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STRUCTURAL SYSTEMS

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SUMMARY

The expected earthquake response of reinforced concrete buildings with different ratios of wall-to-floor areas has been investigated. Frame systems were compared to wall and mixed systems. Recent severe records, such as Viña del Mar 1985, Llolleo 1985, Mexico 1985, Northridge 1994 and Kobe 1995 were used as a basis for predicting the response.

Drifts and global displacement ductilities were calculated. Global displacements were related to local inelastic demands. Damage indexes were computed for all buildings. The stiffness of the structural system plays an important role in displacement control. A large reduction in damage can be achieved by including walls as an earthquake resisting system. Interstory drifts can be reduced from 1.3% to 0.85% for Kobe and from 1.9% to 1% in Northridge, in flexible structures, and up to 0.85% for Llolleo and Viña del Mar records, related with moderate damage. If some walls are added, drifts can be diminished to 0.5%, with damage being reduced to very slight or none.

Even in regular structures, it is possible to reach the ultimate limit state in a critical section under interstory drifts that are not very large. Some beams of buildings designed with the Chilean code would have reached the ultimate limit state for Northridge and Mexico records, for interstory drifts close to 1.8%, related with moderate to severe global damage, showing that even moderate damage could be related to global drifts, severe and even collapsed could occur at critical sections. Then even global distortion and interstory drift are related with global damage (structural and non-structural damage); no accurate information can be obtained for local damage.

INTRODUCTION

The predominant form of building construction used in Chile can be classified as "bearing wall construction". This technique has proven economical compared with moment resisting and dual systems. The good performance of buildings during the last major earthquake in Chile (March 3,1985) suggests that structural walls are an effective structural system.
To evaluate the importance of walls for a good behavior of buildings under seismic actions, a detailed analytical study was conducted for five buildings (Figure 1) having different wall-to-floor ratios.

STRUCTURES

Five twelve story buildings were selected for this study. The first three have an interstory height of 3.65[m] (11.9 ft), and the others have 2.7[m] (8.9 ft).

Figure 1 illustrates the structural configuration of the studied buildings. Dimensions of principal elements are shown in Table 1.

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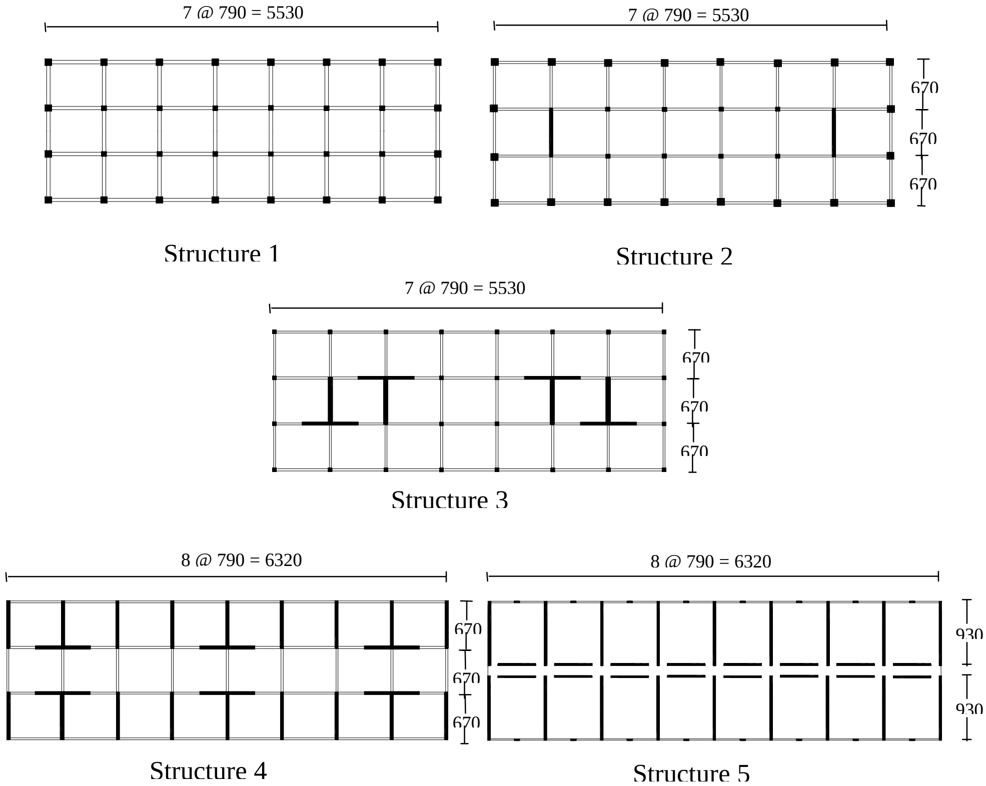


