Characteristics of Reinforced Concrete Shear Wall Buildings Damaged During 2010 Chile Earthquake

R. Jünemann, M. Hube & J.C. De La Llera
Department of Structural and Geothechnical Engineering, Pontificia Universidad Católica de Chile, Chile

E. Kausel
Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, USA

SUMMARY
This article succinctly describes some statistical results on the geometry and the earthquake behavior of medium to high rise Chilean "fish-bone" type shear-wall buildings damaged during the February 27, Great Maule earthquake (Mw=8.8). The objective of the research summarized herein was to consolidate in one complete database all of the information on damaged buildings so as to assess their common characteristics from the point of view of seismic design. This paper makes the case that most of the damage took place in newer high rise buildings, caused in part by the use of ever slenderer walls in progressively taller buildings, and more importantly, was mostly the result of brittle failure in the walls at lower elevations due to high compressive loads in tall buildings, say those with more than ten stories. These findings strongly suggest that new shear wall design aspects should be incorporated in Chilean seismic codes.

Keywords: reinforced concrete, seismic behavior, shear walls, Chile earthquake

1. INTRODUCTION

The February 27th 2010 Maule earthquake was one of the strongest ever measured (Mw=8.8, EERI 2010). Its effects were felt over 500 km of the central Chile coast, affecting more than 12 million people, which is about 70% of the country's population. The earthquake also triggered a tsunami that devastated several coastal towns in south-central Chile. Both the motion and the tsunami resulted in about 560 deaths, more than 800,000 injuries (Ministerio de Vivienda y Urbanismo 2010), and serious damage to residential buildings, hospitals, schools, industries, lifelines, and other infrastructure.

A large majority of reinforced concrete (RC) buildings performed well during the earthquake, but extensive localized damage occurred in some of these structures. Close to 2% of the estimated 2,300 RC buildings taller than 9 stories suffered substantial damage during the earthquake. Some examples of the typical "unzipping" (bending-compression) failure observed in the shear walls at lower elevations are shown in Fig. 1. Considering that other buildings with similar structural concepts performed rather well during this earthquake, it behooves to elucidate some of the reasons underlying one type of behavior over the other.

Figure 1. Examples of typical failure in walls

Additionally, the typical Chilean building behaved very well during the large, previous 1985 Chile earthquake, and one of the main reasons for this behavior may have been their conservative design, as reflected in the large amount of total shear-wall to floor area of, say, 5-6% (Hidalgo et al 2002, Wood 1991). Considering that construction practices and design precepts have evolved significantly in Chile since 1985, one of the goals of the research described herein was to discern how the design practice may have changed and thus influenced the seismic performance of tall buildings.

This article presents results of a large initiative that collected, classified and analyzed all the valuable information provided by the ‘natural experiment’ to which the RC shear-wall buildings were subjected to during the 2010 Chile earthquake. As the damage was spread throughout different cities of the country and as the structural information was not always available to the public, one of the main goals of this research was to consolidate all the information of damaged buildings into one database and present it in a standard format. The focus was on Chilean “fish-bone” type buildings taller than 9 stories and located in the densest cities affected by the earthquake: Santiago, Viña del Mar and Concepción. From a total of 47 RC buildings that suffered moderate to severe damage during the earthquake, complete information was obtained for 34 cases. Structural drawings as well as soil mechanics and damage inspection reports were collected for each case, generating the most complete database of damaged buildings available at present. Three damage levels where defined based on the habitability conditions of the buildings immediately after the earthquake: damage level I means a building with restricted use; damage level II stands for a building declared non-habitable; and damage level III is assigned to a collapsed building or one that has collapse risk. The damage level for a structure was defined in most cases after a visual inspection of the building performed by different teams throughout the country. Although limited in scope, nonetheless some definite trends in the data suggest that most of the damage occurred in new and tall buildings, and the issue is why. To answer this question, the information was classified and structural characteristics were calculated and analyzed. The main building properties that relate to the observed damage are presented in the next sections.

