Damage analysis due to 2010 Chilean earthquake in Viña del Mar residential buildings

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SUMMARY:
After the 2010 Chile earthquake (Mw 8.8, Imax = IX EMS), 2054 buildings of Viña del Mar city were inspected. 252 of them, visibly damaged, were typologically classified, and their damage and security state assessed. Even though the shaking had a PGA = 0.35g (being> 0.1g for 25s), only 12.27% of the inspected buildings were damaged, 13.05 % of them with grade 3 or 4 (EMS scale). Damage occurred mainly along the sea and the river Marga-Marga shores, zones with thick fluvial and marine deposits, and a water table of about 4 m depth, showing the influence of soil conditions. Results show that damage level is dependent on some building parameters: age, height (natural period), density of walls (ratio of wall to floor area), and stiffness (H/T). Most of the seriously damaged buildings (grade ≥ 3) were RC structures built before 1985 earthquake, and with a height ≥ 10 storeys.

Keywords: Maule 2010 earthquake, building typologies, vulnerability factors, earthquake damage.

1. INTRODUCTION

On February 27, 2010 at 06:34:14 UTC (03:34 am local time) the south central region of Chile experienced a great earthquake (Mw 8.8). The earthquake occurred as a thrust faulting with epicentre at 36.289ºS, 73.239W (offshore Maule), and a focal depth of 30 km (National Seismological Survey of Chile). The focus was centred in a rupture zone 550 km long and 100-150 km wide, according to the aftershock distribution (Fig.1). The earthquake occurred in an area identified as a seismic gap mature to generate, in a worst case scenario, a subduction earthquake as large as 8-8.5 in magnitude (Ruegg et al., 2009). Nevertheless, earthquake magnitude was overcome and the rupture zone extended beyond the boundaries of this gap. In the first 5 days following the main shock, there were 142 aftershocks of Mw ≥ 5.0. A large number of significant aftershocks (19 of Mw ≥ 6.0 and more than 1300 with Mw ≥ 4.0) occurred within the first month and caused additional damage to already damaged buildings (Fig. 1). The 2010 Chile earthquake was the second largest Chilean earthquake instrumentally recorded, and the sixth largest worldwide event in modern times.

In the South central Chile region, Nazca plate has a convergence of about 7 cm/yr (Khazaradze y Klotz, 2003) and subducts bellow South American plate. Large-magnitude earthquakes (Mw ≥ 8.0) occurred along this subduction region in 1570, 1575, 1647, 1657, 1730, 1751, 1822, 1835, 1837, 1914, 1906, 1928, 1939, 1943, 1960 and 1985. Rupture zone of several of these earthquakes are shown in Fig.1.

Chile central and south regions have a long history of large and destructive earthquakes. The 1960 Valdivia earthquake (located south of 2010 event) was the largest event (Mw= 9.5) and much bigger in terms of ground effects and damage. After this quake, seismic code and practice changed drastically, taking into account lessons learned.

The 2010 quake was a landmark event in which the largest seismic event ever recorded by strong motions instruments in the source region took place. The event shook a wide area of high seismic hazard level (PGA ≥ 0.8g) according to seismic hazard studies carried out by Leyton et al (2009) and tested with high intensities and immense population of buildings designed following building code provisions. The peak ground acceleration (PGA) of the main shock recorded at Cauquenes city, the nearest station to the epicentre, exceeded 1 g, and reached 0.65g at Concepcion city, where extensive damages were observed. In the Viña del Mar city, located on the northern edge of the rupture zone of the 2010 earthquake, and founded on marine and alluvial deposits, PGA was of 0.35 g. The shake higher than 0.1 g lasted more than 25 s there.