Figure 1. Structural systems.

Table 1, Element dimensions. (Units: centimeters)

Element	Building 1	Building 2	Building 3	Building 4	Building 5
Beam	50x60	50x60	25x60	25x60	20x90
Inside Columns	70x70	70x70	55x55	-	-
Outside Columns	95x95	115x115	55x55	-	-
T-Shaped wall web thickness	-	-	50	15	-
Rectangular wall thickness	-	20	-	15	20

DESIGN OF THE STRUCTURES

Buildings were analyzed according to the Chilean Code(NCh433.Of96. The code proposes a linear design spectrum and a modification response factor R, which is a function of the building fundamental period. The elastic and the design spectra are shown in Figure 2. A minimum base shear is specified (6.7% for high seismic zone) in order to control displacements under frequent earthquakes. To obtain this larger design base , a smaller R* factor must be used with respect to a severe earthquake elastic spectrum. Since reduction is specified to a working stress level, a load factor equal to 1.4 must be utilized in designing with the ACI318-95 Code. As material properties, a $f`_c$ = 30[Mpa] concrete, and f_y =420[Mpa] steel reinforcement were considered

All the buildings were designed on soft ground for a height seismic zone.

The computer program ETABS was used for the dynamic analysis. Fundamental periods and calculated weight and wall-to-floor ratios are shown in Table 2.

Table 2, Modal Spectal Analysis

Building	Analysis Direction	T* [seg]	R*	Wall/Floor Area [%]
1	X	1.71	2.13	-
	Y	1.73	2.13	-
2	X	1.77	2.07	-
	Y	1.39	2.94	0.24
3	X	1.42	3.18	0.43
	Y	1.14	4.07	1.21
4	X	0.85	4.97	0.31
	Y	0.56	7.05	1.42
5	X	0.93	4.55	1.31
	Y	0.53	7.51	2.63

T* : Mayor traslational mass period.

R* : Modification response factor

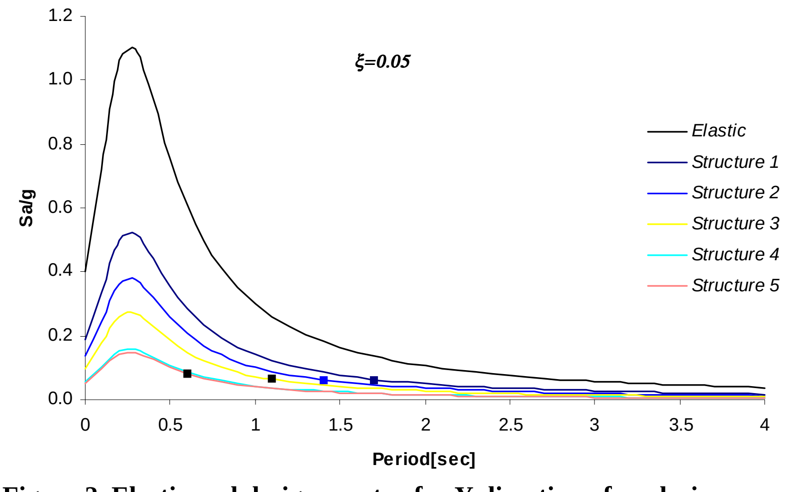


Figure 2. Elastic and design spectra for Y direction of analysis

BUILDING RESPONSE CHARACTERISTICS

The five structural systems shown in Figure 1 were analyzed using the general-purpose program RUAUMOKO (Dynamic Analysis of Inelastic Plane Structures). Records of recent severe earthquakes such as Viña del Mar 1985, Llolleo 1985, Mexico 1985, Northridge 1994 and Kobe 1995, were considered.

