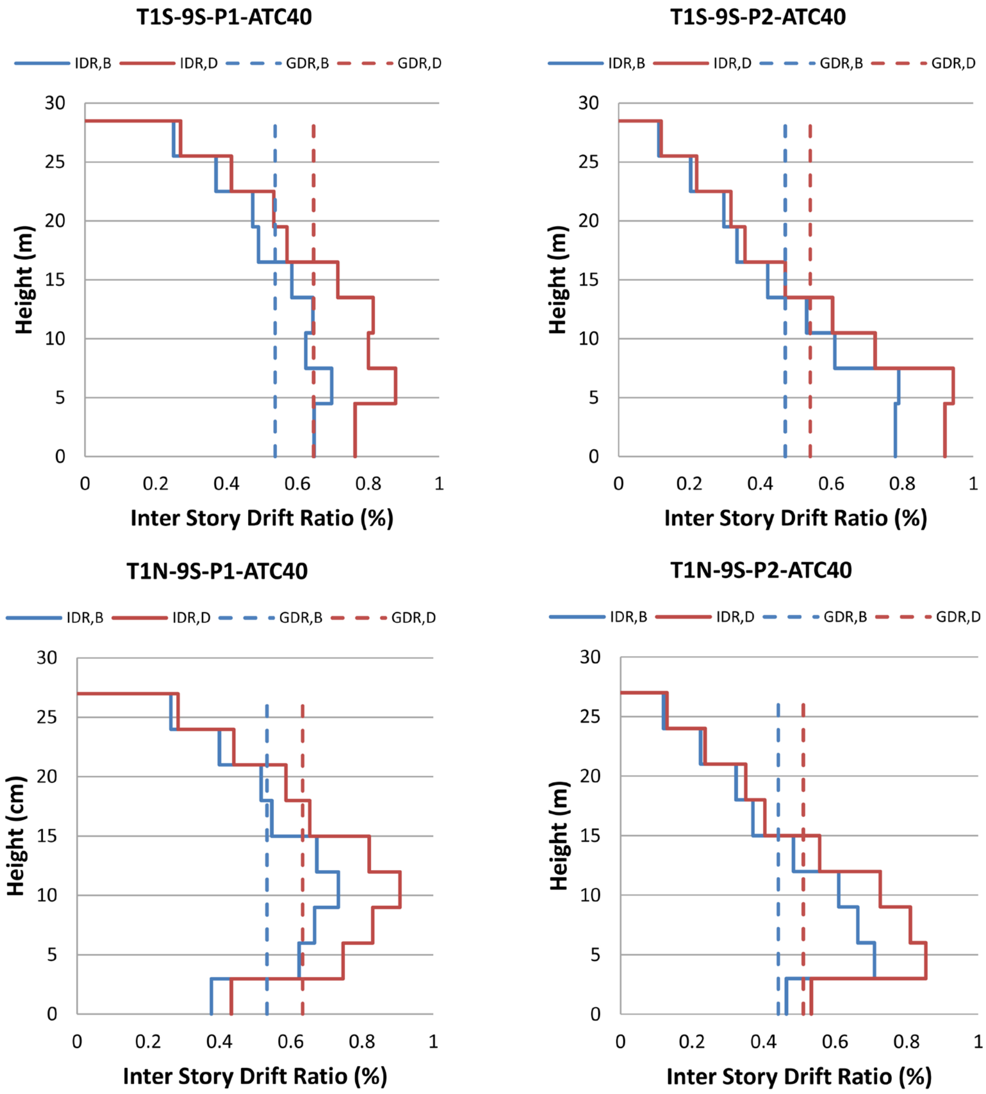
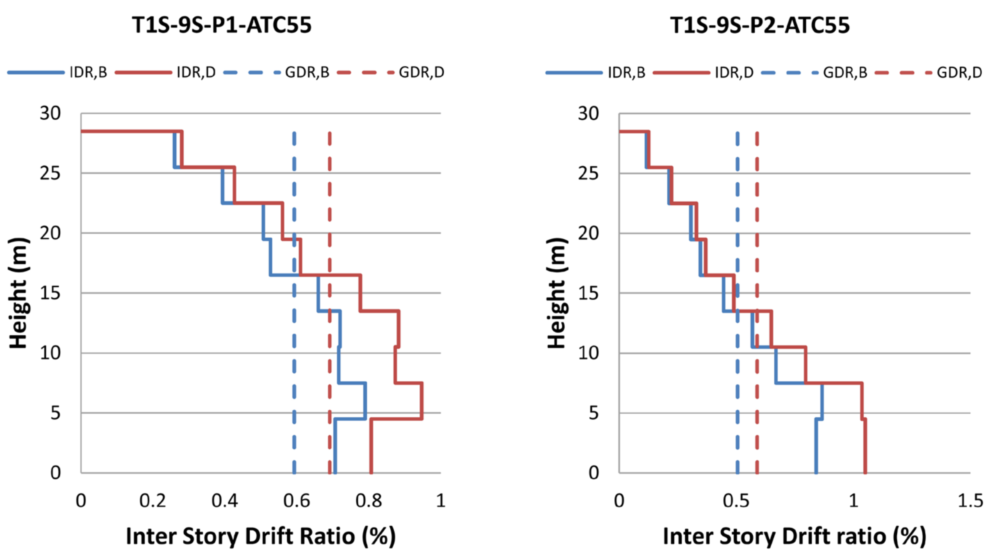
