# The 2010 Chile Earthquake: Observations and Research Implications


**Jeff Dragovich**

**Jay Harris**


9 December 2010

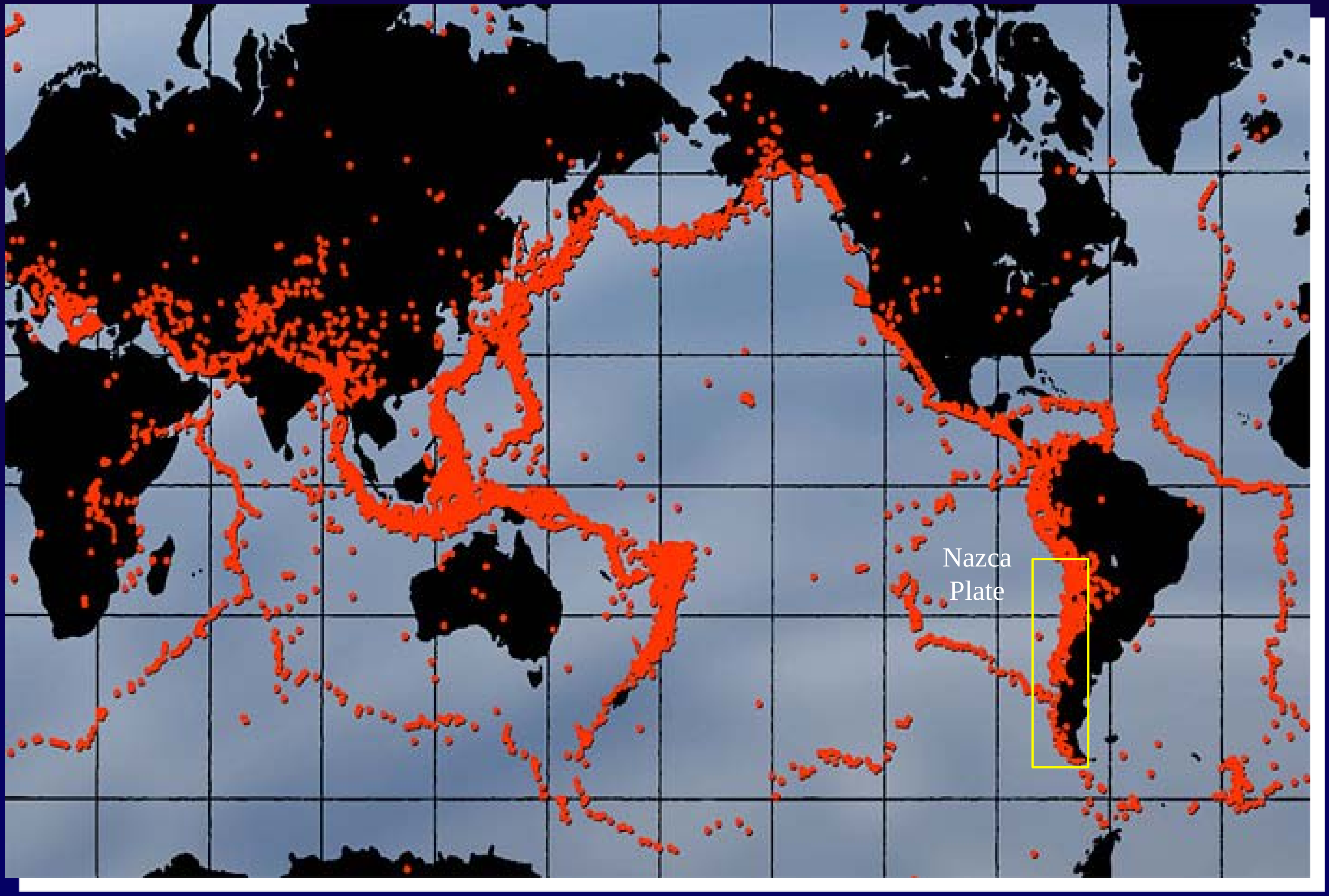
# Presentation Outline

- The earthquake and seismic hazard
- Design practices
  - Chile
  - US/Canada
- NIST mobilization
- Observations:
  - Reinforced concrete
  - Steel
  - Irregularities
  - Separation/non-structural
- Initiated Research

# What Will Not Be Covered

- Detailed Seismology
- Geotechnical
- Transportation
- Tsunami
- Ports / harbors
- Lifelines
- Organizational Issues
- Socio-economic

# “Ring of Fire”



# World’s Largest Earthquakes

| No | Rank | Year | Location | Name | Magnitude |
|---|---|---|---|---|---|
| 1 | 1 | 1960 | Valdivia, Chile | 1960 Valdivia earthquake | **9.5** |
| 2 | 2 | 1964 | Prince William Sound, USA | 1964 Alaska earthquake | 9.2 |
| 3 | 3 | 2004 | Sumatra, Indonesia | 2004 Indian Ocean earthquake | 9.1 |
| 4 | 4 | 1952 | Kamchatka, Russia | Kamchatka earthquakes | 9.0 |
| 5 | 4 | 1868 | Arica, Chile (then Peru) | 1868 Arica earthquake | **9.0** |
| 6 | 4 | 1700 | Cascadia subduction zone | 1700 Cascadia earthquake | 9.0 |
| 7 | 7 | 2010 | Maule, Chile | 2010 Chile earthquake | **8.8** |
| 10 | 10 | 1965 | Rat Islands, Alaska, USA | 1965 Rat Islands earthquake | 8.7 |
| 11 | 10 | 1755 | Lisbon, Portugal | 1755 Lisbon earthquake | 8.7 |
| 12 | 10 | 1730 | Valparaiso, Chile | 1730 Valparaiso earthquake | **8.7** |
| 13 | 13 | 2005 | Sumatra, Indonesia | 2005 Sumatra earthquake | 8.6 |
| 16 | 16 | 2007 | Sumatra, Indonesia | September 2007 Sumatra earthquakes | 8.5 |
| 20 | 16 | 1922 | Atacama Region, Chile | 1922 Vallenar earthquake | **8.5** |
| 21 | 16 | 1751 | Concepción, Chile | 1751 Concepción earthquake | **8.5** |
| 22 | 16 | 1687 | Lima, Peru | 1687 Peru earthquake | 8.5 |
| 23 | 16 | 1575 | Valdivia, Chile | 1575 Valdivia earthquake | **8.5** |

# Event Summary

- The February 27th, 2010 magnitude 8.8 offshore Maule Chile earthquake is one of the 5 largest earthquakes ever recorded.
- Magnitude $M_w$=8.8, thrust faulting due to subducting Nazca Plate beneath South America Plate.
- The death toll as of May 15, 2010 is 521, down from early reports of 802 (~250 attributed to tsunami)
- ~ Approximately 1.5 M people displaced.
- ~ 3,000 tall buildings (>10 stories) in Chile.
- Estimated economic loss: ~$30B.
- Moved the city of Concepción at least 3 meters to the west.

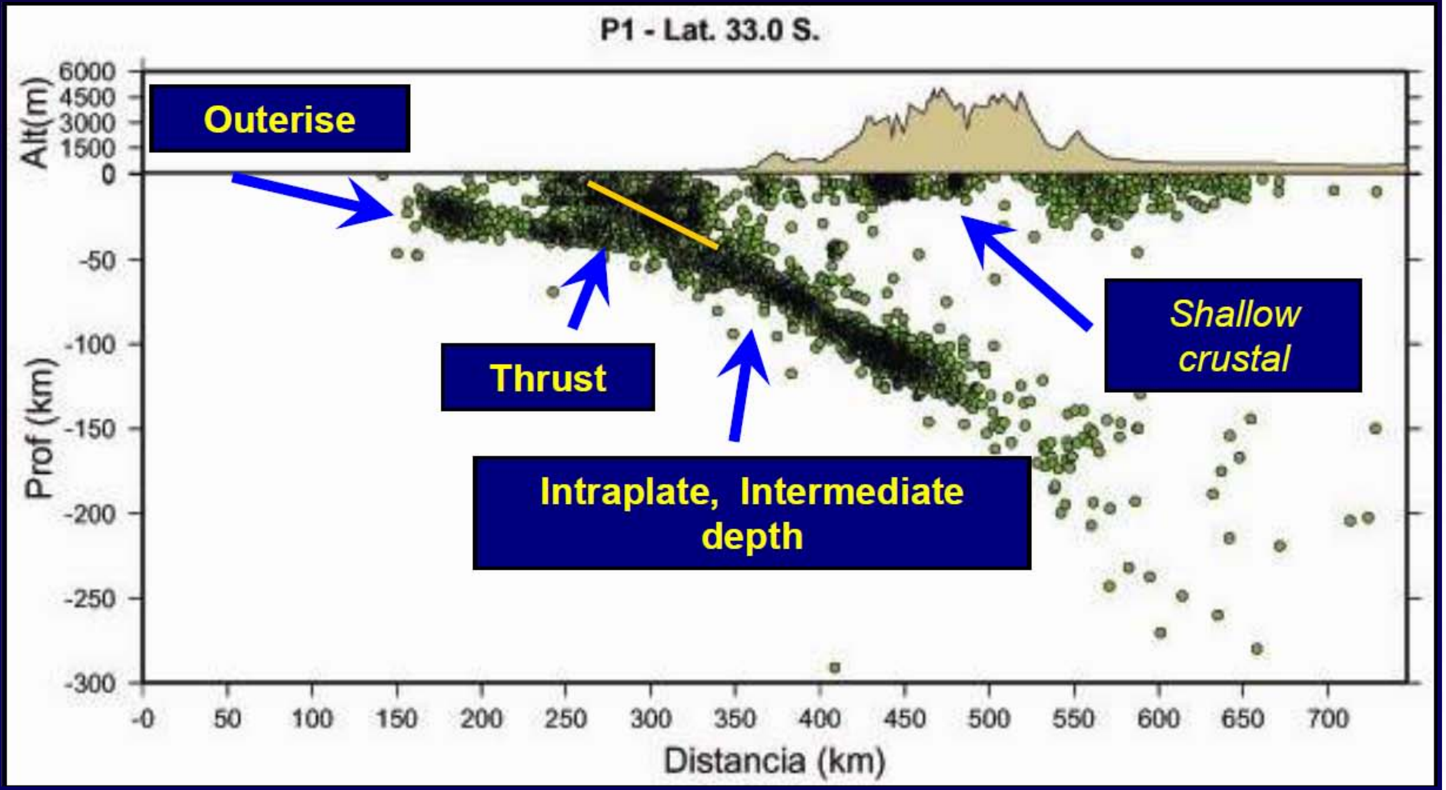
# How Did the Buildings Perform?