2. REINFORCED CONCRETE SHEAR WALL BUILDINGS IN CHILE

The most common residential Chilean building is that of the “fish-bone” type. These rely almost exclusively on a system of RC shear walls to withstand gravity and lateral loads. They are characterized by a typical plan with a central longitudinal corridor with shear walls and transverse walls that separate building apartments and interior rooms. Transverse walls run from the corridor toward the building exterior creating a topology like a “fish bone” (Fig. 2). Usually, a couple of basement stories are included, and no lintels are used to link the walls. They typically range between 5 to 25 stories in height and on average they have 13 floors, but buildings over 15 floors are now more common, especially since 1996 (Calderón 2007, Gómez 2001, Guzmán 1998).

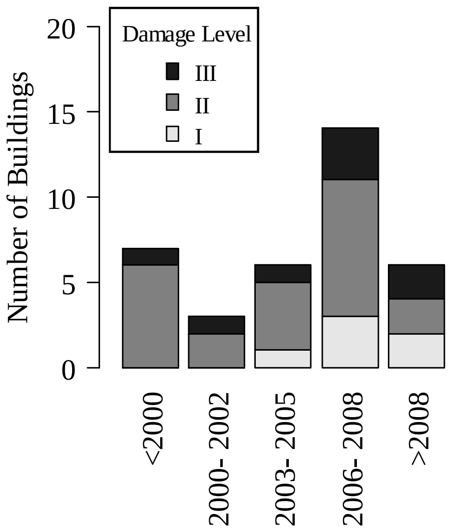
Figure 2. Typical floor plan and core elevation of a “fish-bone” Chilean residential building in Santiago

Furthermore, the ratio of wall area to floor plan area i.e. the wall density is relatively large compared with buildings of similar height in seismic regions of the U.S. Wall densities in Chile range most commonly between 1.5% to 3.5% in each direction, with a mean value of 2.8%, a characteristic that has remained almost constant in time (Calderón 2007, Gómez 2001). Walls are rather uniformly distributed in the two principal directions and the large amount of wall area results in very stiff buildings (Guendelman et al1997, Moroni 2011).

3. CHARACTERISTICS OF DAMAGED BUILDINGS

Focusing on the inventory of damaged buildings, two aspects arise immediately: i) damaged buildings are mainly new structures; and ii) average wall densities of damaged buildings are similar to those of standard Chilean buildings.

On the one hand, analysis of data indicates that most of damaged buildings are mainly new structures. Fig. 3a) shows that although most damaged buildings (Damage Level III) are well distributed by year of construction, most of the inventory was constructed after the year 2000. In fact, 81% of the inventory of damaged buildings (considering all damage levels) was constructed from year 2000 compared to 68% in the case of the inventory of total buildings[1] (Fig. 3b)). This leads us to conclude that as of the date when the earthquake struck, there was a huge number of medium to high-rise structures constructed before year 2000 which did not suffer as much damage as the newer ones. Thus, the earthquake affected mainly relatively new structures.



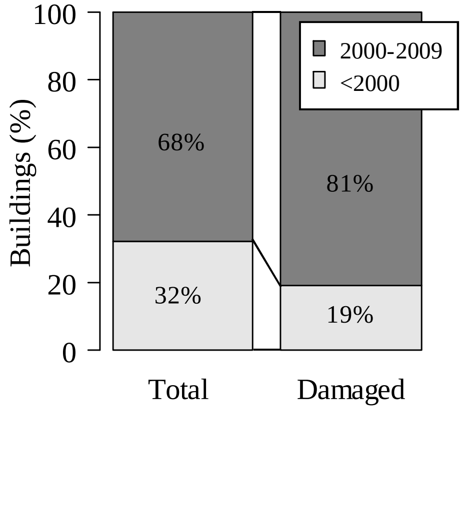


Figure 3. Distribution by year of construction. a) Distribution of damaged buildings by damage level. b) Comparison of total buildings versus damaged buildings

On the other hand, analysis of data indicates that the average wall density has not changed over the time. Moreover, it has also remained fairly constant for the buildings constructed in the past decade and is similar to those observed during 1985 earthquake. In the case of damaged buildings, wall densities in both directions have mean values which are very close: 2.76 and 2.87% for the longitudinal and transverse directions respectively (Fig. 4**)**. These values are similar to those provided in past reports by other authors who have studied Chilean RC shear-wall buildings (Calderón 2007, Gómez 2001, Wood 1991).

