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Performance of tall buildings in Concepción during the 27 February 2010 moment magnitude 8.8 offshore Maule, Chile earthquake

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SUMMARY

Concepción, near the southern end of the fault rupture zone of the offshore Maule, Chile earthquake, suffered significant damage to all types of structures. Tall reinforced concrete buildings in the region were also affected, some severely. Spectacular collapse and partial collapse were experienced in two buildings, and many buildings had failure of thin shear walls that lacked sufficient boundary element confinement. Concrete spalling and crushing occurred and reinforcing steel buckled and were sometimes fractured.

1. INTRODUCTION

The 27 February 2010 Magnitude 8.8 Chile earthquake created a unique opportunity for the performance evaluation of tall buildings designed according to modern codes similar to those used in the USA. Due to the extent of the rupture area during the earthquake, many large cities in Chile were affected with different levels of intensity and peak ground acceleration (PGA); one of these cities is Concepción, which is located about 105 km (65 miles) south of the epicentre (Figure 1), where the recorded PGA was over 0.6 g. There was horizontal surface displacement of over 3 m to the west-south-west as recorded by GPS.

Concepción is the capital city of the Concepción Province and is located in the Biobío region (VIII Region) of Chile with a total population of around 225 000 people and an area of 222 km^2 (86 square miles) (Wikipedia, 2010). Concepción is a large urban area that suffered considerable damage during the earthquake with the collapse of 1 building and severe damage to 10 other buildings. The collapsed building caused eight fatalities. In addition to damage to buildings, the water and power systems were severely damaged. Five days after the earthquake, only 47% of the water system and 40% of the electrical system was working in Concepción; 8 days after, 60% of the electrical system was working; 13 days after, 65% of the water system was working; and 95% of the water system was working after 23 days (Superintendencia de Servicios Sanitarios, 2010). This paper will concentrate in the description of the damage observed in the different tall buildings studied by the Los Angeles Tall Building Structural Design Council (LATBSDC) Reconnaissance Team in the Concepción downtown area.

1.1. Soil conditions

Concepción is located next to the Bio-Bío River, resulting in the upper surficial soils up to 40 to 50 m deep, consisting of native sand from river sediments. In some areas, there is a superficial thin layer

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Figure 1. Location of Concepción (OCHA, 2010).

of artificial deposits (unconsolidated clays, silts and sands) over the layer of native sand. Only two areas of Concepción have sedimentary rock exposed at the surface, and these are shown in Figure 2 (in green colour) (Instituto de Investigaciones Geologicas Chile, 1965). In addition, the phreatic level (water level) is around 7-m deep. Some areas of Concepción were formerly swamps, especially where the University of Concepción is now located.

Five inactive geological faults are known in the Concepción area: these are Caracol, Lo Pequen, La Polvora, Chepe and Chacabuco (Instituto de Investigaciones Geologicas Chile, 1965), which cut Concepción in different areas. The majority of these faults are in the direction perpendicular to the Bio-Bío River (Figure 2).

The upper soils in downtown Concepción are classified typically as Soil Type III according to the National Building Code, NCh433.Of96 (National Institute of Normalization, 1996), and in some places as Soil Type IV, where the sand is very loose and where no soil compaction has been used. Concepción is located in Seismic Zone 3 according to NCh433.Of96, which implies an effective acceleration value of $A_o = 0.4\ g$. Figure 3 shows the elastic design spectra for soil types III and IV to be used for the area of Concepción.

In summary, the area of Concepción is mantled with unconsolidated recent deposits, which consist of unconsolidated sand of fluvial origin, clays and fine sediment deposited in water in the swamps, and river deltas (Galli and Sanchez, 1963).

1.2 Recorded ground motions

The moment magnitude 8.8 Chile earthquake occurred at 03:34 local time in the central area of Chile; the rupture started at 36°12′ 28″ S and 72°57′ 46″ W at an estimated depth of 47 km. The area of the total rupture was 450 km long by 130 km wide (U.S. Geological Survey, 2010 and Servicio Sismologico, Universidad de Chile, 2010). Because of the length of the rupture, the build-up of pulses

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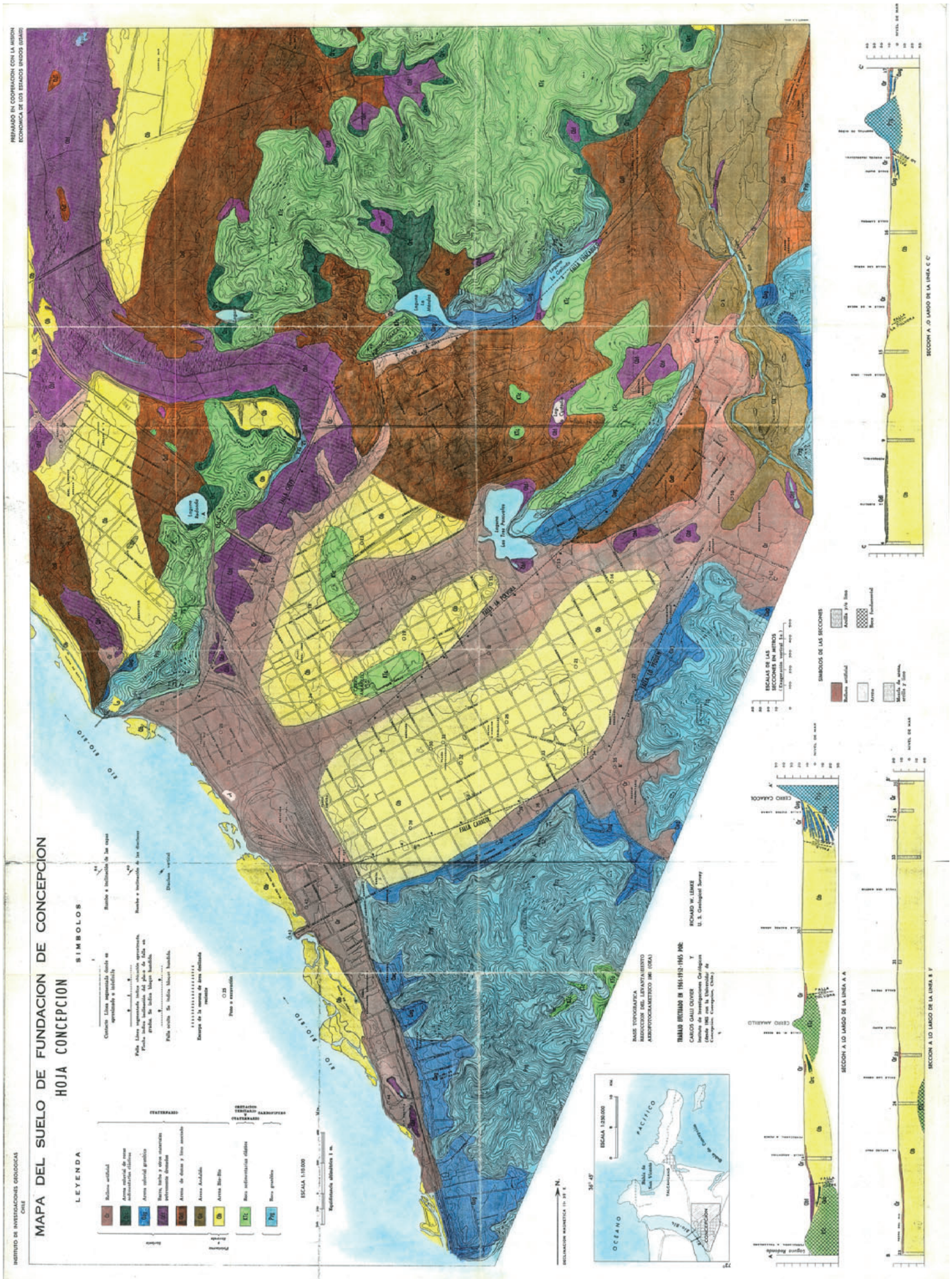

Figure 2. Soil map for Concepción (Instituto de Investigaciones Geologicas Chile, 1965).