LATERAL DISPLACEMENTS

The greatest demands were computed for Northridge and Kobe. The stiffness of the structural system plays an important role in displacement control. Interstory drifts can be reduced from 1.3% to 0.85% for Kobe and from 1.9% to 1% for Northridge by adding some convenient walls, leading to minor damage.

Even Chilean records do not have important demands, flexible structures could reach interstory drifts up to 0.85% for Llolleo and Viña del Mar records, meaning only light to moderate damage occurs. A big reduction in damage can be achieved by including walls in a building, which results in drifts less than 0.5%, causing no important structural damage. Well-designed frames could be used under this ground motion. The Chilean Code is very demanding in displacement control since large design base shear (6.7% at service level) and small target displacements (less than .2% at center of mass) are specified thinking in the serviceability limit state for frequent earthquakes.

Mexico is a peculiar case, since the ground motion is a long duration harmonic wave, an appropriate stiffness and strength can reduce considerably the building response. Using walls an elastic response can be achieved without increasing the construction cost, as proven in Chile in 1985. As shown, the calculated drifts for the Mexico record varied from 2.1% for Building 1 to less than 0.3% in Buildings 4 and 5.

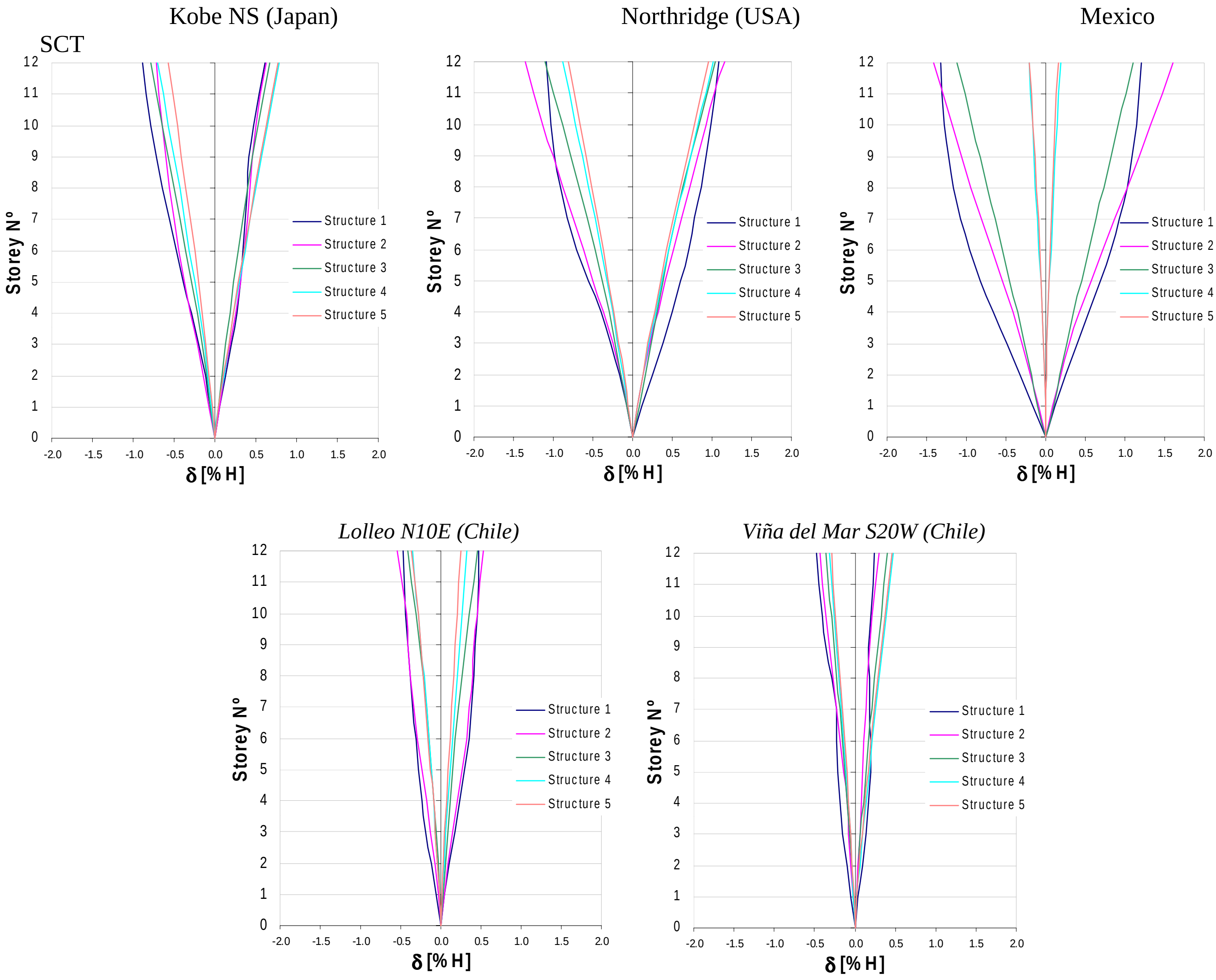


Figure 3. Lateral displacements.

The maximum displacement demands can be estimated from the earthquake displacement spectra using the expression:

$$\delta_{max} = \alpha \, Sd\,(\sqrt{2}\,T\,;\,\xi=5\%).$$

Table 3 shows calculated values with the nonlinear analysis and estimations using the above formula taking α=1.3 . [Moehle, 1996].

Table 3. Top lateral displacements, calculated for nonlinear dynamics analysis and from displacements spectra.

Building	T	$T\sqrt{2}$	Top Lateral displacements (Building height %)									
			Kobe		Northridge		Mexico		Llolleo		Viña del Mar	
			(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
1	1.73	2.447	0.89	1.05	1.08	2.21	1.33	3.19	0.48	0.58	0.48	0.31
2	1.39	1.966	0.72	1.1	1.36	1.77	1.60	2.84	0.54	0.71	0.43	0.36
3	1.14	1.612	0.79	1.2	1.09	1.5	1.11	0.85	0.45	0.52	0.4	0.38
4	0.56	0.792	0.79	0.96	1.01	0.63	0.21	0.17	0.36	0.44	0.48	0.55
5	0.52	0.735	0.77	0.95	0.95	0.62	0.2	0.17	0.36	0.43	0.46	0.54

(1) Nonlinear dynamics Analysis

(2) Calculated from displacement spectra for $T\sqrt{2}$ and a critical damping of 5%.

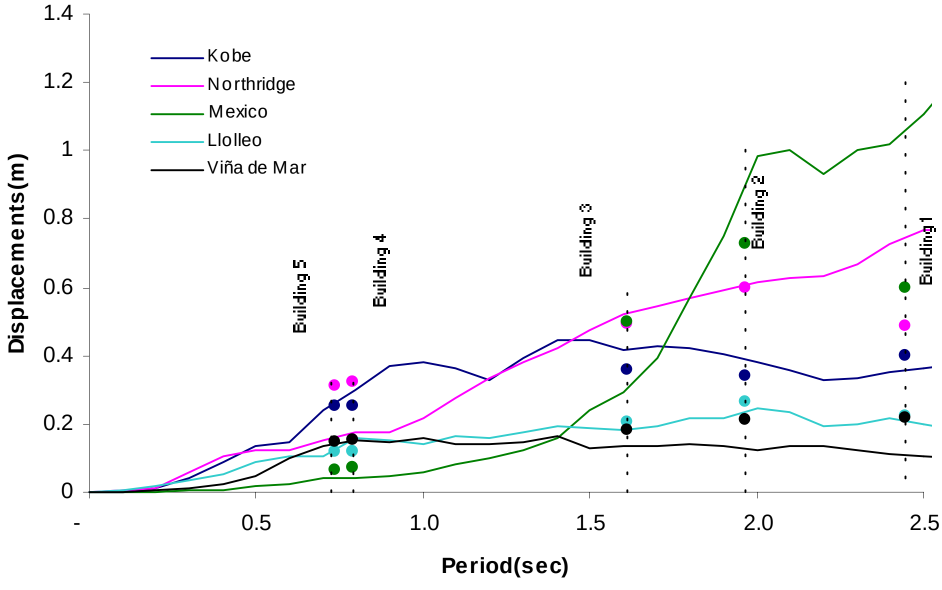
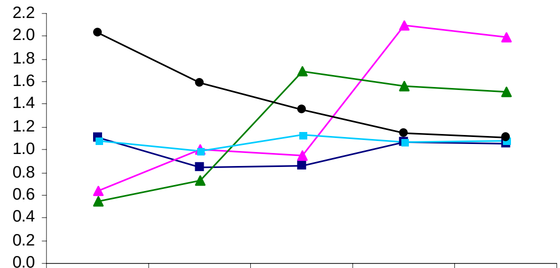