[1] Estimated using available statistics from INE

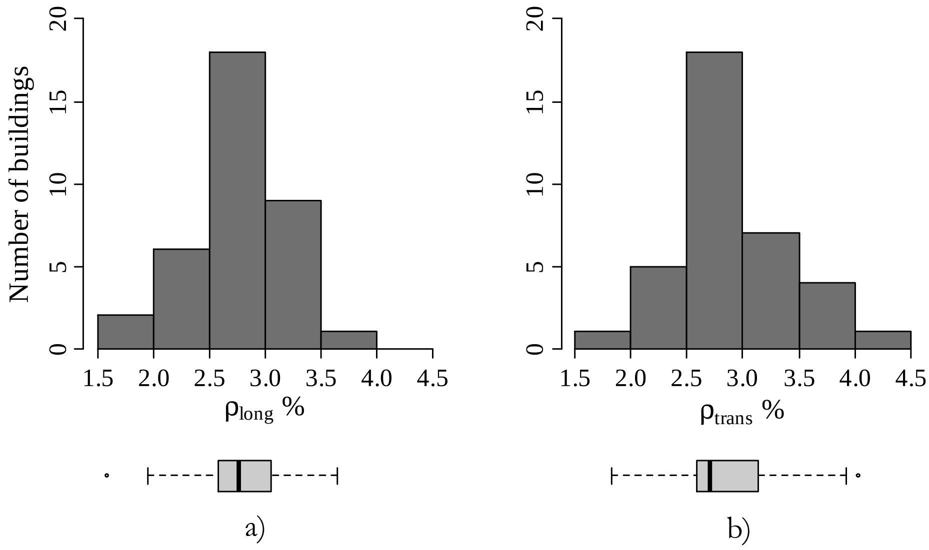


Figure 4. Wall density distribution in damaged buildings. a) Longitudinal direction. b) Transverse direction.

As most of damaged buildings were built mainly after year 2000 and thus were not struck by the previous 1985 earthquake, it behooves to find the main structural characteristics that have changed in the intervening years. Analysis of damaged buildings database suggests that what has actually changed is: i) buildings tend to be taller on average; ii) wall thicknesses have decreased; iii) buildings are more slender; and iv) buildings tend to have large vertical irregularities, and especially so at the ground level. As a result, the initial state of stress of walls caused by gravity forces is higher now than it has been in the past.

Indeed, construction practice in Chile has evolved and current RC buildings tend to be taller. In fact, the percentage of dwelling units in buildings of 9 stories or more over the total number of dwelling units has increased from 7% in 2001 to 20% in 2009 (INE 2001-2009), according to available national data. However, looking at the distribution by number of stories of the inventory of damaged buildings (Fig. 5a), most buildings had between 10 and 14 floors, and with one exception, none was taller than 24 stories. Fig. 5b) compares the distribution by number of stories of total inventory of buildings versus the inventory of damaged buildings constructed in the period 2002-2009 since in that period available data is found. As can be observed, there is a larger proportion of buildings in the damaged inventory in the range 10-14 floors and 20-24 floors than there is for ranges 15-19 or > 24 floors when compared to the total inventory of buildings. Particularly interesting to observe is the low percentage of damaged buildings of more than 24 floors, which begs the question as to why. Most probably, because of their status as iconic structures as well as their expense, such buildings may have received a more careful, conservative design, may have relied on modern devices for motion control and energy dissipation, and may have employed better materials. For example, Titanium Tower was the highest building in Chile at the time of the earthquake (52 over ground floors plus another 7 underground floors), and its dissipation devices were responsible in part of the outstanding behavior.