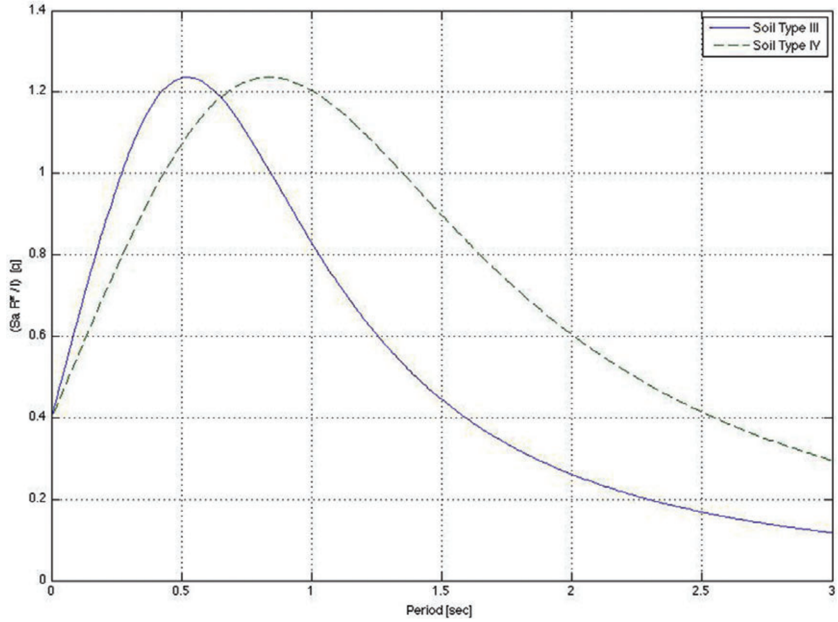

Figure 3. Nch433.Of96—elastic design spectrum for the Concepción area.

produced strong ground motions that were felt over all the central and southern part of Chile; in Concepción, the duration of the total strong ground shaking was roughly 3 minutes.

In the area of Concepción, two accelerometer stations were working at the time of the earthquake. Each instrument recorded three components (N–S, E–W and Vertical); the first instrument was located in the centre of downtown, but this record has not been yet released to the public at the time of this writing. The second record near Concepción was recorded in San Pedro High School located on the other side of the Bio-Bio River in the region of the San Pedro de la Paz at roughly 3 miles from the downtown area of Concepción (Servicio Sismologico, Universidad de Chile, 2010). The observed peak ground acceleration was 0.65 g in the north–south direction, 0.58 g in the east–west direction and 0.6 g in the vertical direction; the duration of the record is around 3 minutes, with near 60 s of strong ground motion (Servicio Sismological, Universidad de Chile, 2010), as shown in Figure 4.

In addition to the accelerometers, a GPS station located in the Transportable Integrated Geodesic Observatory at the University of Concepción, about 1.5 mi from downtown Concepción, recorded a ground displacement of Concepción of roughly 3 m in the west-south-west direction (Ohio State University, 2010 Research News) (see Figure 5). Most of this 3-m displacement appears to have occurred over duration of about 20 to 25 s.

1.3. General characteristics of buildings

The construction of buildings over three storeys in Concepción is similar to that in the rest of the Chile. The principal structural system used in the design of mid- to high-rise residential buildings (over three storeys) is shear wall construction with a storey height about 2.5 m with wall thicknesses that are typically 15, 20 or 25 cm. In office buildings, the structural system has been changing in the last few years from shear wall to dual systems consisting of frame-wall systems. Reinforced concrete is the preferred material used in construction in Chile according to a study made in 2001 by Gomes that found that 76.7% of Chilean buildings had shear wall systems and only 22% had frame-wall systems (Figure 6).

Guendelman *et al*. (1997) have used two parameters to characterize the Chilean buildings; the first parameter is the ratio of the building height, H, to the fundamental period of the building, T, or H/T.

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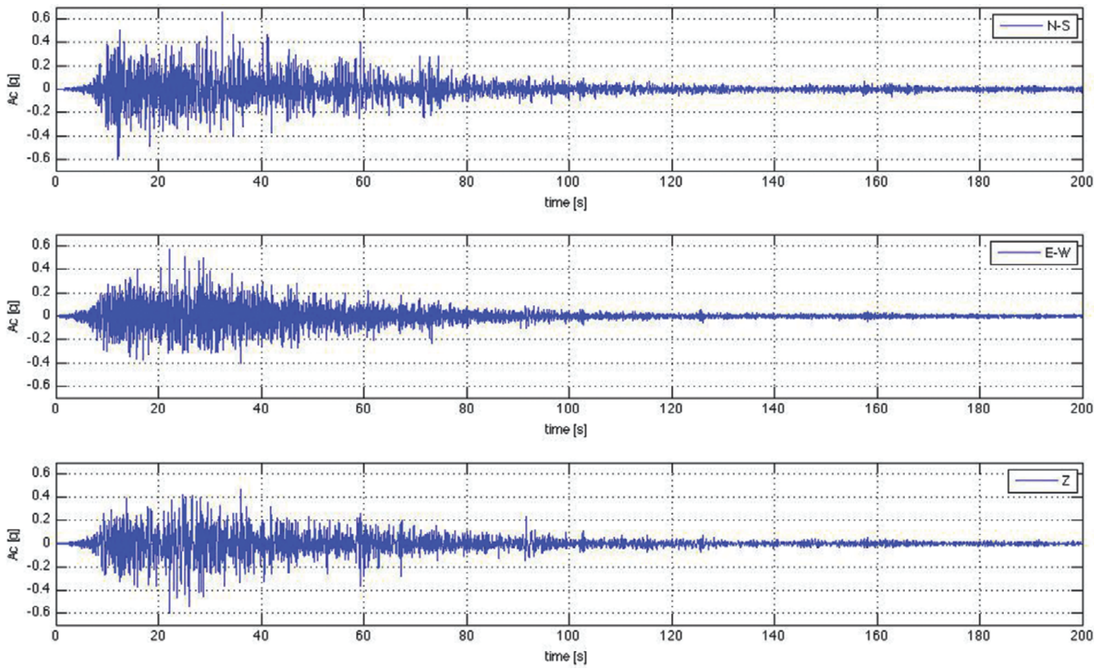

Figure 4. Record at San Pedro High School, Concepción (27 February 2010).

