

# February 27, 2010 Chile Earthquake Reconnaissance Team Investigation



Concepcion (AP Photo)

## Reinforced Concrete Buildings



## Team Task and Members

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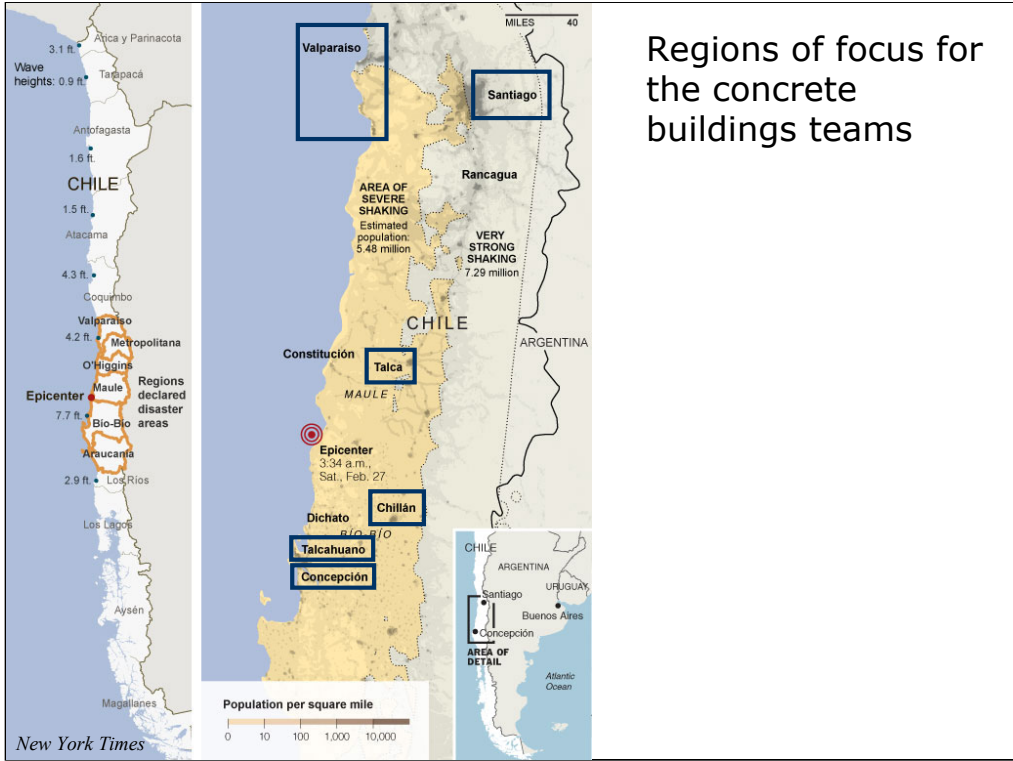
Investigate the performance of reinforced concrete buildings (typically 3 – 25 stories) during 8.8 Offshore Maule Earthquake



Jack Moehle, Carlos Sempere, Juan Jose Besa, Jeff Dragovich, & Benjamin Westenenk



John Wallace (not pictured) , Alvaro Celestino, Joe Maffei, and Arturo Millán, Santa Maria, Valparaíso Claudio Frings & Juan Pablo Herranz, Católica



Regions of focus for the concrete buildings teams

## Team Observations

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- **General**
  - The damage rate in the affected region was relatively low. Approximately four buildings collapsed out of a population of 10,000 buildings three stories and taller constructed since 1985.
  - Most mid- to high-rise buildings in Chile are predominantly of shear wall construction, though dual frame-wall systems sometimes are used. Ratios of wall area to floor area is relatively higher than is typical in the U.S.
- **Building codes**
  - The seismic loading code uses a design response spectrum that drops rapidly with increasing period. Spectral ordinates calculated from some recorded ground motions are above the design spectrum in the longer period range.
  - Design strengths are based on force reduction factor  $R$  that varies with period.
  - There are no specific provisions or prohibitions of building irregularities.
  - ACI 318-95 seismic provisions are used except the confinement requirements for wall boundaries are specifically exempted.

## Team Observations

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- Factors commonly associated with failures
  - Shear wall compression failures apparently associated with high axial stresses or high flexural compression stresses in flanged walls.
  - Insufficient transverse reinforcement, both in quantity and detailing, to confine walls and restrain longitudinal bars.
  - Thin walls became unstable after compression failures.
  - Wall vertical irregularities sometimes concentrated demands on lower-levels.
  - Lap splices occurred at some of the failure locations, and may have been a contributing factor

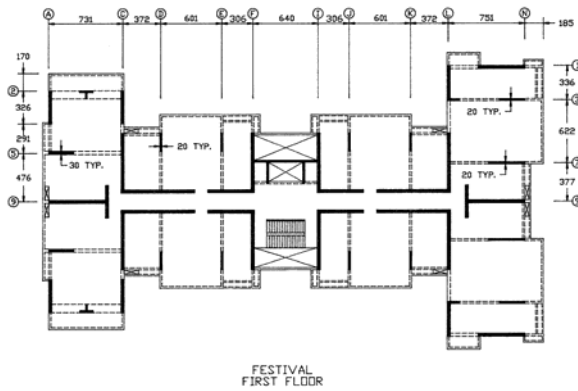
## Team Observations

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- Other damage and failure noted
  - Damage to link (coupling) beams and to slabs that coupled walls
  - Damage to wall piers
  - Damage associated with various vertical and plan irregularities
- Nonstructural damage
  - Nonstructural infills sustained damage in some cases where separations from structure were absent
  - Many doors were jammed in buildings
  - Damage observed in mechanical equipment when not anchored. Anchored equipment generally performed well.