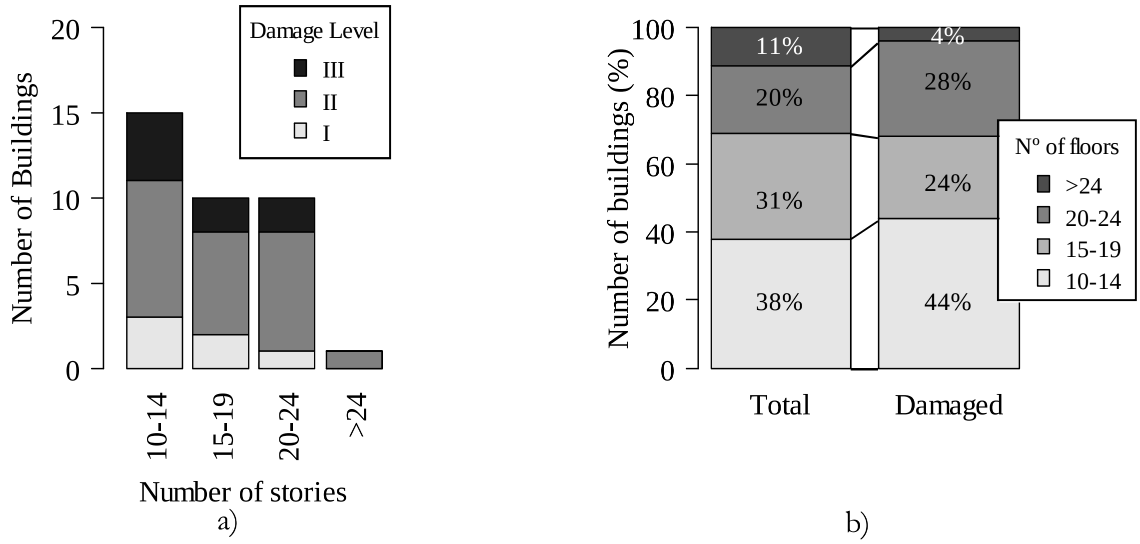


Figure 5. Distribution by number of stories. a) Distribution by damage level. b) Comparison of total buildings versus damaged buildings in the period 2002-2009

Second, wall thickness has decreased and the average value in the inventory of damaged buildings is 19 cm, with the distribution shown in Fig. 6. It is shown that 25% of the inventory has wall thickness lower than 17 cm and 80% of the building inventory has values lower than 21 cm. This thickness-dimension is very low when compared with the thickness of 30 to 50 cm observed in buildings in Viña del Mar whose date of construction preceded the 1985 earthquake i.e. buildings that date back to a time when Chilean codes required at least 20 cm thick walls (Wood 1991).

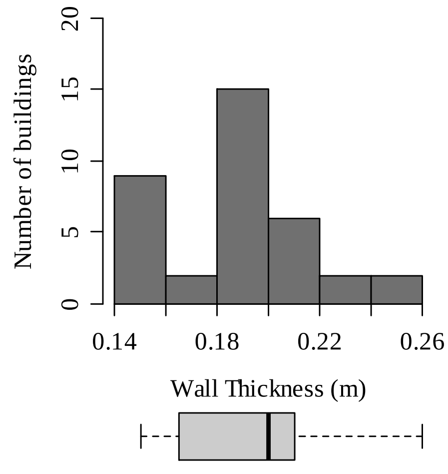


Figure 6. Wall thickness distribution in damaged buildings

Third, the average slenderness ratio calculated as the total height of the building versus average maximum transverse dimension of the plan $(H/\overline{b_t})$ is 2.2 and the value of more damaged buildings tends to be higher than the ratio for less damaged ones (Fig. 7).

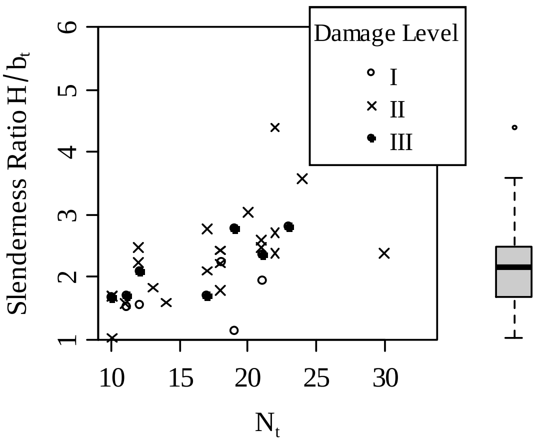


Figure 7. Slenderness ratio in damaged buildings

As a result of the combination of these three factors, the initial state of stress of walls in the first floor is on average $0.10f'_c$ (Fig. 8), which is relatively high considering that axial loads increase considerably due to seismic overturning forces.