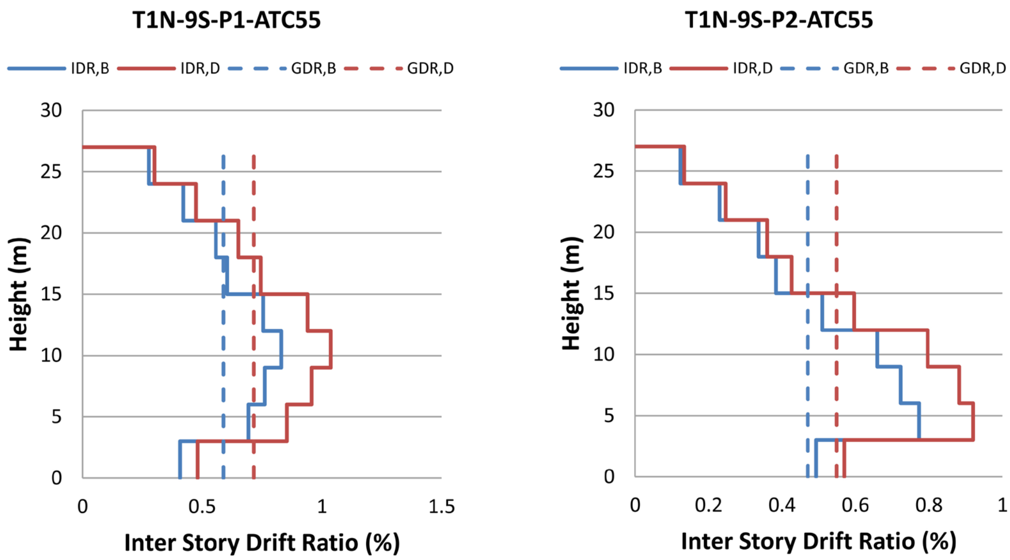