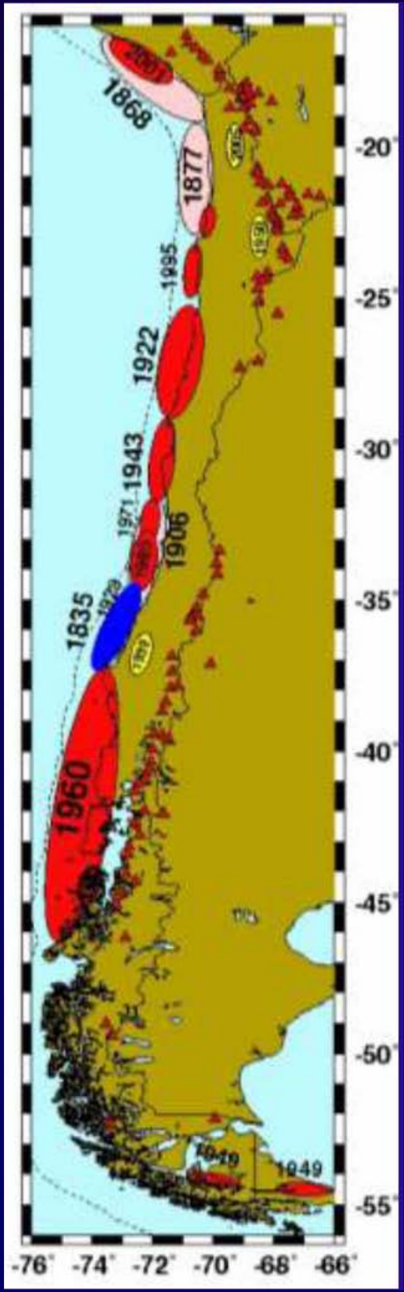
- **Estimate by Rene Lagos:**

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 | |
| • Failures 3 + story buildings: | 0.5% | |
| • Failures 9 + story buildings: | 2.8% | |

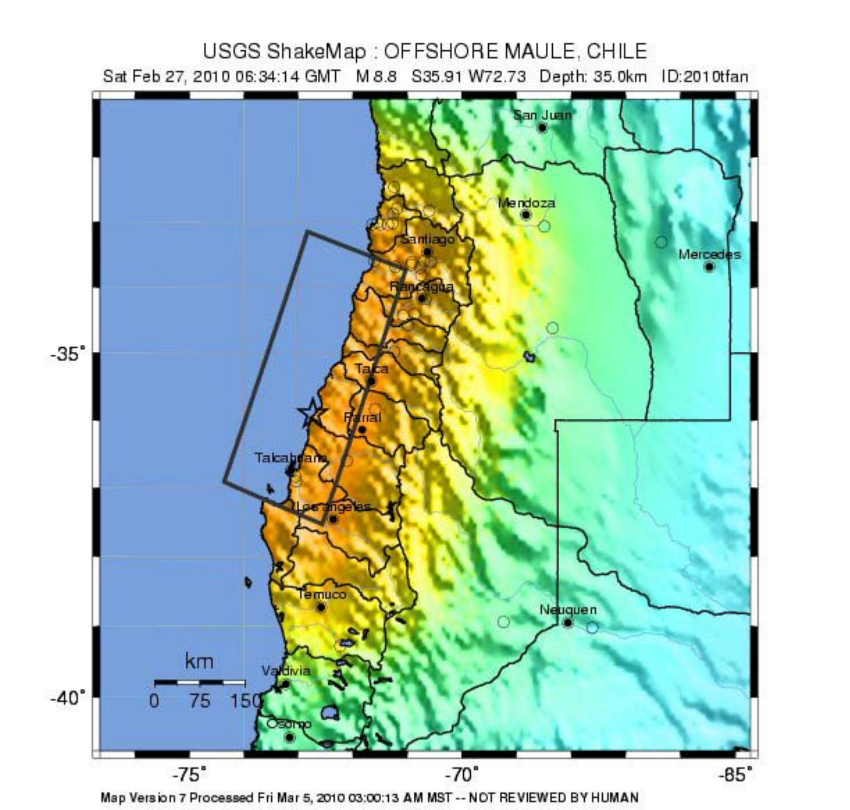
# Chilean Seismology



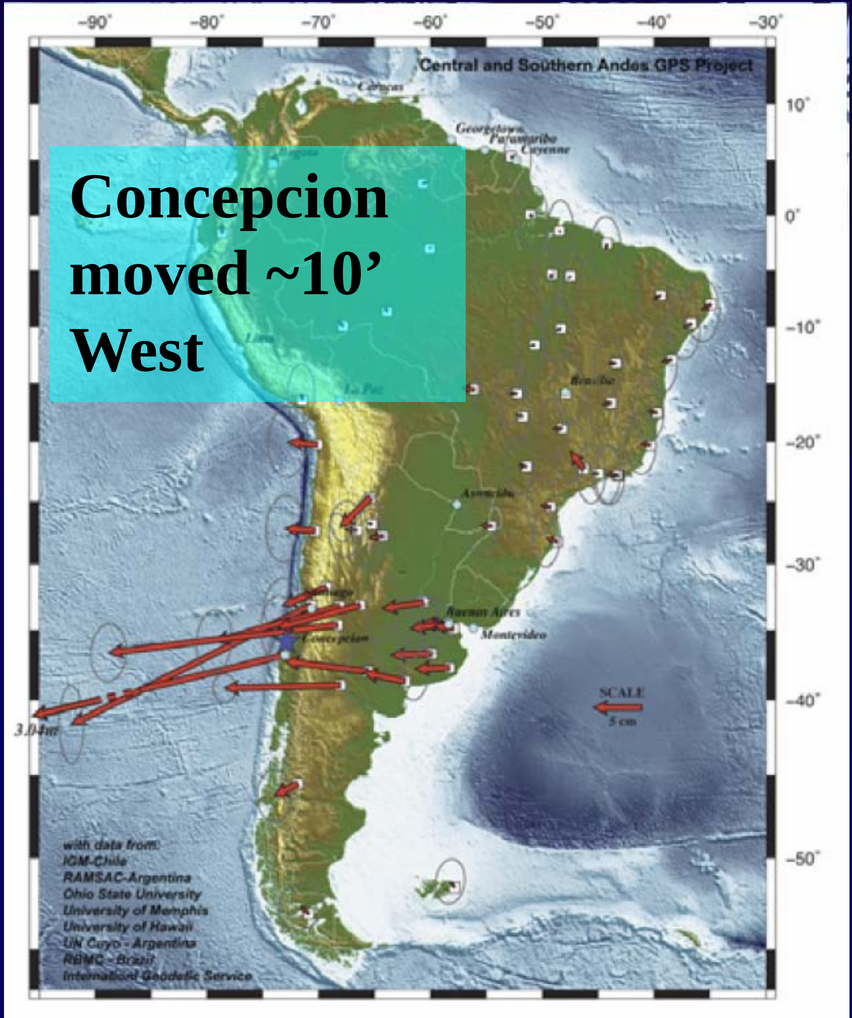
# The Earthquake

## USGS Pager



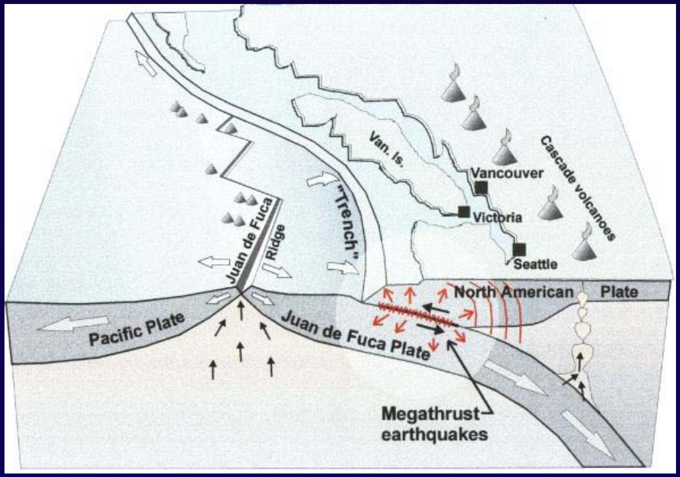

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

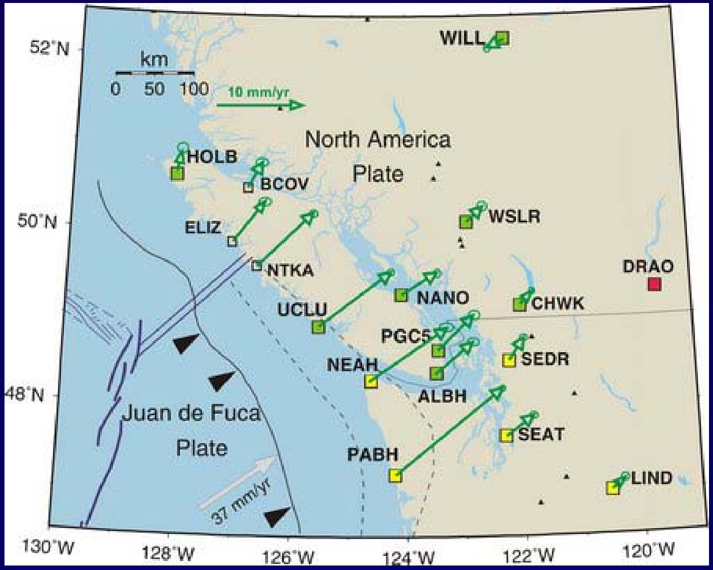
## GPS Data




**Concepcion moved ~10' West**

# The Pacific Northwest Analogy




- "Megathrust" earthquakes are known to have occurred in the Pacific Northwest (1700 AD)
- Seattle, Vancouver, Portland are particularly vulnerable

# Ground Motion

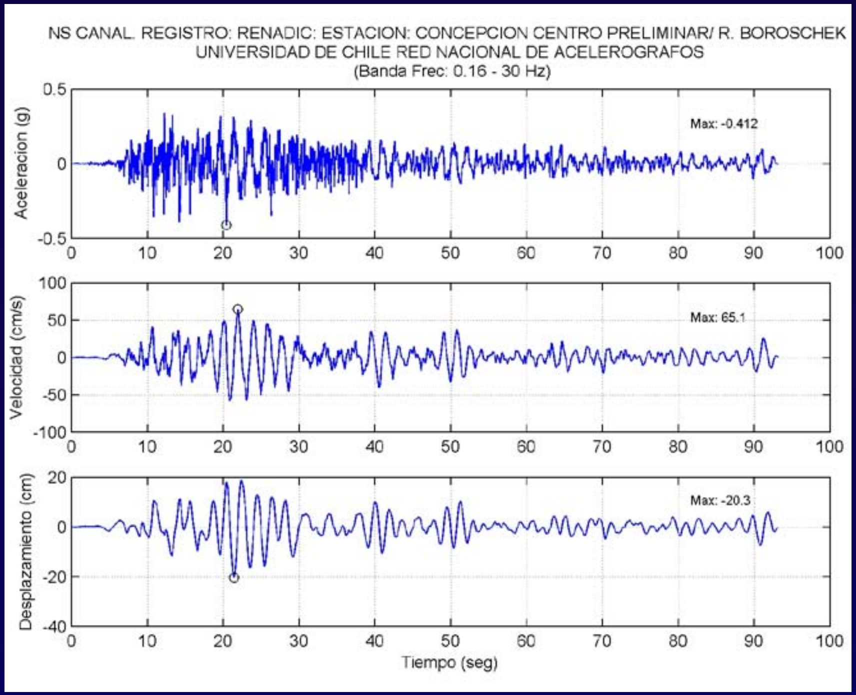
| Localidad | Aceleración Máx. Horizontal N-S | Aceleración Máx. Horizontal E-W | Aceleración Máx. Vertical |
|---|---|---|---|
| Colegio San Pedro, Concepción | 0.65 | 0.58 | 0.60 |
| Cerro Calán, Santiago | 0.20 | 0.23 | 0.11 |
| Campus Antumapu, Santiago | 0.23 | 0.27 | 0.17 |
| Cerro El Roble | 0.19 | 0.13 | 0.11 |