Figure 4. Elastic displacement spectra.

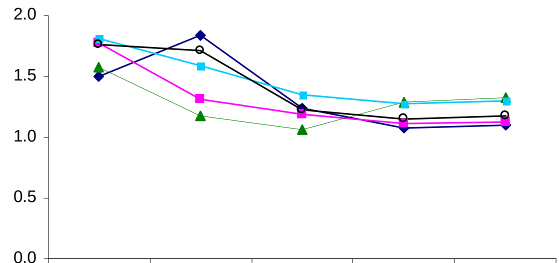
Maximum lateral roof displacements calculated with the dynamic nonlinear analysis were pointed out in Figure 4, to be compared with displacement spectra values. Figure 5 shows α values should be used to obtain a good approximation. A unique value for α to be recommended was not found. Results varied from 0.54 to 2.03, showing a great dispersion.

To estimate the maximum interstory drift drm, directly from the global distortion Drm (roof lateral displacement / building height) , the ratio β= drm / Drm, must be known. Figure 6 shows obtained values showing that β=1.5, as recommended by Moehle [Moehle, 1996] is a reasonable approximation



	Structure 1	Structure 2	Structure 3	Structure 4	Structure 5
Kobe	1.11	0.85	0.85	1.07	1.05
Northridge	0.64	1.00	0.95	2.09	1.99
Mexico	0.54	0.73	1.69	1.56	1.50
Llolleo	1.08	0.98	1.13	1.07	1.08
Viña del Mar	2.03	1.58	1.36	1.14	1.11

Figure 5. Alpha (α) ratios.



	Structure 1	Structure 2	Structure 3	Structure 4	Structure 5
Kobe	1.50	1.84	1.24	1.08	1.10
Northridge	1.78	1.31	1.18	1.11	1.12
Mexico	1.58	1.18	1.06	1.29	1.33
Llolleo	1.81	1.59	1.36	1.28	1.31
Viña del Mar	1.77	1.71	1.23	1.15	1.18

Figure 6. Interstory drift to top lateral displacement ratios (β).

DAMAGE

Damage indexes were computed for critical sections. The Park and Ang damage index was selected for this study because it is widely used. This index was calculated for a beam at the 6th story and a column and a wall at the first story and was added in Table 4, giving more precise information about the expected damage at elements. The design spectra used in the analysis are very similar to the Viña del Mar record spectrum. All the structures would have light damage under similar conditions. At a critical section in beams, damage would ranges between minor and moderate. Walls and columns would have had between slight and moderate damage. This design is then satisfactory.

Buildings designed with the Chilean code would have behaved quite differently under other conditions. Beams would have reached the ultimate limit state for Northridge in Buildings 3 and 4, and for Kobe in structure 4. Severe damage would have occurred in Northridge and Mexico in Buildings 1 and 2. Even some important damage would be expected in vertical elements, they would have behaved satisfactory in all cases.

Table 4 shows that even moderate damage could be related to global drifts, severe and even collapsed could occur at critical sections. Even global distortion and interstory drift are related with global damage (structural and non-structural damage); no accurate information can be obtained for local damage.