Figure 6. (a) Drifts of the nine story buildings according to ATC40; (b) Drifts for the nine story buildings according to ATC55.


T1S-9S-P1-ATC40
IDR,B
IDR,D
GDR,B
GDR,D
Height (m)
Inter Story Drift Ratio (%)
T1S-9S-P2-ATC40
IDR,B
IDR,D
GDR,B
GDR,D
Height (m)
Inter Story Drift Ratio (%)
T1N-9S-P1-ATC40
IDR,B
IDR,D
GDR,B
GDR,D
Height (cm)
Inter Story Drift Ratio (%)
T1N-9S-P2-ATC40
IDR,B
IDR,D
GDR,B
GDR,D
Height (m)
Inter Story Drift Ratio (%)

(a)


T1S-9S-P1-ATC55
IDR,B
IDR,D
GDR,B
GDR,D
Height (m)
Inter Story Drift Ratio (%)
T1S-9S-P2-ATC55
IDR,B
IDR,D
GDR,B
GDR,D
Height (m)
Inter Story Drift ratio (%)



(b)

Figure 7. (a) The inter-story drift ratio for the nine story building according to ATC40; (b) The inter-story drift ratio for nine story buildings according to ATC55.

The average inter-story drift ratio for the building is:

$$\mathrm{IDR}_{av} = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta_i - \Delta_{i-1}}{h_i} \tag{4}$$

If the same height, $h_\circ$, is used to the stories, then the roof drift ratio, RDR, is equal to the average inter-story drift ratio, IDR_{av} of the building

$$\mathrm{IDR}_{av} = \frac{1}{N \cdot h_\circ}\sum_{i=1}^{N}\left(\Delta_i - \Delta_{i-1}\right) = \frac{\Delta_N}{H} = \frac{\Delta_{roof}}{H} = \mathrm{RDR}$$

This result is interesting because the story drifts, in the formula, cancel each other leaving only that of the roof even for buildings with different story heights, the error is negligible.

In FEMA and ATC documents, the maximum IDR in a building is adopted as the main important criteria for evaluation of building performance. The RDR could also be used as a global indicator for evaluation by finding an approximate relationship between RDR and the maximum IDR. For the investigated buildings it is found that for patterns P1 and P2 the following approximate relations are satisfactory (**Figure 8**). The error found using these approximate formulas is not more than about 5%

$$\mathrm{IDR} = 1.73\mathrm{RDR} - 0.225 \tag{5}$$

$$\mathrm{IDR} = 2.06\mathrm{RDR} - 0.224 \tag{6}$$

Equations (5) and (6) could be used to convert the objective limits from IDR to RDR and then use them to locate the objective limits on the normalized capacity curves. **Figure 9** shows those for the nine story buildings. The roof drift ratios and the exact maximum inter-story drift ratios for seismic hazard E3 are show in **Table 4(a)** and **Table 4(b)**, respectively.

10. Plasticization

Furthermore, plasticization on the frames of the investigated buildings was performed in order of formation of plastic hinges. **Table 5** shows the number of plastic hinges that were created in the buildings due to the E3 hazard level. **Figure 10** shows those for the nine story buildings 9S. It is obvious that ATC55 produce more hinges than ATC40.

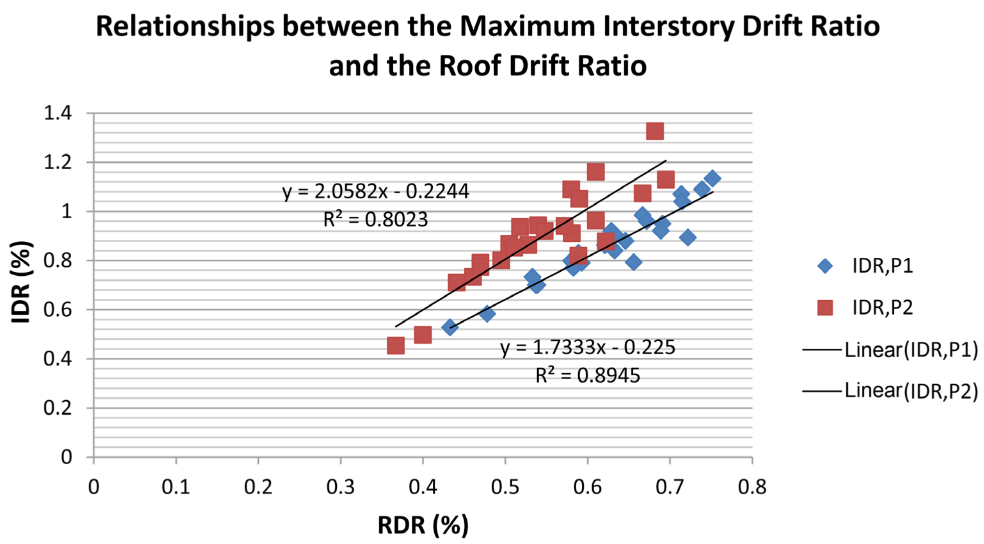


Figure 8. Relations between maximum inter-story drift ratio and the roof drift ratio.

Table 4. (a) The roof drift ratio for seismic hazard E3; (b) The maximum inter-story drift ratio for seismic hazard E3.