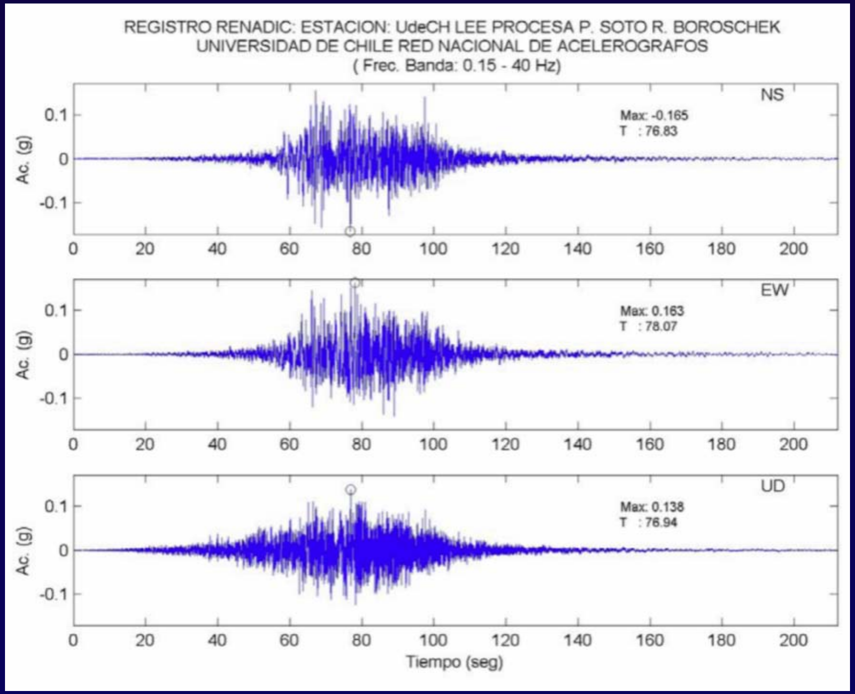
**Servicio Sismológico U. de Chile**

| Localidad | Aceleración Máx. Horizontal | Aceleración Máx. Vertical |
|---|---|---|
| Depto. Ing. Civil, U. de Chile | 0.17 g | 0.14 g |
| Estación Metro Mirador | 0.24 g | 0.13 g |
| CRS Maipú, R.M. | 0.56 g | 0.24 g |
| Hospital Tisne, R.M. | 0.30 g | 0.28 g |
| Hospital Sótero del Río R.M. | 0.27 g | 0.13 g |
| Hospital de Curicó | 0.47 g | 0.20 g |
| Hospital de Valdivia | 0.14 g | 0.05 g |
| Viña del Mar (Marga-Marga) | 0.35 g | 0.26 g |
| Viña del Mar (Centro) | 0.33 g | 0.19 g |

Ingeniería Civil U. de Chile (RENADIC)

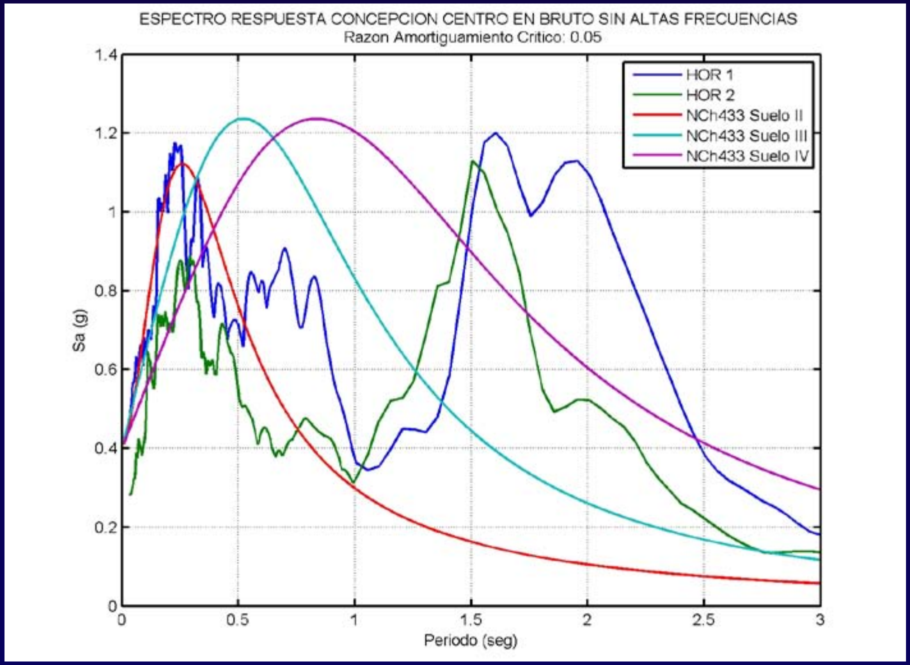
# Ground Motions

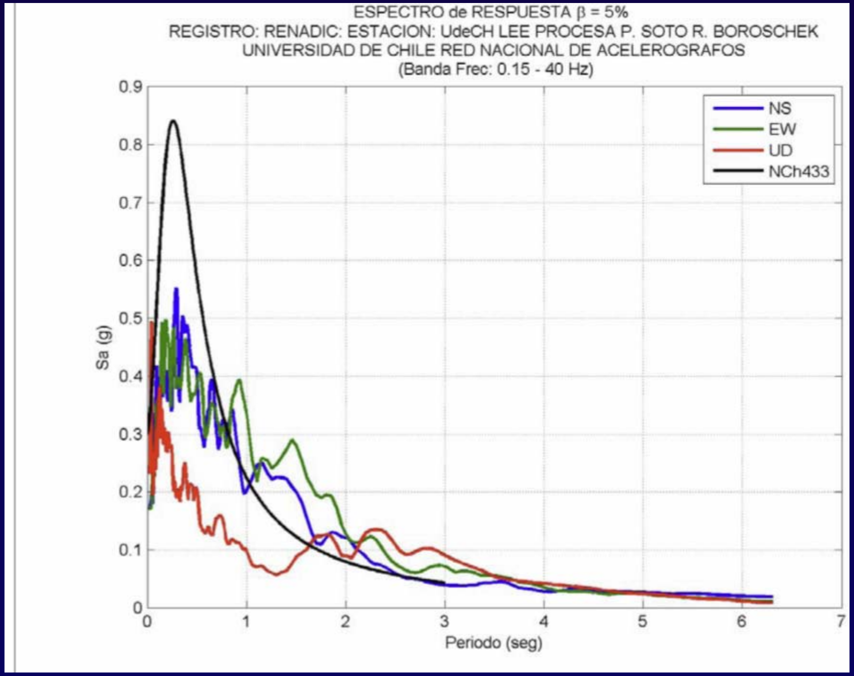



**Concepción (110 km)** **Santiago (340 km)**

# Response Spectra




**Concepcion (110 km)** **Santiago (340 km)**

# Chilean Design

| | Number | Name | Date |
|---|---|---|---|
| Actions | NCh431 | Snow Loading | 1977 |
| | NCh432 | Wind Loading | 1971 |
| | NCh1537 | Dead / Live Loads Specification | 1986 |
| Materials / Design | NCh427 | Design of Steel | 1977 |
| | NCh430 | Design of Reinforced Concrete (ACI 318) | 2008 |
| | NCh1198 | Design of Wood | 2006 |
| | NCh1928 | Design of Reinforced Masonry | 2003 |
| | NCh2123 | Design of Confined Masonry | 2003 |
| Earthquake | NCh433 | Earthquake resisting design of buildings | 1996 |
| | NCh2369 | Earthquake resisting design of industrial structures and facilities | 2003 |
| | NCh2745 | Earthquake resisting design of base isolated buildings | 2003 |

E. F. Cruz , 2009

NCh433

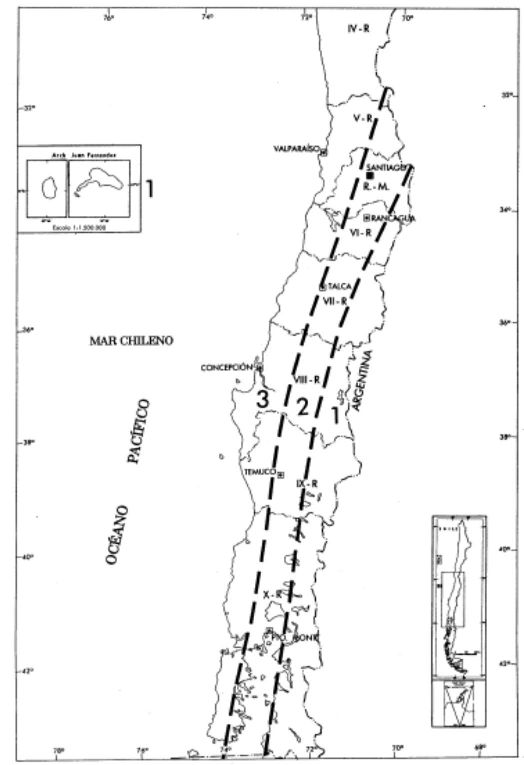



Figure 4.1 b) - Seismic zonation of regions IV, V, VI, VII, VIII, IX, X and Metropolitan

OFFICIAL CHILEAN STANDARD *NCh* 433.Of96

INSTITUTO NACIONAL DE NORMALIZACION • INN-CHILE

Earthquake resistant design of buildings

*Diseño sísmico de edificios*

First edition : 1996
Reprinted : 2005

# Chilean Design

**Annex B**

(Enforced)

**Transitory references**

**B.1** As long as the NCh427 code is not revised, the provisions of the *Specification for Structural Steel Buildings* from the American Institute of Steel Construction, Inc., in its versions *Allowable Stress Design*, 1989, or *Load and Resistance Factors Design*, 1993, complemented with *Seismic Provisions for Structural Steel Buildings*, from AISC, 1992, shall be used. For cold-formed members *Specification for the Design of Cold-Formed Members*, American Iron and Steel Institute, 1996, shall prevail.