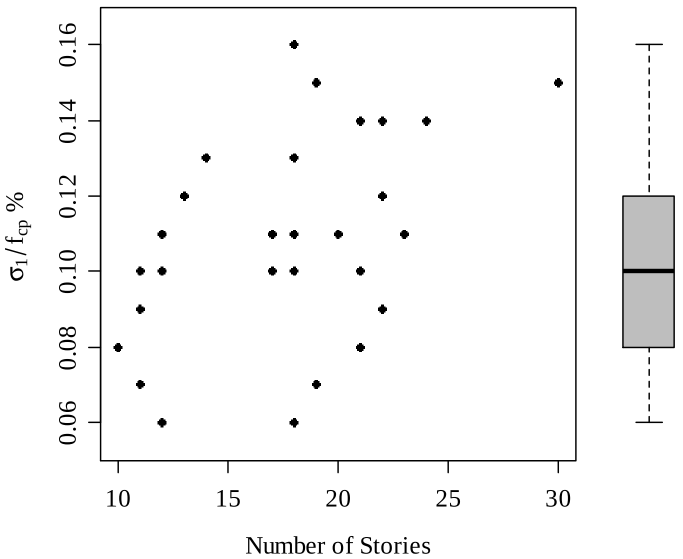


Figure 8. Average axial stress in first floor as a fraction of concrete strength in damaged buildings

Finally, most of damaged buildings show abrupt irregularities in the transition from above to below ground level and in the first stories. On the one hand, the ratio of average floor plan area above ground level ($\overline{A_a}$) versus average floor plan area below ground level ($\overline{A_b}$) defined as $\overline{A_a}/\overline{A_b}$ is on average 0.66 for the inventory of damaged buildings, which means a huge increase in floor plan area in the basements. This is generally accompanied by an increase in the wall area, which traduces in an average wall density below ground level $\overline{\rho_b}$ that is very similar to the average above ground level $\overline{\rho_a}$ (on average $\overline{\rho_a}/\overline{\rho_b}$=0.98). However, the similar wall density is a tricky value, since the layout of the walls in the basements is in general very different from the one in the first floor, as perimeter walls appear and core walls are commonly discontinued to ensure the transit of cars. In fact, on average only 83% of the wall area from the first floor continues directly in the first subterranean level. This implies that average axial stresses in the first subterranean level are around 20% higher than the ones in the first floor, thus, the average axial stresses below ground level is around $0.12f'_c$. Therefore, the lower elevations of recent vintage buildings exhibit higher axial stresses, and this happens precisely at locations where some of these walls exhibit discontinuities to make up for car ramps in basements. Thus, a typical damage observed has been as of a brittle failure in lower elevations.

The Chilean codes for seismic design of RC buildings at the time of the earthquake (Instituto Nacional de Normalización 1996, 2008) did not impose restrictions on compressive load in walls and did not establish minimum thickness for shear walls. Additionally, those codes were based on the ACI 318-95 (American Concrete Institute, 1995) seismic provisions but the confinement requirement for wall boundaries was specifically exempted. After the 2010 earthquake, two decrees were promulgated that changed the previous codes. First, Decree N60 modified the Chilean code for reinforced concrete design (Decreto N60 2011, Nch430Of.2008) which limited the maximum compressive stress in walls to $0.35f'_c$ and defined new criteria for wall confinement. Second, Decree N61 modified the Chilean code for seismic design of buildings (Decreto N61 2011, Nch433Of.1996) which changed the soil classification requiring in-situ test, and defined a more conservative displacement spectrum to estimate the roof displacements of RC buildings. Although there have been improvements in design codes, based on the data considered in this study we believe that new codes should establish limits on the initial state of stress in the walls, on the minimum wall thickness and also on the allowable vertical irregularities, which were all aggravating factors observed in the damaged buildings.