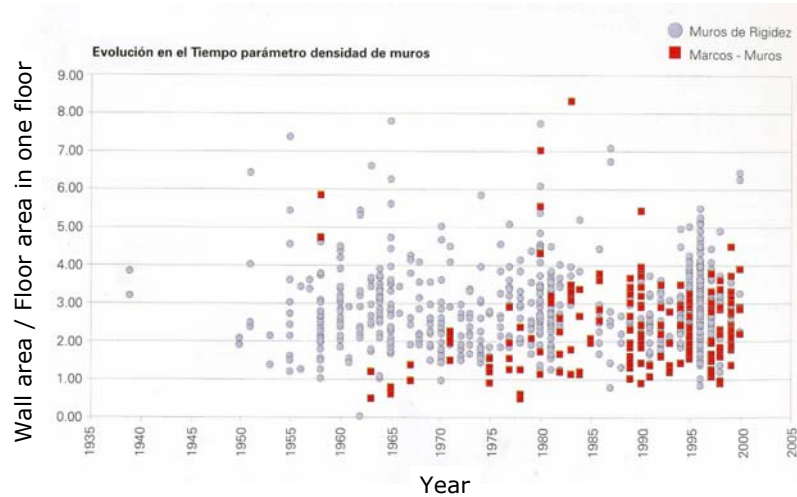
## Team Observations

- Festival Building, Viña del Mar, 14 Stories, 1978 construction. Illustrates typical wall building configuration.



A typical building plan has two corridor walls longitudinally with transverse walls.

# Ratio of wall to floor area

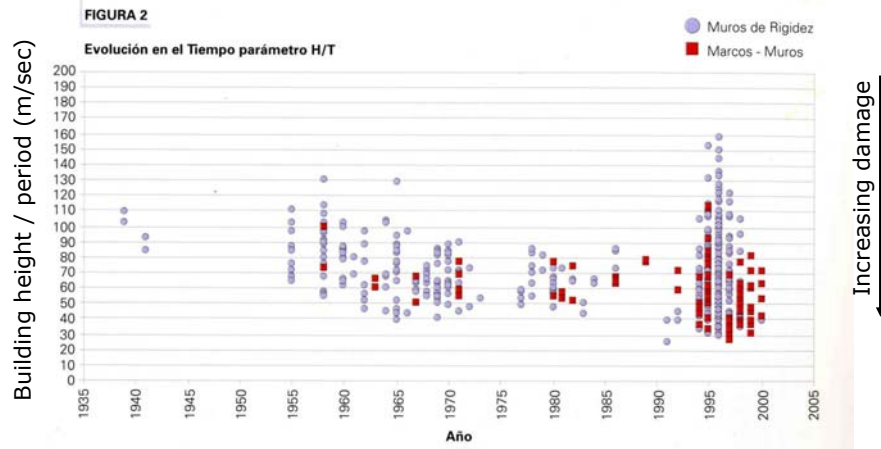


*"Edificios Chilenos de Hormigón Armado," ICH Instituto del Cemento y del Hormigón de Chile, 2002*

The ratio of wall area to single floor area is relatively large in comparison with US practices. Although the ratio has remained relatively constant, the building heights have increased in later years.



# Increasing building flexibility



Building data after Guendelman, et al., 1997.  
Damage rating after Moroni, EERI World Housing Encyclopedia

Buildings are becoming more flexible with time. According to Moroni, the damage rate for Chilean buildings increases as the flexibility increases.

## Chile Building Code, NCh433 (1996)

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**5.1.1** This standard ... aims to achieve structures that:

- a) resist moderate intensity seismic actions without damages;
- b) limit damage to non-structural elements during earthquakes of regular intensity;
- c) prevent collapse during earthquakes of exceptionally severe intensity, even though they show some damage.

...

In particular, the provisions for reinforced concrete wall buildings are based on their satisfactory behavior during the earthquake of March, 1985.

The Chile Building Code has been translated into English. The stated performance objectives are similar to traditional objectives implicit in US codes.

The code explicitly states that the provisions for wall buildings are based on their satisfactory behavior during the earthquake of March 1985.

## Chile Building Code, NCh433 (1996)

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- **6.2.3.1** The seismic coefficient  $C$ , is obtained from the expression:

$$C = \frac{2.75A_o}{gR} \left( \frac{T'}{T^*} \right)^n$$

- There are no specific provisions or prohibitions for vertical irregularities.
- **B.2.2** When designing reinforced concrete walls it is not necessary to meet the provisions of paragraphs 21.6.6.1 through 21.6.6.4 of the ACI 318-95 code.

The seismic design forces are adjusted by an R factor which is dependent on period of vibration. R values are similar to those in US practice.

Vertical irregularities were commonly observed for walls owing to architectural/functional requirements in first and subterranean levels. The code has no specific provisions for such cases.

The referenced sections of the ACI building code refer to boundary element confinement. According to this provision of the Chile Building Code, confinement of wall boundaries is not required.

**NUMBER OF RESIDENTIAL BUILDINGS: 3 STORY +  
CONSTRUCTION PERMITS FROM 1985 TO 2009**

Building Height	Regions affected by the earthquake						Total
	V	Metro	VI	VII	VIII	IX	
3 story	598	3.412	390	202	673	75	5.350
4 story	213	517	37	23	93	32	915
5 story	143	548	20	17	63	37	828
6 story	53	75	3	3	22	15	171
7 story	22	290	2	13	20	7	354
8 story	63	330	5	2	12	5	417
9 story +	413	1.310	10	27	102	77	1.939
<b>TOTAL</b>	<b>1.505</b>	<b>6.482</b>	<b>467</b>	<b>287</b>	<b>985</b>	<b>248</b>	<b>9.974</b>

Source: Statistics from INE



Data estimated by Rene Lagos on basis of building permit statistics from the Instituto Nacional de Estadísticas de Chile

## How did buildings perform?

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Considering only buildings between 1985 to 2009

- Buildings that collapsed: 4 (app.)
  - Buildings to be demolished: 50 (estimate)
  - Number of buildings 3 + story 9.974
  - Number of buildings 9 + story 1.939
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- Failures 3 + story buildings: 0.5%
  - Failures 9 + story buildings: 2.8%



Collapse and future demolition data estimated by Rene Lagos. The EERI LFE team observed four collapsed buildings. On the basis of LFE team discussions with other experts in Chile, the number of heavily damaged buildings is roughly consistent with the estimate of buildings to be demolished as reported here. Complete statistics are not available at this time.