**B.2** Until the new version of the NCh430 code, which substitutes the NCh429.Of57 and NCh430.Of61 codes, become official, the provisions of the *Building Code Requirements for Reinforced Concrete, ACI 318-95*, shall be used. In particular, the structural elements that form part of reinforced concrete frames intended to resist seismic loadings, must be dimensioned and detailed according to the provisions for zones of high seismic risk, located in chapter 21 of said code.

**B.2.1** In the case of buildings that are structured with reinforced concrete walls and frames, in which the walls take at each level and for each direction of analysis a percentage of the total shear of the level, equal to or greater than 75%, the frame design must meet, as a minimum, provisions 21.8.4 and 21.8.5 of the ACI 318-95 code, provided that the individual frame is responsible for taking less than 10% of the total shear at each one of its levels. Frames whose seismic loadings have been calculated with $R_o = 1$ or $R = 2$ factors, may also resort to this provision.

**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.

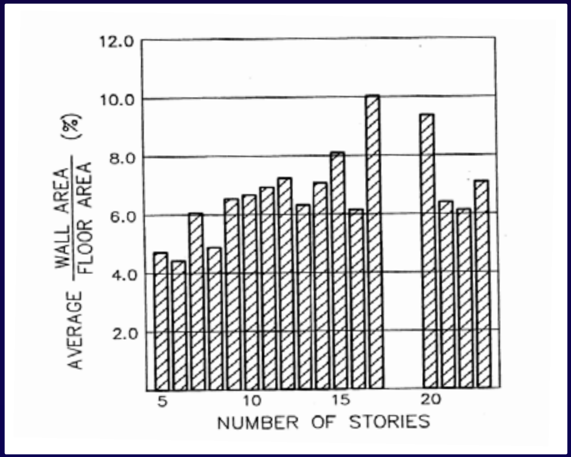
## Nch433of.1996

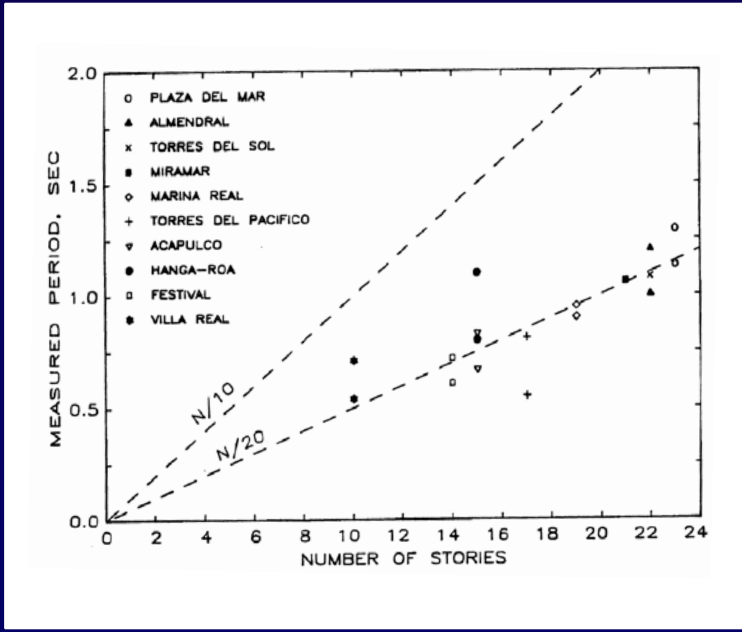
- ACI 318-95 in effect for most buildings damaged
- Note B.2.2: Wall confinement steel not required

# Performance During 1985 Earthquake

**Introduction**

This note is concerned with the observed behavior of a class of reinforced concrete buildings in Vina del Mar during the March 1985 earthquake. The buildings of interest include 322 structures, documented by Riddell, Wood, and de la Llera (1). A dominant characteristic of these reinforced concrete buildings, which will be referred to as the Vina del Mar inventory of buildings or simply as the inventory, was the generous use of structural walls to resist gravity loads and to stiffen the buildings for lateral loading. The typical value of the wall index, ratio of total cross-sectional area of wall oriented in one direction to the floor area, was 3 %. As summarized by Stark (2), calculated and measured initial periods for the inventory were approximately N/20 (where N is the number of stories). Although there were cases of severe damage (3,4) in this group of buildings, their overall behavioral record during the earthquake was admirable (1).



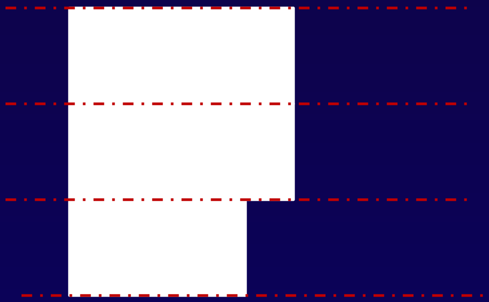

[1] M. A. Sozen, *Earthquake Response of Buildings with Robust Walls*, $5^{th}$ Chilean Conference on Earthquake Engineering, 1989.

# 1985 Earthquake Implications

- Increased confidence of Chilean engineers
- More aggressive building configurations
  - Thinner walls:

# 1985 Earthquake Implications

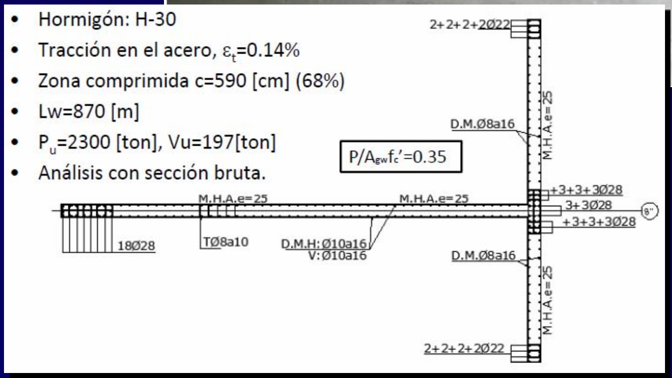
- “flag” walls (in elevation):

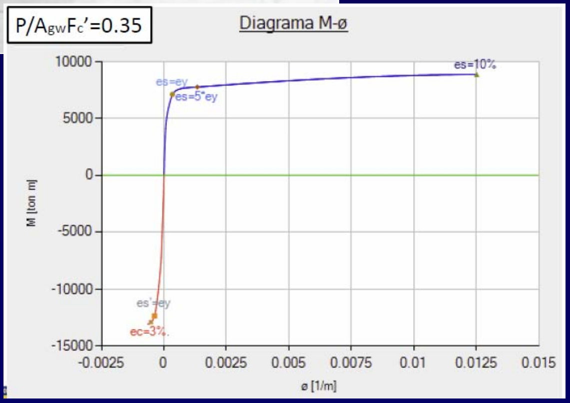


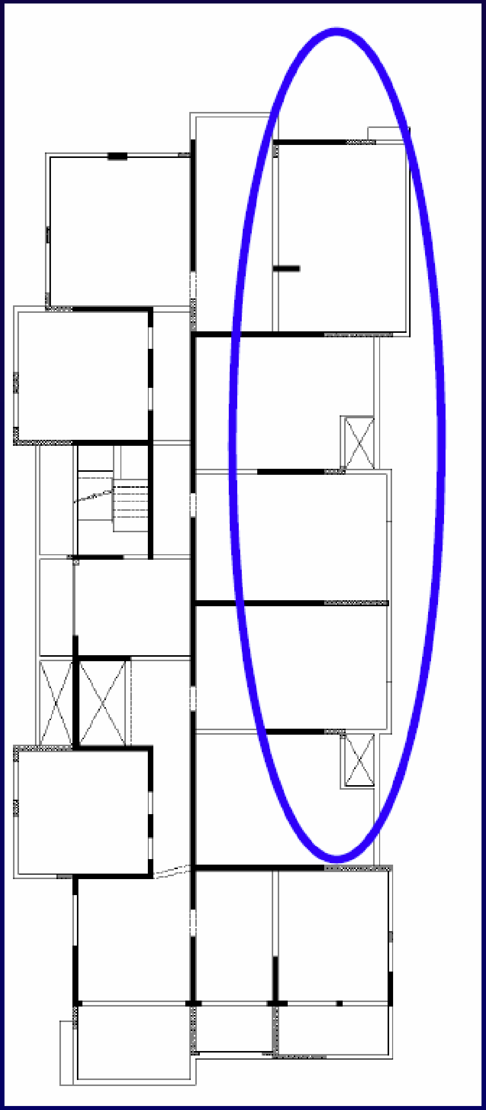
Elevation

# 1985 Earthquake Implications

- “fishbone” ground floor configurations:



# US Confinement Practices

Seismic Design Category C (~similar to Chilean spacing with seismic hooks)

Seismic Design Category D+

# Deprecated UBC Requirements

## UBC 1994

***1921.6.5.6 Shear wall boundary zone detail requirements.*** *When required by Section 1921.6.5.1 through 1921.6.5.5, boundary zones shall meet the following:*

*1. Dimensional requirements.*

*1.1 All portions of the boundary zones shall have a* ***thickness of $l_u$/10 or greater****.*

## UBC 1997

***1921.6.5.6 Shear wall boundary zone detail requirements.*** *When required by Section 1921.6.5.1 through 1921.6.5.5, boundary zones shall meet the following:*

*1. Dimensional requirements.*

*1.1 All portions of the boundary zones shall have a* ***thickness of $l_u$/16 or greater.***

## UBC 1994,1997

***1921.6.6.3*** *Walls and portions of walls with* $\boldsymbol{P_u > 0.35P_o}$ *shall not be considered to contribute to the calculated strength of the structure for resisting earthquake-induced forces.*

# Canadian Code

**21.6.7 Ductility of ductile shear walls**

**Note:** *This Clause applies to individual walls that are effectively continuous in cross-section from the base of the structure to the top of the wall and are designed to have a single plastic hinge at the base.*

**21.6.7.3**

The inelastic rotational capacity of a wall, $\theta_{ic}$, may be taken as

$$\theta_{ic} = \left( \frac{\varepsilon_{cu} \ell_w}{2c} - 0.002 \right) \leq 0.025 \qquad \textbf{(21-11)}$$

where

$\ell_w$ = the length of the individual wall

$\varepsilon_{cu}$ shall be taken as 0.0035 unless the compression region of the wall is confined as a column in accordance with Clause 21.6.7.4. The value of 0.025 is the upper limit on inelastic rotation capacity governed by tension steel strain. The distance to the neutral axis, $c$, shall be determined by plane section analysis or as follows:

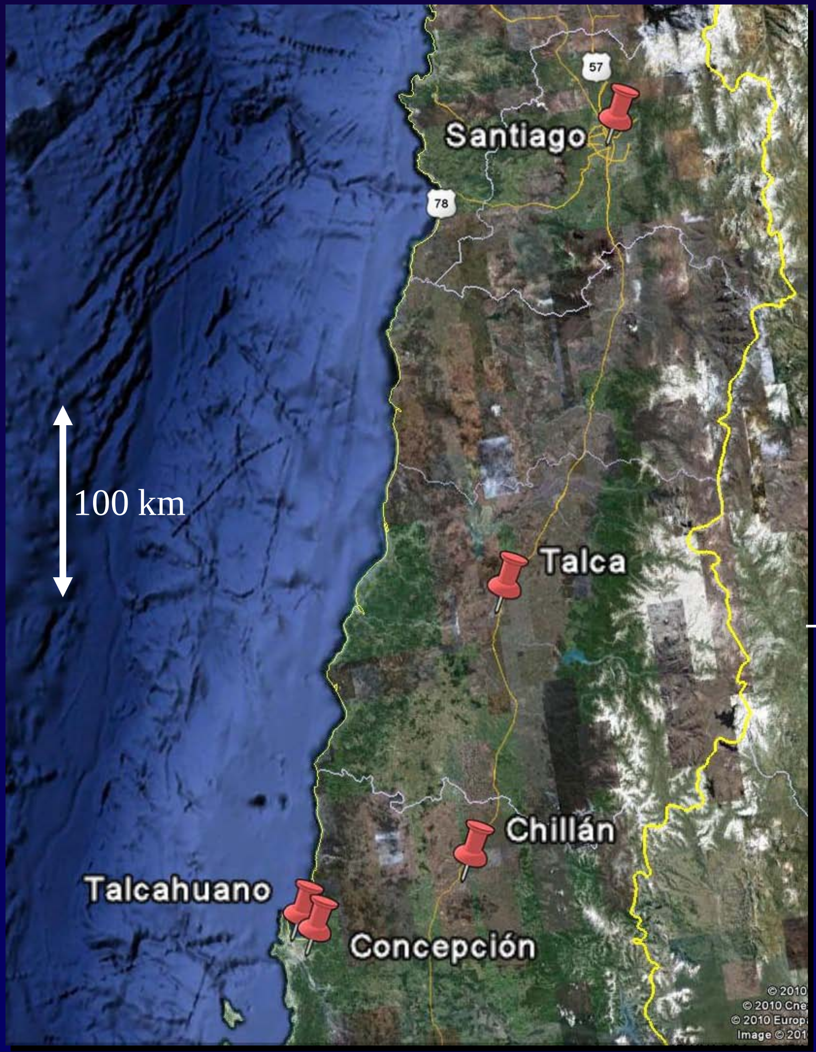
***"… most engineers in Vancouver try to avoid confining the boundary zone by using a max concrete strain of 0.0035."***

# Multi-agency Response Planning

- Led By USGS Earthquake Hazards Program
- Known Deployment Teams to Chile[1]:
  - NSF-sponsored RAPID GPS deployment group
  - American Society of Civil Engineers (ASCE)
  - Earthquake Engineering Research Inst. (EERI) Learning from Earthquakes (LFE)
  - Geo-engineering Extreme Events Reconnaissance (GEER)
  - U.S. Geological Survey (USGS) seismology group
  - Ocean Bottom Seismometer (OBS) and seafloor imaging
  - Integrated Research Institutions for Seismology (IRIS)
  - USGS members accompanying UNESCO coastal survey group
  - Department of Transportation (DOT)
- Private engineering firms and Universities

1. Memorandum, Michael Blanpied, USGS Earthquake Hazards Program, March 5, 2010.

# Logistics




## EERI-LFE Group

| | |
|---|---|
| Composition : | ~35 total in the following teams: (2) Concrete structures, masonry, steel, bridges, heath care, non-structural, geotechnical, instrumentation, social science, and tsunami. Assistance from Pontifical Catholic University of Chile. |
| Travel Dates: | March 12th - 22nd |
| NIST Participant: | Jeff Dragovich, concrete structures |
| Primary Regions: | Talca, Chillán, Concepción, Talcahuano |

## ASCE Group

| | |
|---|---|
| Composition: | Structures: 3 teams of 3<br>Existing: 1 team of 4<br>Industrial / non-struct: 1 team of 3<br>Timber: 1 team of 4 |
| Travel Dates: | April 4th – 11th |
| NIST Participant: | Jay Harris, structures |
| Primary Regions: | Santiago, Concepción |

# EERI-LFE Team

Team Leaders: Jack Moehle (UCB), Rafael Riddell (UC), Ruben Boroschek (UCh)

- Buildings
  - Reinforced Concrete Buildings I
    - Jack Moehle (UCB)
    - Jeff Dragovich (NIST)
    - Carlos Sempere (Forell/Essler)
  - Reinforced Concrete Buildings II
    - John Wallace (UCLA)
    - Alvaro Celestino (Degenkolb)
    - Joe Maffei (R&C)
  - Masonry
    - Jennifer Tanner (U. Wyoming)
  - Steel and Industrial Facilities
    - Roberto Leon
    - Farzin Zareian (UC Irvine)
    - Team Leaders
  - Non-structural
    - Eduardo Miranda (Stanford)
    - Gilberto Mosqueda (U. Buffalo)
    - Gokhan Pekcan (UNR)
  - Structural/Instrumentation
    - Mehmet Celebi (USGS)
    - Mark Sereci (Digitexx)
- Bridges
  - Scott Ashford (OSU)
  - Ian Buckle (UNR)
  - Luis Fargier (Venezuela)
  - Mark Yashinsky (Caltrans)
- Hospitals/Health
  - Rick Bissell (U. Maryland, BC)
  - Bill Holmes (R&C)
  - Mike Mahoney (FEMA)
  - Tom Kirsch (Johns Hopkins U.)
  - Judy Mitrani-Reiser (John Hopkins U.)
- Social Science/Planning/Policy/Recovery
  - Guillermo Franco (AIR)
  - William Siembieda (Cal Poly, SLO)
  - Rick Tardanico (Florida International U.)
- Tsunami Effects on Structures
  - Gary Chock (Martin & Chock)
  - Ian Robertson (U. Hawaii)
- Geotechnical Engineering
  - Through collaboration with GEER

# ASCE Team

Team Leader: John Hooper

- Structural
  - Team A
    - John Hooper (MKA)
    - David Bonneville (Degenkolb)
    - Ramon Gilsanz (Gislanz/Murray)
  - Team B
    - Ron Hamburger (SGH)
    - John Tawresey (KPFF)
    - Jim Rossberg (SEI/ASCE)
  - Team C
    - Jim Harris (JA Harris & Co)
    - Jay Harris (NIST/NEHRP)
    - Martin Johnson

- Industrial
  - Bob Bachman (RE Bachman)
  - Greg Soules (CBI)
  - John Silva (Hilti)

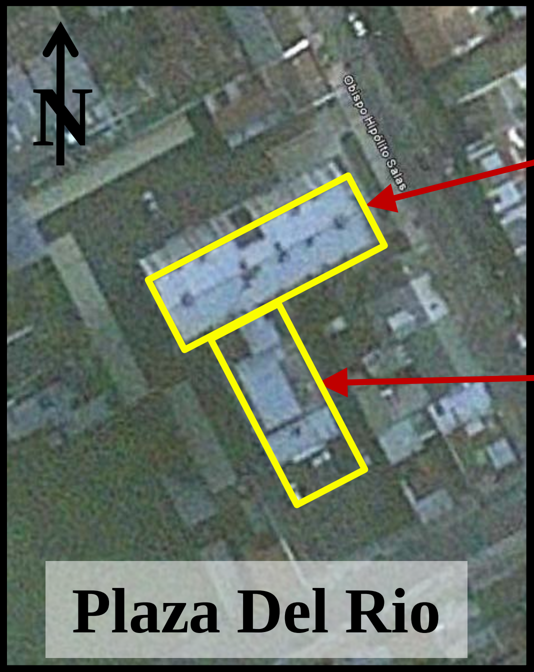
- Existing Buildings
  - Jon Heintz (ATC)
  - Bob Pekelnicky (Degenkolb)
  - Dominic Kelly
  - Sergio Brena

- Wood
  - Dan Dolan (WSU)
  - John Van deLindt
  - S Pryor
  - Doug Ramner

*Coordination with EERI/ASCE was imperative in order to access sites, informtion and local professionals.*

# Performance of Reinforced Concrete Structures

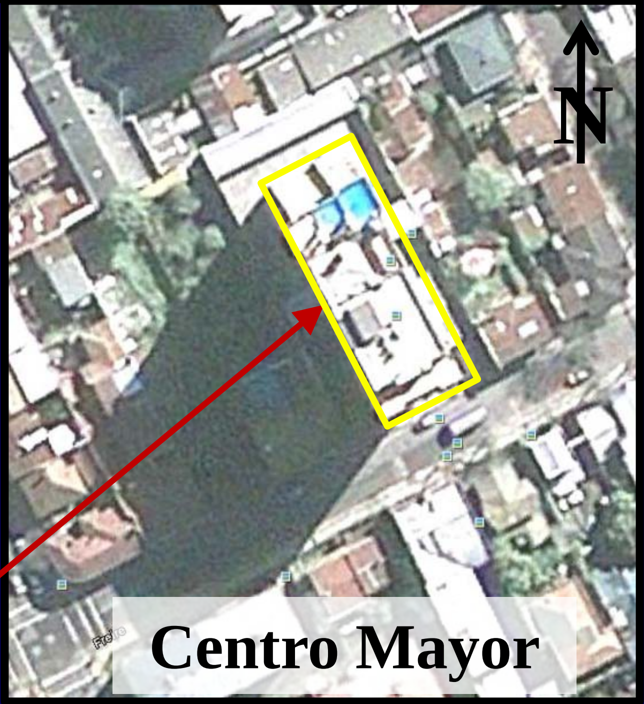
# Concepción


Building B: Minor damage
~ 38m x 12m in plan
13 stories

Building A: Significant damage
~ 25m x 12m in plan
13 stories

Significant damage
~ 45m x 18m in plan
18 stories



# Plaza Del Rio

# Plaza Del Rio

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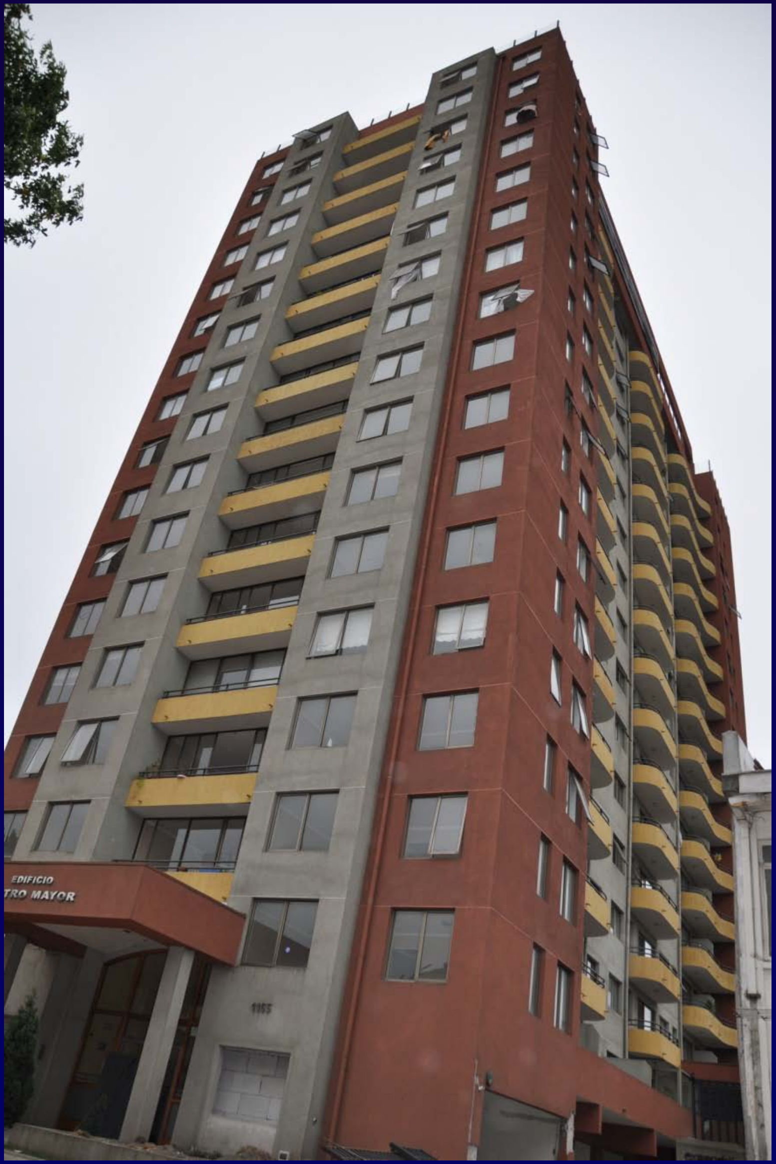
# Plaza Del Rio

