

University of Ljubljana
*Faculty of Civil and Geodetic
Engineering*

Institute of Structural
Engineering, Earthquake
Engineering and Construction IT



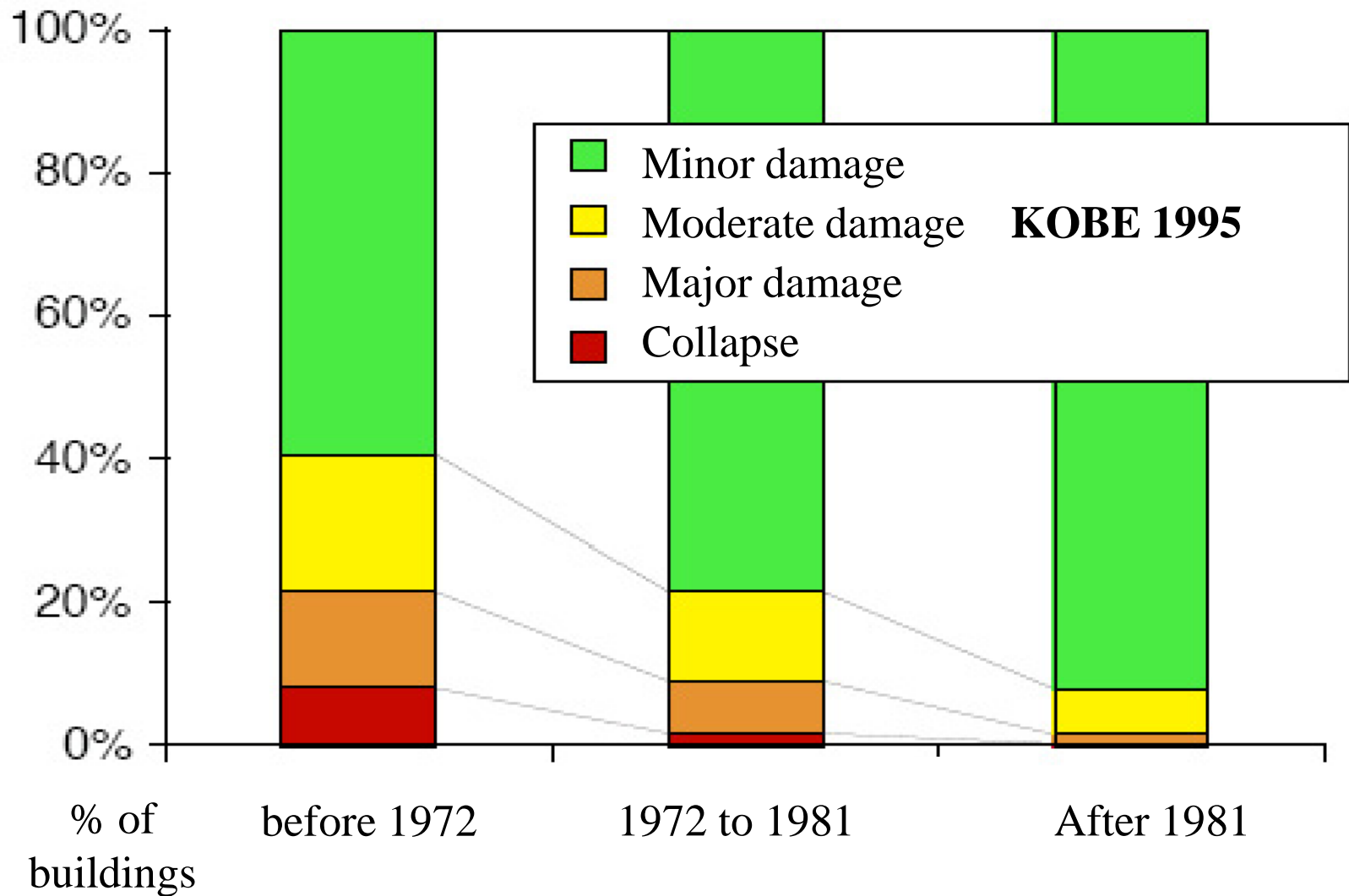
Seismic behaviour of buildings

Peter Fajfar

Intern. Conference on Seismic Design and Rehabilitation of Buildings

Tbilisi, 29. May 2014

Damage versus year of construction



Recent earthquakes

L'Aquila, Italy, 2009

Haiti, 2010

Chile, 2010

Christchurch, New Zealand 2010, 2011

Tohoku, Japan, 2011

Emilia, Italy 2012

Lessons learned/confirmed

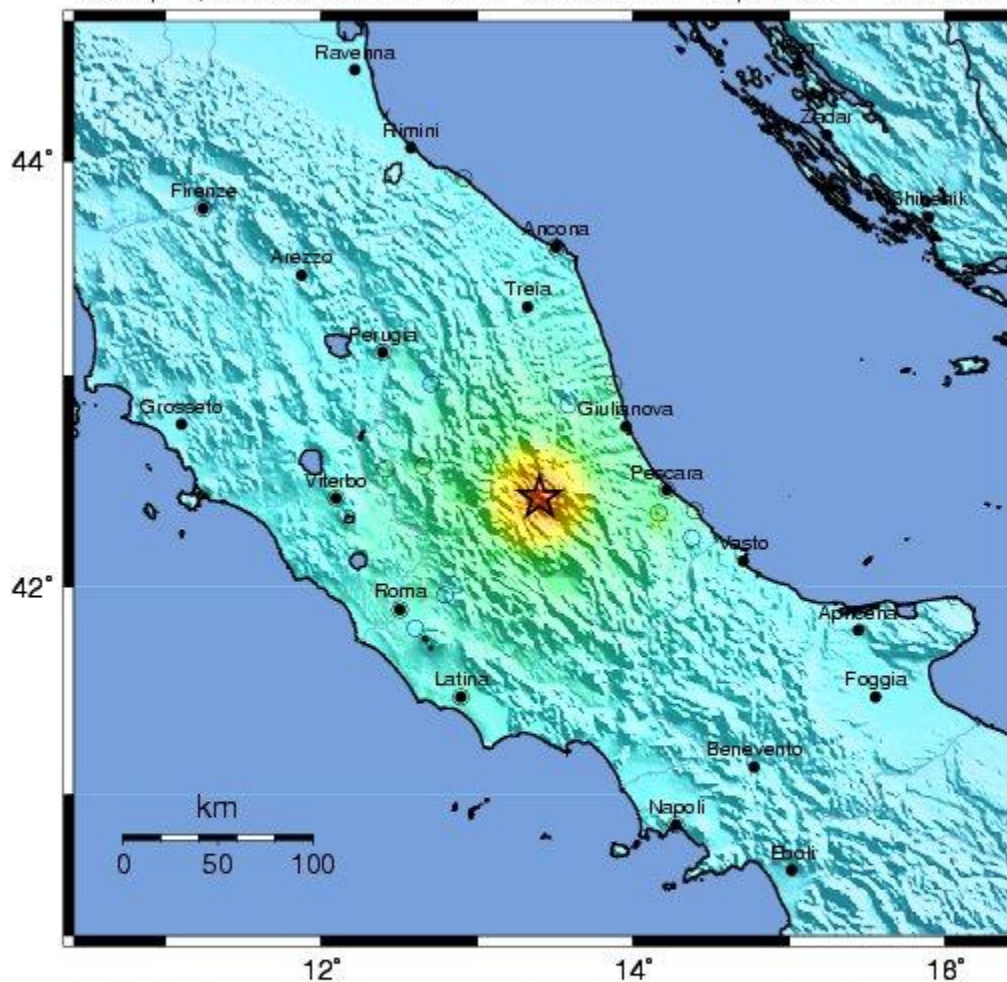
- Present codes and guidelines generally provide adequate protection against collapse
- Major problem are older structures
- Failure of some new structures
- Often large non-structural damage
- Ground motion can be much stronger than expected

L'Aquila, Italy, 2009

- **M=6.3**
- **287 deaths**
- **About 40.000 homeless**
- **About 20 billion Euro damage**
- **Historical center of L'Aquila destroyed**

USGS ShakeMap : CENTRAL ITALY

Mon Apr 6, 2009 01:32:42 GMT M 6.3 N42.42 E13.39 Depth: 10.0km ID:2009fcaf



Map Version 2 Processed Sun Apr 5, 2009 09:30:50 PM MDT – NOT REVIEWED BY HUMAN

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+



Italy L'Aquila 2009



Observations

- Moderate magnitude, short duration, large intensity
- Heavy damage and complete collapses of many old masonry buildings
- Horizontal ties prevented collapses
- Heavy damage and complete collapses of some reinforced concrete buildings