(a)

Type of Building	No. of Stories	Baghdad Zone				Dehok Zone			
		P1		P2		P1		P2	
		ATC40	ATC55	ATC40	ATC55	ATC40	ATC55	ATC40	ATC55
T1S	3S	0.629	0.667	0.581	0.610	0.714	0.752	0.667	0.695
	6S	0.580	0.621	0.518	0.580	0.672	0.739	0.610	0.682
	9S	0.537	0.593	0.470	0.505	0.646	0.619	0.540	0.590
T1N	3S	0.433	0.478	0.367	0.400	0.656	0.722	0.589	0.622
	6S	0.539	0.583	0.461	0.495	0.633	0.689	0.528	0.572
	9S	0.533	0.589	0.441	0.470	0.633	0.715	0.511	0.548

(b)

Type of Building	No. of Stories	Baghdad Zone				Dehok Zone			
		P1		P2		P1		P2	
		ATC40	ATC55	ATC40	ATC55	ATC40	ATC55	ATC40	ATC55
T1S	3S	0.920	0.985	0.911	0.962	**1.070**	**1.133**	**1.073**	**1.129**
	6S	0.798	0.862	0.936	**1.090**	0.960	**1.090**	**1.160**	**1.327**
	9S	0.700	0.790	0.790	0.867	0.880	0.950	0.943	**1.051**
T1N	3S	0.527	0.583	0.453	0.497	0.793	0.893	0.820	0.877
	6S	0.700	0.770	0.733	0.800	0.840	0.920	0.863	0.94
	9S	0.733	0.830	0.710	0.773	0.907	**1.040**	0.853	0.92

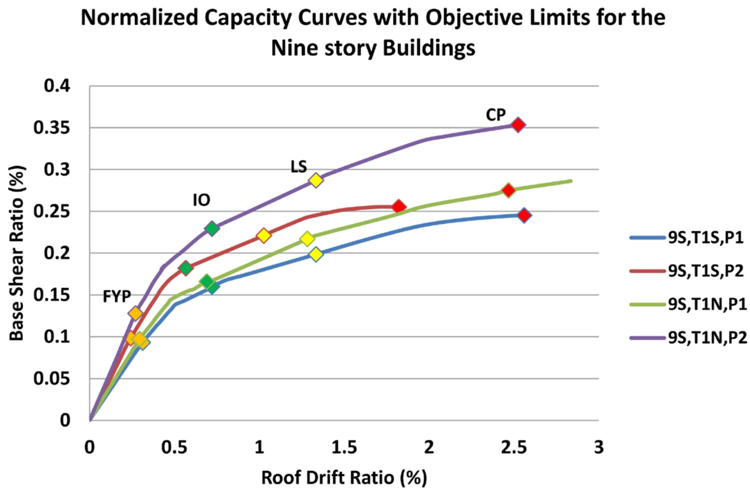


Figure 9. Normalized capacity curves for the nine story buildings with objective limits.