# Centro Mayor



# Centro Mayor

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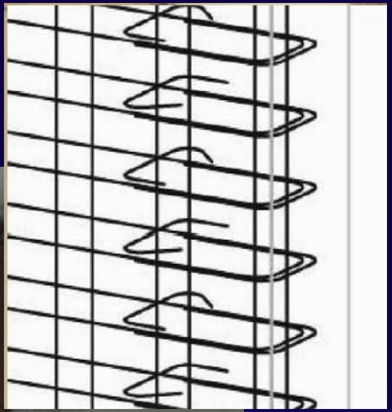
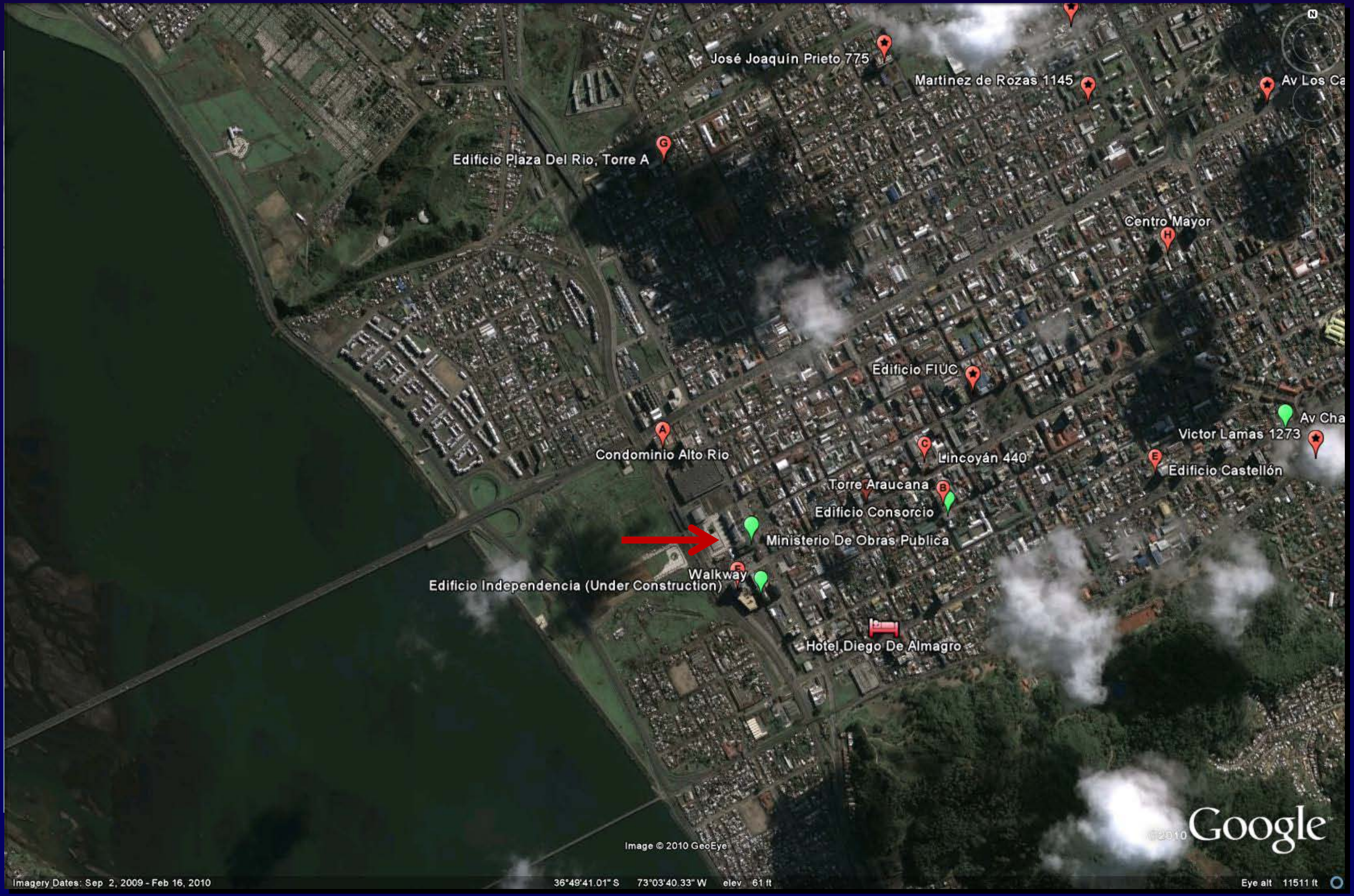


# Centro Mayor

# Performance of Structural Steel Components

# Concepcion



José Joaquín Prieto 775
Martinez de Rozas 1145
Av Los Ca
Edificio Plaza Del Rio, Torre A
Centro Mayor
Edificio FIUC
Av Cha
Victor Lamas 1273
Condominio Alto Rio
Lincoyán 440
Edificio Castellón
Torre Araucana
Edificio Consorcio
Ministerio De Obras Publica
Walkway
Edificio Independencia (Under Construction)
Hotel Diego De Almagro
Image © 2010 GeoEye
©2010 Google
Imagery Dates: Sep 2, 2009 - Feb 16, 2010
36°49'41.01" S 73°03'40.33" W elev 61 ft
Eye alt 11511 ft

# Ministerio de Obras Publica

# Ministerio de Obras Publica

# Edificio Independencia

# Performance of Buildings with Structural Irregularities

Jeff Dragovich and Jay Harris

# Concepcion

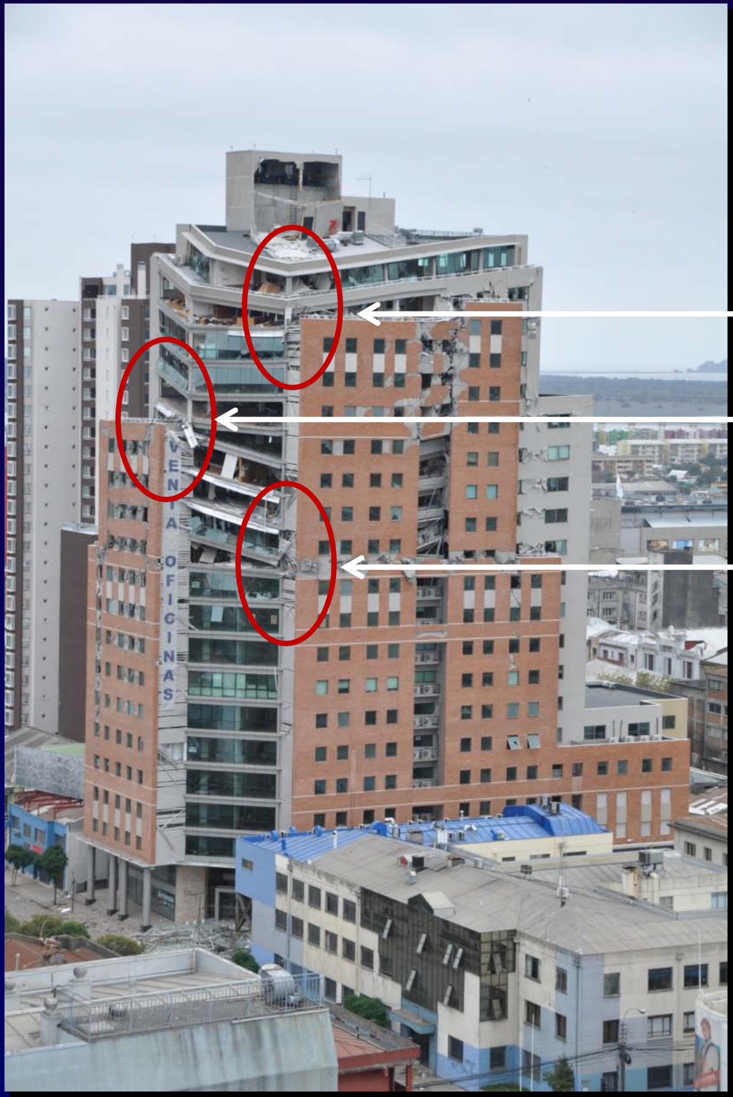

José Joaquín Prieto 775
Martinez de Rozas 1145
Av Los Ca
Edificio Plaza Del Rio, Torre A
Centro Mayor
Edificio FIUC
Av Cha
Victor Lamas 1273
Condominio Alto Rio
Lincoyán 440
Edificio Castellón
Torre Araucana
Edificio Consorcio
Ministerio De Obras Publica
Walkway
Edificio Independencia (Under Construction)
Hotel Diego De Almagro
Image © 2010 GeoEye
©2010 Google
Imagery Dates: Sep 2, 2009 - Feb 16, 2010
36°49'41.01" S 73°03'40.33" W elev 61 ft
Eye alt 11511 ft