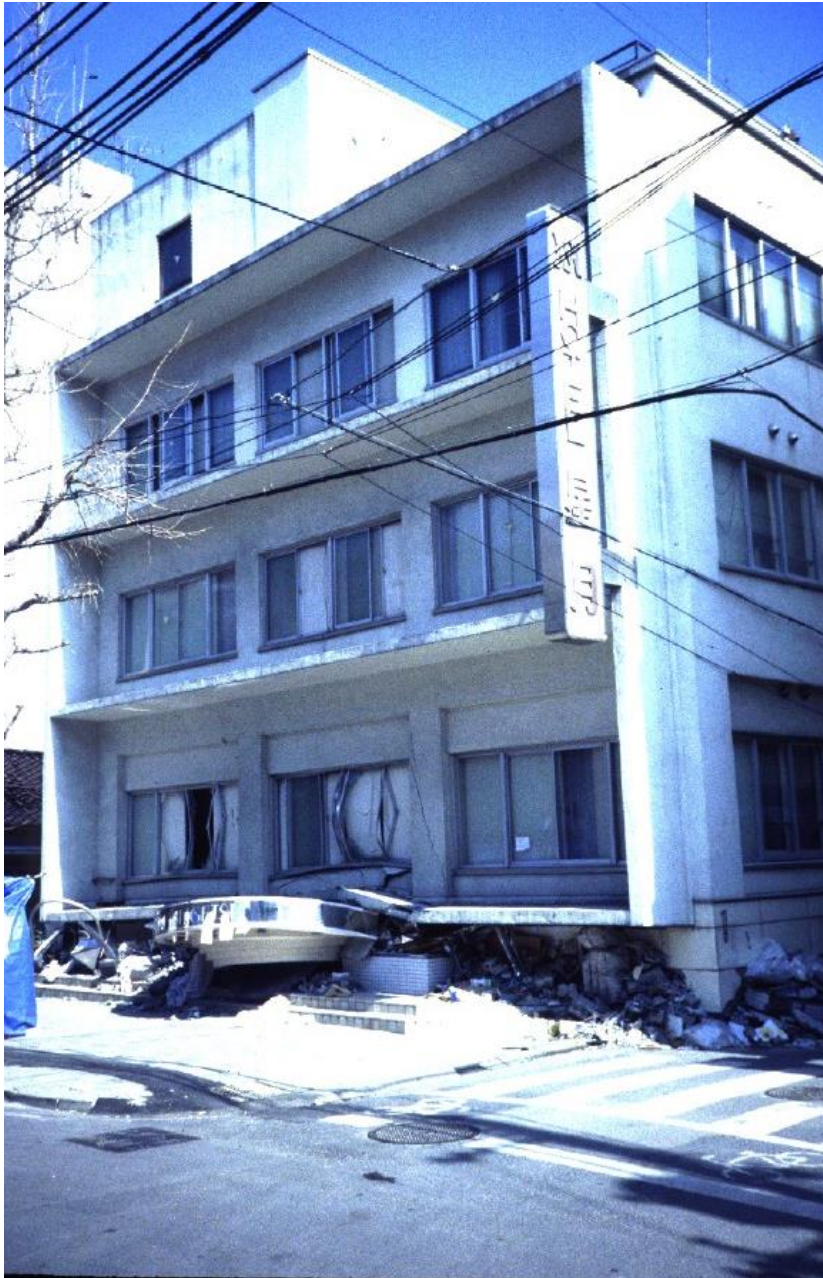










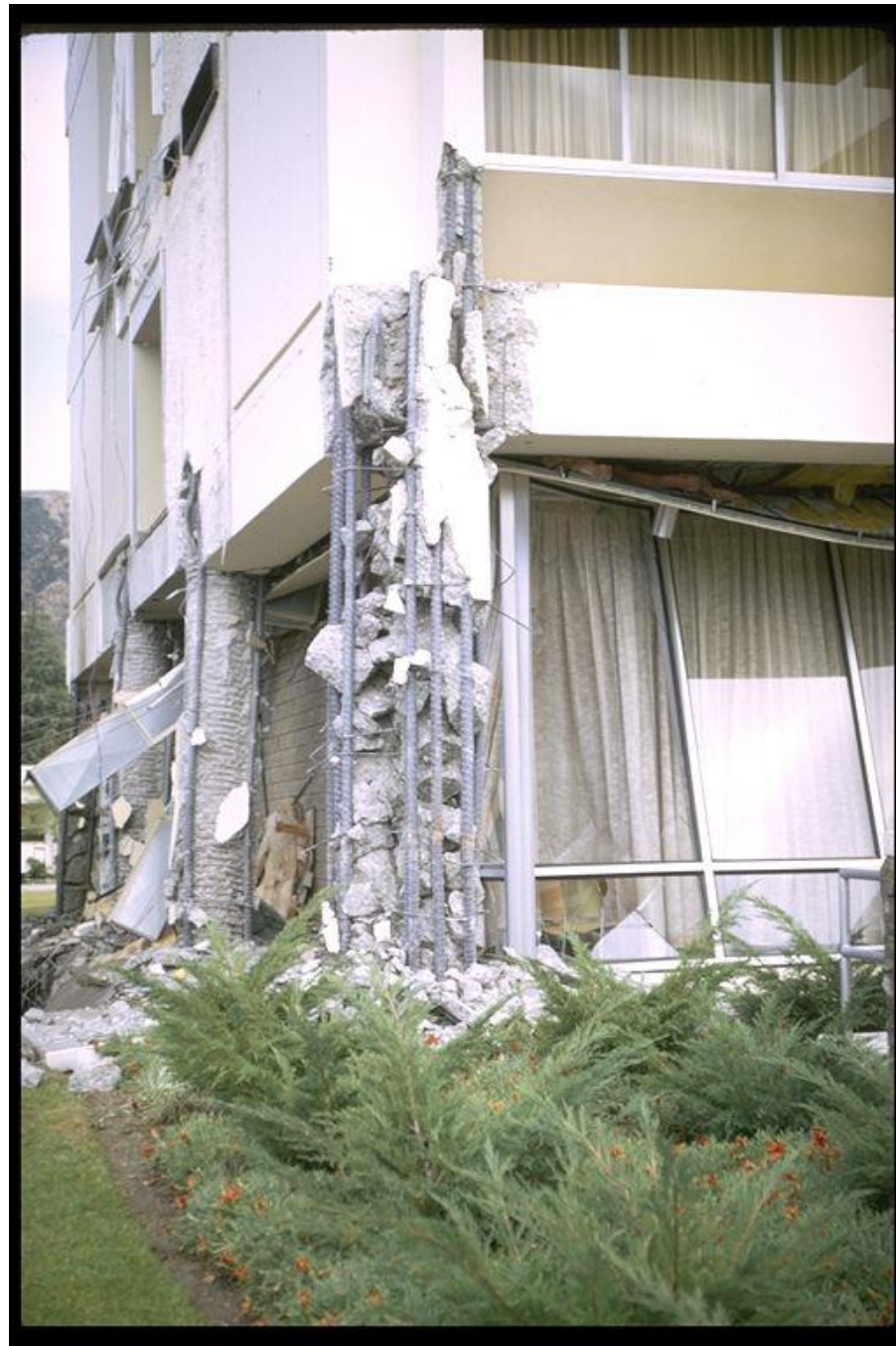


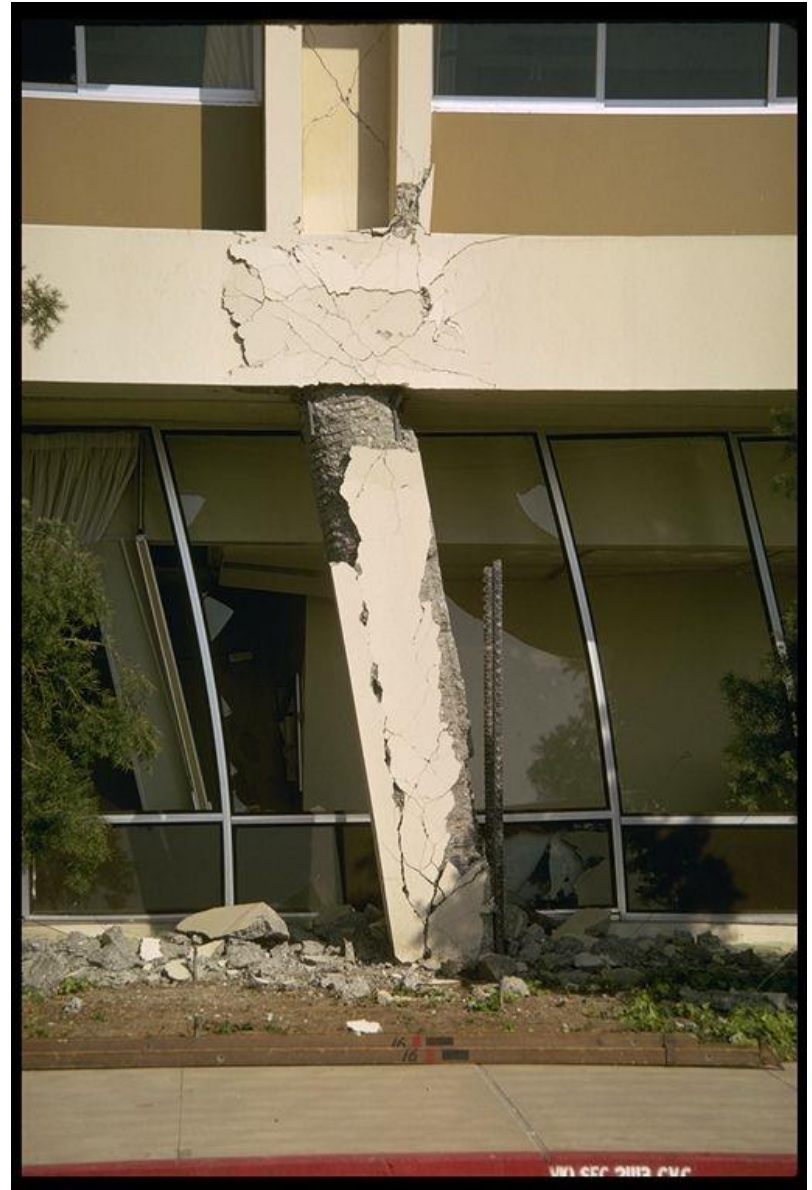