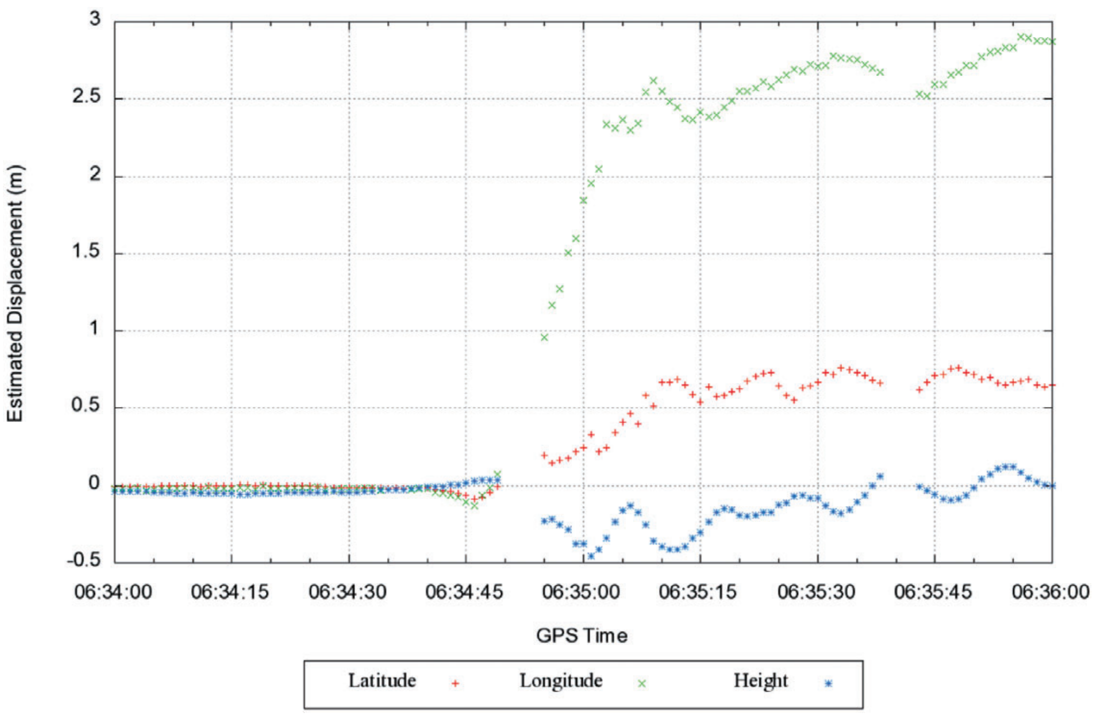

Figure 5. GPS station CONZ, 27 February 2010 (GEO's Chile Event Supersite Website, 2010).

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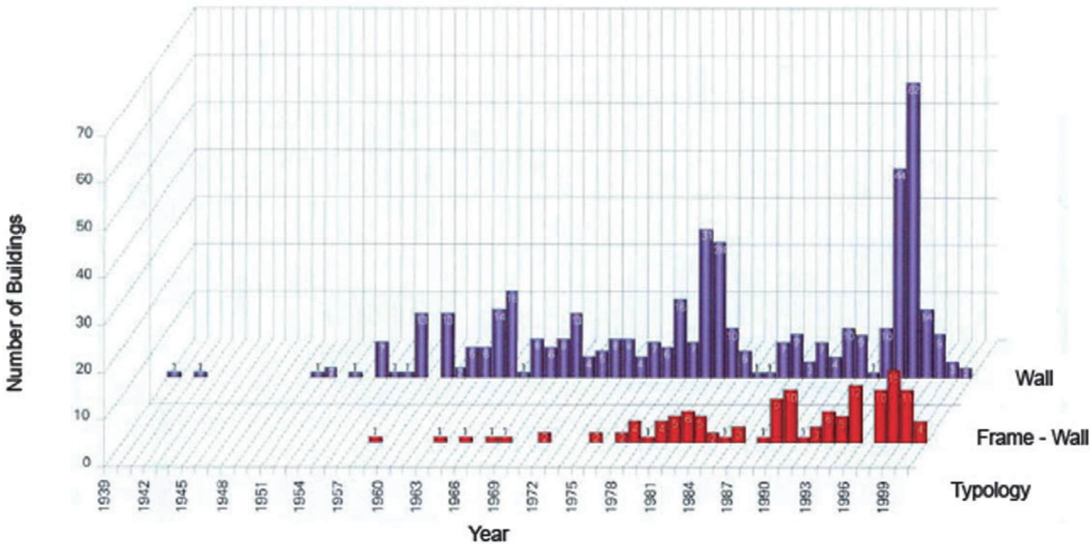

Figure 6. Variation of the construction system in Chile with time (Instituto del Cemento y del Hormigón de Chile, 2002).

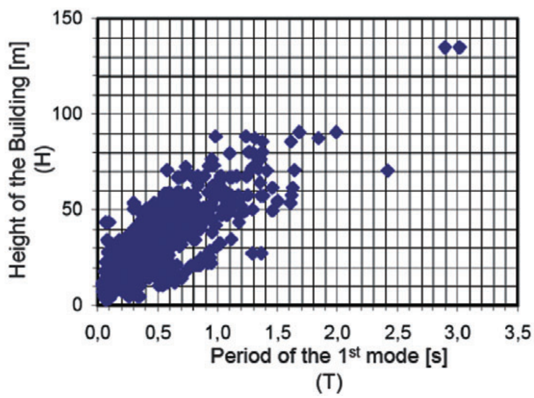

Figure 7. Relation of height of the building versus fundamental period (Guendelman *et al*., 2000).

Guendelman *et al*. (1997) found that the average value of H/T was between 40 and 70 m/s for buildings in Chile, as shown in Figure 7; a lower value would indicate a more flexible building and a higher value would indicate a stiffer building.

The second parameter used by Guendelman *et al*. (1997) is the density of walls in buildings. The density of wall is calculated as the wall area in one direction divided by the total area of the floor. The value of this parameter has been remained relatively constant, between 2 and 3%, in the last few years (Instituto del Cemento y del Hormigón de Chile, 2002); see Figure 8. However, it is important to note this parameter does not reflect the fact that the height of the buildings in Chile have been increasing in the past few years.

Due to the higher seismic risk along the coast of Chile and the presence of relatively soft soil, the structures in Concepción are more stiff than the structures in Santiago, which is reflected in values of H/T around 60 m/s and wall density of about 3%.

In addition to reinforced concrete buildings, downtown Concepción has a high population of buildings below three storeys in height constructed with confined, unconfined or reinforced masonry, as well as some adobe structures.

