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Seismic Design of Structures in Low Seismicity Regions

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ABSTRACT >> Seismic design codes are developed mainly based on the observation of the behavior of structures in the high seismicity regions where structures may experience significant amount of inelastic deformations and major earthquakes may result in structural damages in a vast area. Therefore, seismic loads are reduced in current design codes for building structures using response modification factors which depend on the ductility capacity and overstrength of a structural system. However, structures in low seismicity regions, subjected to a minor earthquake, will behave almost elastically because of the larger overstrength of structures in low seismicity regions such as Korea. Structures in low seismicity regions may have longer periods since they are designed to smaller seismic loads and main target of design will be minor or moderate earthquakes occurring nearby. Ground accelerations recorded at stations near the epicenter may have somewhat different response spectra from those of distant station records. Therefore, it is necessary to verify if the seismic design methods based on high seismicity would be applicable to low seismicity regions. In this study, the adequacy of design spectra, period estimation and response modification factors are discussed for the seismic design in low seismicity regions. The response modification factors are verified based on the ductility and overstrength of building structures estimated from the force-displacement relationship. For the same response modification factor, the ductility demand in low seismicity regions may be smaller than that of high seismicity regions because the overstrength of structures may be larger in low seismicity regions. The ductility demands in example structures designed to UBC97 for high, moderate and low seismicity regions were compared. Demands of plastic rotation in connections were much lower in low seismicity regions compared to those of high seismicity regions when the structures are designed with the same response modification factor. Therefore, in low seismicity regions, it would be not required to use connection details with large ductility capacity even for structures designed with a large response modification factor.

Key words low seismicity region, near-fault earthquake, fundamental periods of vibration, response modification factor, overstrength factor, system ductility demand

1. INTRODUCTION

In last century, there have been few damaging earthquakes in Korea while plenty of historic records of earthquakes are available covering almost two thousand years. Therefore, Korea is classified as a low or moderate seismicity region and the seismic design code for building structures is introduced in 1988 and modified in 2000 and 2005. Most of the seismic design codes in low seismicity regions are developed based on those developed in high seismicity regions. Since seismic behavior of structures may be different at high and low seismicity regions, the design codes developed for high seismicity regions may be not adequate for the design of structures in a low seismicity region.

Ground accelerations observed at nearby or distant location from the epicenter may have different frequency contents resulting in different response spectra. In the low seismicity regions, structures will be designed not to distant major earthquakes but to nearby minor earthquakes. Therefore, the design spectra for the low seismicity regions should be determined to account for the seismicity of a region. Structures in the low seismicity regions may have longer vibration periods than those in the high seismicity regions, because they are designed to a lower level of seismic loads leading to slender

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본 논문에 대한 토의를 2007년 10월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

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structural members. Less significant influence of seismic loads in the design of structures may result in a larger overstrength in low seismicity regions. Therefore, the less inelastic deformations in structures will be expected requiring the smaller ductility capacity in structural members.

Seismic design codes such as UBC97 and IBC 2000 classifies moment resisting frames into three structural systems such as ordinary moment resisting frame (OMRF), intermediate moment resisting frame (IMRF) and special moment resisting frame (SMRF) according to their ductility capacity and corresponding response modification factors are used to reduce seismic loads. Since larger inelastic deformations are expected, OMRF and IMRF are prohibited in high seismicity regions while OMRF is not allowed in moderate seismicity regions.

The response modification factor mainly depends on overstrength and ductility capacity of structures. Overstrength of structures designed to smaller seismic loads would be larger because structures are designed to resist dead load and wind load as well as seismic load. Jain (1995)[(1)] performed extensive study on example structures and concluded that overstregth of frames in lower seismicity regions is larger than those for high seismicity regions. Meli (1992)[(2)] showed that the available overstrength varies widely depending on the type of structure and characteristics of ground motion. In UBC97, it is recommended to use larger response modification factor for structures in low seismic regions. Footnote 6 of Table 16-N reads "Ordinary moment resisting frames in Seismic Zone 1 meeting the requirements of Section 2211.6 may use a R value of 8". However, section 2211.6 was missing maybe by editorial mistake.

Overstrength factors of structures in low, moderate and high seismicity regions are evaluated for 5, 10 and 15-story example structures designed to UBC97 and the influence of the seismicity on response modification factors is investigated in this study. Inelastic static and dynamic analyses are performed to estimate plastic rotation and system ductility demand.

2. GROUND MOTION AND DESIGN SPECTRA

The main target of seismic design of structures in low seismicity regions is to resist minor or moderate earthquakes occurring near the site, not to resist distant major earthquakes because the probability of having such event is quite low. Therefore, the ground motion to be used in seismic design should be determined based on the near-fault earthquake records which may have somewhat different characteristics from far-fault records.

Twelve earthquake records used by Mavroeidis (2004)[(3)] as listed in Table 1 are used to investigate the difference in the acceleration response spectrum of near-fault earthquakes from the design response spectrum defined in the seismic design code, KBC-2005 in this study. All of the records are scaled to have PGA of 1.0g for the purpose of comparison. Acceleration response spectrum of the 1994 Northridge earthquake shown in Fig. 1(a) implies significant underestimation of spectral acceleration in the longer period range. The average acceleration spectrum for the earthquakes of magnitude M_w less than 6.5 plotted in Fig. 1(b) representing the earthquakes in moderate seismicity regions is significantly underestimated by the KBC-2005 design spectra for soil profiles S_B and S_E. Therefore, it can be recommended to use a design response spectrum that can account for this observation for the seismic design in low seismicity regions.