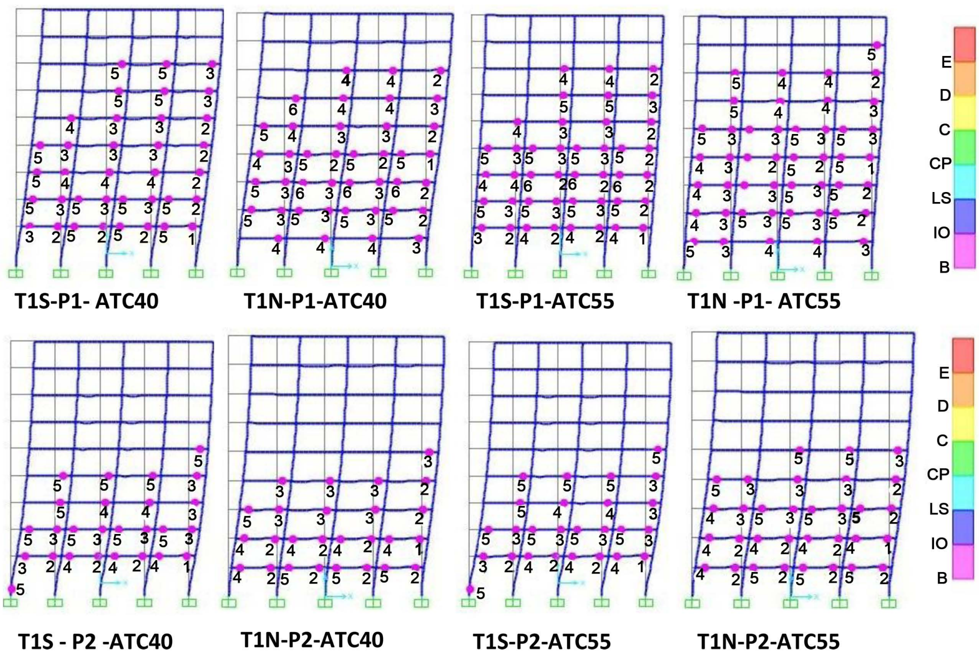


Figure 10. Plasticizing sequence of the nine story buildings due to P1 and P2 according to ATC40 and ATC55 in Baghdad Zone, for Seismic Hazard E3.

Table 5. Number of plasticizing sections created in the buildings due to E3 hazard level (Note: the asterisked bold numbers mean some hinges reach the LS state).

Type of Building	No. of Stories	Baghdad Zone				Dehok Zone			
		P1		P2		P1		P2	
		ATC40	ATC55	ATC40	ATC55	ATC40	ATC55	ATC40	ATC55
T1S	3S	73	79	62	74	89	**96***	80	**80***
	6S	138	150	103	110	161	174	**113***	**126***
	9S	188	222	130	140	237	248	160	180
T1N	3S	43	61	25	36	105	111	85	**87***
	6S	138	161	109	118	173	183	136	150
	9S	208	236	138	172	238	262	177	188

11. Performance Levels of the RC Buildings

For the three seismic hazard levels, maximum plastic rotations for each component end and maximum inter-story drift ratios for each story are determined for each building configuration pushed until the related maximum displacement demand is achieved. Performance levels of the buildings are determined by comparing the maximum plastic rotation and story drift values with the relevant limit values relating to performance levels (IO, LS, and CP) defined in ATC 40 [3].

Considering the results obtained performance levels of each building configuration can be expressed as follows:

1. For levels E1—It is determined that performance of every modeled building, is better than the IO performance level, actually it is less than the first yield point (FYP) which means that all structures will remain elastic for all of the 48 cases investigated;
2. For level E2—It is determined that the performance levels of all buildings, for all the 48 cases, are between FYP and IO;
3. For level E3—It is determined that the performance level of all buildings is better than IO except for the 10 cases according to the drift criteria (**Table 4(b)**) where the performance level is between IO and LS and 5 cases according to the rotation criteria (**Table 5**), where some hinges reach the LS.

12. Comparison of Seismic Demands for the Two CSM Versions

In order to compare the structural and nonstructural response demands obtained from the two CSM versions (ATC 40 and ATC 55), seismic response quantities related to the RC building configurations are determined and compared to each other by considering various parameters as follows:

1. Roof drift and shear strength demands.
2. Number and type of plastic hinges.
3. Inter-story drift ratio demands.
4. Roof drift ratio demands.

12.1 Roof Drift and Shear Strength Demands

Roof drift and shear strength demands obtained from CSM of ATC 40 and ATC 55 for each building are shown in **Table 6**. The roof drift and shear strength demands determined with ATC 55 are always greater than those obtained from ATC 40. Both demands required for any building, due to a certain hazard level of earthquake, are always higher for ATC55, Dehok Zone, P1 pattern compared with ATC40, Baghdad Zone and P2 pattern, respectively. The demands are always more for higher buildings (9S > 6S > 3S). The Roof drift demands are higher for soft story buildings (T1S > T1N), while the shear strength demands are higher for normal story buildings (T1N > T1S).

Table 6. Roof drift demands (cm) and shear strength demands (kN) due to (E3).