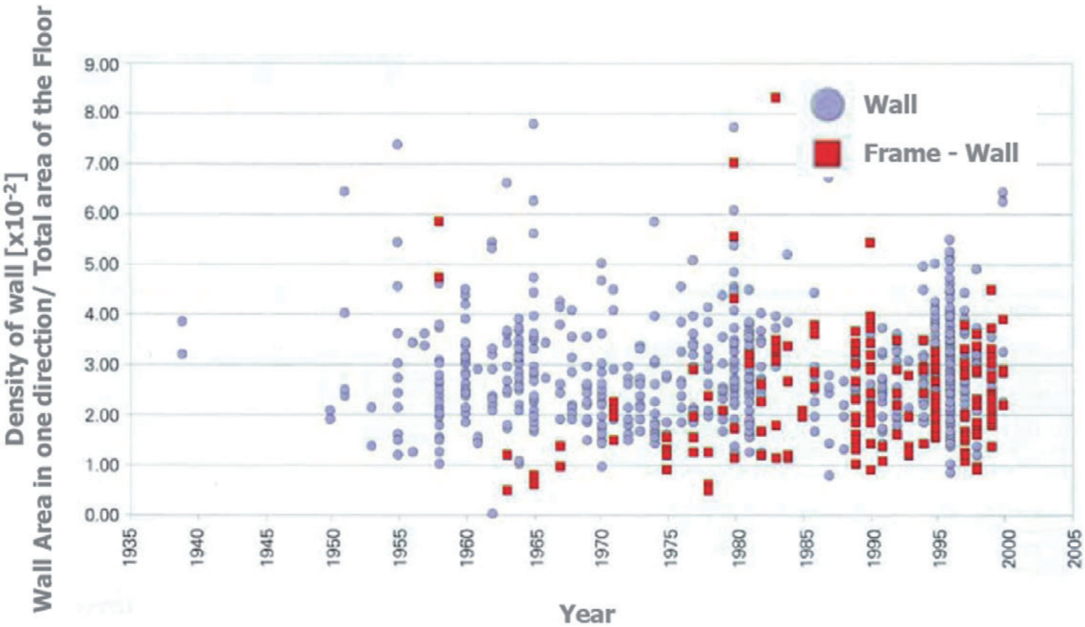

Figure 8. Density of walls at one floor as a function of time (Instituto del Cemento y del Hormigón de Chile, 2002).

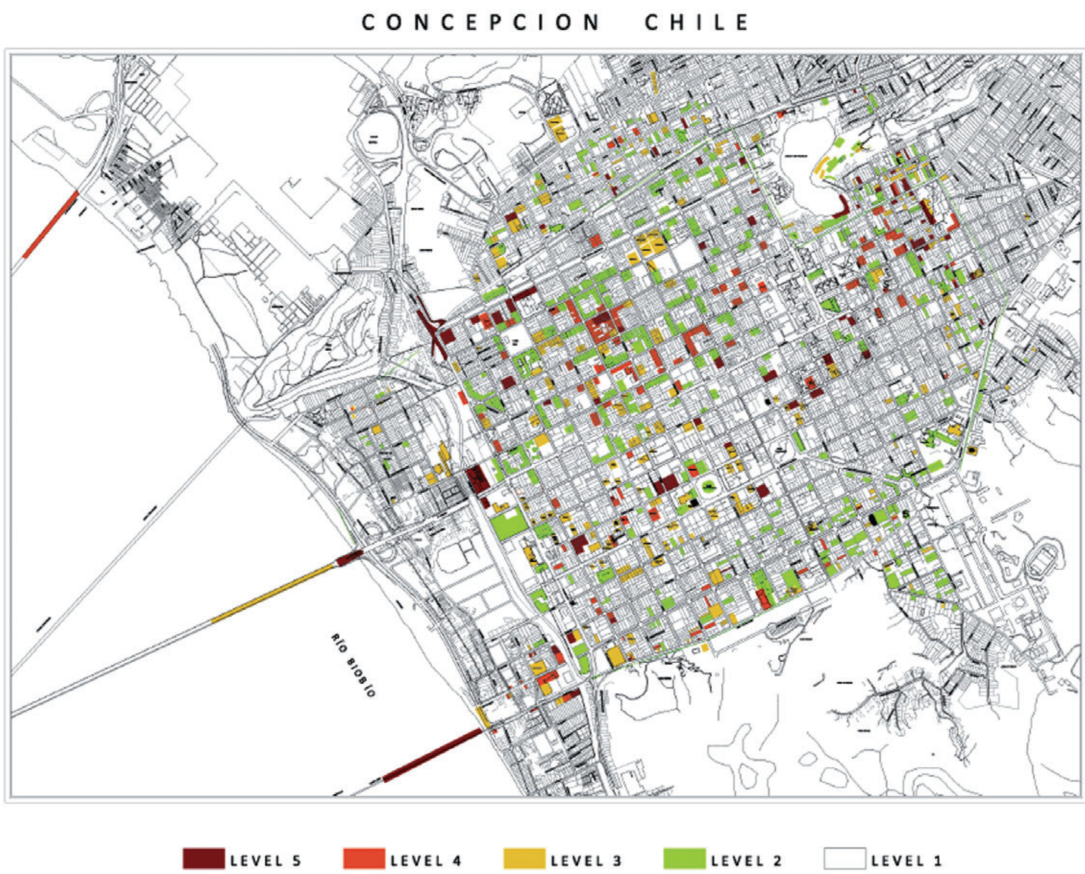

Figure 9. Map of distribution of damage in Concepción (Betanzo, 2010).

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1.4. Damage observed after the 27 February 2010 M_w 8.8 Chile earthquake

Different degrees of damage were observed in bridges, houses, silos, buildings, roads, water systems and power systems in Concepción. Betanzo (2010) established a damage scale, with level 1 corresponding to minimal or no damage, and up to level 5 corresponding to collapse of structures. The map of damage shown in Figure 9 includes all types of structures, such as bridges, houses, buildings and industrial structures, and shows the damage in Concepción. The distribution is not homogeneous, showing some concentrations with major damage; these areas need to be investigated to determine the possible causes of these concentrations of damage.

The Los Angeles Tall Building Structural Design Council (LATBSDC) dispatched a reconnaissance team of structural and geotechnical engineers to specifically study the effects of the earthquake on mid- and high-rise buildings, in the three principal cities (Santiago, Viña del Mar and Concepción). This paper focuses only on the city of Concepción and the damages observed in buildings over three storeys.

The principal damage to the mid- to high-rise buildings in the city of Concepción consists of one collapsed, one partially collapsed and another nine buildings with different levels of severe damage. Of these nine buildings, seven were occupied at the time of the earthquake and two were still under construction. The occupied buildings were evacuated and closed for fear of imminent danger of collapse according to the local authorities. The locations of the buildings studied by the LATBSDC Reconnaissance Team are shown in Figure 10.