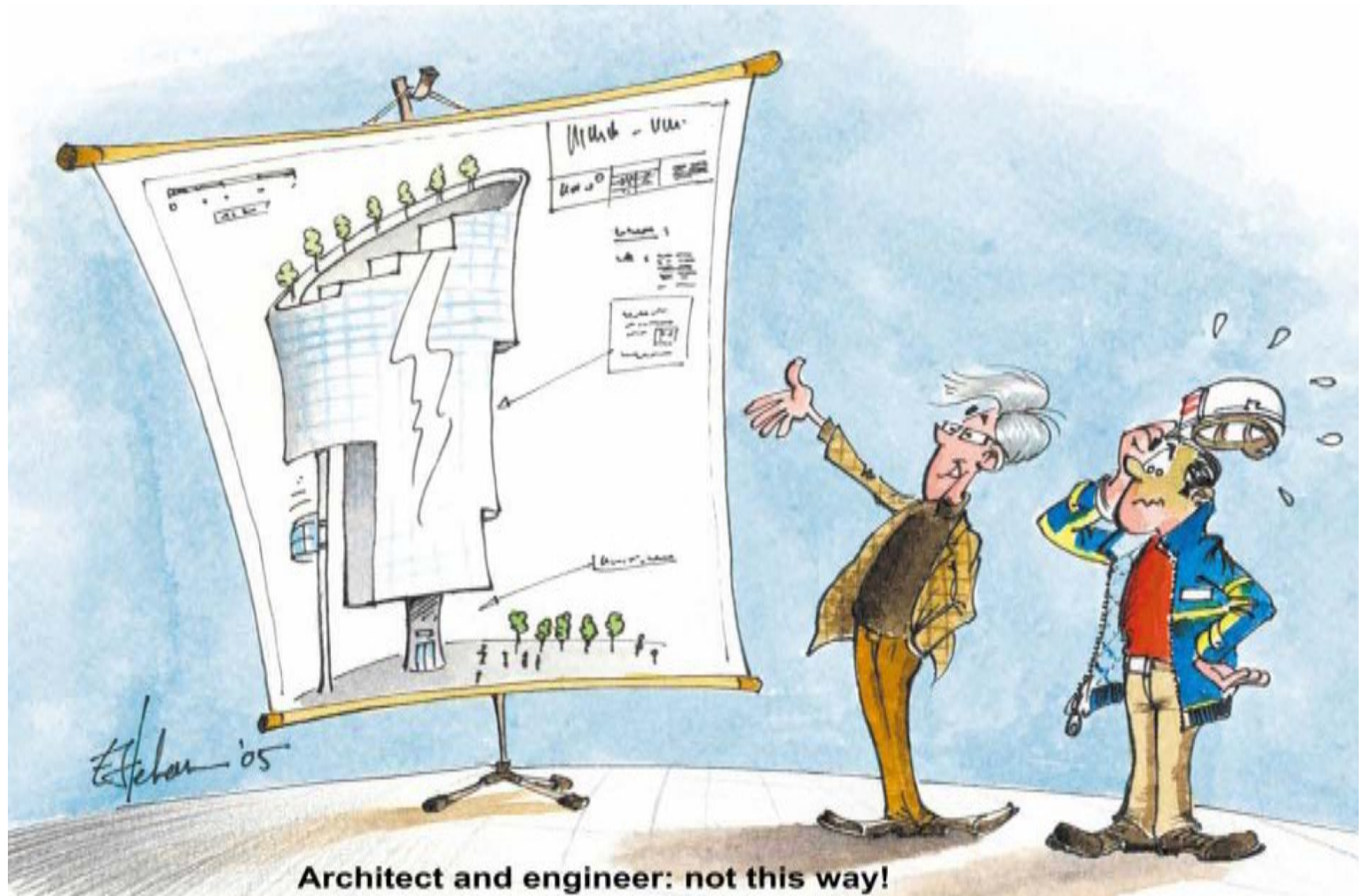




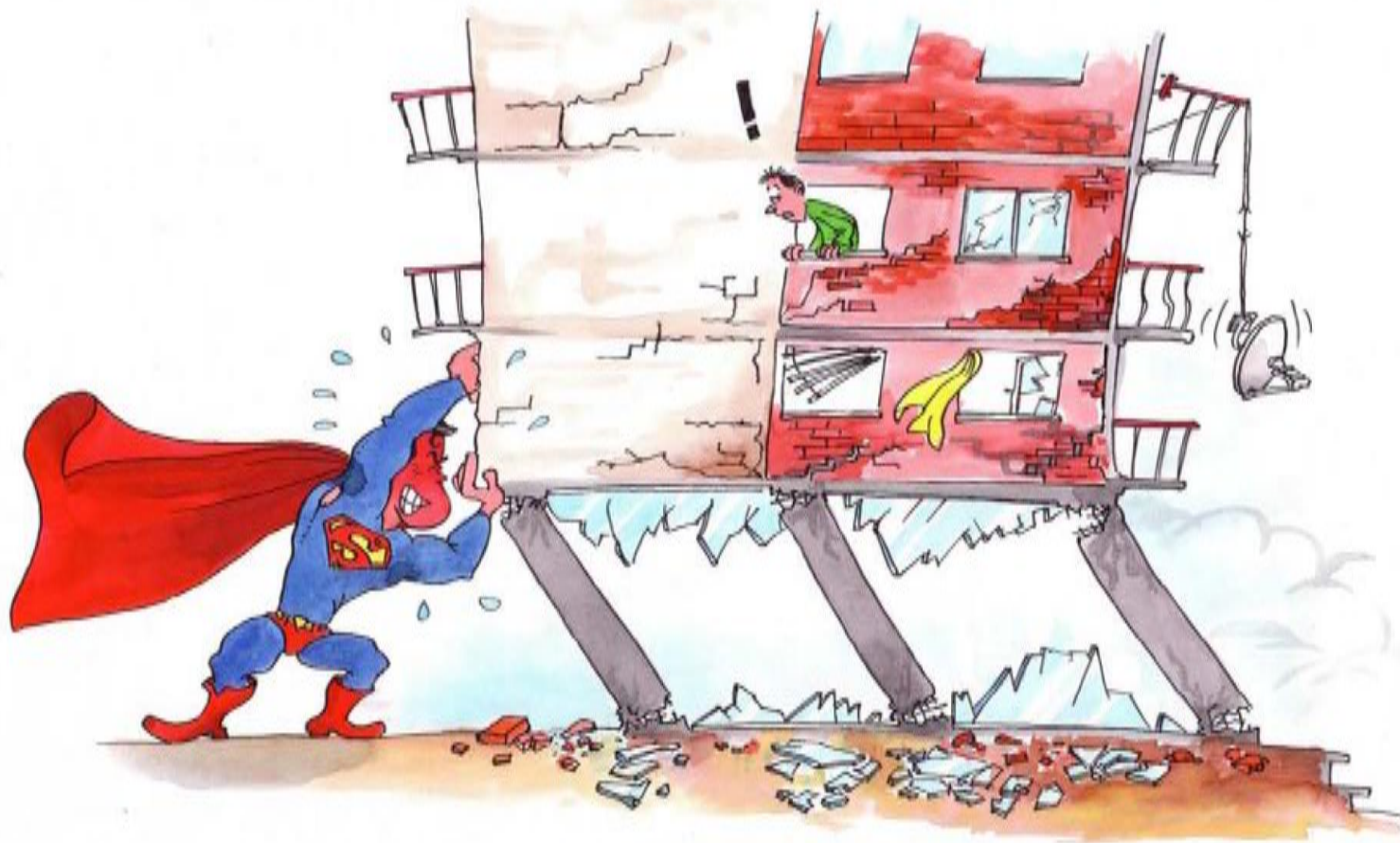








Architect and engineer: not this way!