## Santiago (Ñuñoa), Bldg A



Los Cerezos 33, Ñuñoa, Santiago.  
~ 26 story building.

## Santiago (Ñuñoa), Bldg A



Los Cerezos 33, Ñuñoa, Santiago.

~ 26 story building. Note walls at sides of entry are “clipped.” Wall to left is continuous into subterranean levels and is crushed at the top. Wall to right is supported on column in first subterranean level, resulting in wall crushing at the connection with the column.

## Santiago (Ñuñoa), Bldg A



Los Cerezos 33, Ñuñoa, Santiago.

~ 26 story building. Crushing at top of wall to left of entry.



## Santiago (Ñuñoa), Bldg A



Los Cerezos 33, Ñuñoa, Santiago.

~ 26 story building. Crushed wall from the outside (left) and inside (right). Column below was essentially undamaged.

## Santiago (Ñuñoa), Building B

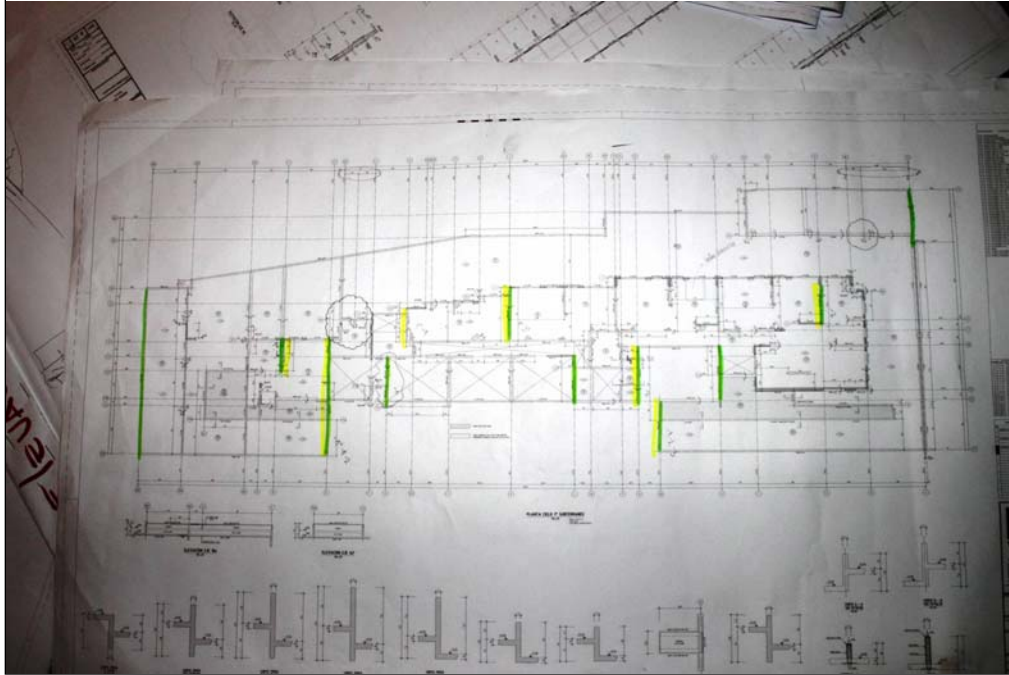


Av. Irarrázaval 2931, Ñuñoa, Santiago.

Emerald Building. ~ 16 stories tall, plan narrow in front, widening to the back.

Roof leaning 22 cm to the left, over walls crushed in the first subterranean level.

## Santiago (Ñuñoa), Building B

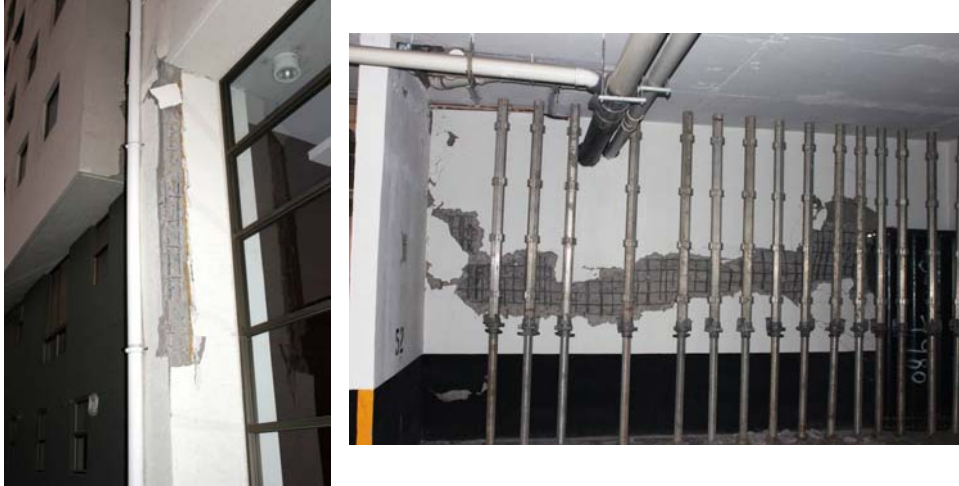


Av. Irarrázaval 2931, Ñuñoa, Santiago.