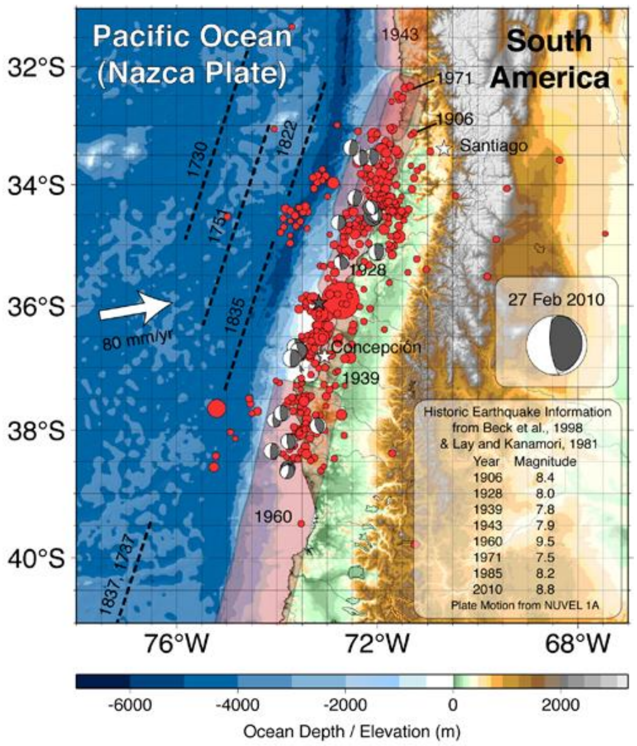

Figure 1. Map of the source region of the 2010 Chile earthquake sequence, with radius scaled proportional to seismic magnitude at the USGS locations. Focal mechanisms solutions for main shock and larger aftershocks are also shown. The approximate rupture extent of the previous large earthquakes in the region is indicated by dashed lines or by pink elongated areas (Lay et al., 2010).

Viña del Mar is a city located on central Chile's Pacific coast and part of the Valparaiso metropolitan area. The city, located near the Marga-Marga river mouth to the Pacific Ocean, it is mostly built on a plain formed by deposits of marine and alluvial sedimentary materials consisting mainly of sand and gravel, sand mixed with silt (in some places), and anthropic filling. The water table is very shallow, and it is located about 4 m bellow the ground surface.

Viña del Mar has been repeatedly damaged by large historical earthquakes and also by recent ones, most notably those of the 1960 and 1985. This city is located at one of the most dangerous seismic zones in Chile. The maximum acceleration expected in 475 years is greater than 0.7 g (Leyton et al., 2009). According to the Chilean seismic design code (NCh 433-Of96) it has an effective seismic acceleration of 0.4 g.

The shaking of the 2010 earthquake reached an intensity degree of VIII (EMS) in the downtown area and had a lower intensity in the surrounding hills. During the earthquake serious damages were caused to buildings, especially tall reinforced concrete (RC) buildings, mainly those sited along the sea and the river Marga-Marga shores, showing the influence of site conditions. This paper mainly analyses the dependence of damage level with the building vulnerability factors.

2. METHODOLOGY

The post-seismic damage assessment methodologies have been generally proposed for the damage level quantification, and the habitability classification of the buildings affected by the earthquake (e.g. ATC20-1; FEMA 1992, HAZUS99 1999; EERI 1996) or the recently proposed ones (e.g. Goretti and Di Pasquale, 2002, Lantada, 2007; Carreño et al, 2009).

For the damage assessment and the habitability classification two forms were developed, both based on the methodologies of Risk-UE and HAZUS. The first form contains the building data, their typology and vulnerability classification. The second one was organized in order to asses the damage and security state of each of the affected buildings.

The most relevant aspects for the vulnerability assessment collected in the first form are: general information, materials and structural system, typology and vulnerability classification (EMS-98 and Risk-UE), vulnerability index I_v and behaviour modifiers according to Risk-UE, for masonry buildings (M) and Reinforced Concrete buildings (RC). The second form includes some important aspects for the damage and security assessment: general information, damage state (type, grade, %), building risk classification facing aftershocks, building habitability classification, security recommendations and measures. Notes, diagrams, pictures and related information are also included.

Finally, a card summarizes the two forms results for each of the buildings. The card contains aspects related to the building (location, use, structure type, etc.), detailed information about the damage (grade, location, extent, etc.), about the vulnerability (type according to EMS-98, Iv), damage classification (including pictures), security classification and a summary of structural and non-structural elements characteristics. In Fig. 2 an example of one of these cards is shown.

Figure 2. Card summarizing the most relevant aspects for the vulnerability, damage and risk assessment of one of the affected buildings (text in Spanish).