Do not rely on Superman!

Haiti 2010

- **M=7.0**
- **About 300.000 deaths**
- **About 300.000 wounded**
- **About 1,300.000 homeless**
- **Loss amounts to 120 % of GDP**
- **The most destructive earthquake that any country has experienced when measured in terms of the number of people killed relative to its population**

Haiti 2010



Haiti 2010

- **Inadequate Construction Practice**
 - **Powerty**
 - **Lack of professionals in construction industry**
 - **No seismic code**

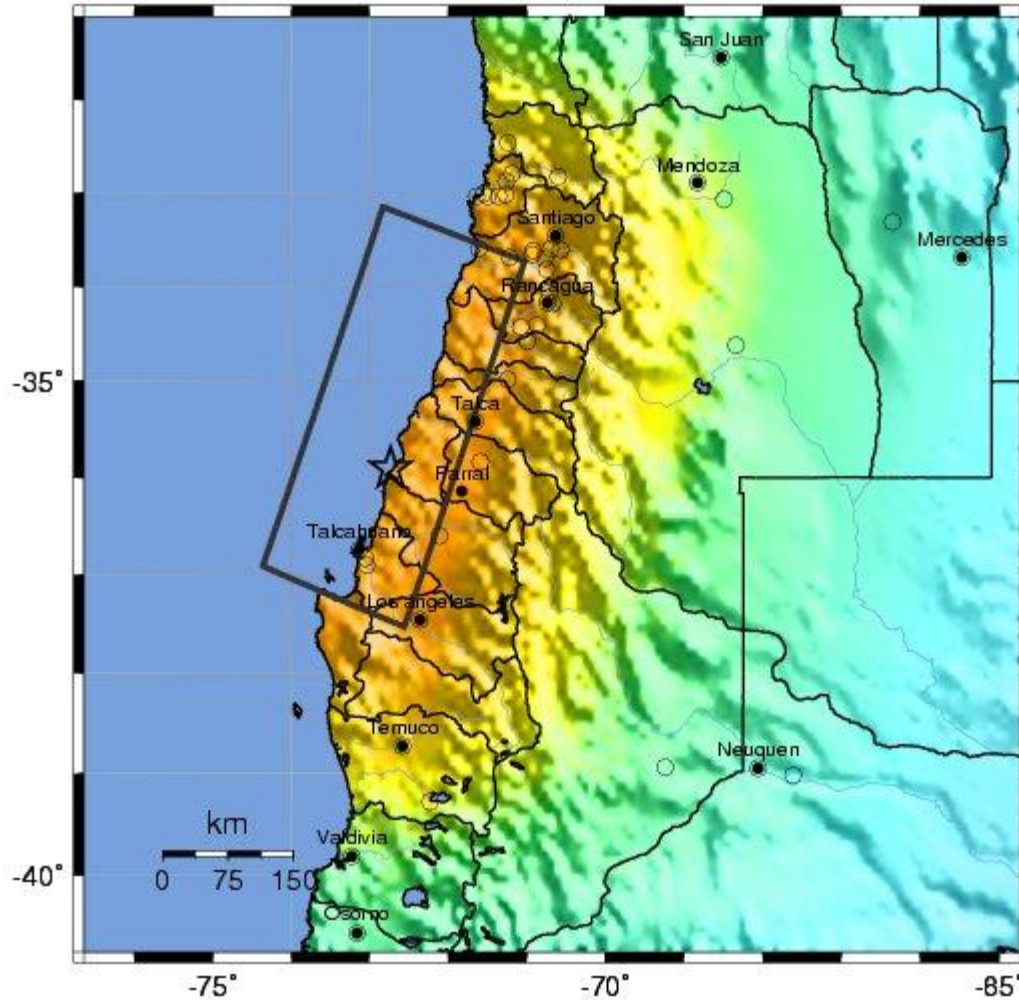
Chile 2010

- **M=8.8**
- **About 580 deaths**
- **About 800.000 homeless**
- **About 40 billion Euro damage**

- **Good behaviour of engineered structures**
- **Some problems with code**

USGS ShakeMap : OFFSHORE MAULE, CHILE

Sat Feb 27, 2010 06:34:14 GMT M 8.8 S35.91 W72.73 Depth: 35.0km ID:2010tfan



Map Version 7 Processed Fri Mar 5, 2010 03:00:13 AM MST -- NOT REVIEWED BY HUMAN

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+

CHILE 2010

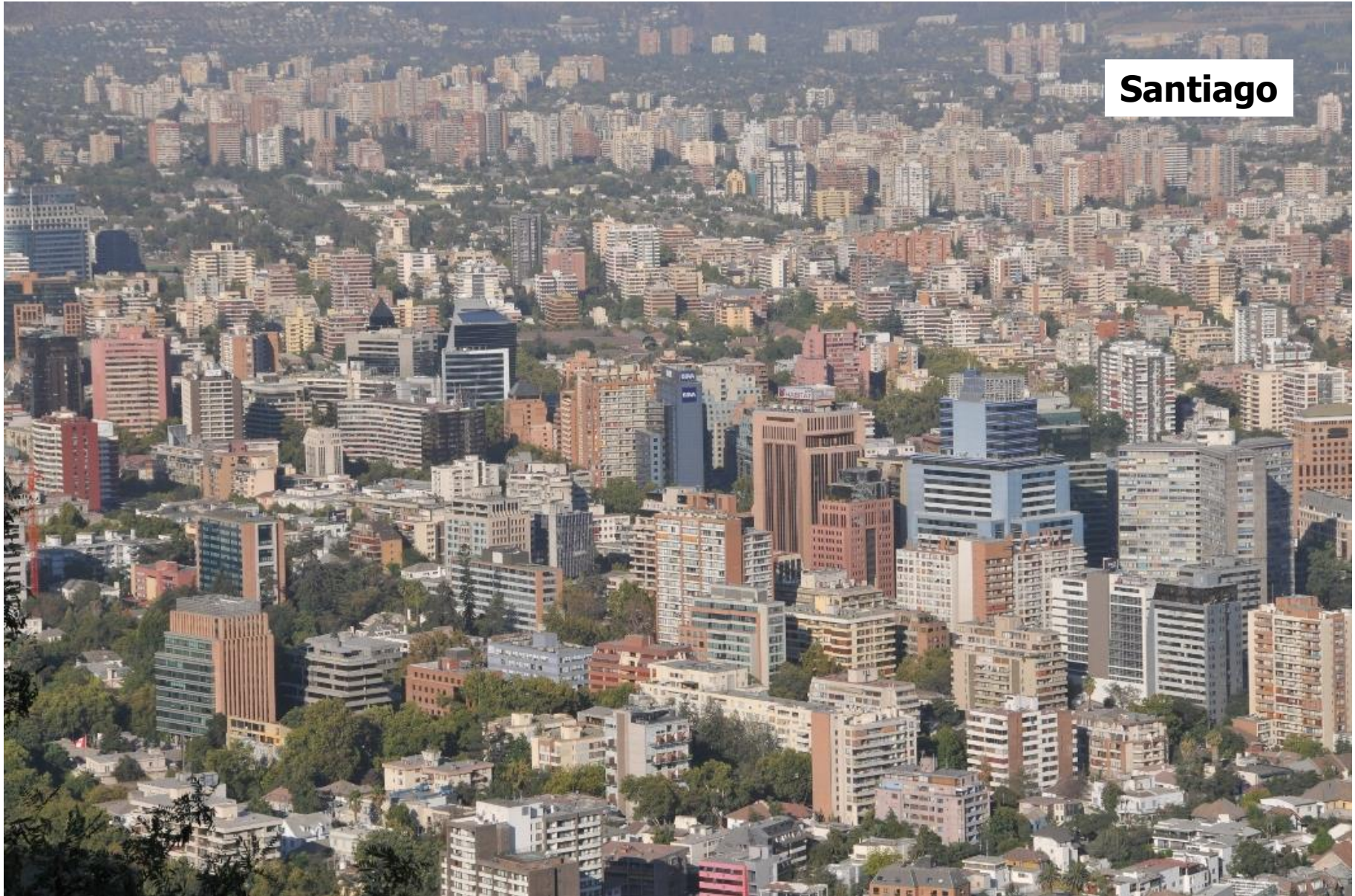


Chile 2010



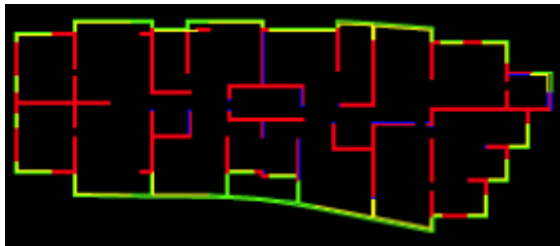
Observations

- Extreme magnitude, long duration, moderate intensity
- Majority of engineered structures behaved well
- Some buildings, including very new ones, heavily damaged
- **New: Systematic local brittle failures of slender walls with large compression in new buildings, especially in first basement. Inadequate confinement for high axial stress.**