Floor plan

## Santiago (Ñuñoa), Building B

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Av. Irarrázaval 2931, Ñuñoa, Santiago.

Photo to left shows damage to lap splice at first story above grade. This half of the building showed signs of being in tension (lap splice damage, tension cracks).

Photo to the right shows crushing of wall below grade on opposite side of building (compression side).

## Santiago (Ñuñoa), Building B

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Av. Irarrázaval 2931, Ñuñoa, Santiago.

Buckled wall below grade.

## Santiago (Ñuñoa), Building B

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Av. Irarrázaval 2931, Ñuñoa, Santiago.

View of details of reinforcement and failure at one crushed wall boundary. Note lack of cross ties in the field of the wall. Note wide spacing and 90-degree bends on transverse reinforcement in boundary.

## Santiago (Maipu), Building C

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Maipu, Santiago. Edificio Don Tristan

This building collapsed during the main event.



## Santiago (Maipu), Building D



Maipu, Santiago.

Building similar to Building C, located within two blocks.



## Santiago (Maipu), Building D



Maipu, Santiago.

Building similar to Building C, located within two blocks. Viewing from road side (relatively undamaged) toward back (collapsed). The wall with the large inclined “crack” showed inclined cracking in both directions.

## Santiago (Maipu), Building D

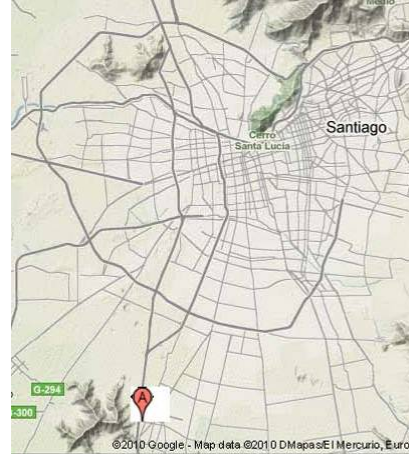


Maipu, Santiago.

Building similar to Building C, located within two blocks. Back end of building collapsed.

## Santiago (San Bernardo), Buildings E

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San Jose 1062, San Bernardo, Santiago, Chile.

Two nominally identical buildings constructed as mirror images of one another within 100 ft of one another.

## Santiago (San Bernardo), Buildings E



San Jose 1062, San Bernardo, Santiago, Chile.

Two nominally identical buildings constructed as mirror images of one another within 100 ft of one another.

## Santiago (San Bernardo), Buildings E



San Jose 1062, San Bernardo, Santiago, Chile.

Two nominally identical buildings constructed as mirror images of one another within 100 ft of one another.

## Santiago (Macul), Buildings F



Sol Oriente I and II, Macul, Santiago, Chile.

Complex of highrise condominiums.



## Santiago (Macul), Buildings F

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Sol Oriente I and II, Macul, Santiago, Chile.

Complex of highrise condominiums.

Joint between two towers showing different damage in each. The roof is leaning 13 cm away from this side of the building.

## Santiago (Macul), Buildings F



Sol Oriente I and II, Macul, Santiago, Chile.

Complex of highrise condominiums. Typical crushed transverse wall. The longitudinal walls were intact with no appreciable signs of damage.



## Santiago (Macul), Buildings F



Sol Oriente I and II, Macul, Santiago, Chile.

Complex of highrise condominiums. Fractured boundary element longitudinal bars was not uncommon in buildings of this type.

## Santiago (Macul), Buildings F



Sol Oriente I and II, Macul, Santiago, Chile.

Complex of highrise condominiums.

Crushed transverse walls were all on one side of the longitudinal walls. Photo is from 2<sup>nd</sup> story on side opposite the crushed walls. Note cracks in wall, suggesting tension in the slab toward the left of the photo, consistent with internal forces expected as the slab acted to tie the crushed part of the building back into the other half.

## Santiago (Providencia), Building G

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Av Los Leones 1841, Providencia, Santiago, Chile.

12 story reinforced concrete condominium with subterranean parking.

## Santiago (Providencia), Building G



Av Los Leones 1841, Providencia, Santiago, Chile.

12 story reinforced concrete condominium with subterranean parking.

One of a few crushed walls in first level below grade.

## Santiago (Providencia), Building G



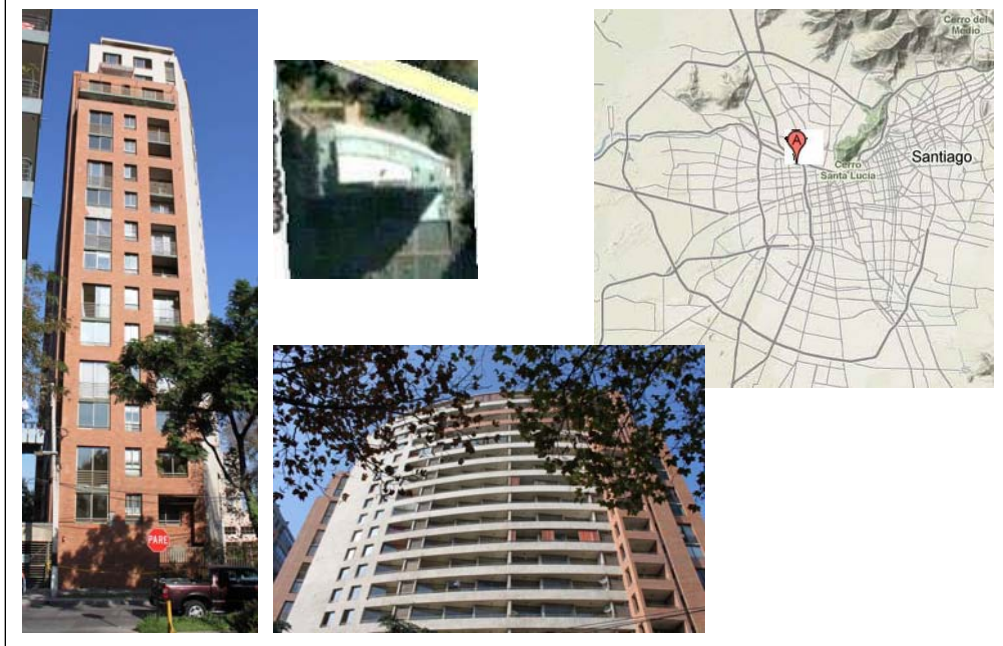
Av Los Leones 1841, Providencia, Santiago, Chile.