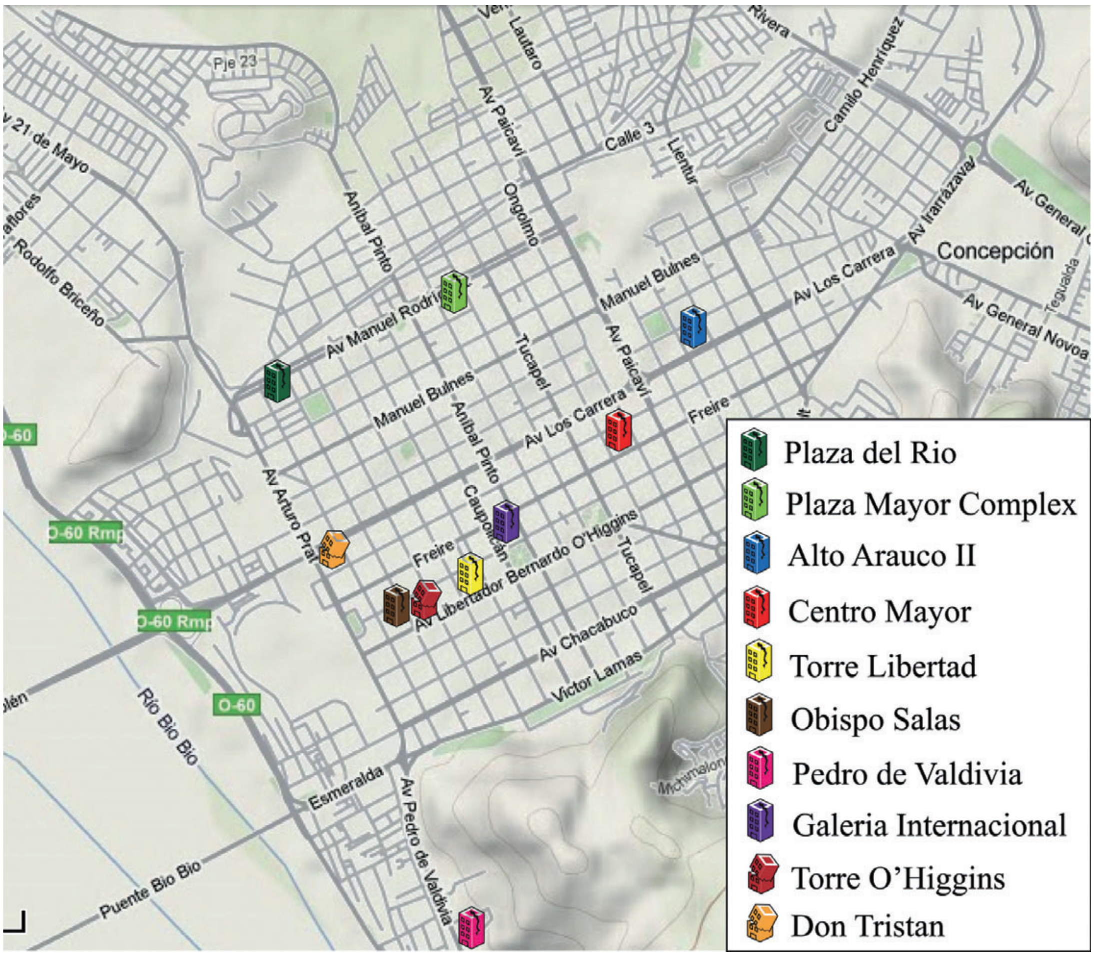


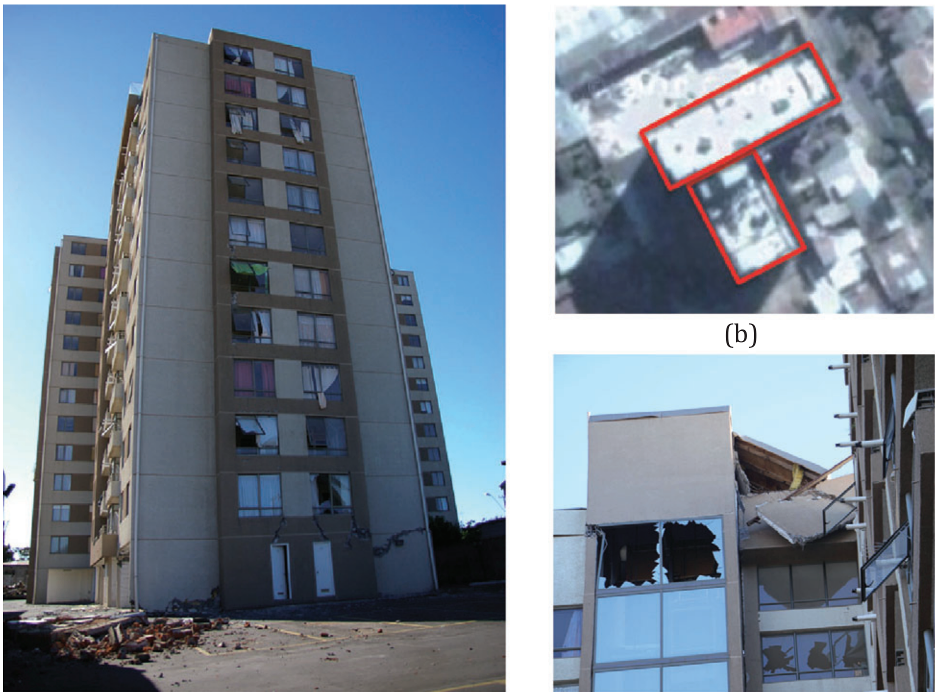
Figure 10. Map of distribution of Buildings over three storeys with severe damage in downtown Concepción studied by the LATBSDC reconnaissance team (after Google Maps, 2010).

DOI: 10.1002/tal

1.4.1. Building A (Plaza del Rio)

This L-shape reinforced concrete building is 13 storeys in height with no basement and consists of two structures separated with a seismic joint (see Figure 11). The two structures or wings are shown in Figure 11b. The south wing suffered more severe structural damage than the other wing.

There was evidence of some soil compaction problems of backfill settlement around the building basement (Figure 12c) and there was failure in tension and compression of the walls (piers) in the



(a) (b) (c)

Figure 11. (a) Elevation view of Building A (b) Plan view (Google Maps, 2010), (c) seismic joint between the two structures.

(a) (b) (c)

Figure 12. (a) Tension failure in pier and crushing failure in concrete (El Sur, 2010), (b) failure of beam (c) soil backfill settlement in parking area.

DOI: 10.1002/tal

Figure 13. Wall failures at the first floor in Building A.

end and corner walls of the building (Figure 12a) as no confinement in the boundary elements was observed; also some diaphragm cracking were observed.

In addition to the tension and compression failures, other damage probably occurred due to discontinuities in walls, producing short beam shear failures as shown in Figure 13.

1.4.2. Building B (Plaza Mayor)

Plaza Mayor is a complex of six reinforced concrete buildings that was built in four phases. Figure 14 shows the layout of the six buildings; Plaza Mayor I and Plaza Mayor III consist of a single each and Plaza Mayor II and IV consist of two buildings each.

DOI: 10.1002/tal

Figure 14. Plaza Mayor I (left) and plan view of Plaza Mayor complex (right).