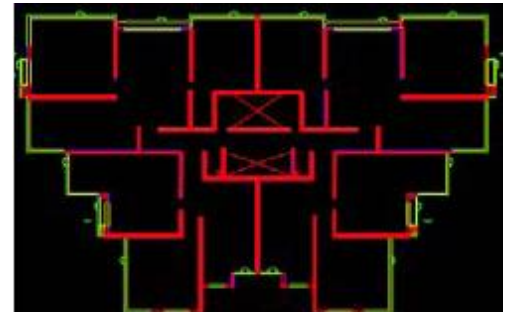


Santiago

Typical high-rise buildings - Chile



19 Stories + 3 Basement



Behaviour of buildings

Chile (buildings built between 1985 to 2009 in the earthquake affected areas, data from Rene Lagos)

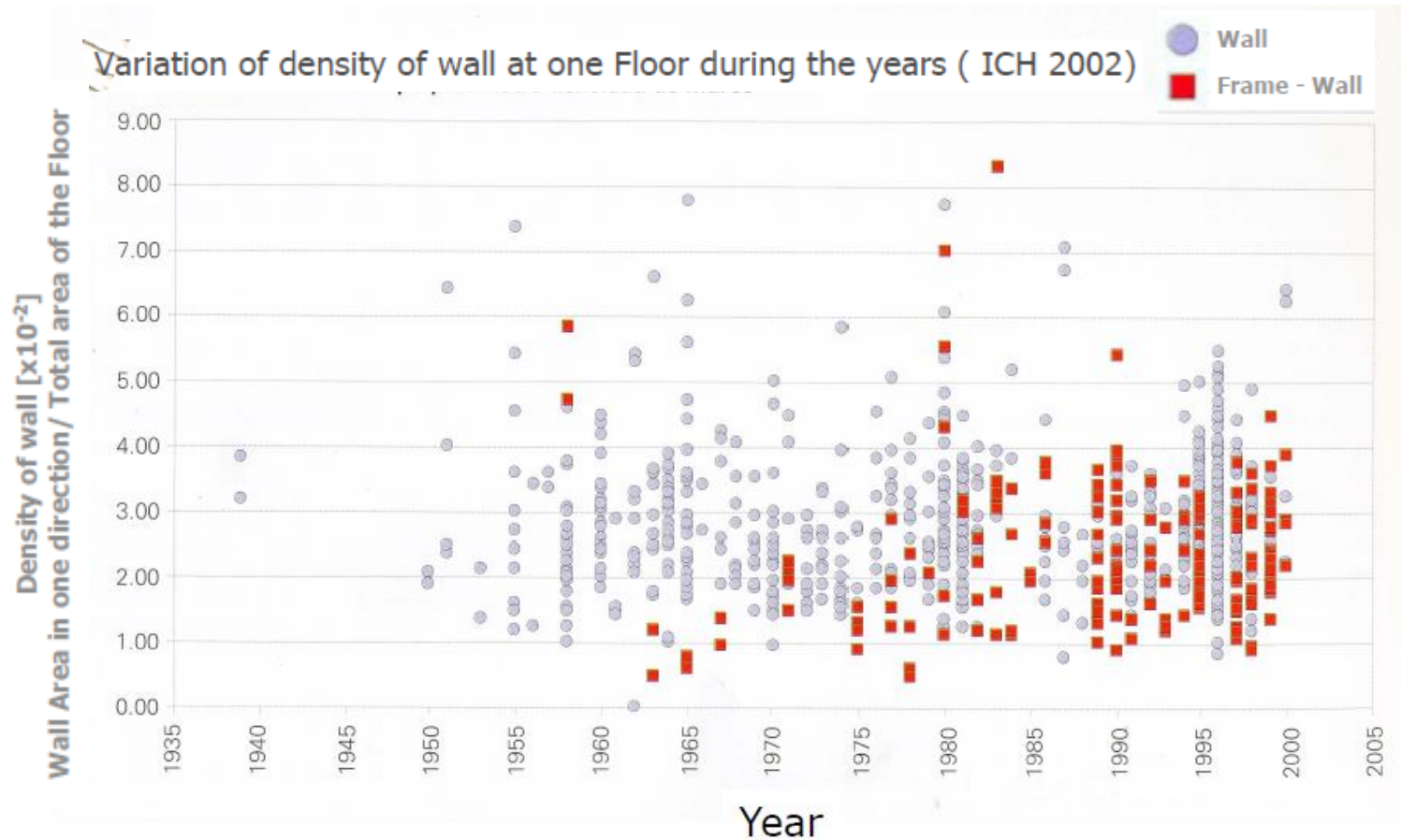
- Number of buildings 3+ story 9.974
- Number of buildings 9+ story 1.939
- Buildings that collapsed 4 (app.)
- Buildings to be demolished 50 (estimate)

- Failure 3+ story buildings 0.5%
- Failure 9+ story buildings 2.8%

Concepcion (buildings taller than 9 stories, data from Fabian Rojas)

- Number of buildings 9+ story 48 (estimate)
- Buildings that collapsed 1 complete + 1 partial
- Buildings to be demolished 8

Characteristics of building structures



"Edificios Chilenos de Hormigón Armado," ICH, 2002

Problem

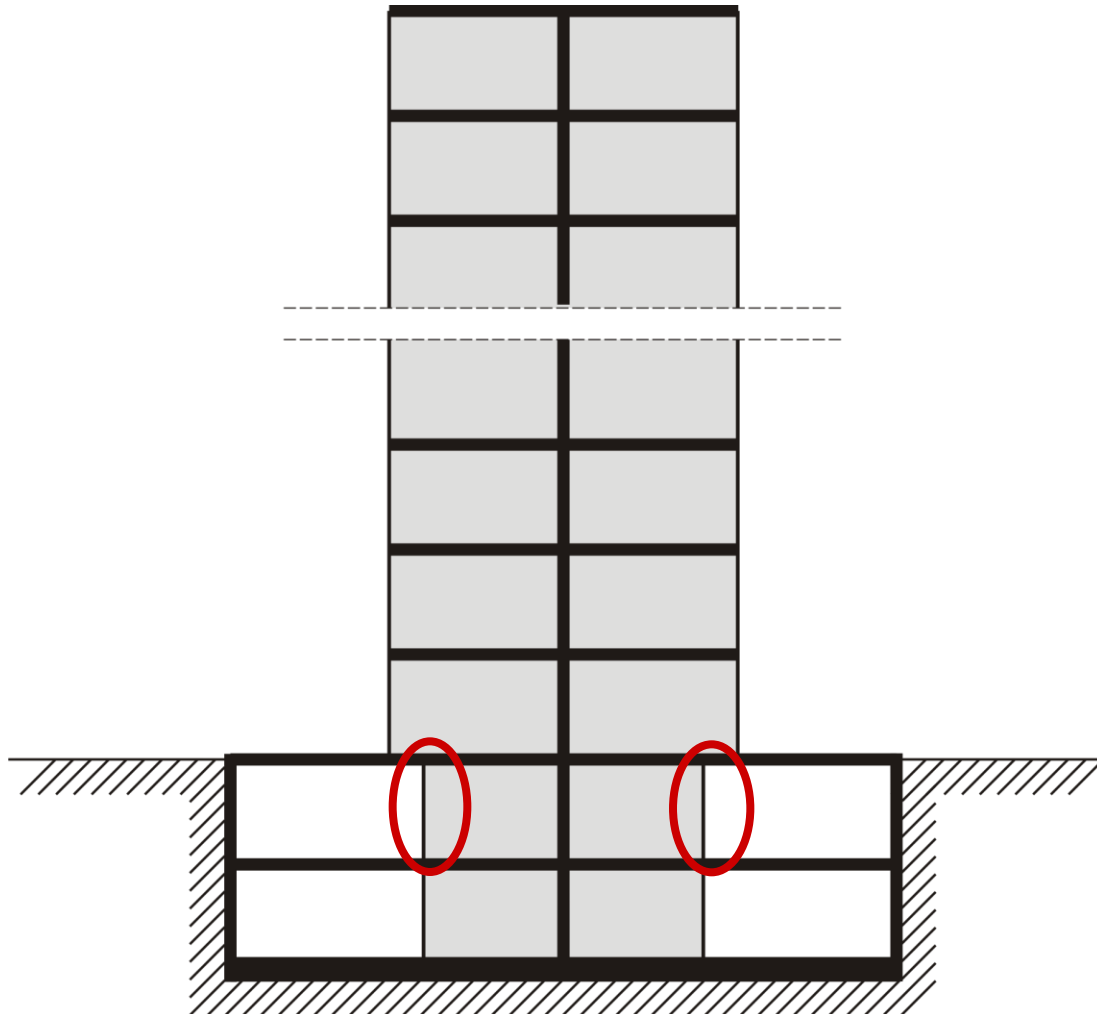
The area of walls as a fraction of the total floor area has remained about constant, but the number of stories has increased significantly, resulting in higher axial stresses in the walls.