In many cases, the soil condition of the construction sites may be classified as S_A or S_B in Korea leading to larger seismic loads for lower structures. However, significant earthquake damages can be expected in mid- or high-rise building structures designed to current design code based on the observations of Fig. 1(b). In general, the vertical component of ground motion is more significant near the epicenter. Thus, the effect of the vertical ground motion, which is usually ignored in the design of structures, should be accounted for properly.

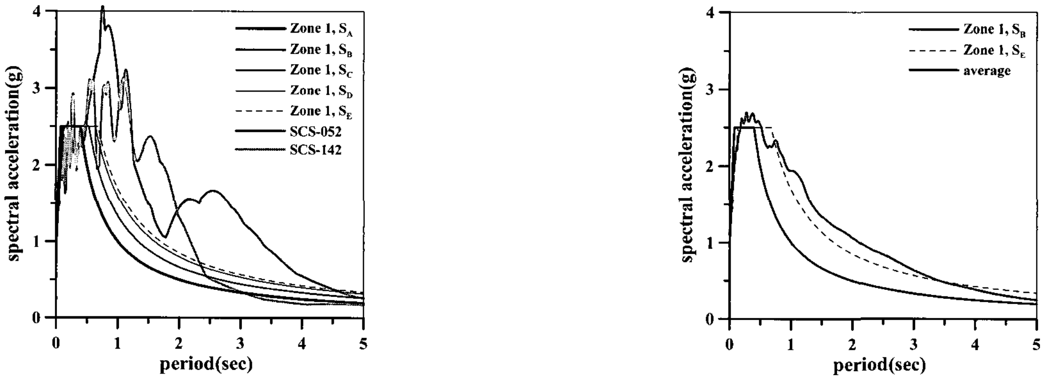
3. EXAMPLE STRUCTURES

Example structures used in this study are 5-, 10- and 15-stories reinforced concrete framed structures. Example structures have the same plan as shown in Fig. 2(a) and the elevation of example structures are illustrated in Fig. 2(b)-(d).

Design wind loads may be larger in y-direction since

〈Table 1〉 Near-fault earthquake records

No.	Record ID	Earthquake	Station	Data Source	Record/Component	PGA (g)	PGV (cm/s)	PGD (cm)
1	P0030	Parkfield 1966/06/28 04:26	1013 Cholame #2	CDMG	PARKF/C02065	0.476	75.1	22.49
2	P0082	San Fernando 1971/02/09 14:00	279 Pacoima Dam	CDMG	SFERN/PCD164	1.226	112.5	35.5
3	P0127	Gazli, USSR 1976/05/17	9201 Karakyr		GAZLI/GAZ000	0.608	65.4	25.29
4	P0144	Tabas, Iran 1978/09/16	9101 Tabas		TABAS/TAB-TR	0.852	121.4	94.58
5	P0151	Coyote Lake 1979/08/06 17:05	57383 Gilroy Array #6	CDMG	COYOTELK/G06230	0.434	49.2	7.77
6	P0176	Imperial Valley 1979/10/15 23:16	955 El Centro Array #4	USGS	IMPVALL/H-E04230	0.36	76.6	59.02
	P0177	Imperial Valley 1979/10/15 23:16	952 El Centro Array #5	USGS	IMPVALL/H-E05230	0.379	90.5	63.03
	P0178	Imperial Valley 1979/10/15 23:16	942 El Centro Array #6	CDMG	IMPVALL/H-E06230	0.439	109.8	65.89
	P0179	Imperial Valley 1979/10/15 23:16	5028 El Centro Array #7	USGS	IMPVALL/H-E07230	0.463	109.3	44.74
7	P0454	Morgan Hill 1984/04/24 21:15	57191 Halls Valley	CDMG	MORGAN/HVR240	0.312	39.4	7.66
8	P0720	Superstitn Hills(B) 1987/11/24 13:16	5051 Parachute Test Site	USGS	SUPERST/B-PTS225	0.455	112	52.8
	P0725	Superstitn Hills(B) 1987/11/24 13:16	01335 El Centro Imp. Co. Cent	CDMG	SUPERST/B-ICC000	0.358	46.4	17.5
9	P0770	Loma Prieta 1989/10/18 00:05	16 LGPC	UCSC	LOMAP/LGP000	0.563	94.8	41.18
	P0779	Loma Prieta 1989/10/18 00:05	58065 Saratoga - Aloha Ave	CDMG	LOMAP/STG090	0.324	42.6	27.53
10	P0802	Erzincan, Turkey 1992/03/13	95 Erzincan		ERZIKAN/ERZ-NS	0.515	83.9	27.35
11	P0873	Landers 1992/06/28 11:58	24 Lucerne	SCE	LANDERS/LCN275	0.721	97.6	70.31
12	P0963	Northridge 1994/01/17 12:31	0655 Jensen Filter Plant	USGS	NORTHR/JEN022	0.424	106.2	43.06
	P1005	Northridge 1994/01/17 12:31	77 Rinaldi Receiving Sta	DWP	NORTHR/RRS228	0.838	166.1	28.78
	P1023	Northridge 1994/01/17 12:31	74 Sylmar - Converter Sta	DWP	NORTHR/SCS052	0.612	117.4	53.47
	P0990	Northridge 1994/01/17 12:31	90056 Newhall - W. Pico Canyon Rd.	USC	NORTHR/WPI046	0.455	92.8	56.64

