Next Generation of Precast Concrete Seismic Resilient Buildings

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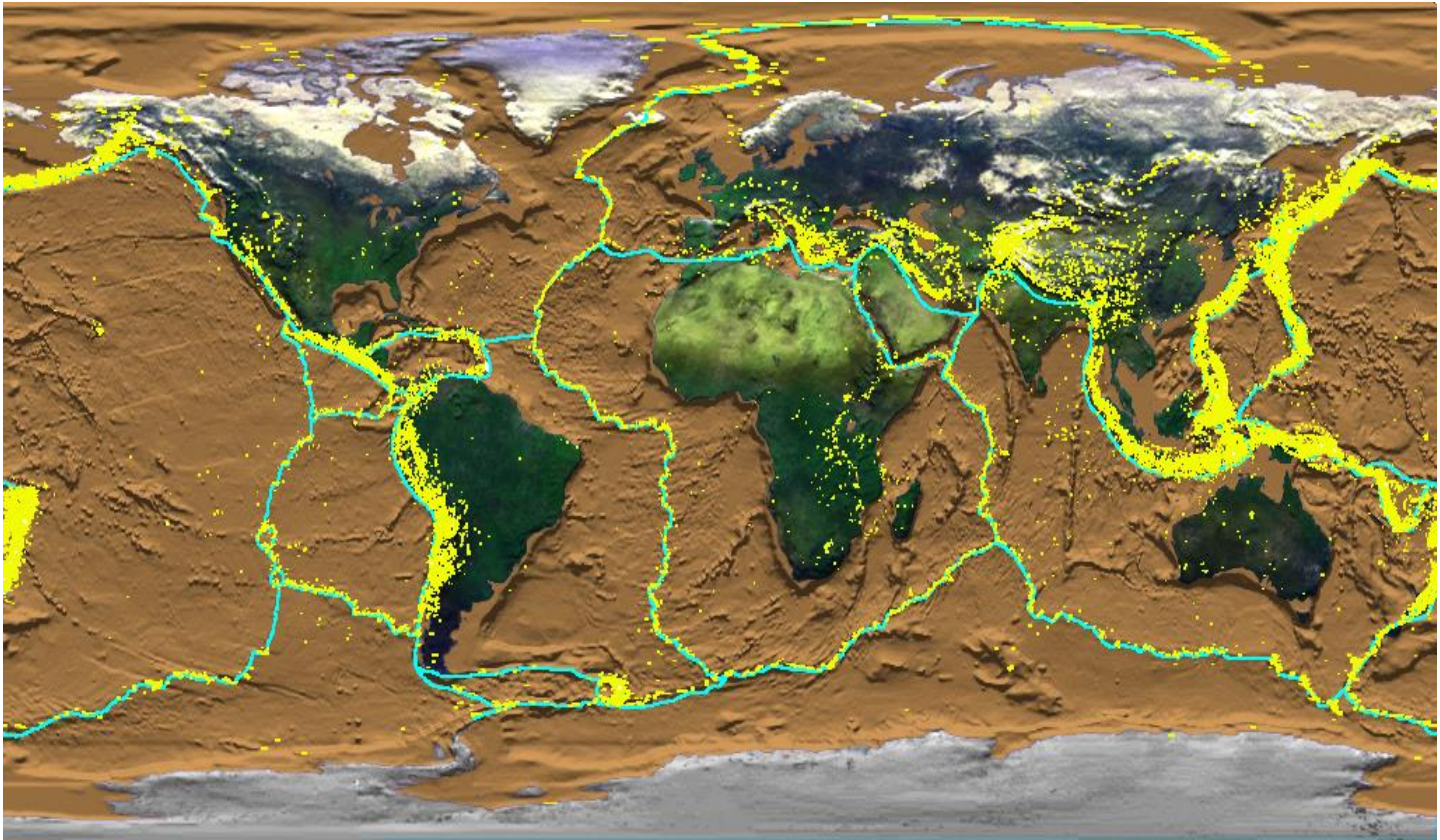
Sapienza University of Rome, Italy

World Earthquakes Map



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PRECAST CONCRETE STRUCTURES IN SEISMIC REGIONS

- The use and development of **precast concrete structures** in seismic zones have been limited by:
  - lack of confidence on their performance
  - absence of rational seismic design provisions

- **Common trend** in the major model codes (U.S., Japan, New Zealand, Europe):
  - ***emulation*** of cast-in-place reinforced concrete (wet connections)
  - ***strong*** connections: inelastic response accomodated <u>outside</u> the joint region
  - ***jointed ductile connections*** **(new)**: inelastic response within the connection