Additional problems

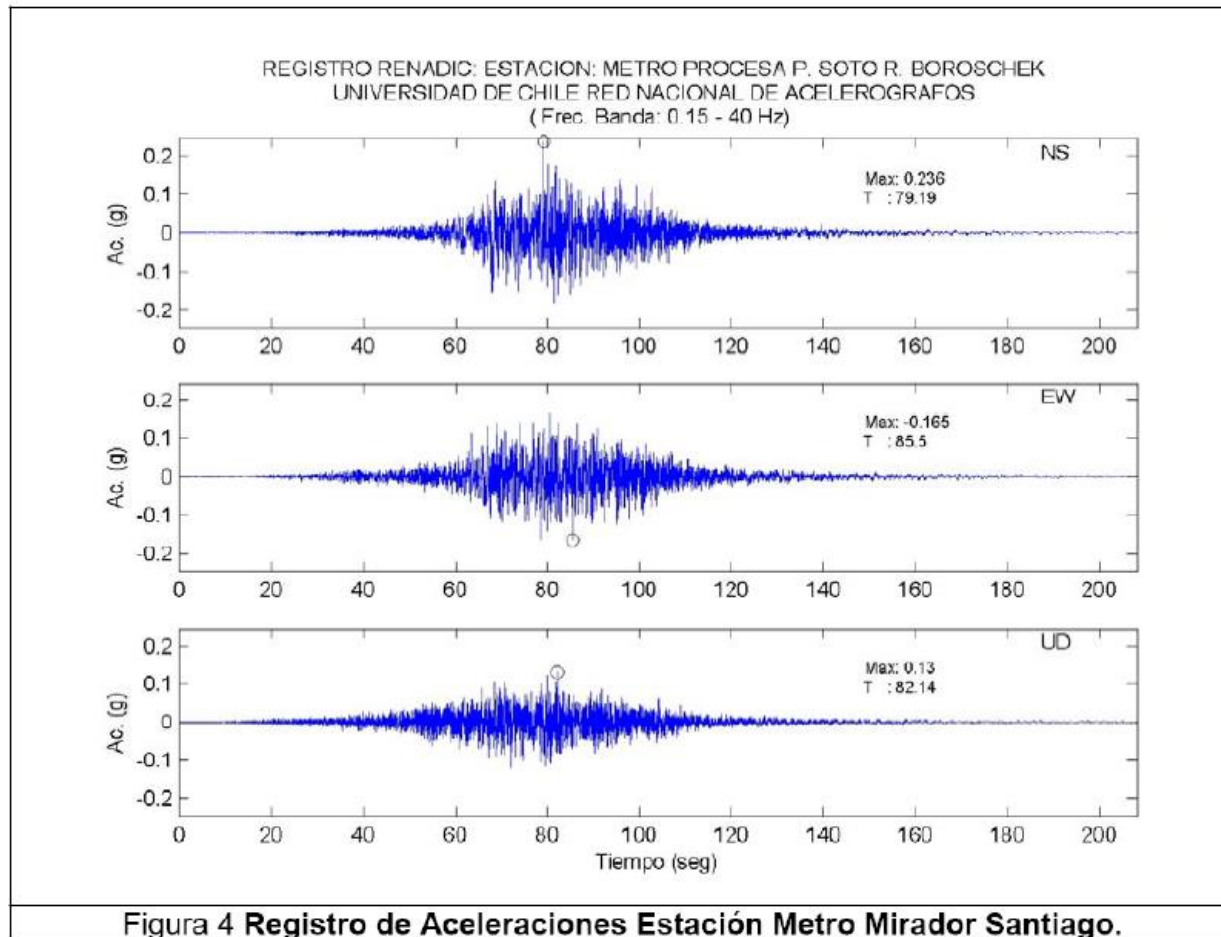
Vertical irregularities, mostly vertical setbacks (narrowing of walls near base – “flag wall” configuration)

Long duration of earthquake – a large number of loading cycles – and strong aftershocks

First basement



Accelerogram Santiago



L'Aquila





1974 and 1975
1976 and 1977

5-1

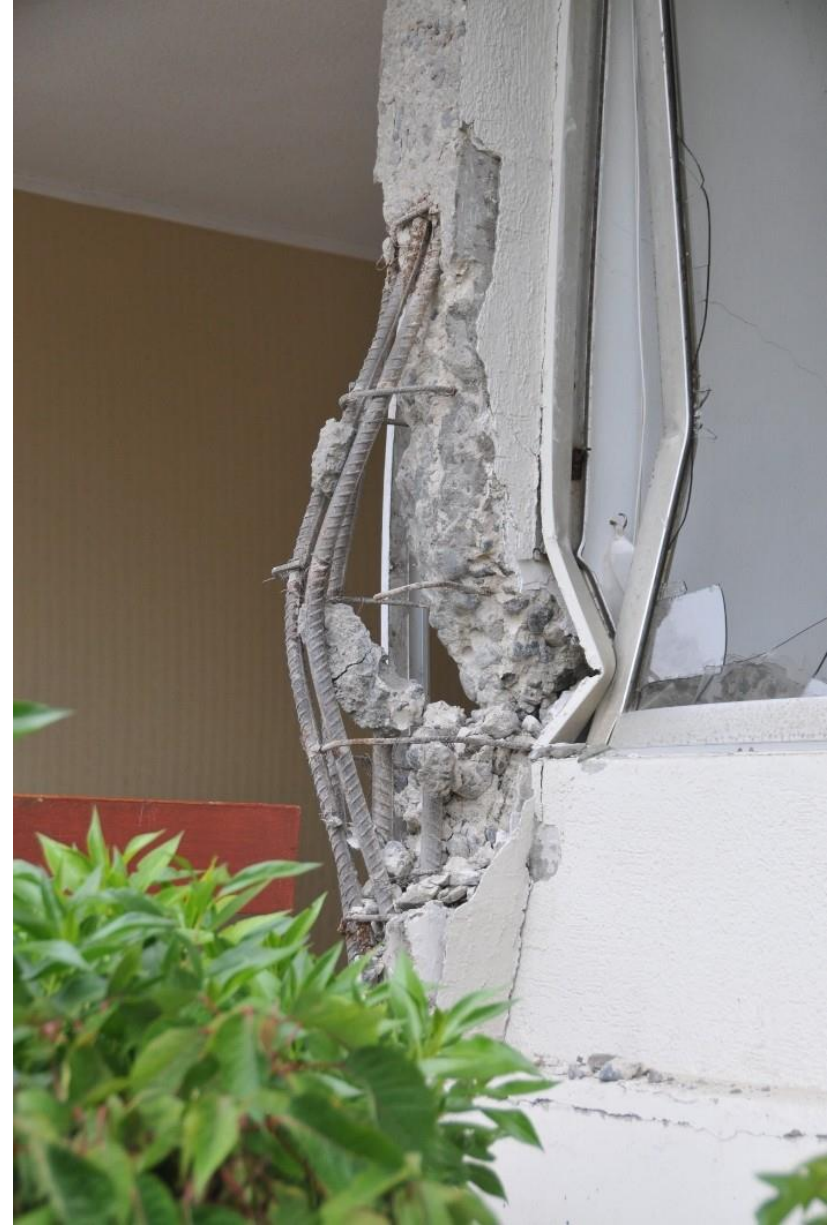
totol 5-1 = 43, $F_{\text{alt}} =$
 10/03/10 = 30 / 20
 10/03/10 = 30 / 19
 11/03/10 = 31 / 12
 16/03 = 42 / 1

