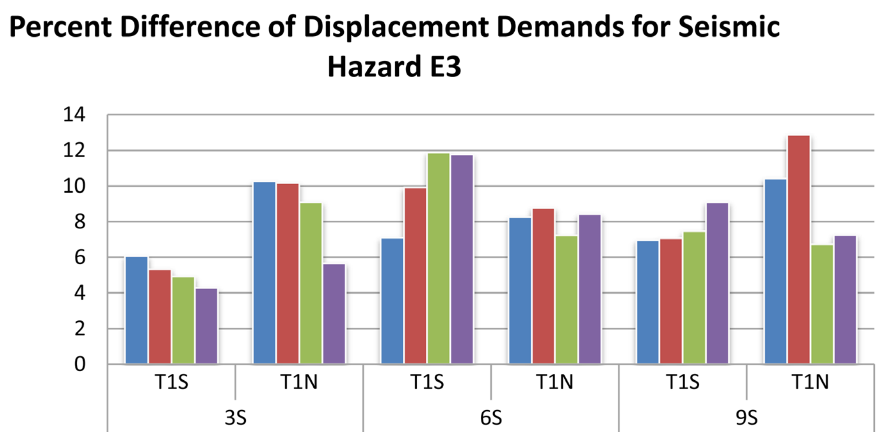
Profile	Region	Procedure Version	3S				6S				9S			
			T1S		T1N		T1S		T1N		T1S		T1N	
			RDD	SSD	RDD	SSD	RDD	SSD	RDD	SSD	RDD	SSD	RDD	SSD
P1	Baghdad	ATC40	6.6	4853	3.9	5516	11.3	6090	9.7	6715	15.8	6848	14.4	7182
		ATC55	7.0	4951	4.3	6006	12.1	6285	10.5	6925	16.9	7029	15.9	7415
	Dehok	ATC40	7.5	5087	5.9	6700	13.1	6477	11.4	7155	18.4	7280	17.1	7604
		ATC55	7.9	5165	6.5	6906	14.4	6646	12.4	7415	19.7	7495	19.3	7947
P2	Baghdad	ATC40	6.1	5131	3.3	5848	10.1	6726	8.3	8056	13.4	8068	11.9	8809
		ATC55	6.4	5220	3.6	6240	11.3	6975	8.9	8313	14.4	8343	12.7	9042
	Dehok	ATC40	7.0	5347	5.3	7261	11.9	7100	9.5	8599	15.4	8593	13.8	9375
		ATC55	7.3	5409	5.6	7411	13.3	7401	10.3	8840	16.8	8824	14.8	9655

The results show that the investigated CSM versions give considerable different displacement demands, independent from the building configurations.

Figure 11 and **Figure 12** depict the percentile differences of the displacement and strength demands, obtained from CSM-ATC55 with respect to CSM-ATC40, for hazard level E3. For displacement demands the value ranges between 4.29% to 12.87%, while it ranges between 1.16% to 8.88%. It is clear from the figures that the discrepancy is higher for the displacement demands compared with strength demands.

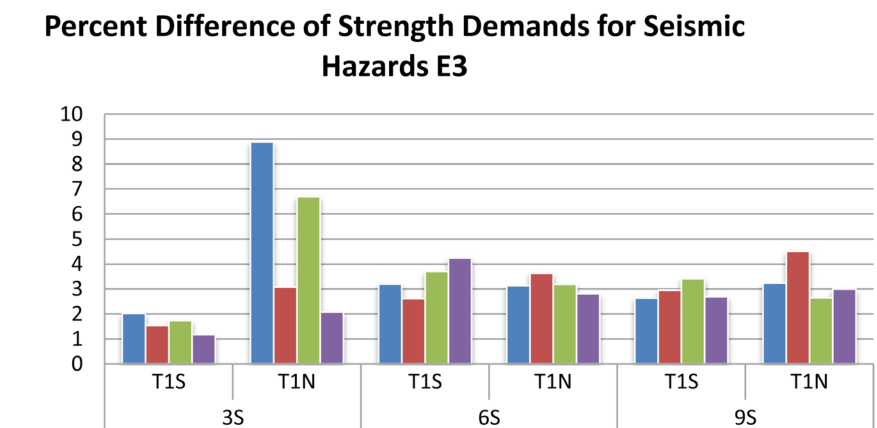
12.2. Number and Type of Plastic Hinges

As shown in **Table 5** and **Figure 10**, the number and type of plasticizing sections (beam and column plastic rotation demands) obtained from CSM of ATC 55 for the building configurations are generally greater than those



	T1S	T1N	T1S	T1N	T1S	T1N
	3S		6S		9S	
P1 Baghdad DD	6.06	10.26	7.08	8.25	6.96	10.42
P1 Dehok DD	5.33	10.17	9.92	8.77	7.07	12.87
P2 Baghdad DD	4.92	9.09	11.88	7.23	7.46	6.72
P2 Dehok DD	4.29	5.66	11.77	8.42	9.09	7.25

Figure 11. Percent differences of the displacement demands obtained from CSM-ATC55 with respect to CSM-ATC40, (E3).