In April 2010, a first in situ inspection of the 2054 buildings (158 blocks) located in the flat area of the city was carried out, and 252 damaged buildings were assessed. During a second survey, carried out in December 2010, 51 still damaged buildings were revised again, and the repairs and reinforcement details of the other 201 affected buildings were analyzed. Each of the affected buildings forms were filled out, carrying out a photographic record of each of the damaged buildings, showing where and how it has been affected.

Detailed information about the code provisions under which the Viña del Mar buildings were constructed was collected, taking into account their construction dates. The structures were classified in four historical periods corresponding to changes in the applied earthquake resistant regulation NCh433. Several factors conditioning the buildings response have been considered, being the height (or number of storeys N) one of them, making a general classification within low ($N \leq 3$), medium (N between 4 and 9) and high (N from 10 to 24). The structure building materials have been another of the factors (wood, W; masonry, M; and reinforced concrete, RC).

The revision of the NCh433 code and the Viña del Mar buildings characteristics has allowed the buildings classification into 5 different constructive typologies. In Table 1 a classification of the Chilean typologies based on the observed characteristics and the proposals made by Alcocer et al. (2003a - e), Gómez (2001), among others, is shown. The typological structures have been compared to those of HAZUS, EMS and Risk-UE (Table 1), and their vulnerability has been classified according to the EMS-98 scale and the typological vulnerability index (Iv*) as defined by Giovinazzi and Lagomarsino (2004). Most of Viña del Mar structures belong to the ECh 3 and 4 typological types (~75 %) and the rest correspond to the ECh 1 and 2 types. ECh 5 structures barely exist.

3. RESULTS

The response spectra (Fig. 3), obtained from the records of the two existing acceleration station of the city, show higher motion energy in a period range from 0.5 to 0.8 s in the case of the Viña del Mar station, and from 0.4 to 1.1s for the Viaducto Marga-Marga station. Based on the relationship $T = 0.045\ N$ (period T/ number of storeys N), obtained by Guendelman et al. (1997) for the RC buildings, the building with periods close to the predominant periods of the ground motion suffered more damages, particularly those with $N \geq 10$ floors. Although the shaking had amax of 0.35 g and it exceeded 0.1g for more than 25 s, reaching an intensity of grade I = VIII (EMS), only 12.27% of the 2054 buildings suffered damages, and none of them collapsed (Table 2). 8.03% suffered very light damage, 2.63% suffered light damage, 1.07% suffered moderate damage and 0.54% suffered severe damage (grades 1, 2, 3 and 4 of the EMS scale, respectively).

The more damaged buildings, having moderate or severe damages (grades 3 and 4 of EMS scale), are located in the city area with the softest soils, alluvial deposits belonging to the Marga Marga river mouth delta and to marine deposits (Fig. 4). This damage distribution was also observed by the EERI work teams who visited the damaged areas. On the ground, longitudinal cracks were detected, both in sidewalks and roads and in buildings patios and car parks. Centimetric settlements were also observed.

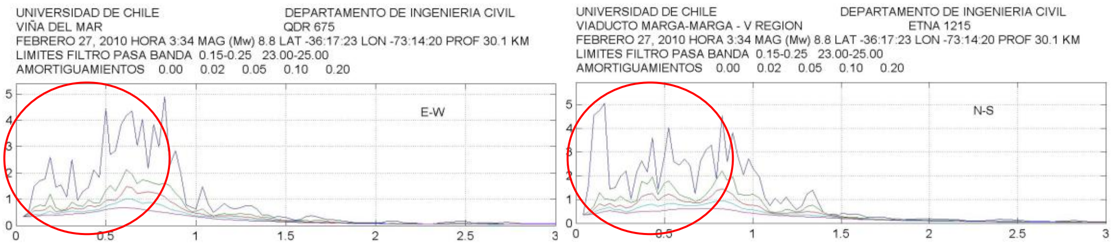

Figure 3. Response spectra of the ground motion (in two station of Viña del Mar) for different damping (Boroscheck et al, 2010). The red circle shows the period range with higher energy contribution.