# Torre O'Higgins

Photo Credit: skyscraper.com

Photo Credit: skyscraper.com

# Torre O'Higgins



$18^{th}$ Floor

$14^{th}$ Floor

$10^{th}$ Floor

# Torre O'Higgins


Photo Credit: skyscraper.com

# Torre O'Higgins

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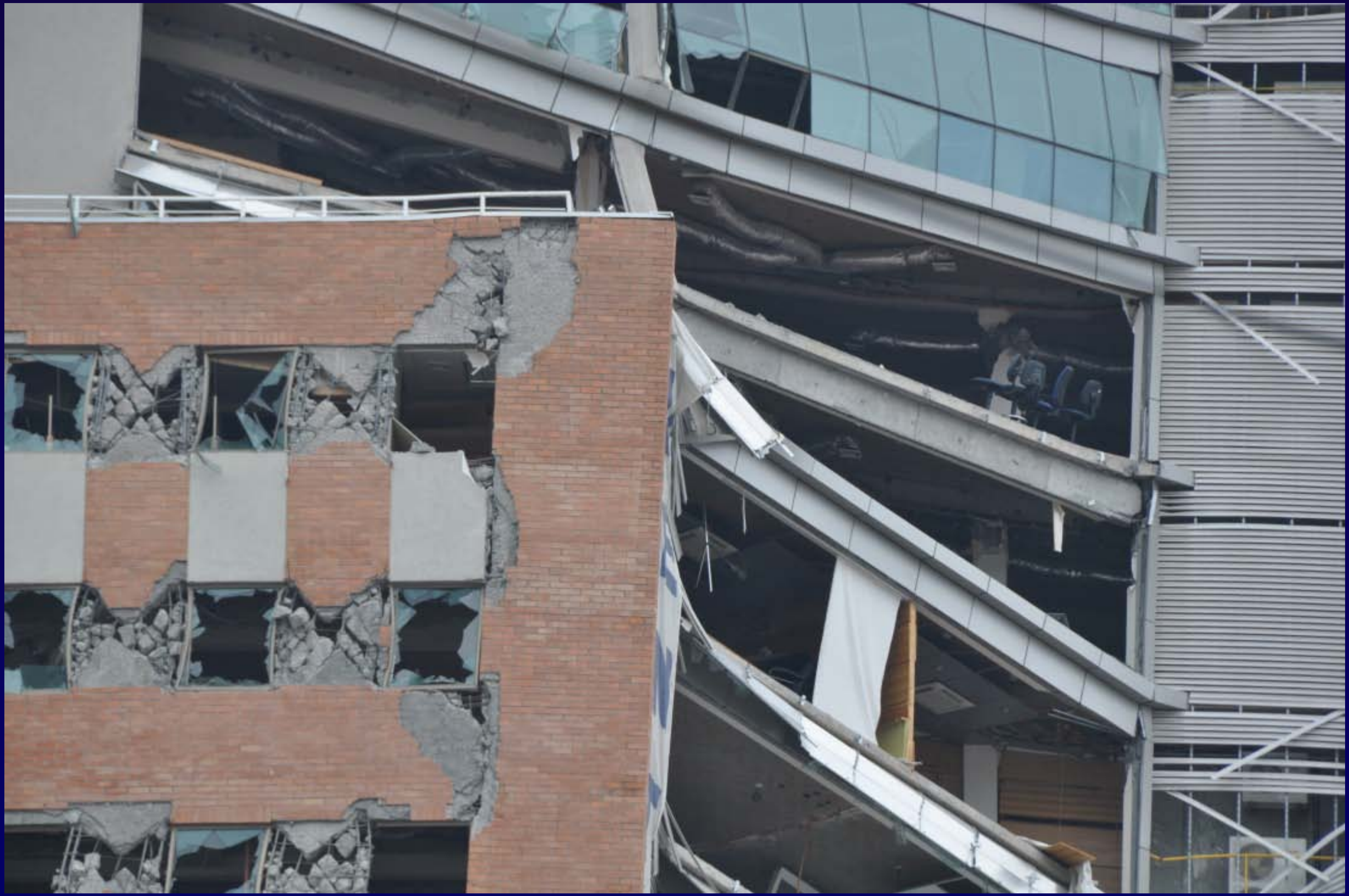


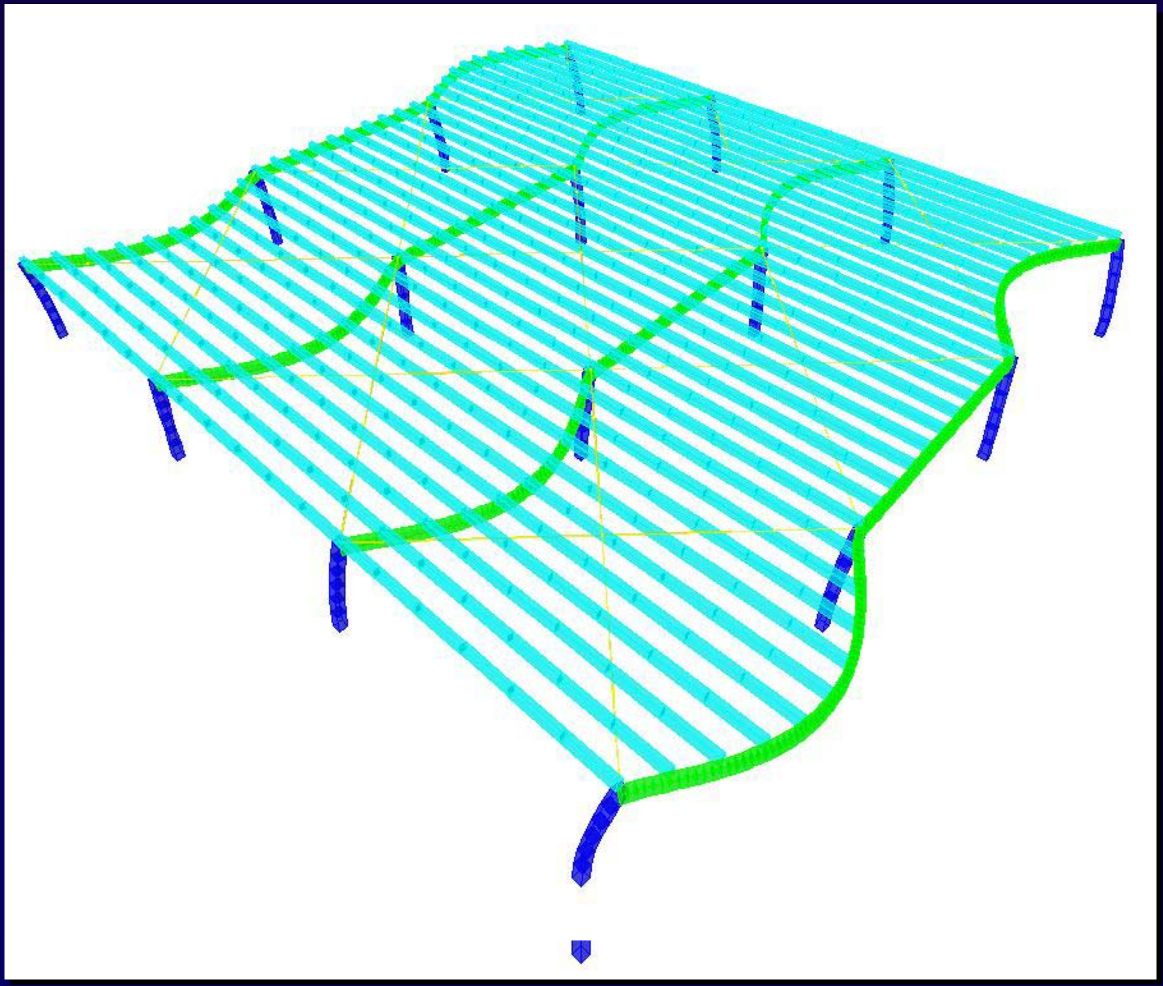
nehrp

national earthquake hazards reduction program

# Performance of Diaphragms and Continuity

# Sodimac Distribution Center

# Sodimac Distribution Center



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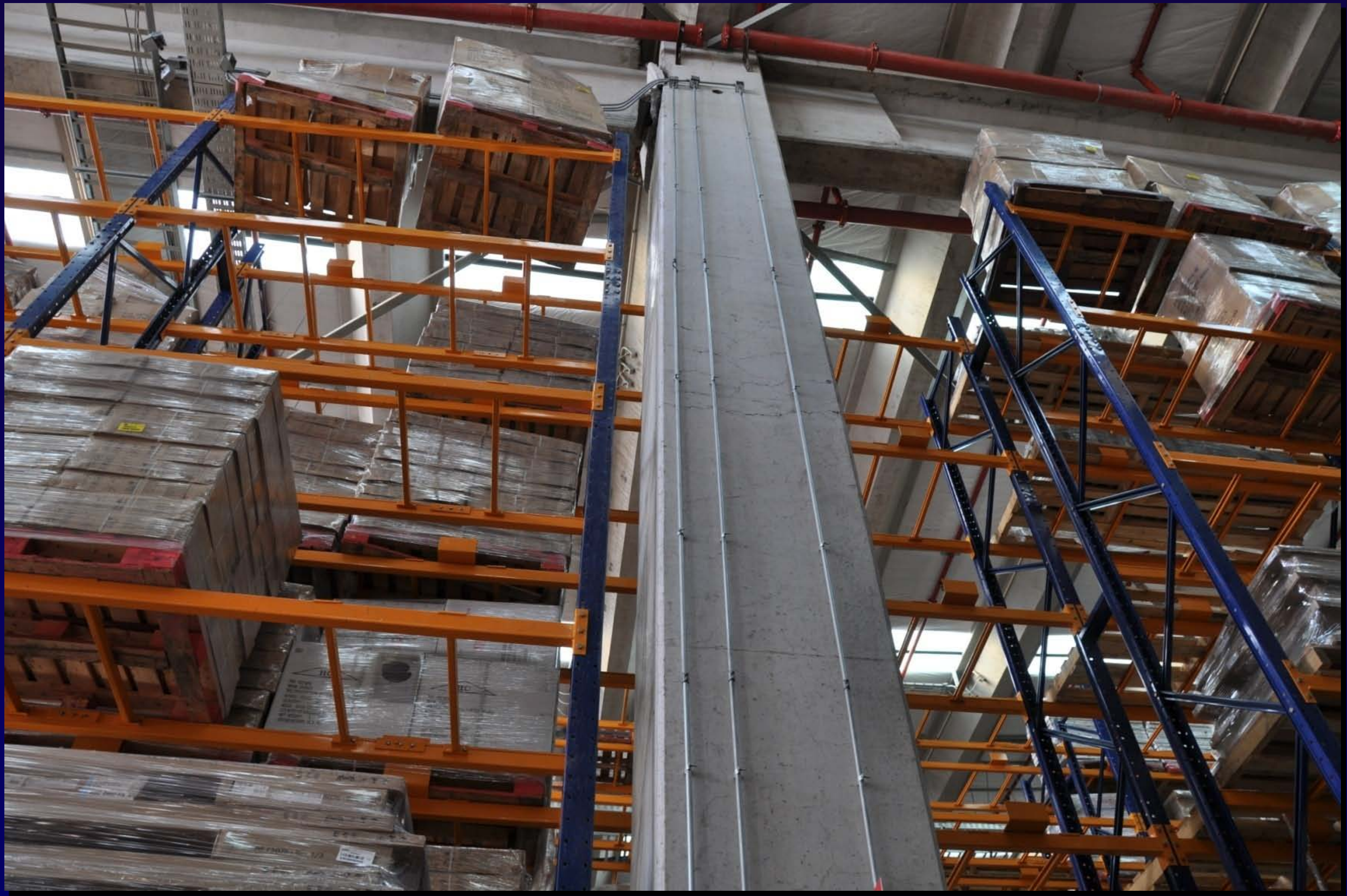