12 story reinforced concrete condominium with subterranean parking.

One of a few crushed walls in first level below grade.



## Santiago (Providencia), Building H



[Av Presidente Balmaceda 2150](#), Providencia, Santiago, Chile.

High rise concrete building. See centrally located Google.earth satellite photo. Elevation to the left is of the narrow part (East face). The bottom center photo is the north face.

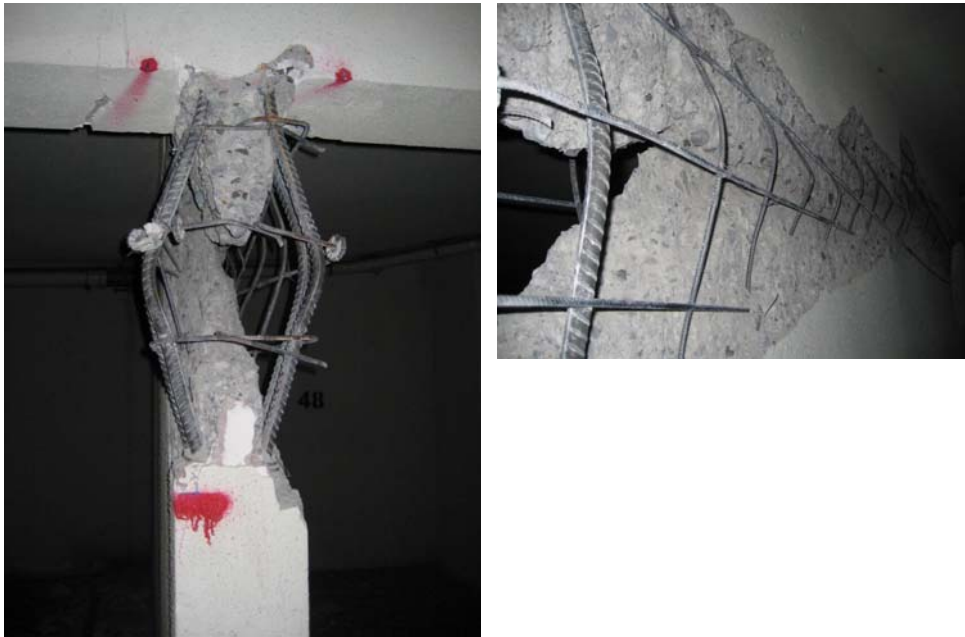
## Santiago (Providencia), Building H



[Av Presidente Balmaceda 2150](#), Providencia, Santiago, Chile.

Failure of structural elements along the east part of the north face at the lower level.

## Santiago (Providencia), Building H



[Av Presidente Balmaceda 2150](#), Providencia, Santiago, Chile.

Interior photos taken by social science members of the EERI LFE team, who had observed a condo-owner meeting. The notes of the EERI LFE Team are copied below.

- Damages in Santiago have been in general isolated to a few buildings.
- However, this situation has raised more difficulties than one would suspect at first sight.
- This community in Santiago, in the "Central Park" building on Balmaceda Street has suffered structural damages in their high-rise apartment building, which houses about 150 units.
- Some families have insurance, mainly through bank mortgages, and they advocate for the demolition of the building. Others, who paid in full and did not buy private insurance advocate for the repair of the building since they do not want to lose their investment.
- Additionally, the emotional stress is enormous because they felt the strong shaking and they know that there are serious structural damages in their building.
- The construction company is pressuring them to accept a partial compensation deal in exchange for not being sued.
- The situation has resulted in a serious drama that affects middle-income strata of the Santiago population.
- This is an example of how the earthquake has triggered complex dynamics even though (or maybe because) there is absence of generalized severe damages.