In the RC buildings, the main damages are horizontal or shear cracks and fractures in support pillars, cracks in X in the buildings walls and pillars. This caused their eviction while decisions on whether to repair or demolish them were taking. Grade 3 buildings were 8.7 % of the damaged buildings, most of them Reinforced Concrete structures (63.6 %), with $N \geq 10$ storeys and constructed before 1985. Grade 4 buildings were 4.3 % of the damaged buildings, and most of them (81.8 %) were also found in RC buildings with more than 10 storeys (Table 2). None of the buildings constructed between 1985 and 1993 suffered severe structural damages (grade$\geq$ 4).

The existence of fluvial and marine deposits and a phreatic level of approximately 4 m in many places of the city influenced the seismic intensity distribution. The seismic ground motion modification had been estimated before in the seismic microzonification of the city carried out by Moehle et al (1986). The damages (particularly those of grade $\geq$3) occurred mainly near the sea and the Marga-Marga river (Fig. 4), showing the soil influence. This spatial distribution of building damage was similar to the one observed in the earthquake of 1985.

Table 1. Comparison of the analysed Chilean typologies found in Viña del Mar to the typologies of HAZUS, EMS and Risk-UE and vulnerability class according to the EMS scale and vulnerability index Iv. (The type that do not exist in the city are shown in *italics*).

Chilean Structures	HAZUS typology	EMS-98 typology	Risk-UE typology	Iv* index of Risk-UE	EMS-98 Vulnerability class
ECh- 1. Concrete frame and shear wall building	C1H. Concrete moment frame	RC frame with high level of ERD	RC4. RC dual systems, RC frame and walls	0.386	E*, F+,D-
ECh- 2. Concrete shear wall buildings	C2H Concrete shear walls	RC frame with high level of ERD	RC2. RC shear walls	0.386	E*, F+,D-
ECh- 3. Buildings with hybrid masonry walls	W1. Wood, light frame	Timber structures	W. Wooden structures	0.447	D*, C+, E+, B-
	URM L Unreinforced masonry bearing walls	*Bearing walls masonry with RC floors*	M3.4. *URM bearing walls with reinforced concrete slabs*	*0.616*	*C*, B-, D+*
	RM2L. Reinforced masonry bearing walls	Reinforced masonry or confined	M5. Overall strengthened masonry	0.694	D*, E+, C-
ECh- 4. Reinforced brick/concrete block masonry building. (reinforced masonry or confined masonry)	RM1M. Reinforce masonry with wood or metal deck diaphragms	Reinforced or confined masonry	M3.1. Wooden slabs URM	0.74	B*, A+, C-
	RM2L. Reinforced masonry bearing walls	Reinforced or confined masonry	M4. Reinforced or confined masonry	0.451	D*, C+, E+, B-
ECh- 5. Steel frame with shear walls	S2H. Steel braced frame	Steel structures	S4. Steel frame and cast in place shear walls	0.224	E*, D+, F-, C-

* Probable value + Upper limit - Lower limit URM: *Unreinforced masonry* ERD: *Earthquake resistant design* RC: *Reinforced concrete*

From the information analysed, we can deduce that in the RC damaged buildings the relationship H/T (or its equivalent N/T) is the defining parameter in order to explain the existence of damage in buildings with 10 or more storeys, along with the soil effect.

The dependence of the damage level with the building date of construction, height and stiffness parameter has also been analysed. The results indicate that 52.7 % of all of the damaged buildings were built before the earthquake of 1985, 15.5 % date from 1985-1993, 22.6 % date from 1994-2003 and finally 9.1 % date from 2004-2010 (Fig. 5).

Colour	Damage classific.	Grade
	None	0
	Very Light	1
	Light	2
	Moderate	3
	Severe	4
	Collapse	5

Figure 4. Viña del Mar city 3D image (from NW) showing the damaged buildings. Damage dependence with the buildings height and location on the softest soils is observed.

A striking result is the fact that the buildings with less than 3 storeys (of different materials and typologies, ECh types 3 and 4) (which are 74.25% of the total), had a lower % of damaged buildings (0.93%) than the buildings with N ≥ 3 storeys (mostly RC structures, ECh types 1 and 2). There was also a lower percentage of damage of grade 3 and 4 in low storeys (0.4 %) than in high storeys (Table 2). It's worth noting that the damaged buildings were only 12.3% and that most of them (el 86.9 %) have only suffered damages of grade 1 or 2.