Alto Rio, Concepcion



- 15 stories, RC, Apartments
- 2 underground stories
- built in 2008

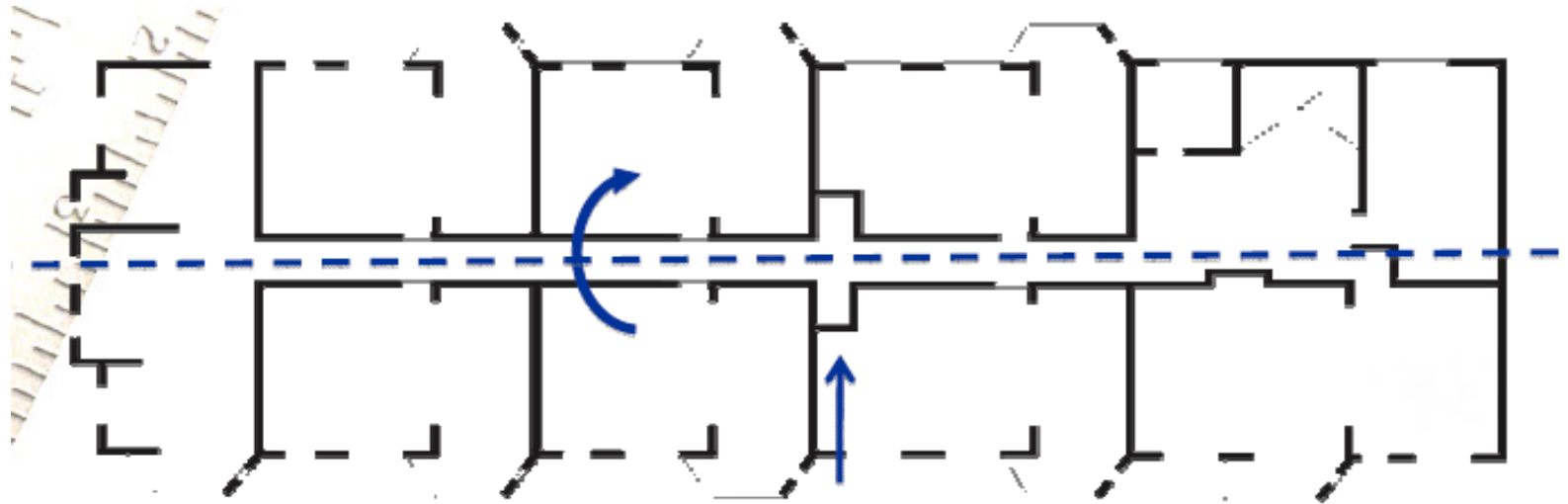


During the earthquake 87 persons in building

- 8 deaths
- 79 survivors

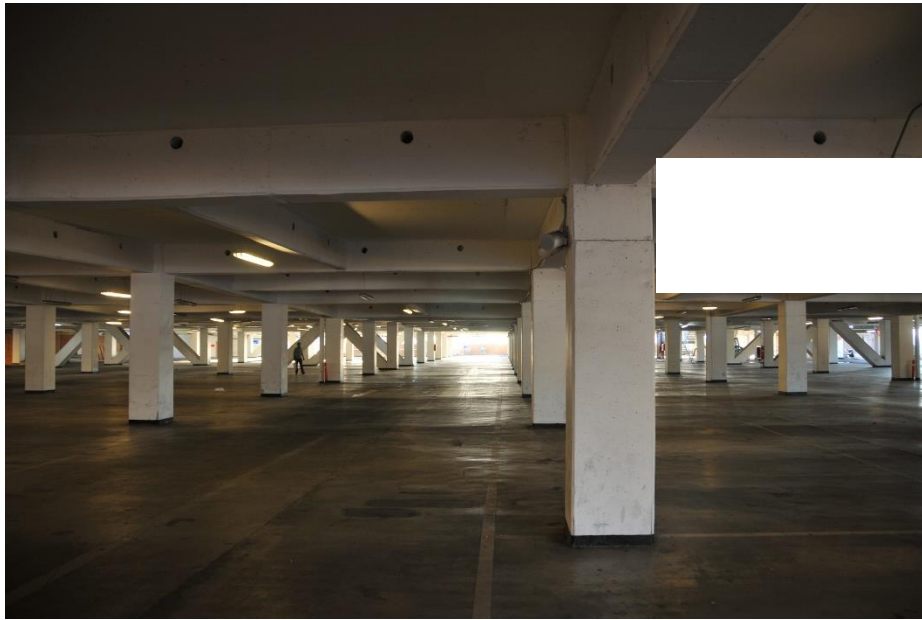
52 came from building themselves
27 rescued

Alto Rio



Sketch Floor Plan





Christchurch 2010, 2011

- **4.9.2010: $M=7.1$, $a_{gmax} = 1.26 \text{ g}$**
- **22.2.2011: $M=6.3$, $a_{gmax} = 2.20 \text{ g}$, 185 deaths**
- **13.6.2011: $M=6.3$**
- **23.12.2011: $M=5.8$**

- **Much stronger ground motion than expected**
- **Heavy damage (150000 homes damaged)**
- **Liquefaction**
- **More than 10000 aftershocks**



Christchurch 2010



Christchurch 2011

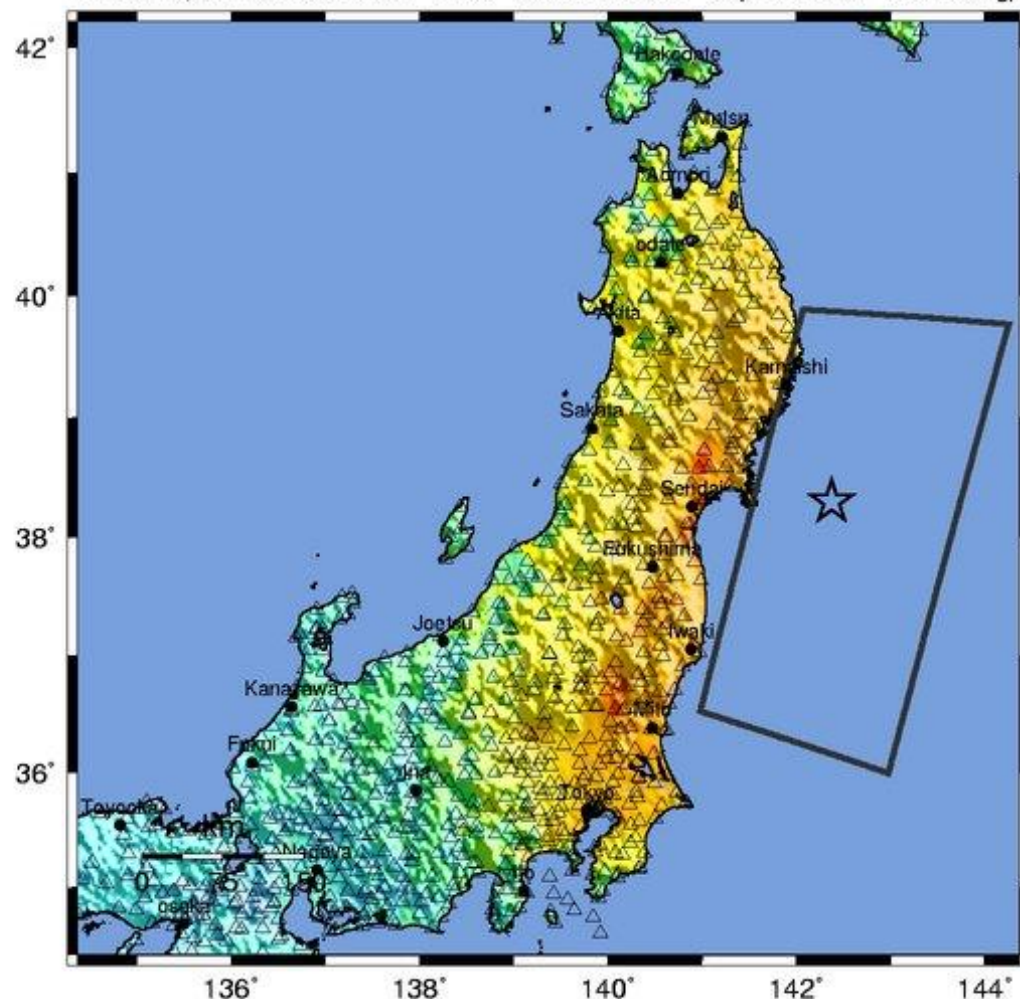


Japan 2011

- **M=9.0 + tsunami**
- **About 25.000 deaths (mostly from tsunami)**
- **About 300.000 homeless**
- **About 200 billion Euro damage**
- **PGA = 3g**
- **Good behaviour of engineered structures**
- **Severe underestimation of tsunami**
- **Nuclear disaster**
- **Early warning**