	T1S	T1N	T1S	T1N	T1S	T1N
	3S		6S		9S	
P1 Baghdad SD	2.02	8.88	3.2	3.13	2.64	3.24
P1 Dehok SD	1.53	3.07	2.61	3.63	2.95	4.51
P2 Baghdad SD	1.73	6.7	3.7	3.19	3.41	2.65
P2 Dehok SD	1.16	2.07	4.24	2.8	2.69	2.99

Figure 12. Percent differences of the strength demands obtained from CSM-ATC55 with respect to CSM-ATC40, (E3).

obtained from CSM of ATC 40. These differences in terms of the maximum plastic rotation demands for the same hazard levels may lead to shifting of the performance levels of the RC buildings with respect to ATC 40 and ATC 55. The total number of plastic hinges created in the buildings due to earthquake where always higher for ATC 55, Dehok Zone, P1 pattern compared with ATC40, Baghdad Zone and P2 pattern, respectively. The number of hinges are more for higher buildings (9S > 6S > 3S). Generally, the buildings with soft story T1S has lower numbers than those without T1N except for the 3S in Baghdad.

12.3. Inter-Story Drift Ratio Demands

When the analysis results in terms of the story drifts are investigated, the distribution of the story drifts along the building height obtained from CSM of ATC 55 are always greater than those obtained from CSM of ATC 40 (**Table 4(b)**, **Figure 7**). These differences in the analysis results for the E3 seismic hazard levels do change the performance levels of some buildings. The maximum inter-story drift ratios of the buildings are higher for ATC 55 than ATC 40 and Dehok Zone than Baghdad. Generally the ratio is higher for higher buildings for T1N type and lower for higher buildings for T1S type.

12.4. Roof Drift Ratio

The global, roof drift ratio demands of the buildings due to earthquake were always higher for ATC 55, Dehok Zone, P1 pattern compared with ATC 40, Baghdad Zone and P2 pattern, respectively. Those demands were less for higher buildings (9S < 6S < 3S), in general. The buildings with soft story T1S requires higher roof drift demands than those with normal ones T1N.

13. Performance States Due to Plastic Rotation versus Inter-Story Drifts

Determining the performance levels of the buildings according to the plastic rotation demands in structural members are more justified in its judgments than the maximum inter-story drift demands because the decision of the former is built upon local (component) level of investigation, while that of the latter is built upon global (overall structure) demands. As shown in **Table 4(b)** and **Table 5**, the number of cases exceeding the IO limit is 5 due to plastic rotation demands, while it is 10 due to inter-story drift demands. The coincidence is in only 4 cases obtained according to CSM of ATC 40 and ATC 55.

In order to determine the effects of the different CSMs in the performance evaluations of the buildings, the performance levels obtained from ATC 40 and ATC 55 are compared to each other in terms of maximum displacement demands. For all buildings, the CSMs versions do not change the performance levels except in some cases for E3, where the performance level of the building has crossed over from IO to LS. This happened for three cases: 3S-T1S-P1, 3S-T1S-P2 and 3S-T1N-P2 in Dehok Zone when the maximum rotation approach was adopted and in five cases: 9S-T1N-P1, 9S-T1S-P2, 6S-T1S-P1 & 6S-T1S-P2 in Dehok Zone and 6S-T1S-P2 in Baghdad Zone when the drift approach is adopted.

14. Performances of RC Buildings Designed According to ISC

Each building performance is evaluated by comparing performance results with the performance objectives of the ISC 1997. The comparison suggests these observations:

1. For all buildings (144 case), each one has shown much better performance than the stipulated level for low-intensity (E1) and somewhat better performance than the stipulated level for the design earthquake (E2) and the maximum (E3).
2. For the identical, peer, cases the demand values for Baghdad zone are always lower than those for Dehok Zone.
3. The demand values due to ATC55 are always higher than those due to ATC40.
4. The P1 pattern of the equivalent seismic load distribution always produces higher values for the displacement demands than the P2 pattern of uniform load, while lower values for strength demands.