Table 2. Damaged buildings classified by their height and damage grade.

	All buildings	Damaged buildings	Undamaged (G0)	VL (G1)	L (G2)	M (G3)	S (G4)	C (G5)
Number of buildings	2054	252	1802	165	54	22	11	0
% of total	100%	12.27%	87.73%	8.03%	2.63%	1.07%	0.54%	0.00%
Buildings N ≥ 3 storeys	529	233	296	164	44	16	9	0
% of total	25.75%	11.34%	14.41%	7.98%	2.14%	0.78%	0.44%	0.00%
Buildings N< 3 storeys	1525	19	1506	1	10	6	2	0
% of total	74.25%	0.93%	73.32%	0.05%	0.49%	0.29%	0.10%	0.00%

VL: *Very Light* L: *Light* M: *Moderate* S: *Severe* C: *Collapse*

The H/T parameter (height H/period T relationship, in m/s) is used in order to estimate the traslational stiffness of a reinforced concrete building. This relationship has been used to analyse the behaviour of Chilean buildings with less than 40 storeys (Ríos et al., 2005, Gómez 2001). The reinforced concrete buildings can be classified with the H/T parameter value (Guendelman et al., 1997) as: too flexible H/T< 20 [m/s], flexible 20<H/T<40 [m/s], normal 40<H/T<70 [m/s], stiff 70<H/T<150 [m/s], and too stiff H/T>150 [m/s]. Most of the Viña del Mar buildings have a normal stiffness with values between 40<H/T<70 [m/s]. The H/T versus damage relationship obtained by Moroni and Astroza (2002) while analysing the earthquake on March 3rd of 1985 in Viña del Mar residential buildings (Table 3) gives an estimation of the damage level very similar to the one observed in the earthquake of 2010.

Table 3. Expected damage level according to H/T parameter values for I = VIII.

H/T (m/s)	Level of damage
> 70	Negligible
50 a 70	Non-structural damage
40 a 50	Light structural damage
30 a 40	Moderate structural damages

The wall density values (wall area /plan area) of Chilean buildings, ranging from 0.015 to 0.035 (or from 1.5 to 3.5 %, Wood, 1991), are much higher than those of other countries, such as USA or Japan, where tall buildings generally have very few partition walls due to their use as offices or because they are designed with a combination of elastic and ductile behaviour. Most of tall Chilean buildings have a housing use, and the General Ordinance of Urbanism and Construction demanded the laying of partition walls between the dwellings (Calderón 2007). This way, reinforced concrete buildings, both those with structural walls and those with frames with shear walls, are more stiff, thus reducing total displacement and relative displacement between storeys, and reducing the seismic damage level. Viña del Mar is a good example. In general the buildings behaviour was fairly satisfactory, since most of the damage were light, with the exception of some specific cases where the buildings have already suffered damage during the earthquake of 1985 (which due to their stiffness didn't collapse at that time).

The damage assumed by Moroni and Astroza (2002) according to the wall density per unit floor (Table 4) are similar to those being estimated in Viña del Mar for the quake of 2010. In other cases, what influenced the damage was the fact that the ground period was close to the buildings or that there was some design failure, provoking more serious damaged than acceptable.

Table 4. Relation between the level of damage and the wall density per unit floor (dn).

dn (%)	Level of damage
dn ≥ 1.15	Light (0 and 1)
1.15 > dn ≥ 0.85	Moderate (2)
0.85 > dn ≥ 0.50	Severe (3)
dn < 0.50	Heavy (4 and 5)

Out of the 22 buildings classified in this paper with damage of grade 3, only 8 of them were evicted for their repair (6 from them were of a great height, N> 10 storeys). The 11 damaged buildings with grade 4 were evicted for their demotion, but 4 of them were used too early. This emphasizes the importance of carrying out a proper initial assessment of the damage and the security level of the buildings facing strong aftershocks.