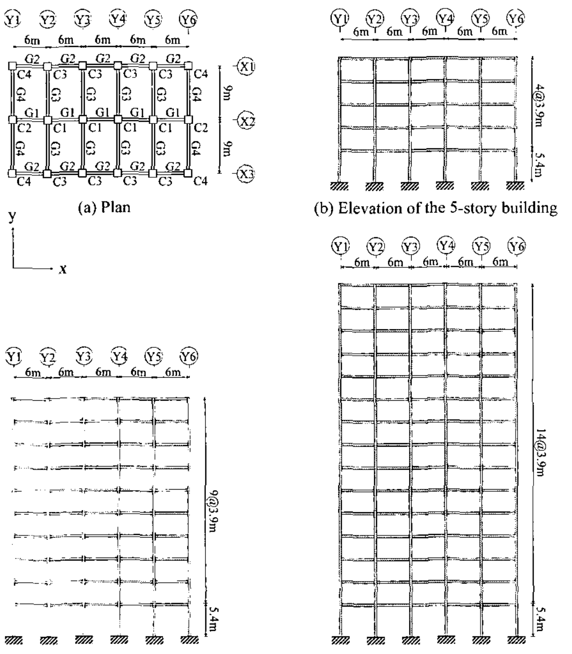


(a) Northridge EQ
Closest Fault Distance: 6.2 (km)

(b) Design spectrum and Average spectrum
($M_w \leq 6.5$)

〈Figure 1〉 Acceleration spectrum of near-fault earthquakes the structures have a rectangular plan while seismic loads may be the same in both directions. Therefore, seismic loads would have larger influence in x-direction on the design of example structures.

Example structures were designed with dead load and live load of 650kgf/cm^2 and 250kgf/cm^2, respectively. Wind load and seismic load are determined according to UBC 97. The basic wind speed of 30m/sec was assumed to determine wind load. The soil profile type was assumed to be S_B and the importance factor of 1.0 was used to determine seismic load. Example structures with 5, 10 and 15 stories are designed for seismic zones 1, 2B and 4 to investigate inelastic response of building in low, moderate and high seismicity regions using the modification factors of 3.5, 5.5 and 8.5 for three levels of ductility capacity such as OMRF, IMRF and SMRF. The use of OMRF is prohibited in seismic zones 2A, 2B, 3 and 4 and IMRF is not allowed in seismic zones 3 and 4 in UBC97. Therefore, structures with 5, 10 and 15 stories are designed for 6 different seismic loads as listed in Table 2. The design of example structures was performed by 3 leading engineering companies in Korea to account for the engineering practice.



(a) Plan

(b) Elevation of the 5-story building

(c) Elevation of the 10-story building

(d) Elevation of the 15-story building

〈Figure 2〉 Plan and elevation of the example structures

4. PERIOD OF STRUCTURES

Fundamental periods of vibration of 18 example structures designed by each company are obtained from numerical analysis and the average for each example structure can be found in table 2. These periods seem to be quite longer than expected because the effects of floor slabs and nonstructural components are not included in the analysis. However, the difference in the stiffness of frames according to the seismicity can be noticed in this table. In addition to this issue, the structural systems used in low seismicity regions may be different from those of high seismicity regions. The most popular structural system used for the construction of high-rise apartment buildings in Korea is the box system which consists of floor slabs and shear walls without complete 3D moment resisting frames and flat plate system is getting popular recently. The difference in the structural system requires adequate estimation of fundamental period of structures for seismic design of such structures because mid- or high-rise building structures may be subjected to seismic loads larger than expected based on current seismic design code.

〈Table 2〉 Periods of example structures (average)

		5-story			10-story			15-story		
		OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5
x-dir	HSR	-	-	1.1827	-	-	2.0828	-	-	2.6879
	MSR	-	1.3778	1.3912	-	2.4007	2.4007	-	2.8391	3.1224
	LSR	1.3912	1.3912	1.3912	2.4007	2.4007	2.4007	2.8391	3.1224	3.1224
y-dir	HSR	-	-	1.3263	-	-	2.2274	-	-	2.9432
	MSR	-	1.5590	1.5724	-	2.7643	2.7643	-	3.2609	3.6522
	LSR	1.5724	1.5724	1.5724	2.7643	2.7643	2.7643	3.2609	3.6522	3.6522