Figure 15. Failure of piers in Plaza Mayor I at the second floor.

Plaza Mayor I was the tower that suffered the most damage. Figure 15 shows two examples of the typical damage (tension-compression failure). Some damage to boundary elements was also observed, as shown in Figure 16.

The Plaza Mayor II (two buildings) and III (one building) did not suffer severe damage, only some soil settlement of backfill probably due to poor compaction and some cracks in walls (Figure 17).

Plaza Mayor IV (two structures) was the last building built in the complex. It also suffered structural damage. Damage due to poor construction execution (Figure 18c) was observed and some wall failures were also observed.

DOI: 10.1002/tal

Figure 16. Failure of the connection of beams with boundary elements in Plaza Mayor I.

(a)

(b)

(c)

Figure 17. (a) Short column shear failure (b and c) soil settlement at Plaza Mayor II.

DOI: 10.1002/tal

Figure 18. (a,b) Elevation view of the two towers of Plaza Mayor IV (c) problem in construction execution (d) failure of concrete and buckling of reinforcing steel.

1.4.3. Building C (Alto Arauco II)

The Alto Arauco II is an 18-storey reinforced concrete building without a basement. The structural system is a wall system. This structure suffered severe structural damage in the first floor of the building and at the fifth floor where some irregularities in plan configuration occur as shown in Figure 19.

The east side of the building (Figure 20) experienced damage up the structure due to the compression failure of the wall at the lower portion of the building (Figure 21); the reduction of the height of the wall in the first floor produced the damage in the beams (Figure 20).

DOI: 10.1002/tal

Figure 19. Front (south) and Right (east) elevation of Alto Arauco II.

Figure 20. Failure of beam in the centre of the right (east) elevation, due to the failure of the central pier at the first floor.

DOI: 10.1002/tal

Figure 21. Failure of the centre pier of the east elevation at first floor (right), failure in singularity point at top of fifth floor in the front elevation (left).

Figure 22. Elevation View Building D (La Tercera, 2010).

1.4.4. Building D (Centro Mayor)

The Centro Mayor is a 17-storey reinforced concrete building without a basement, with plan dimensions of 17 m by 45 m (Betanzo, 2010); this building suffered damage in the first and second floors (Figure 22).

The observed damage is principally compression and tension failure in the walls (Figure 23) and crushing of the boundary of the walls elements with buckling and fracture of the reinforcing steel bars; a lack of confinement of the ends of the walls was observed. Also, it was observed that there were some shear failures in the walls (Figure 24).

DOI: 10.1002/tal

Figure 23. Failure in compression and tension in the back of the building D (Moehle *et al*., 2010).

Figure 24. Concrete crushing and buckling of reinforcing rars (right) (Moehle *et al*., 2010) and shear failure in wall (left) (Betanzo, 2010)).

DOI: 10.1002/tal

Figure 25. (a) Elevation view (b) failure at the connection of beam with wall, (c) compression failure of the wall at ground level.

1.4.5. Building E (Torre Libertad)

The Torre Libertad is an 18-storey building without underground levels; the system of the building consists of concrete walls. The first two storeys consist of a podium used for retail stores. The principal damages in this structure are crushing of walls and buckling of steel reinforcing bars at the ground level.

In addition, failures were observed at the connections of beams with walls; the beams were connected to the weak side of the walls, see Figure 25b.

1.4.6. Building F (Obispo Salas)

The Obispo Salas is a 24-storey building with two underground levels. The building was in the last stage of the construction when the earthquake occurred. It is a reinforced concrete building with a structural wall system. It suffered damage in the first underground level (Figure 26c) and at the ground level. Crushing of the concrete and the buckling of the steel bars due to tension and compression at

DOI: 10.1002/tal

(a) (b) (c) (d)

Figure 26. (a) Elevation view (b) failure in the wall at the entrance (c) failure in the top of the wall at the basement (Moehle *et al*., 2010) (d) failure in the wall at the back of the building.

the end of the walls occurred; confinement of the boundary elements of the walls was not observed (Figures 26b and 26d).

1.4.7. Building G (Pedro de Valdivia)

The Pedro de Valdivia is a 13-storey reinforced concrete building without underground levels, and has a structural wall system with coupling beams. The damage observed in the structure is concentrated in the connections of the beams and piers in the stairs (Figures 27e and 27f) which were not able to resist the seismic demands, and in the coupling beams inside of the building such as those above door openings (Figure 27b). Also, the building had a service area to accommodate water and power systems protruding outside of the stairs at one level; these elements worked as a short column and failed in shear, see Figure 27c.

DOI: 10.1002/tal

Figure 27. (a) Elevation view (b) failure in the coupling beam inside of the apartment (c) failure of coupling element in the stair area (d) elevation view of the stair area (e) column failure in the stair (f) failure of non-ductile coupling beam.

1.4.8. Building H (Galeria Internacional)

This is an 11-storey building, where the upper three storeys were added to the original eight-storey structure. The building is constructed of reinforced masonry. The upper three storeys have a smaller floor area with respect to the lower storeys (see Figures 28a and 28b), which cause a change in the stiffness of the structure. There was concentrated damage at the ninth floor, with failures of masonry walls in shear (Figure 28d) and failure of some of the reinforced columns that were used to confine the masonry (Figure 28c).

1.4.9. Building I (Torre O'Higgins)

The Torre O'Higgins is a 21-storey building with 2 underground levels. It suffered the collapse of the piers at the 12th floor. The structural system consists of a wall system that is located in the back (west

DOI: 10.1002/tal

Figure 28. (a,b) Elevation Views (c) damage inside of an apartment at the ninth floor (Betanzo, 2010) (d) shear failure of a masonry wall.

side) of the building, and a perimeter system of piers and spandrels on the other sides. The building has a series of irregularities, although the height produced for the reduction of the floor are at different levels (i.e. at floors 2, 5, 7, 9, 12 and 16).

In contrast with other buildings in Concepción, this structure did not have damage at the ground level (Figure 29c). The damage is concentrated in the front of the building over the 12th floor (Figure 30), where there is a change of the floor area, causing a variation in the stiffness of the structure. In addition, according to a report on the website of Radio Bio-Bio, dated May 2010, the Director of the Public Works of Concepción stated that some structural modifications were made on the building by tenants above the 10th floor.

The partial collapse of the 12th floor caused the upper floors to slope and induce damage to coupling beams, as shown in Figures 30 and 31.

On the south side of the building, some shear damage failure was present in the short columns (Figure 32b) and coupling beams, and also at the point of discontinuities (Figure 32c).

Figure 29. (a) Elevation (east) view (b) View of the back (west side) of the Building (c) front entrance (d, e) view of the collapsed piers at the 12th floor.

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Figure 30. Panoramic view of the elevation with collapsed floor (courtesy of P. Correa).

Figure 31. Failure of the coupling beams at top floors.