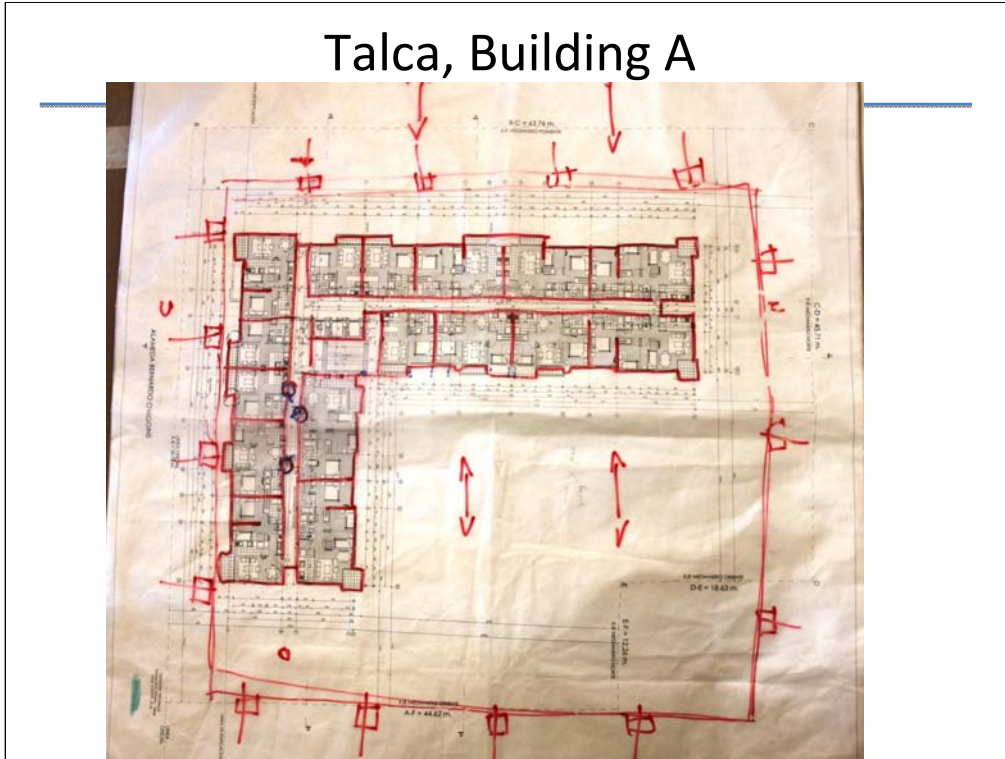
## Talca, Building A



[Av Bernardo O'Higgins 901](#), Talca, Chile

21 story concrete building. Under construction. Met with construction engineer for tour.

## Talca, Building A



[Av Bernardo O'Higgins 901](#), Talca, Chile

21 story concrete building. Under construction. Met with construction engineer for tour.

Plan view, with real-time illustrations of structural system in red by construction engineer.

## Talca, Building A

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[Av Bernardo O'Higgins 901](#), Talca, Chile

21 story concrete building. Under construction.

Typical damage to slab coupling two walls either side of doorway. Note there is no beam here.

## Talca, Building A



[Av Bernardo O'Higgins 901](#), Talca, Chile

21 story concrete building.

View from underside of slab.

# Chillan, Building A

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18 de Septiembre 235, Chillan, Chile

15 story concrete building with subterranean levels. Met with construction representative who was conducting repairs.

## Chillan, Building A

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18 de Septiembre 235, Chillan, Chile

15 story concrete building with subterranean levels. Met with construction representative who was conducting repairs.

Walls showed characteristic damage at two locations.



## Chillan, Building A



18 de Septiembre 235, Chillan, Chile

15 story concrete building with subterranean levels. Met with construction representative who was conducting repairs.

Series of door openings aligned over height and ended with solid wall at top story and at bottom story. Top and bottom wall segments were damaged in patterns suggesting strong coupling action at those levels.

## Concepción, Building A

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Freire 1165, Concepción, Chile

17 story concrete building without subterranean levels.



## Concepción, Building A



Freire 1165, Concepción, Chile

17 story concrete building without subterranean levels.

## Concepción, Building A



Freire 1165, Concepción, Chile

17 story concrete building without subterranean levels.

## Concepción, Building A



Freire 1165, Concepción, Chile

17 story concrete building without subterranean levels.

Up the parking ramp one story, looking back at building.

## Concepción, Building B

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Av Los Carreras 1535, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

## Concepción, Building A



Av Los Carreras 1535, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

View under 4-story wing to right of building.

## Concepción, Building A

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Av Los Carreras 1535, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

View back toward 4-story wing to the right of the building. Note that the building has subsided, shearing the wing. Similar damage on the other side of the building.



## Concepción, Building B



Av Los Carreras 1535, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

View inside first-story room looking toward the back right side of the building, that was shown subsided in the previous slide.

## Concepción, Building B



Av Los Carreras 1535, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

Back view of the building. Walls are clipped gradually. Bent bars at this location spalled cover. Walls crushed adjacent to the start of the clip.



## Concepción, Building C

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Lincoyan 440, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

## Concepción, Building C



Lincoyan 440, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

Crushed walls at street level.

## Concepción, Building C

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Lincoyan 440, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

First level above grade. Street is toward the right.

## Concepción, Building C



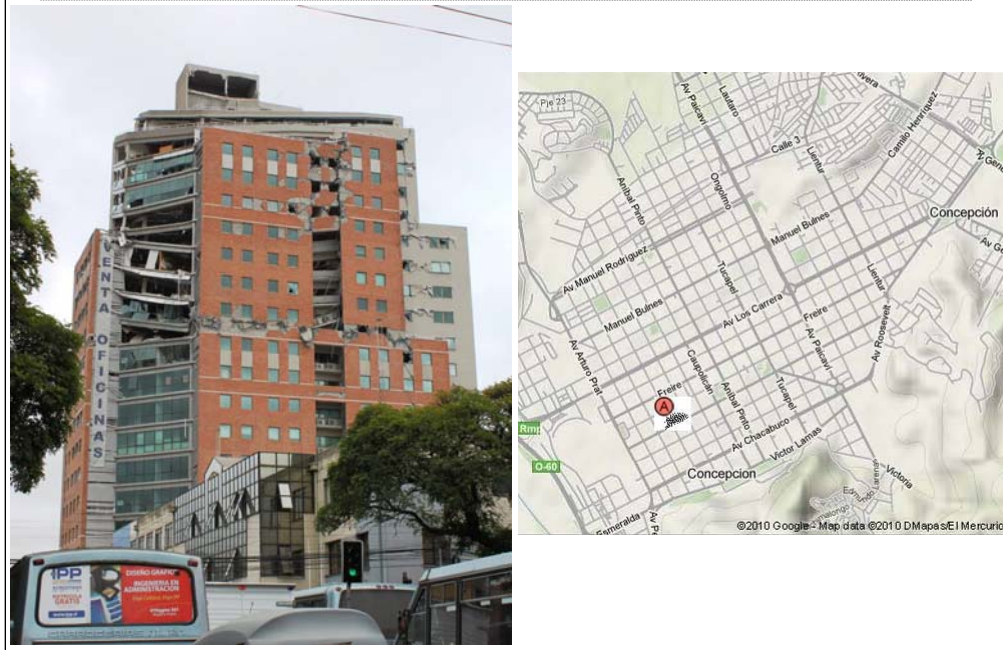
Lincoyan 440, Concepción, Chile

Approximately 18 story concrete building without subterranean levels.