5. RESPONSE MODIFICATION FACTOR

The most important consideration for the low seismicity regions may be the response modification factor which is mainly related to the inelastic deformation in structures. Ductility, overstrength, damping and period of structures are important factors to determine the response modification factor of structural systems. In this study, investigation of response modification factors will be performed mainly based on the ductility factor (R_μ) and overstrength factor (R_Ω) that have major influence on the determination of response modification factors. The relationship between force and displacement for a structure subjected to lateral loads is shown in Fig. 3. The structure was designed to resist the design base shear V_D and the corresponding displacement or design displacement u_D. As the lateral load increases, the structure will undergo inelastic deformation and the force-displacement relationship is plotted as a thick solid curve which can be simplified as the bilinear relationship represented by the thick dashed line in Fig. 3 from which the yield base shear (V_y) and yield displacement (u_y) can be determined. Overstrength of a structure is defined dividing V_y by V_D as follows:

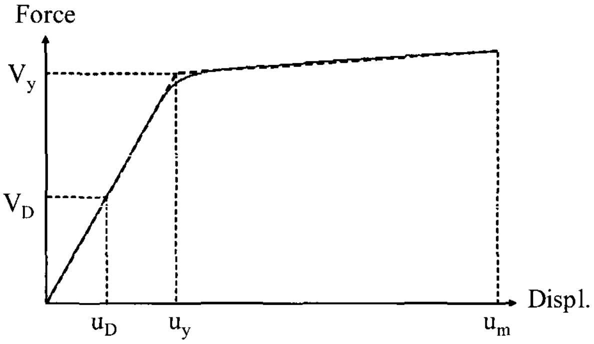
$$R_\Omega = \frac{V_y}{V_D} \tag{1}$$

Overstrength of a structure is introduced by factors such as the load factor and reduction factor used in the design as well as the presence of gravity loads and wind loads.

The ductility factor of a structural system can be determined based on the ductility capacity of structures defined as the ratio of the maximum displacement u_m to the design displacement u_D as follows:

$$R_\mu = \frac{u_m}{u_y} \tag{2}$$

Most of the seismic design codes are using the response modification factor determined by multiplying the ductility factor to the overstrength factor for the reduction of seismic loads in the design of structures.



〈Figure 3〉 Force-displacement relationship of a structure subjected to lateral forces.

5.1 Seismic Design in Low Seismicity Regions

Seismic design methods were developed based on the response of structures subjected to strong earthquakes with emphasis on the design of structures in high seismicity regions. One of the most important procedures in the seismic design of structures is to use reduced seismic loads expecting significant inelastic deformation. Structures with larger ductility capacity can be designed using a larger response modification factor which requires elaborated structural details to allow large plastic deformation, especially in connections.

Seismic design codes, such as UBC97, distinguish low or moderate seismicity regions from high seismicity regions by using reduced seismic coefficients C_a and C_v to account for the lower seismicity. However, extensive investigations on other factors, such as the response modification factor, may be necessary to use such factors in low seismicity regions because most of the structures are designed to significantly lower seismic loads compared to those in the high seismicity regions.

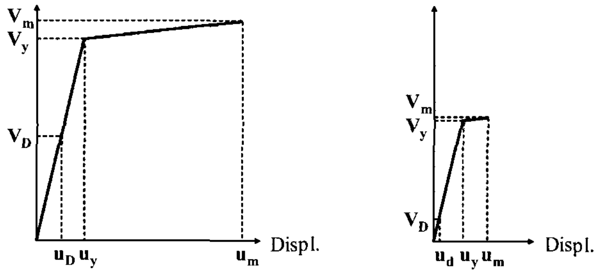
5.1.1 Overstrength factor of structures in low seismicity regions

Structures are designed to seismic load as well as other loads such as gravity loads and wind loads. Seismic load may govern the design in high seismicity regions while the influence of seismic load may be not significant in low seismicity regions. Therefore, the structures in low seismicity regions may have larger overstrength compared to those of high seismicity regions.

In this study, seismic zones 1, 2B and 4 defined in UBC97 are taken as low, moderate and high seismicity regions to investigate inelastic response of building structures. The force-displacement relationships for structures designed assuming the response modification factor to be 8.5 in low and high seismicity regions are illustrated in Fig 4. Design base shear for low seismicity regions will be 1/5 of that for high seismicity regions since the seismic coefficient C_a for two seismic zones is 0.08 and 0.4, respectively. The difference between the yield base shear V_y and design base shear V_D may indicate the effect of gravity loads and wind loads because the yield base shear V_y depends on gravity loads and wind loads as well as seismic loads. When the overstrength factor in high seismicity regions is assumed to be 2, V_y will be twice of V_D. Assuming the gravity loads and wind loads to be the same, the difference between V_y and V_D may be the same in both regions. Therefore, V_y will be 6 times of V_D in low seismicity regions resultind in the overstrength of 6 which is much larger than that of high seismicity regions.

5.1.2 System ductility of structures in low seismicity regions

Since the response modification factor can be determined as the product of the ductility and overstrength factors, ductility demand may be reduced as the overstrength increases in the case of the same response modification factor. As shown in Fig 4(a), the ductility capacity of the structure should be larger than 4.25 because the response modification factor is 8.5 and overstrength factor is 2 in high seismicity regions while the overstrength factor in low seismicity regions is 6 resulting in the ductility capacity larger than 1.42. Therefore, structures in low seismicity regions may have less ductility capacity than those in high seismicity regions to have the same response modification factors.