USGS ShakeMap : NEAR THE EAST COAST OF HONSHU, JAPAN

Fri Mar 11, 2011 05:46:24 GMT M 9.0 N38.30 E142.37 Depth: 30.0km ID:c0001xgp



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+



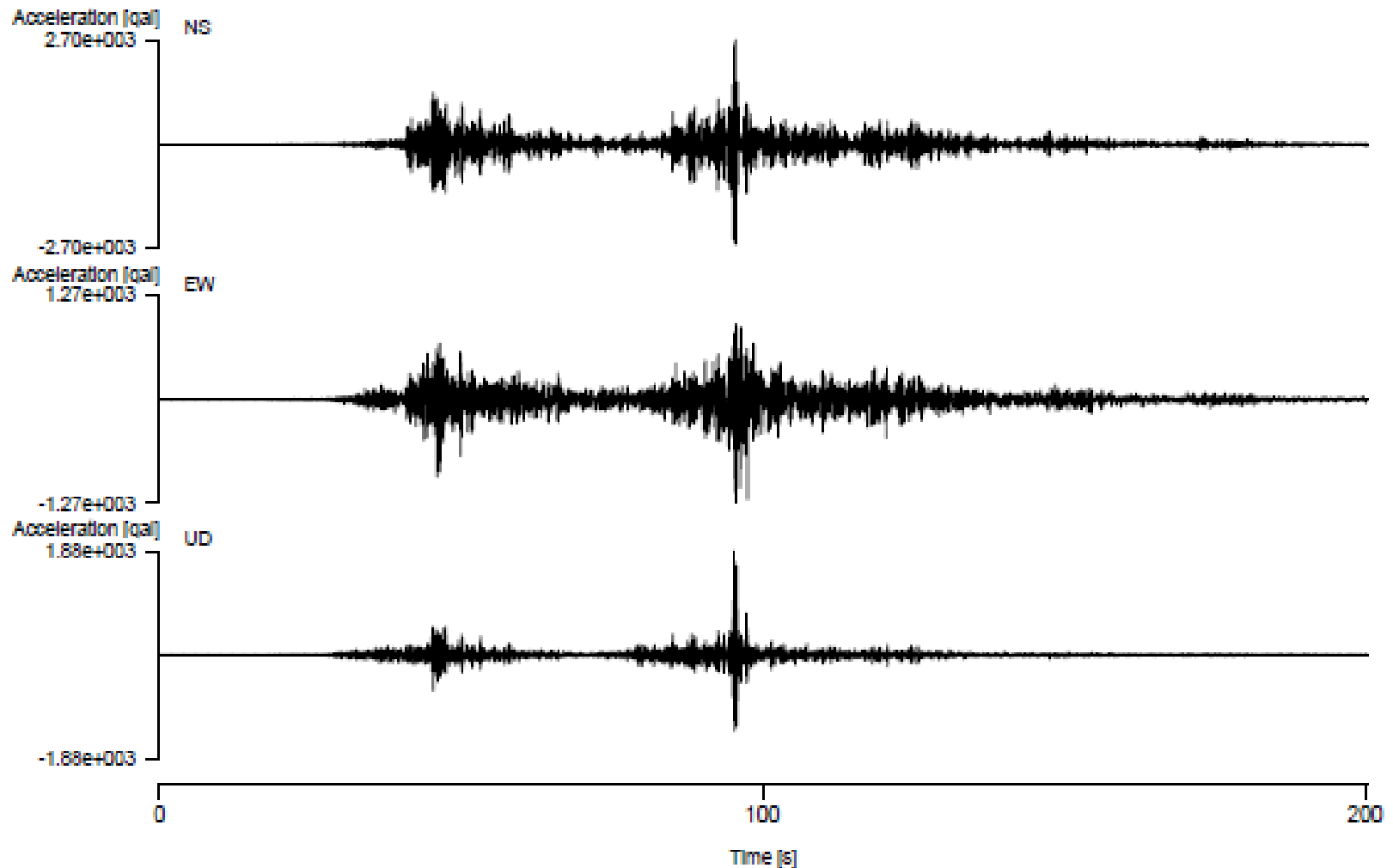
Tohoku Japan 2011



Accelerograms

MYG004 2011/03/11 14:46:36 Seismic Intensity : 6.67 (震度7)

MYG00420110311144636.lwin



Maximum accelerations

Ten largest acceleration recording stations are

1. K-net, Tsukidate (MYG004), 2,933 Gal
2. K-net Shiogama (MYG012), 2,019 Gal
3. K-net Hitachi (IBR003), 1,845 Gal
4. K-net Sendai (MYG013), 1,808 Gal
5. K-net Hokota (IBR013), 1,762 Gal
6. KiK-net Saigo (FKSH10), 1,335 Gal
7. KiK-net Haga (TCGH16), 1,335 Gal
8. K-net Mogi (TCG014), 1,291 Gal
9. KiK-net Iwase (IBRH11), 1,224 Gal
10. KiK-net Yamamoto (MYGH10), 1,137 Gal

Japan 2011



Tohoku University, Sendai







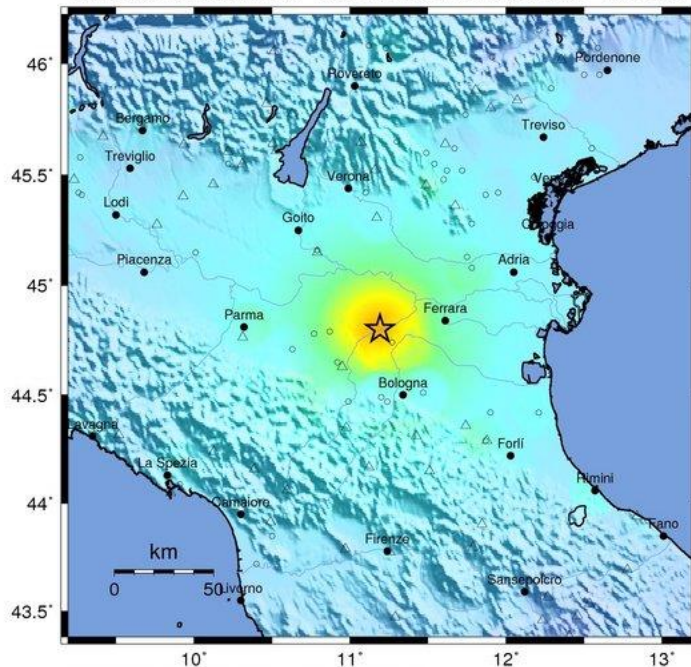
Emilia, Italy, 2012

- $M=6.0$ (20. May)
- $M=5.8$ (29. May)
- 26 deaths
- Collapse of prefabricated RC industrial buildings
- Underestimation of ground motion / inadequate code

Emilia 2012

USGS ShakeMap : NORTHERN ITALY

MAY 20 2012 02:03:52 AM GMT M 6.0 N44.80 E11.19 Depth: 5.0km ID:b0009tk0



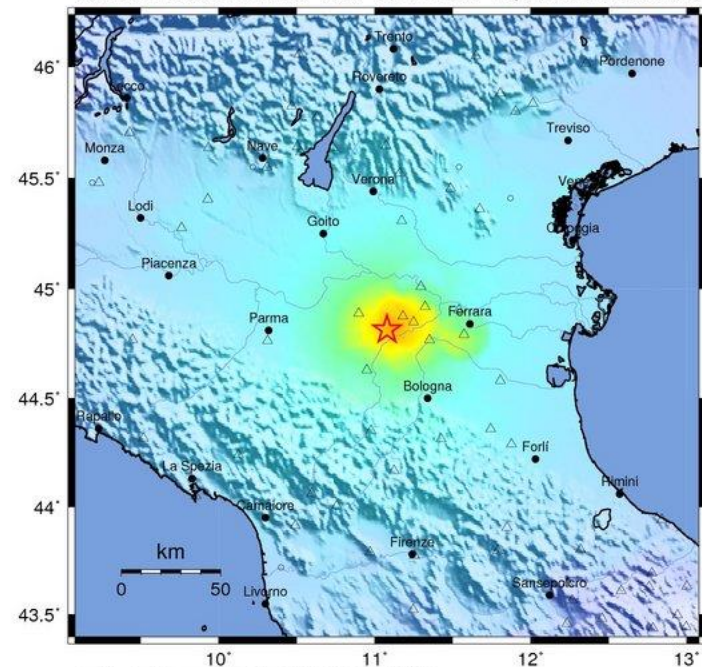
Map Version 6 Processed Sun May 20, 2012 09:03:03 AM MDT

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

USGS ShakeMap : NORTHERN ITALY

MAY 29 2012 07:00:03 AM GMT M 5.8 N44.81 E11.08 Depth: 9.6km ID:b000a1mn



Map Version 2 Processed Tue May 29, 2012 02:50:52 AM MDT

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)



Emilia Italy 2012



Observations

- Moderate magnitude, moderate intensity
- Heavy damage and collapses of masonry buildings, including cultural heritage buildings
- Heavy damage and collapses of numerous prefabricated RC industrial buildings, including relatively new ones
 - The region was until 2003 not defined as „seismic“, in the period 2003-2006 the seismic design loads were quite low









MONTENEGRO 1979





Lessons learned/confirmed

- Present codes and guidelines generally provide adequate protection against collapse
- Major problem are older structures
- Failure of some new structures
- Often large non-structural damage
- Ground motion can be much stronger than expected

Thank you

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