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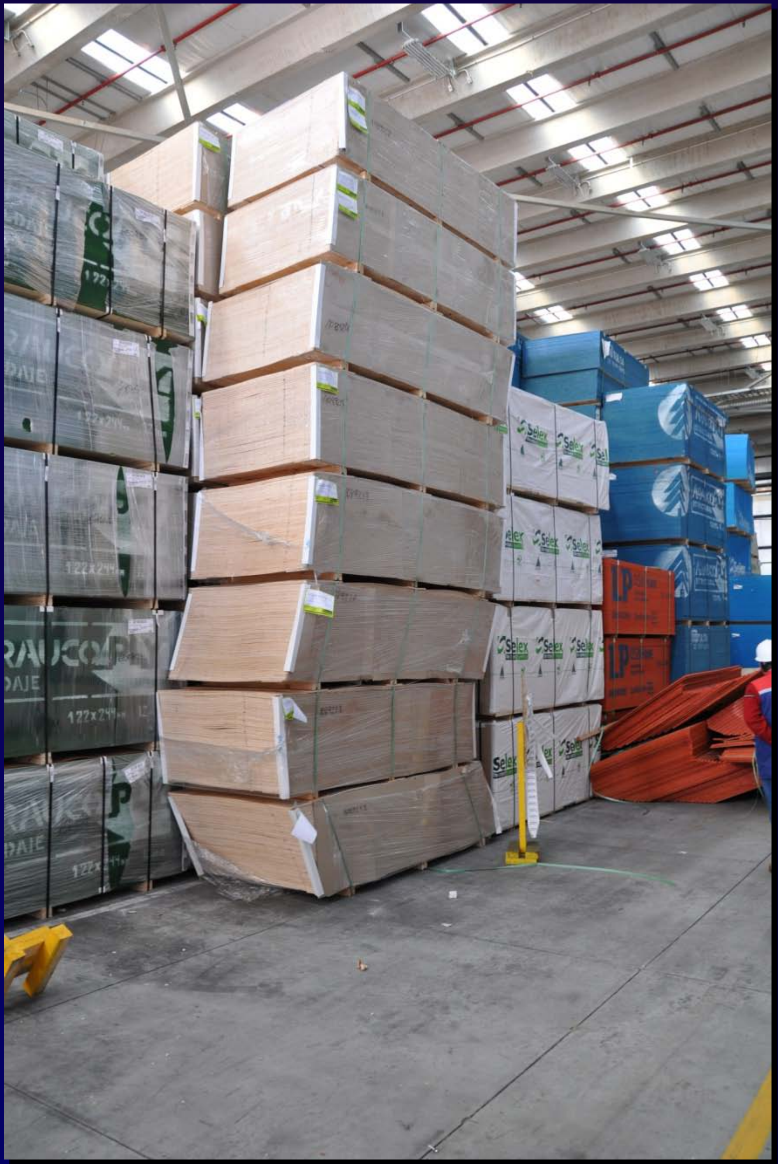

# Performance of Building Separations and Non-SFR Structural Elements

# Patio Mayor 961

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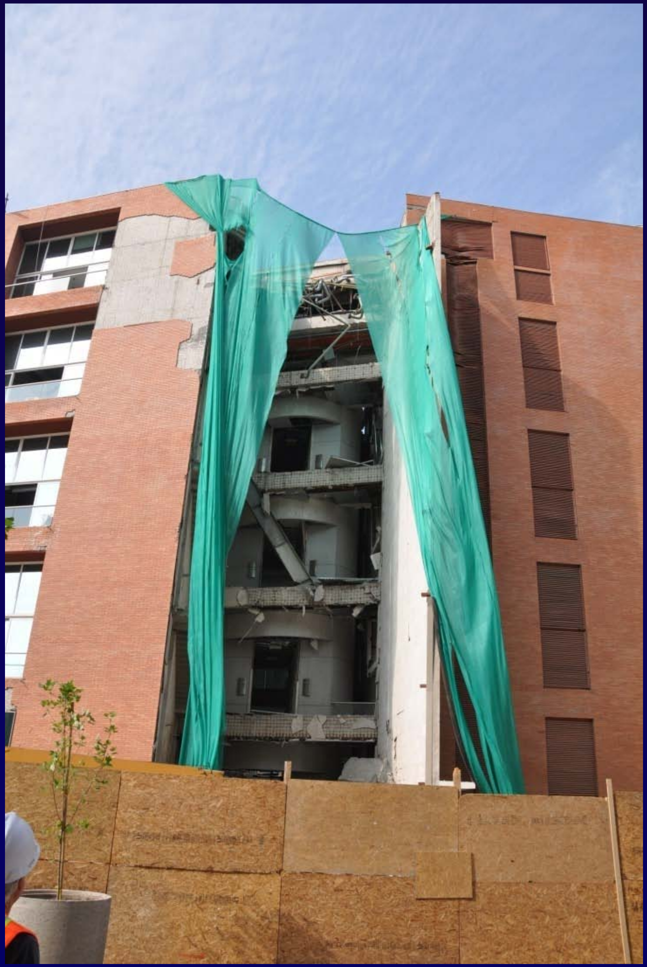

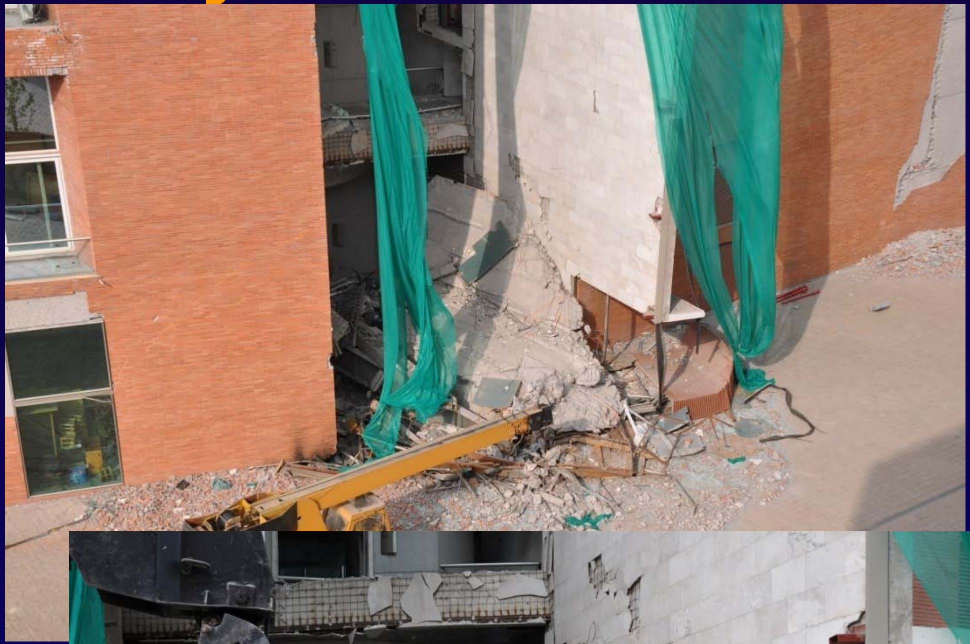

# Patio Mayor 961

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# Summary and Preliminary Conclusions

- In Concepción, there is apparent correlation of damage location with building plan orientation, consistent with the directionality of the earthquake
- Wall confinement detailing apparently led to inadequate performance
- Walls seem to have failed in net tension as well as compression due to loss of confinement
- Failure of some walls does not follow failure modes typically assumed in design » need for updated modeling capabilities
- Future studies of building behavior can support future US building code improvements
- Building separation requirements with expansion joints » new provision in ASCE 7-10
- While ASCE 7-10 explicitly deals with building irregularities, unique problems arose » possible future research
- Continuity of diaphragm is an issue » possible future research

# Initiated Research

- **Research Workshops**
  - Chile Earthquake Reconnaissance Meeting – Hosted by NIST
    - June 2, 2010
  - Chile Research Needs Report – hosted by EERI and NSF
    - August 19, 2010
- **Proposed Research**
  - Improved Prescriptive Seismic Provisions for U.S. Building Codes
    - This project will evaluate seismic code provisions for structural irregularities and lateral design force distributions prescribed in ASCE 7-10 and develop recommended provisions to mitigate their negative impacts, using observed structural performance data from specific buildings damaged in the 2010 Chile earthquake. Currently proposed efforts will be completed in 2013.
  - Improved Performance-Based Seismic Engineering Methodologies for Buildings
    - This project will evaluate current reinforced concrete wall models used in high-fidelity nonlinear dynamic analysis for PBSE to assess seismic response accurately, recommend improvements to these models if needed, and develop improved models based on the latest research results. Currently proposed efforts will be completed in 2013.

# Initiated Research

- **Proposed Research (cont'd)**
  - Comparison of Present Chilean and U.S. Model Building Code Seismic Provisions and Seismic Design Practice
    - The primary purpose of this task is to analyze and compare present (post-1990) seismic design provisions in Chilean building codes with applicable U.S. model building code and standard provisions for new buildings, principally ASCE 7 and ACI 318. This work will detail where the Chilean and U.S. code provisions are alike and where they are different, including difference in design response spectra in Chilean seismic zones and ASCE 7. Work will also document similarities and differences in seismic analysis and design practice for new buildings as performed in the United States and Chile.
  - Analysis of Seismic Performance of Reinforced Concrete Buildings in the 2010 Chile Earthquake, Including Effects of Non-Seismic-Force-Resisting Building Structural Elements
    - The primary objectives of this task are to: (1) Conduct an evaluation of critical issues in the design of reinforced concrete walls and development of improved wall design requirements; (2) Conduct research on the effects of non-seismic-force-resisting building structural elements on building performance.

# Initiated Research

- **Proposed Research (cont'd)**
  - Ground Motion and Building Performance Data from the 2010 Chile Earthquake
    - The primary purpose of this task is to develop a cost-effective and event-specific web-based data repository for the Chile earthquake that is based upon publicly available information that is available from U.S. and Chilean post-earthquake reconnaissance team members.
    - The proposed Chile earthquake repository shall contain the following types of information: Ground motion data (both directly recorded, e.g. digitized accelerograms, and derived, e.g. response spectra); building inventory (geospatial information, age, story height, occupancy, and other parameters) from the key earthquake impacted regions; structural drawings (AutoCAD or PDF format) from buildings that were impacted; photos of impacted buildings, accompanied by appropriate descriptive details; mapped structural damage (crack patterns, damaged zones) from damaged buildings; Computer & Structures Inc. (CSI)-ETABS (or equivalent) models of buildings that have been analyzed; instrumented building response data; building-relevant geotechnical information (e.g., soils reports, liquefaction study reports, site boring logs, foundation performance); public domain literature (PDF); bibliographic information; and, links to other relevant websites.

# Thank You!