(a) High seismicity region (b) Low seismicity region

〈Figure 4〉 Inelastic response of a structure for lateral loads

5.1.3 Response modification factor for structures in low seismicity regions

Structures in low seismicity regions may be designed with larger response modification factor than those of high seismicity regions when structural details are the same to provide the same ductility capacity because overstrength factor may be larger in the low seismicity regions. When the same response modification factor is used in the design of structures, structural detail with smaller ductility capacity may suffice the ductility demand.

Response modification factors for low seismicity regions can be determined by modifying that of high seismicity regions based on the results of investigations on inelastic seismic response of many structures in low, moderate and high seismicity regions. Pushover analysis can be used to evaluate overstrength and ductility capacity of structures.

6. OVERSTRENGTH AND SYSTEM DUCTILITY FACTORS OF EXAMPLE STRUCTURES

Overstrength and system ductility can be estimated from the force-displacement relationship of structures to evaluate response modification factors for example structures. For this purpose, a computer code MIDAS-GEN was used to perform 3-dimensional pushover analysis.

6.1 Force-Displacement Relationship of MDOF Structures

The force-displacement relationship shown in Fig. 3 can be easily obtained for SDOF structures while it is not easy to define this relationship for MDOF structures. Roof displacement and base shear are used in ATC-40 to obtain force-displacement relationship for MDOF structures. However, the method proposed by Lee (1990)$^{(6)}$ was employed in this study because it can account for the deformed shape of structures.

The main idea of this method is to evaluate the first mode component of lateral forces and displacements as the equivalent displacement (D_{eq}) and force (V_{eq}) as shown in Eqs. (3) and (4).

$$D_{eq} = \frac{\mathbf{\Phi}_1^T \mathbf{M} \mathbf{x}}{\mathbf{\Phi}_1^T \mathbf{M} \mathbf{1}} \tag{3}$$

$$V_{eq} = \mathbf{\Phi}_1^T \mathbf{K} \mathbf{\Phi}_1 D_{eq} \tag{4}$$

where Φ_1 and **x** are the first mode shape and displacement vector and **M** and **K** are mass and stiffness matrices.

6.2 Overstrength Factor

Three dimensional pushover analysis was performed to estimate the overstrength of example structures designed by 3 engineering companies and average of overstrength is shown in Table 3.

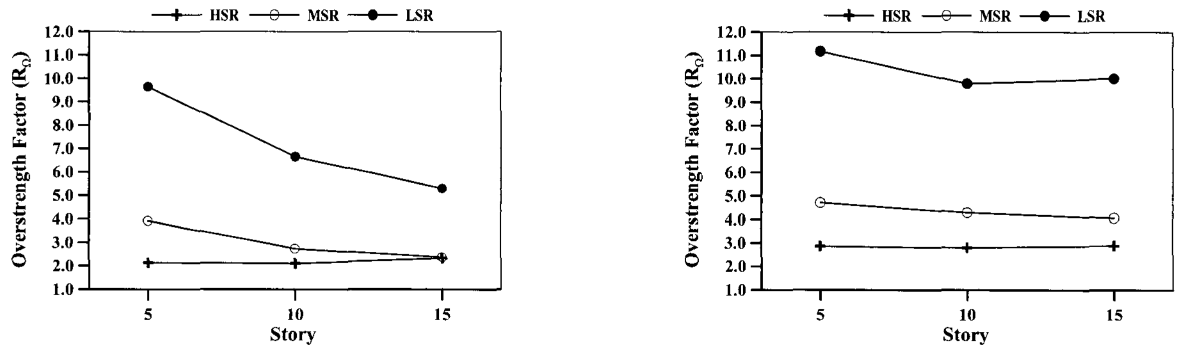
Overstrength factors of structures in low, moderate and high seismicity regions designed with the response modification factor of 8.5 are shown in Fig. 5. Overstrength factors in low seismicity regions turned out to be much larger than those of high seismicity regions as could be expected from Eq. (1). The difference in overstrength factors is more significant in 5-story structures for which the effect of seismic loads is less significant because the design was governed by gravity loads. As the number of stories increases, wind load increases accordingly reducing the effect of seismic load in the design resulting in increased overstrength. Overstrength in y-direction is larger for the same reason. Overstrength factors are close to each other ranging from 2.10 to 2.89 for structures in high seismicity regions because the design may be governed by seismic load. However, in low seismicity regions, overstrength factors are increased ranging from 5.30 to 11.17.

Overstrength factors of structures in low seismicity regions designed with the response modification factors of 3.5, 5.5 and 8.5 are shown in Fig. 6.

It can be noticed that overstrength factors are larger for larger response modification factors which reduces the effect of seismic loads in the design. In low seismicity regions, overstrength factors are close to each other when the response modification factor is 3.5 and the difference in overstrength factors is increased significantly for larger response modification factors.