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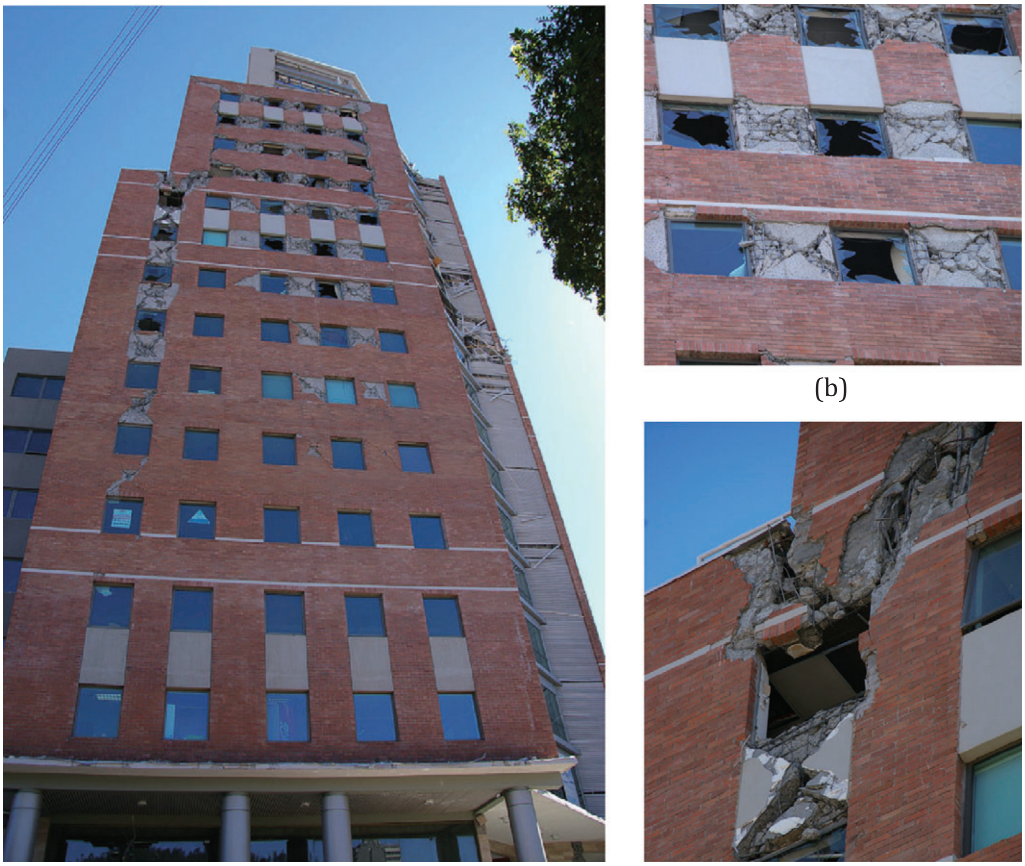

Figure 32. (a) Elevation of south side (b) shear failure of the short column (c) failure at singularity and shear failure of beams.

1.4.10. Building J (Alto Rio)

The Alto Rio is a 15-storey reinforced concrete building with two underground levels that has a structural wall system, see Figure 33. This was the only building over three storeys in height that completely collapsed in the area of Concepción during the earthquake. At the moment of the earthquake, there were 87 occupants in the building; there were 8 deaths with 79 survivors, of which 52 persons were able to evacuate the building on their own, and the remaining 27 were rescued from the debris (El Mercurio, 7 March 2010).

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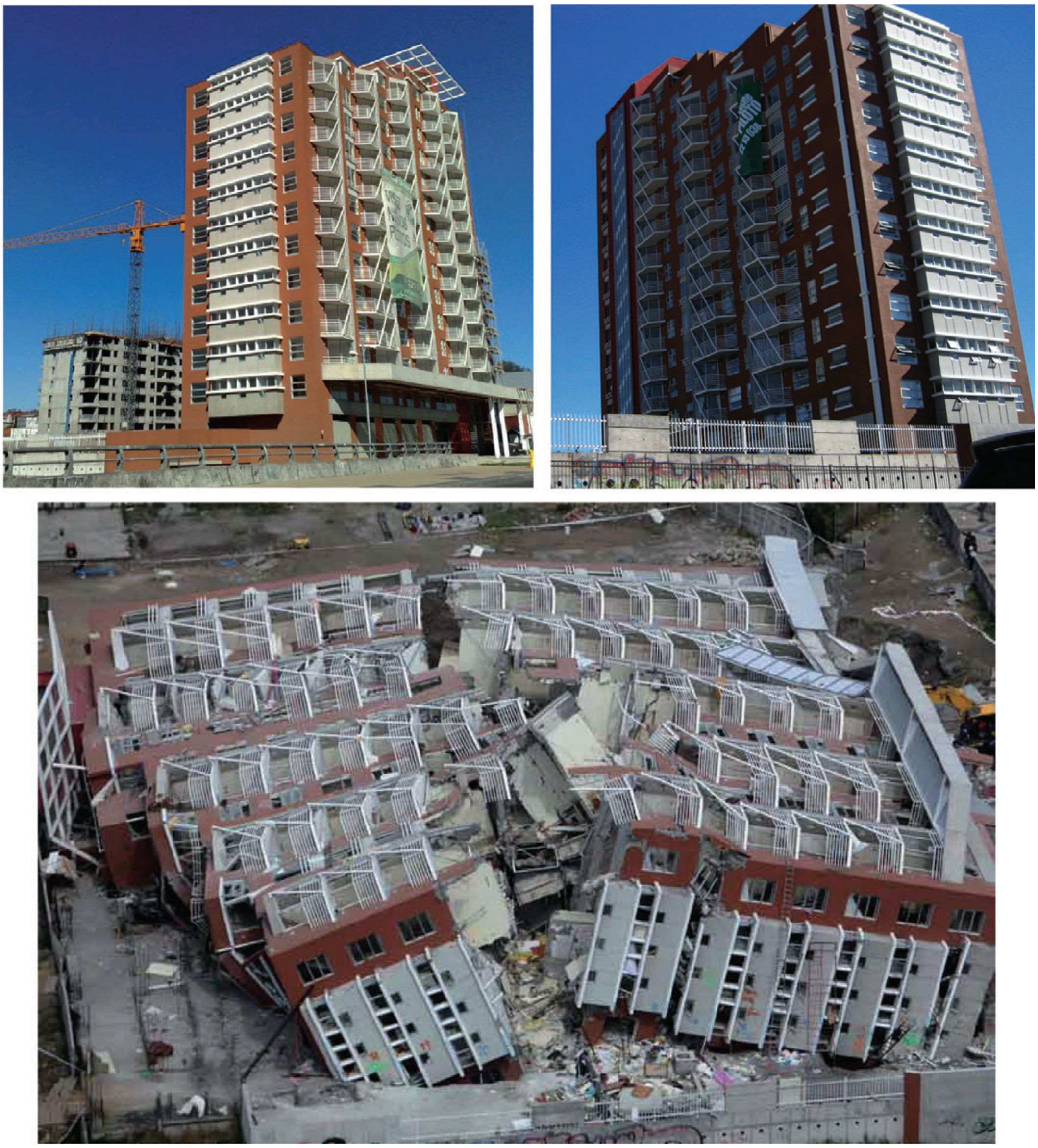

Figure 33. Views of the west and east sides of the building before the earthquake (Concepcion under Construction, 2010) (top), aerial view of the collapsed building (bottom) (El Periodista, 2010).