Table 4. Maximum inter-story drift, overall building damage and local damage

Building	Record	Drift[%]	Story	Overall Building damage	Beams 6th story		Vertical elements bases		
					DI Park & Ang	Possible damage	Elements	DI Park & Ang	Possible damage
1	Kobe	1.335	9	Moderate	0.489	Moderate	Columns	-	Slight
	Northridge	1.921	5	Moderate-Severe	0.953	Severe	Columns	0.403	Moderate
	Mexico	2.103	3	Severe	1.126	Collapse	Columns	0.970	Severe
	Llolleo	0.850	9	Light-Moderate	0.312	Moderate	Columns	-	Slight
	Viña del Mar	0.848	8	Light-Moderate	0.197	Minor	Columns	-	Slight
2	Kobe	1.318	11	Moderate	0.695	Moderate	Wall	0.660	Moderate
							Columns	0.628	Moderate
	Northridge	1.774	11	Moderate - Severe	1.466	Collapse	Wall	0.382	Moderate
							Columns	0.717	Moderate
	Mexico	1.887	8	Moderate - Severe	1.502	Collapse	Wall	0.800	Severe
							Columns	1.000	Severe
	Llolleo	0.86	11	Light - Moderate	0.358	Moderate	Wall	0.369	Moderate
							Columns	0.340	Moderate
	Viña del Mar	0.743	12	Light-Moderate	0.281	Minor	Wall	0.570	Moderate
							Columns	-	Slight
3	Kobe	0.98	11	Moderate	0.80	Moderate	Wall	0.443	Moderate
							Columns	-	Slight
	Northridge	1.29	10	Moderate	1.00	Collapse	Wall	0.696	Moderate
							Columns	0.418	Moderate
	Mexico	1.18	10	Moderate	1.00	Collapse	Wall	0.946	Severe
							Columns	0.629	Moderate
	Llolleo	0.61	11	Light	0.75	Moderate	Wall	0.236	Minor
							Columns	-	Slight
	Viña del Mar	0.49	10	Light	0.67	Moderate	Wall	0.188	Minor
							Columns	-	Slight
4	Kobe	0.850	11	Light	1.000	Collapse	Wall	0.400	Moderate
	Northridge	1.120	11	Light - Moderate	1.000	Collapse	Wall	0.463	Moderate
	Mexico	0.270	11	Negligible	0.138	Minor	Wall	0.063	Slight
	Llolleo	0.460	11	Light	0.285	Minor	Wall	0.188	Minor
	Viña del Mar	0.550	11	Light	0.540	Moderate	Wall	0.238	Minor
5	Kobe	0.850	11	Light	-	-	Wall	0.516	Moderate
	Northridge	1.063	11	Light - Moderate	-	-	Wall	0.575	Moderate
	Mexico	0.265	11	Negligible	-	-	Wall	0.056	Slight
	Llolleo	0.470	11	Light	-	-	Wall	0.241	Minor
	Viña del Mar	0.542	11	Light	-	-	Wall	0.288	Minor

The overall building damage is based on [Visión 2000], and the local damage index and clarifications can be found in [Park J. & Ang, A. H. S. (1985)].

CONCLUSIONS

For all the records used in this study, walls have shown to be an effective system to reduce damage.

Buildings were designed for seismic demands such as Llolleo and Viña del Mar, and the final behavior for these records is satisfactory. Even though the other three records have different characteristics, results show that a wall-structured system can be an ideal solution for the Mexico Earthquake. In earthquakes such as Kobe and Northridge, walled buildings can have some damage, but much less than frame structures. It is very important to note that wall-structured systems have not failed in a soft-story collapse mechanism as have many frames in recent past earthquakes.

The large ordinates for linear elastic acceleration spectra shown by Chilean and Mexico records, would suggest that very large demands could be expected, however walled buildings have behaved almost elastically, with very small non linear incursions.

Local damage can not be related directly to interstory drift because it depends on the structural configuration of the building and the proper detailing of elements. Even in regular structures, it is possible to reach the ultimate limit state in a critical section under interstory drifts that are not very large.

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