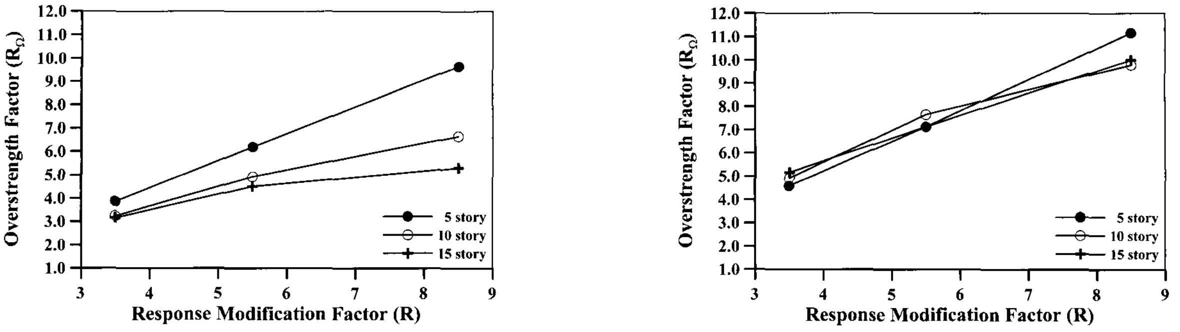
⟨Table 3⟩ Average of overstrength for example structures

Dir.	Seismicity	5-story			10-story			15-story		
		OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5
x	high	-	-	2.13	-	-	2.10	-	-	2.33
	moderate	-	2.61	3.92	-	2.20	2.74	-	2.05	2.37
	low	3.87	6.19	9.64	3.25	4.92	6.65	3.17	4.51	5.30
y	high	-	-	2.86	-	-	2.80	-	-	2.89
	moderate	-	3.41	4.71	-	3.70	4.29	-	3.41	4.07
	low	4.59	7.13	11.17	4.93	7.65	9.79	5.17	7.13	10.01



(a) x-direction (b) y-direction

⟨Figure 5⟩ Overstrength factor of SMRF example structures



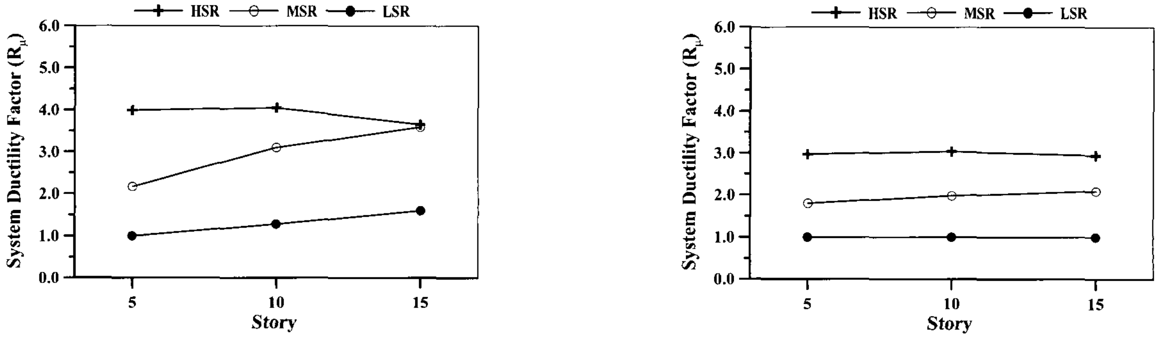
(a) x-direction

(b) y-direction

〈Figure 6〉 Overstrength factor in low seimicity regions

〈Table 4〉 System ductility demand for example structures

Dir.	Seismicity	5 story			10 story			15 story		
		OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5	OMRF R=3.5	IMRF R=5.5	SMRF R=8.5
x	high	-	-	3.99	-	-	4.05	-	-	3.65
	moderate	-	2.11	2.17	-	2.50	3.10	-	2.68	3.59
	low	1.00	1.00	1.00	1.08	1.12	1.28	1.10	1.22	1.60
y	high	-	-	2.97	-	-	3.04	-	-	2.94
	moderate	-	1.61	1.80	-	1.49	1.98	-	1.61	2.09
	low	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



(a) x-direction

(b) y-direction

〈Figure 7〉 System ductility factor of SMRF example structures

6.3 System Ductility Demand

The system level ductility demand calculated by dividing the response modification factor by the overstrength of the example structures is listed in Table 4.

Figure 7 shows ductility demands for structures in low, moderate and high seismicity regions designed with the response modification factor of 8.5. Ductility demands for structures in low seismicity regions turned out to be significantly smaller when those in higher seismicity regions. Therefore, structural details for structures in low seismicity regions may not be required to have the ductility capacity corresponding to the response modification factor in high seismicity regions.

7. RESPONSE MODIFICATION FACTORS FOR LOW SEISMICITY REGIONS

Structures should be designed to have structural details corresponding to the response modification factor to provide required ductility capacity in connections because the ductility capacity of a structure mainly depends on the ductility capacity of connections. Therefore, inelastic deformations in connections of example structures are investigated to evaluate ductility demands in connections when structures are subjected to earthquake ground motions.

The computer code DRAIN-2DX was employed for 2-dimensional pushover analysis of example structures since MIDAS-GEN used for 3-dimensional pushover analysis does not provide inelastic deformation of connections. Therefore, 3-dimensional example structures are replaced by equivalent 2-dimensional frames in x- and y-directions. Since overstrength of a structure is the most important parameter to determine the response modification factor, equivalent 2-dimensional frames are designed to have the overstrength equal to the average overstrength of example structures listed in Table 3.