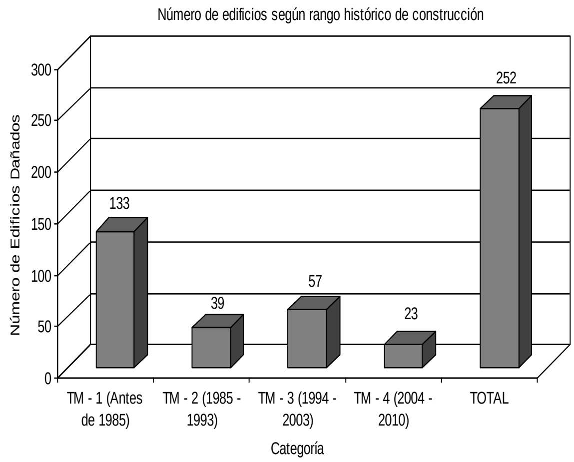

Figure 5. Damaged buildings distribution according to different date of construction (TM).

There has been an intention to repair and reinforce the rest of the buildings with grades 3 y 4, mostly of great height, due to their economic and social value, as happened in the quake of 1985. Some of those buildings suffered again moderate and severe damages. The hazard of the severe damaged buildings recuperation damaged by the shaking of 2010 was explained by Carpenter (2010) as well as by the reports carried out by EERI (2010) (among others) during the preliminary assessment of the more damaged buildings.

4. DISCUSSION AND CONCLUSIONS

The vulnerability analysis of Viña del Mar constructions and the damage suffered during the earthquake of 2010 have proved that new constructions have been gradually incorporating the Seismic Code NCh433 requirements, since the city is located in a high-risk seismic area. However, local soil conditions have to be taken into account more seriously for the structures design and construction practice, particularly in the case of the tallest buildings.

The most noteworthy aspect is the fact that, in spite of clearly reaching degree of VIII (EMS) in the flat area of the city, most Viña del Mar buildings (87.7%) did not suffered substantial damage and only 252 (out of the 2054 revised constructions) suffered visible enough damages to be assessed. Moreover, very light and light damages (grades 1 and 2) affected 10.6 % of the total percentage, but were 86.9 % of the damaged buildings. None of the buildings, either old or new, collapsed.

The building constructive characteristic grouping has allowed them to be classified into 5 types and compared with those of HAZUS, Risk-UE and EMS-98, and to be assigned a vulnerability type or index. The 252 damaged buildings, out of a total of the 2054 revised constructions, were grouped in four historical periods corresponding to changes in the applied earthquake resistant regulation NCh433. Most (52.2 %) of the 252 damaged buildings were constructed before the earthquake of 1985, in spite of being only 6.5% of the total of 2054 buildings. The damaged buildings percentage decreases in the later periods, being the damaged ones by 15.5 % for the 1985-1993 period, by 22.6 % for the 1994-2003 period and finally by 9.1 % for the 2004-2010 period.

Damaged buildings of grade 3 were 8.7 % of the damaged buildings and only 1.1 % of the total. Most (63.6 %) were reinforced concrete buildings with medium and great height and were constructed before de 1985. The buildings with less than 3 storeys, affected with this grade, were only 2.4 %, and all of them were constructed before 1985. No damage of grade ≥ 3 has been produced to buildings constructed after 1985 having less than 10 storeys, although this kind of damage has been found in buildings with 10 or more storeys.

Damaged buildings of grade 4 were 0.5 % of the total and 4.3 % of the damaged ones. These severe damages concentrated in Reinforced Concrete buildings having more than de 10 storeys (81.8 % of this grade). In many of these tall buildings, the ground floor has a greater height than the higher storeys, thus suffering “soft storey” failures.

Low height buildings, (≤ 3 storeys), the most abundant in the city, had a fairly adequate seismic behaviour. Only 9 buildings suffered serious damage (2 of them suffering severe damage) due to the Chilean experience in this type of constructions.

The damage low percentage to RC constructions and the absence of collapses are justified by the wall density parameter high values, ranging from 0.015 to 0.035, compared to those of 0.005 e.g. in USA, and by the H/T parameter ranging from 40 to 70 of the immense majority of the buildings.

The geographic distribution of buildings with structural damages (grade ≥ 3) is limited to the Marga-Marga river deltaic cone soft soils and to the strip close to the coast, which indicates the soil influence on the buildings behaviour and damages. This damage distribution is similar to that observed in the 1985 quake. Another factor that has influenced the damage caused to some of the buildings is the fact of having suffered damage by the 1985 quake, among other historical earthquakes.

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