DOI: 10.1002/tal

Figure 34. Elevation view with the centreline of the building (Concepcion under Construction, 2010), position of the centreline after the collapse, sketch of the typical floor plan.

Figure 34 shows a sketch of the typical floor plan for the building. One hypothesis of the collapse is that the boundary elements of the walls failed from the strong and long duration ground motions. From observations in other buildings, compression in the walls could cause crushing of the concrete and buckling of the steel reinforcement and tension could cause breaking of the bars and possibly pull out of the vertical reinforcement if the development lengths were insufficient. The eastern walls may have failed in compression causing the building to tilt and fall in the eastern direction (Figure 35). Another hypothesis of the collapse is that a large co-seismic displacement generally to the west of about 3 m over a time span of about 25 s caused an overturning collapse of the building; this hypothesis has been examined by Alimoradi and Naeim (2010) in a companion paper.

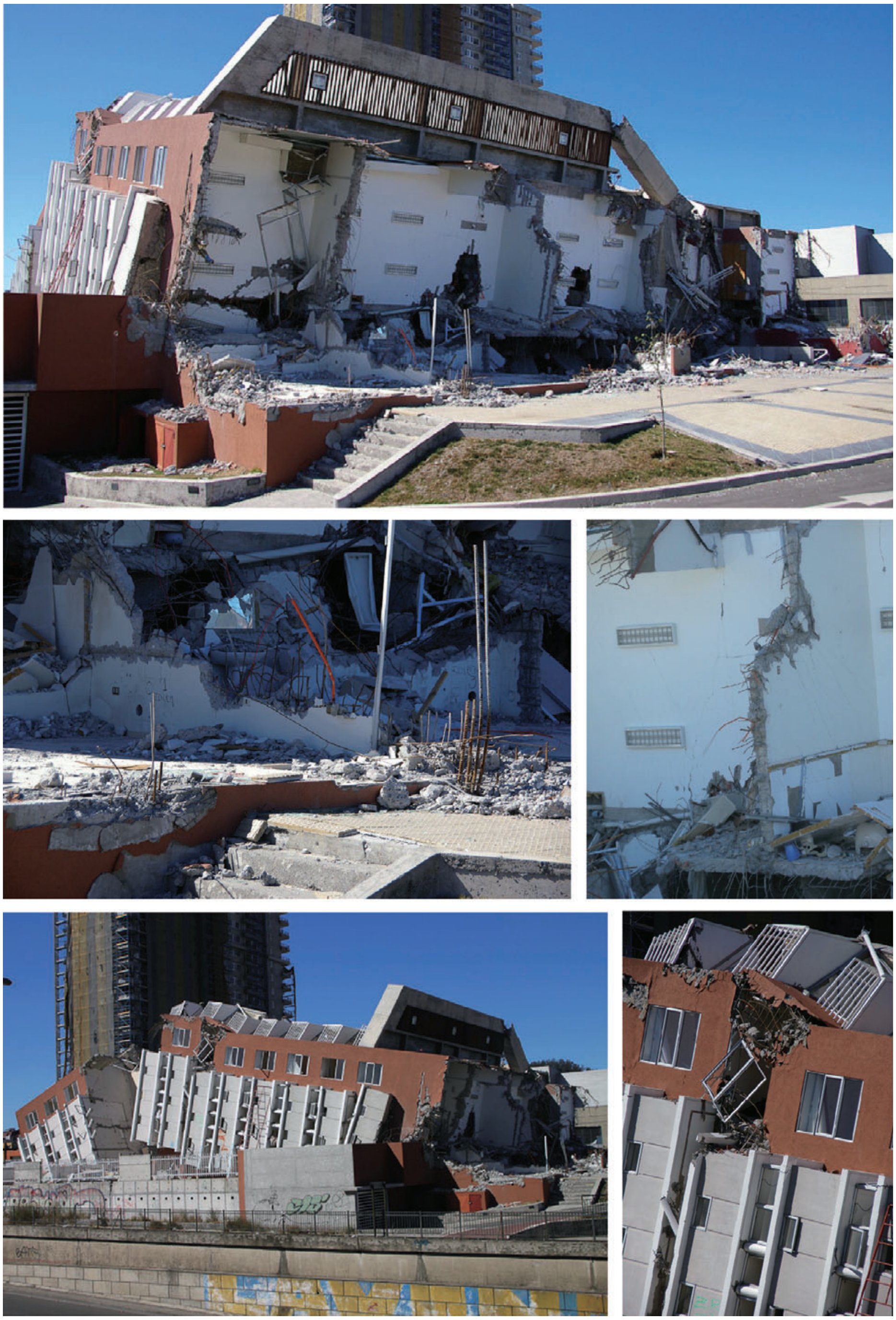

Figure 35. Different views of the damage of the collapsed Alto Rio building.

2. CONCLUSION

The 27 February, 2010 earthquake in Chile provided a unique opportunity to study the behaviour of all kind of structures and, in particular, the behaviour of mid- to high-rise buildings that have been designed with a recent building code and subjected to strong and long duration ground motions. Concepción was the city with more mid- to high-rise buildings that suffered damage due to the earthquake. The downtown area of Concepción has soft soil conditions (i.e. sand from fluvial deposits).

DOI: 10.1002/tal

The buildings have typically wall thicknesses of 15 cm, 20 cm and 25 cm and a storey height of 220 cm to 250 cm.

Different levels of damage were observed in Concepción in all types of structures. There were some collapses of bridges and silos, moderate to severe damage in masonry and adobe structures (Astroza *et al.*, 2010), as well as the damage to mid- and high-rise buildings. The principal type of damage experienced in the tall buildings are located at or near the ground level due to compression and tension effects in the walls, causing the crushing of the concrete due to heavy compression at the end of the elements and the buckling and fracture of the steel bars in the boundaries of the walls. The long duration of the ground motions apparently caused cyclical fatigue during the strong shaking. Also, buckling of the vertical reinforcing steel was almost ubiquitous. As observed in the other areas of Chile, the confinement of the boundary zone of walls was not observed in the construction that failed. This most likely can be attributed to the Chilean code (Nch433.Of 96—Section B.2.2) that allows exceptions to ACI 318-95 which require boundary elements in structural walls. Also, the lack of seismic hooks and cross ties in the wall elements was observed.

In conclusion, it is necessary to review the requirements for confinement of the boundary elements. There is a need to study the behaviour of wall system structures under severe and long duration strong ground motions to analyze the role of the cyclic fatigue in the concrete and reinforcing steel, as well as the reduction in stiffness of the walls. As mentioned by Betanzo (2010), it is also necessary to study the effects of soil response in the area of downtown Concepción; this may lead to microzation that may be useful in city planning and future design and construction.

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