7.1 System Ductility and Inelastic Deformation in Connections

Building structures designed with reduced response modification factor should able to resist the lateral loads corresponding to the target displacement which is the design displacement multiplied by the response modification factor. Therefore, pushover analyses of the equivalent 2-dimensional frames were performed increasing lateral loads until the equivalent displacement reaches the target displacement.

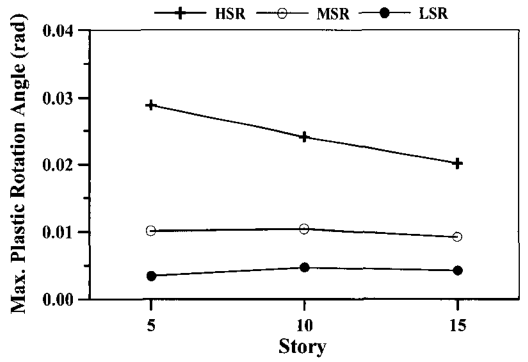
The force-displacement relationships of equivalent frames in x-direction designed with the response modification factor are shown in Fig. 8.

The largest plastic rotations at connections of 5, 10 and 15-story equivalent frames designed with the response modification factor of 8.5 are shown in Fig. 9. Structures in high seismicity regions experienced larger plastic rotations than those in other regions, since the ductility demand was larger in high seismicity regions as shown in Fig. 7.

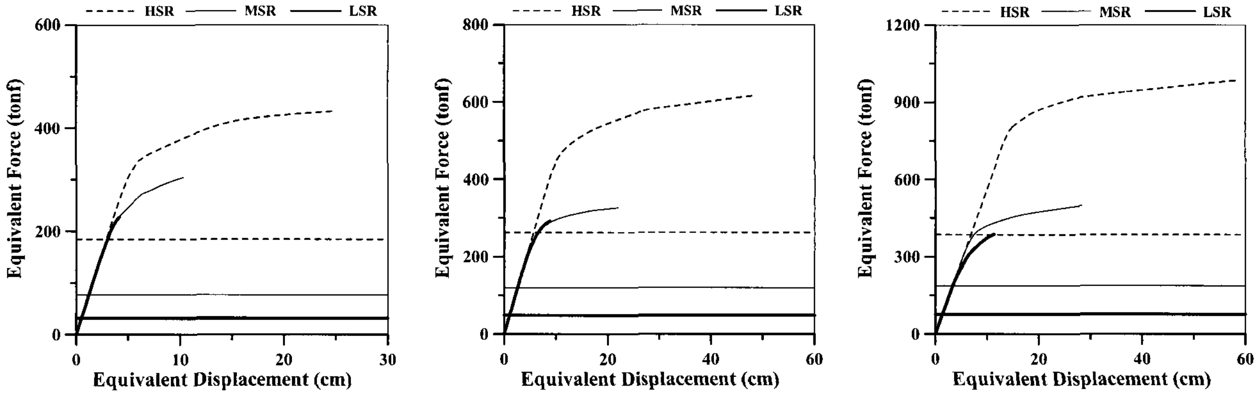
Therefore, even if structures in low seismicity regions are designed with structural details corresponding to the response modification factor of 8.5, plastic rotations will be much less than those of structures in high seismicity regions. Thus, structural details with smaller plastic rotation capacity can be used in low seismicity regions to use the same response modification factor.

7.2 Structural Details and Response Modification Factors

If structures in low and high seismicity regions are designed to the same response modification factor, connections in low seismicity regions would experience significantly smaller amount of plastic rotations when the structures are subjected to design earthquakes compared to those in high seismicity regions. Therefore, structures in low seismicity regions may still have the ductility capacity to accommodate additional displacements. It



〈Figure 9〉 Maximum plastic rotation of SMRF equivalent frames in x-direction



(a) 5-story (b) 10-story (c) 15-story

〈Figure 8〉 Force-displacement relationship of SMRF equivalent frames in x-direction would be interesting to investigate the relationship between this additional displacement capacity and ductility capacity of structures in low seismicity regions.

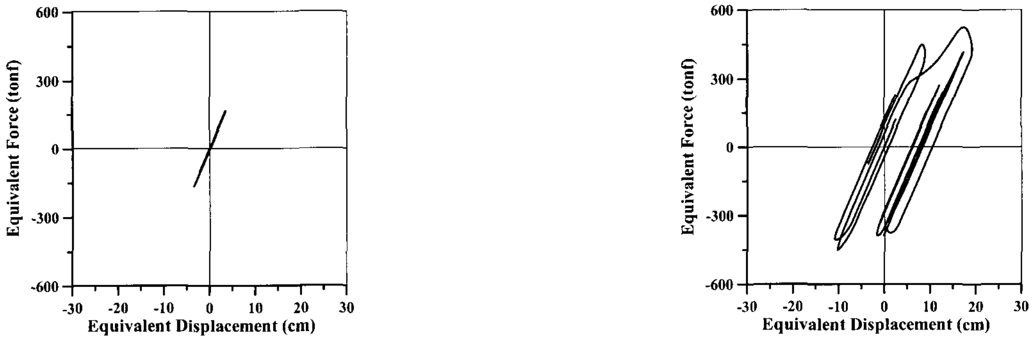
Pushover analyses of equivalent 2-D frames in high seismicity regions are performed to obtain plastic rotations at connections when the equivalent displacement reaches the target displacement. Assuming the same plastic rotation capacity for the same structural details, pushover analyses of equivalent frames in low seismicity regions were performed and the equivalent displacement was obtained when the largest plastic rotation was the same as that of high seismicity regions.