4. CONCLUSIONS

This article summarized an analysis of the structural characteristics and properties of a group of 34 buildings damaged during the 2010 Chile earthquake, which represent 72% of the RC buildings of more than 9 stories which suffered moderate to severe damage during the earthquake.

The data shows that for the most part, the damaged buildings were newer structures built after the year 2000, and that there exist common factors in the RC damaged structures which suggest the need for additional revisions to the Chilean seismic design codes. These are: (i) low wall thickness, (ii) high number of stories, (iii) high vertical irregularities especially in lower levels and (iv) very slender buildings. All of these characteristics may result in high average axial loads in RC walls due to gravity effects, which become critical when seismic stresses are added.

The wall density parameter that was mainly responsible for the good performance of Chilean buildings in the previous 1985 earthquake cannot guarantee similar behavior in future earthquakes if other design characteristics, such as very slender walls and high initial states of stress with the potential to elicit brittle behavior, are ignored.

AKCNOWLEDGEMENT

The Authors are grateful to the many people and institutions which made this work possible. This research was funded by the Chilean *Fondo Nacional de Ciencia y Tecnología*, Fondecyt, through Grant #1110377. The authors are grateful for this support and would like to thank also the following professors: Rafael Riddell, Rodrigo Jordán, and Raúl Alvarez, engineers: Rocío Rivera, Benjamín Westenenk, Juan José Besa, and companies: SIRVE S.A., DICTUC S.A., and Spoerer Ingenieros Asociados SpA.

REFERENCES

American Concrete Institute Committee 318 (1995). Building Code Requirements for Reinforced Concrete (ACI 318-95). American Concrete Institute, Detroit.

Calderón, J.A. (2007). Actualización de Tipologías Estructurales Usadas en Edificios de Hormigón Armado en Chile, Memoria para optar al título de Ingeniero Civil, Universidad de Chile.

Decreto número 60 (2011). Requisitos de Diseño y Cálculo para el Hormigón Armado, Diario oficial de la República de Chile.

Decreto número 61 (2011). Diseño Sísmico de Edificios, Diario oficial de la República de Chile.

EERI (2010). The Mw 8.8 Chile earthquake of February 27, 2010. *EERI earthquake special report*, June 2010.

Gómez, C.E. (2001). Caracterización de Sistemas Estructurales Usados en las Viviendas de Hormigón Armado y Albañilería en Chile, Memoria para optar al título de Ingeniero Civil, Universidad de Chile.

Guendelman, T., Lindenberg, J., Guendelman, M. (1997). Perfil Biosismico de Edificios. *Séptimas Jornadas Chilenas de Sismología e Ingeniería Sísmica*.

Guzmán, M.A., (1998). Caracterización de Tipologías Estructurales Usadas en el Diseño de Edificios Altos en Chile, Memoria para optar al título de Ingeniero Civil, Universidad de Chile.

Hidalgo, P., Ledezma, C., Jordán, R. (2002). Seismic Behavior of Squat Reinforced Concrete Shear Walls. *Earthquake Spectra*, **18: 2.**

Instituto Nacional de Estadística, INE (2001-2009). Anuario de Edificación

Instituto Nacional de Normalización (2008). Hormigón Armado-Requisitos de Diseño y Cálculo, Nch430Of.2008, Santiago, Chile

Instituto Nacional de Normalización (1996). Diseño Sísmico de Edificios, Nch433Of.1996, Santiago, Chile.

Ministerio de Vivienda y Urbanismo MINVU (2010). Programa de Reconstrucción Nacional de Vivienda. Chile Unido Reconstruye Mejor

Moroni, O., 2011. Concrete shear wall construction, World Housing Encyclopedia, http://www.world-housing.net/, 6 pp.

Wood, S.L. (1991). Performance of reinforced concrete buildings during the 1985 Chile earthquake: implications for the design of structural walls. *Earthquake Spectra*, **7:4**.