Second level above grade. Viewing the front side of the building.



## Concepción, Building D



O' Higgins 241, Concepción, Chile

Approximately 24 story concrete building.

Note story collapse (1) at level of setback of the punched wall/frame in the foreground, (2) just above the punched frame to the left above the “venta” sign, and (3) just above the top of the punched wall/frame in the foreground.

## Concepción, Building D

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O' Higgins 241, Concepción, Chile

Approximately 24 story concrete building.

View from roof of nearby building.

## Concepción, Building D



O' Higgins 241, Concepción, Chile

Approximately 24 story concrete building.



## Concepción, Building D



O' Higgins 241, Concepción, Chile

Approximately 24 story concrete building.

## Concepción, Building E

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Obispo Hipolito Salas 1243, Concepción, Chile

13 story concrete building. Subterranean parking was to the North of the buildings, and did not extend beneath the towers.

The North tower was relatively undamaged, with minor cracking. The South tower was heavily damaged, and showed signs of foundation rocking.

## Concepción, Building E

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Obispo Hipolito Salas 1243, Concepción, Chile

13 story concrete building.

View of the South tower. Gauging from the adjacent North tower, it appeared that the South tower was leaning about 1 foot at the roof.

Right photo shows damaged pavement around the west side of the South tower.

## Concepción, Building E

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Obispo Hipolito Salas 1243, Concepción, Chile

13 story concrete building.

Some walls were discontinuous and supported on piers, as shown, resulting in tension and compression damage to the piers, and apparent diaphragm transfers, as were evident in diaphragm cracking.

## Concepción, Building E



Obispo Hipolito Salas 1243, Concepción, Chile

13 story concrete building.

Some walls showed inclined cracks indicative of damage due to shear.

## Concepción, Building E



Obispo Hipolito Salas 1243, Concepción, Chile

13 story concrete building.



## Concepción, Building F

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Castellón 1367, Concepción, Chile

Edificio Plaza Mayor 1, 14 story concrete building.



## Concepción, Building F



Castellón 1367, Concepción, Chile

Edificio Plaza Mayor 1, 14 story concrete building.

Walls damaged above the first floor. Note also the damage to walls at the intersection of the balcony beams with the walls. The appearance is of out-of-plane coupling.

## Concepción, Building F

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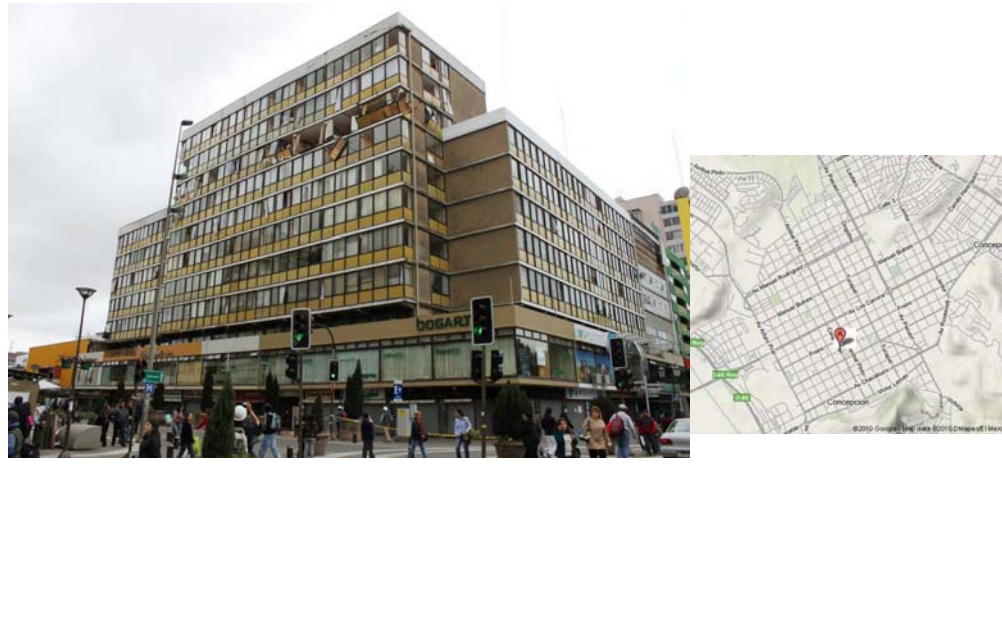
Castellón 1367, Concepción, Chile

Edificio Plaza Mayor 1, 14 story concrete building.

In one room, looking to the right wall is a crushed concrete wall, and looking to the left the partition wall has buckled due to shortening of the story.

## Concepción, Building G

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[Caupolicán 518](#), Concepción, Chile

11 story concrete building.

## Concepción, Building G

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[Caupolicán 518](#), Concepción, Chile

11 story concrete building.

## Concepción, Building H



Salas 445, Concepción, Chile

24 story concrete building.