System ductility factors can be obtained by dividing the equivalent displacement by the yield displacement and these system ductility factors are multiplied by the overstrength factors provided in Table 3 to estimate the response modification factors listed in Table 5. Estimated response modification factors turned out to be much larger in low seismicity regions because of larger overstrength factors and smaller yield displacements. Therefore, it may be feasible to design building structures in low seismicity regions using much larger response modification factors than in high seismicity regions when structural details with the same plastic rotation capacity are used.

Dynamic analysis of example structures was performed using El Centro record (1940, NS) scaled to have the EPA of 0.08g, 0.2g and 0.4g as ground motion. Force-displacement relationships of 10-story SMRFs in x-direction in low and high seismicity regions are shown in Fig. 10. Inelastic deformation in low seismicity regions is significantly smaller than those in high seismicity regions. System ductility demands and plastic rotation demands for 5, 10 and 15-story SMRFs in low seismicity regions are much smaller than those obtained for high seismicity regions as shown in Fig. 11. Therefore, it would be not desirable to use too large response modifi-

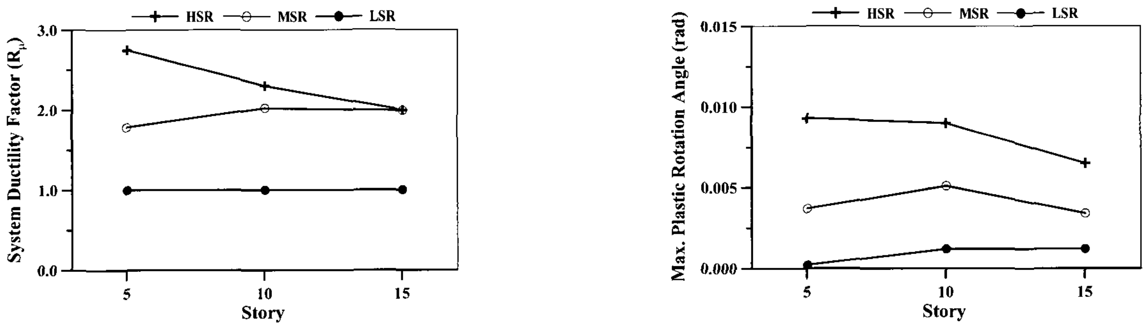
〈Table 5〉 Response modification factors based on the maximum plastic rotations

Seismicity	5-story		10-story		15-story	
	x-dir.	y-dir.	x-dir.	y-dir.	x-dir.	y-dir.
High	8.5	8.5	8.5	8.5	8.5	8.5
moderate	29.3	34.1	28.1	30.7	26.2	26.9
low	70.8	61.1	65.4	79.0	55.3	63.7



(a) Low seismicity region (b) High seismicity region

〈Figure 10〉 Force-displacement relationships of 10-story frame in x-direction; El Centro (1940, NS), R=8.5



(a) System ductility demands (b) Maximum plastic rotation

〈Figure 11〉 System Ductility and maximum plastic rotation for SMRFs equivalent frames in x-direction subjected to El Centro (1940, NS) cation factors in low seismicity regions based on large overstrength factors.

Dynamic analysis of example structures was performed scaled to have the Force-displacement relationships of 10-story SMRFs in x-direction in low and high seismicity regions are shown in Fig. 10. Inelastic deformation in low seismicity regions is significantly smaller than those in high seismicity regions. System ductility demands and plastic rotation demands for 5, 10 and 15-story SMRFs in low seismicity regions are much smaller than those obtained from high seismicity regions as shown in Fig. 10. Therefore, it would be not desirable to use too large response modification factors in low seismicity regions based on large overstrength factors.

8. CONCLUSIONS

Seismic design of structures in low seismicity regions will be somewhat different from that in high seismicity regions because some factors such as the ground motions and vibration periods, overstrength and ductility capacity of structures would be influenced by the seismicity. Overstrength factors and plastic rotation demands for building structures designed in low and high seismicity regions were obtained from 3-dimensional pushover analysis and 2-dimensional dynamic analysis, in this study, to inverstigate response modification factors and corresponding structural details in low seismicity regions. Some of the main conclusions are as follows:

(1) Design response spectrum for low seismicity regions should be determined with emphasis on the near-fault earthquake records.

(2) Vibration periods of structures may be longer in low seismicity regions because of the lower stiffness of structural elements resulted by the lower seismic loads.

(3) Overstrength factors in low seismicity regions are larger than those of high seismicity regions for structures designed with the same response modification factor. Therefore, ductility demand in low seismicity regions turned out to be much smaller than those in high seismicity regions.

(4) Building structures in low seismicity regions have larger ductility capacity than those in high seismicity regions when the same structural details are used. However, it is not desirable to use larger response modification factor in low seismicity regions just because ductility demand is much smaller than ductility capacity. Therefore, ordinary building structures in low seismicity regions may not require SMRF structural details.

(5) Even in low seismicity regions, SMRF details may be required for special structures requiring resistance to rare events far exceeding the design earthquake level.

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