15. Conclusions

This study investigated performance of the multi-story RC buildings designed according to the IBC and reviewed the performance objectives defined in the ISC. There are two purposes of this study: the first is to assess the performance objectives defined in the Iraqi Seismic Code (ISC) in order to make a realistic evaluation related to Performance Based Seismic Design (PBSD) of multi-story reinforced concrete buildings and the second is to compare and evaluate structural response demands obtained from nonlinear static analysis procedures according to two versions of the capacity spectrum method (CSM) which are recommended in ATC 40 and ATC 55.

Two groups (T1N & T1S) of regular RC residential buildings are adopted in this research, where those in the second group have soft stories in their first level. There are three buildings of different numbers of stories (3S, 6S, & 9S) in each group.

Twenty four performance points are determined and evaluated for each building due to two different load patterns (P1 & P2), three seismic hazard levels (E1, E2, & E3) for two Iraqi seismic zones (Baghdad & Dehok), and according to the two versions of CSM (ATC 40 & ATC 55).

The results obtained after investigating the 144 study cases are summarized as follows:

1. It is found that the performance objectives stated in Iraqi Seismic Code (ISC) for low intensity, design, and maximum earthquake hazard levels are accomplished to a great magnitude. In summary, it is determined that the investigated buildings will not collapse in earthquakes in Iraq. If properly designed and constructed, they will have met, even better, performance objectives stipulated in the (ISC).

2. Effects of different CSMs in performance evaluations of the buildings are investigated in terms of several parameters. The structural response demands (displacement, strength, plastic rotation, inter-story drift demands, etc.), obtained by using the CSM of ATC 40 and ATC 55, are compared and evaluated thoroughly. The results can be summarized as follows:

a. It is found that adopting of the two different CSMs may yield different performance levels for Seismic Hazard Levels E3. These performance levels obtained from the analyses may lead to different evaluations of the RC buildings within the performance based seismic design and assessment concept.

b. It is determined that the discrepancies between seismic response demands obtained from the two versions of CSM increase considerably, when the seismic hazard level increases.

c. Displacement and strength demands obtained from ATC 55 are always greater than those obtained from ATC 40 for all seismic hazard levels as independent from structural characteristics, loading pattern, seismic region or hazard level. However, these differences are smaller for lower hazard levels. For seismic hazard E3, the average percent differences of the displacement and strength demands obtained from CSM-ATC55 with respect to CSM-ATC40, are 9% and 5%, respectively.

d. Maximum beam and column plastic rotation demands obtained from ATC 55 for the buildings are always greater than those obtained from ATC 40 in parallel with the maximum displacement demand. These differences, in terms of the maximum plastic rotation or drift demands, obtained from ATC 55 may lead to shifting of the performance levels of the buildings with respect to ATC 40.

e. When analysis results in terms of the story drifts are investigated, the distribution of story drifts along the building height and their maximum values obtained from ATC 55 for each building are considerably greater than those obtained from ATC 40.

3. The global, roof drift ratio could also be used as a global criteria for evaluation of performance by finding an approximate relationship between its value and the maximum inter-story drift value and then reflect that on the capacity curve.

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Notation

The following symbols are used this paper:

C_a, C_v	site seismic coefficients to describe the standard elastic site response spectra;
D	dead load;
e	eccentricity;
E	earthquake load;
h_i, h_j	the heights of the *i*-th and *j*-th floors from the top of the foundation;
h_0	constant story height in a building;
H	height of the building;
IDR_{av}	average inter-story drift ratio of the building;
IDR_i	inter-story drift ratio of story *i* of the building;
N	total number of levels;
S_a	spectral acceleration corresponding to the performance point;
S_d	spectral displacement corresponding to the performance point;
T_1	fundamental vibration period in the direction under consideration;
V	total horizontal seismic shear force;
V_i	seismic design force in the *i*-th level;
V_b	base shear force of the building;
W_i, W_j	the *i*-th and *j*-th floor weights;
α_1	modal mass coefficient for the first natural mode;
β_{eff}	effective viscous damping;
$\delta_{\max}$	displacement demand of building;
Δ_I	drift at floor *I*; and
Δ_{roof}	roof drift of building