## Concepción, Building H

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Salas 445, Concepción, Chile

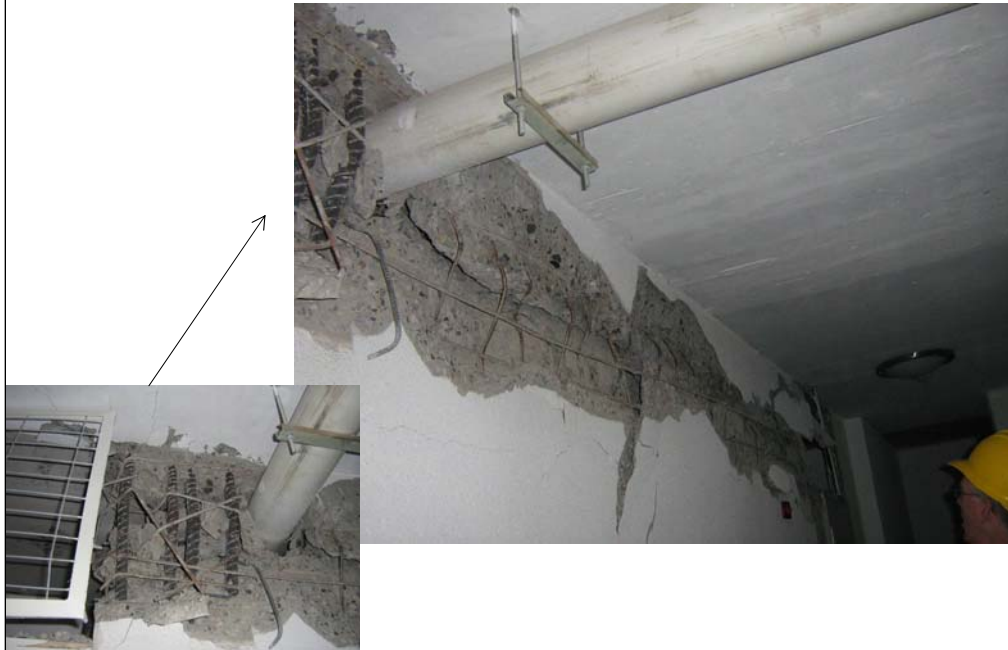
24 story concrete building.

Damage to exterior wall around the right side of the building toward the back.



## Concepción, Building H

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Salas 445, Concepción, Chile

24 story concrete building.

Crushing damage in the first subterranean level.

# Concepción, Building I

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Photo before earthquake



Concepción, Chile

12 story concrete building. Torre Alto Rio.

## Concepción, Building I



Concepción, Chile

12 story concrete building. Torre Alto Rio.

Building fell toward the photographer. Viewing roof.

## Concepción, Building I



Concepción, Chile

12 story concrete building. Torre Alto Rio.

Building fell away from the photographer. Viewing underneath building.

## Concepción, Building I



Concepción, Chile

12 story concrete building. Torre Alto Rio.

Professor Borosc hek standing near corner of first story of building.



## Concepción, Building I



Concepción, Chile

12 story concrete building. Torre Alto Rio.



## Talcahuano, Building A

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Arturo Prat 88, Talcahuano, Chile

Gymnasium building. Reinforced concrete. Ca 1955.

The tsunami filled a two-story basement, which was being pumped during the visit.

The superstructure has a joint down the middle, creating two similar building abutting one another. The building on this end has an end wall. The building on the other end has columns all around.

## Talcahuano, Building A

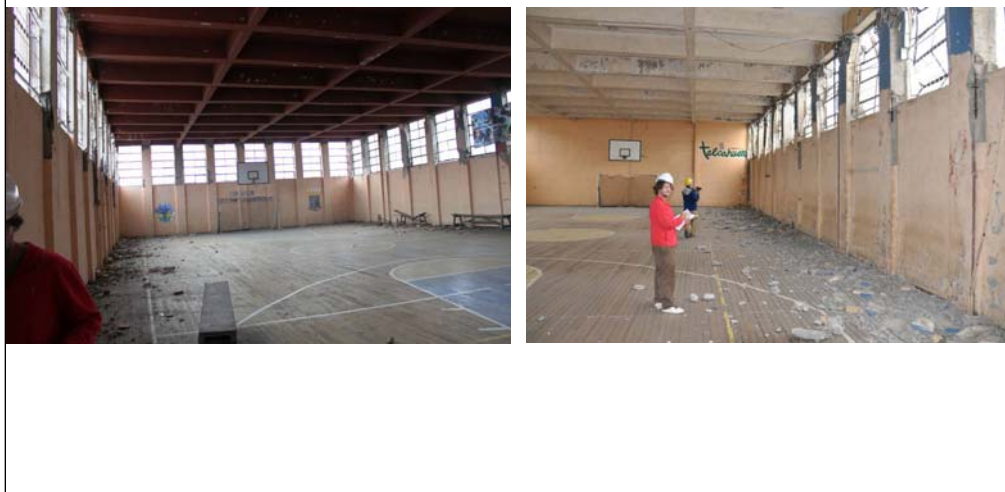


Arturo Prat 88, Talcahuano, Chile

Gymnasium building. Reinforced concrete. Ca 1955.

## Talcahuano, Building A

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Arturo Prat 88, Talcahuano, Chile

Gymnasium building. Reinforced concrete. Ca 1955.

View inside the western half of the building (left) and the eastern half of the building (right)

## Talcahuano, Building A



Arturo Prat 88, Talcahuano, Chile

Gymnasium building. Reinforced concrete. Ca 1955.

# Talcahuano, Building B

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Av Cristóbal Colón 2450, Talcahuano, Chile

## Talcahuano, Building B



Av Cristóbal Colón 2450, Talcahuano, Chile