Fully-functioning three-span industrial plant

Post-earthquake debris

(Some) Fundamental Aspects in Sesimic Design of Precast Concrete Buldings

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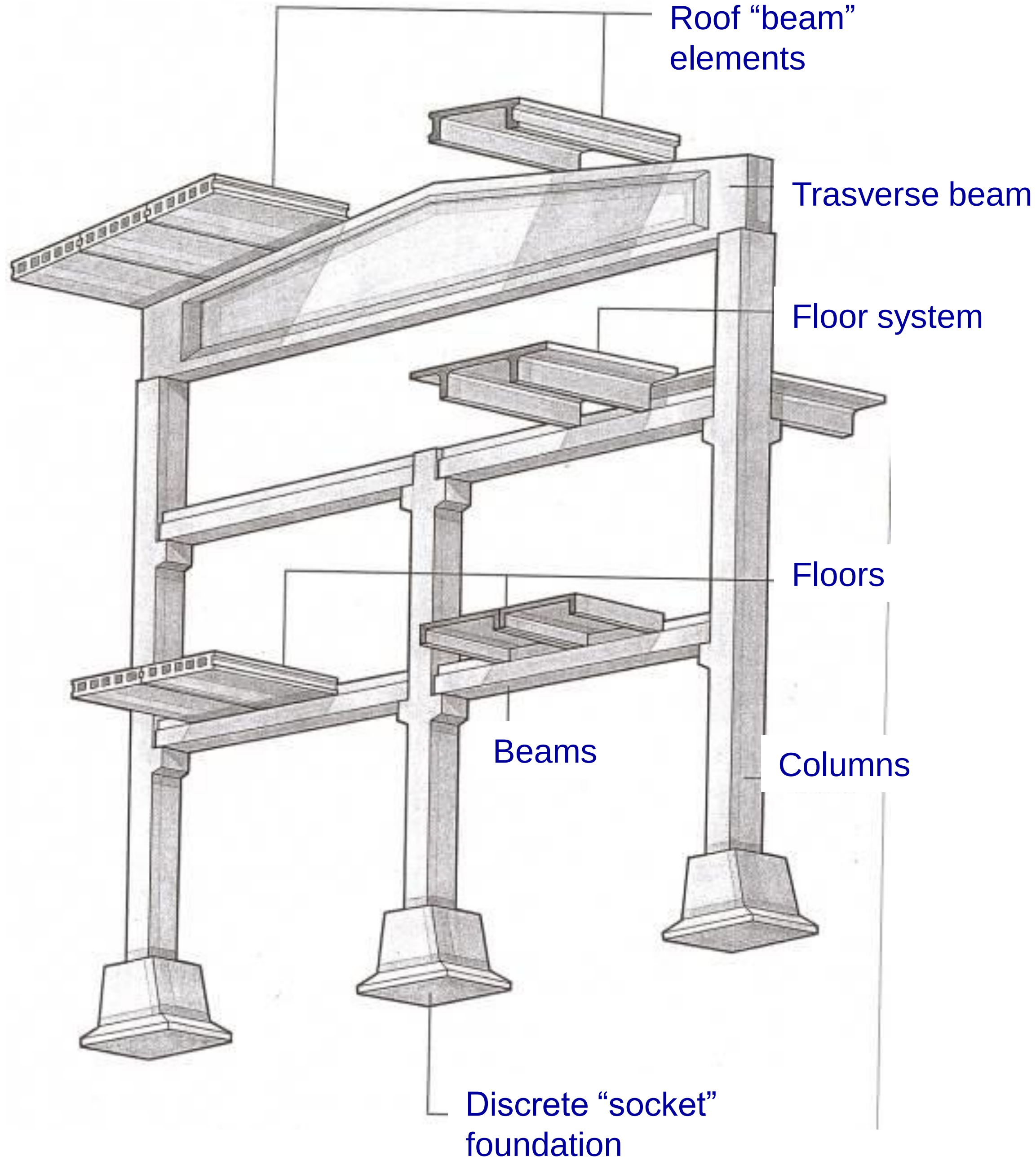
- Appropriate **Design Methodology** (Force-Based Design or Displacement Based Design)
- Understanding overall **Building Behaviour** (structural systems, diaphragm, non-structural elements, foundations)
- **Connections** detailing (ductile behaviour, dissipation)
- **Redundancy and robustness** (preventing progressing collapse)
- **Displacement compatibility** (between lateral-resisting systems, floor-diaphragms, infills facades)
- and….**detailing, detailing, detailing**…(**the devil is in the detail!)**

“HINGED” CONNECTIONS

(typical of Precast Industrial Buildings in Europe)

PRECAST INDUSTRIAL Building

Key elements and nomenclature



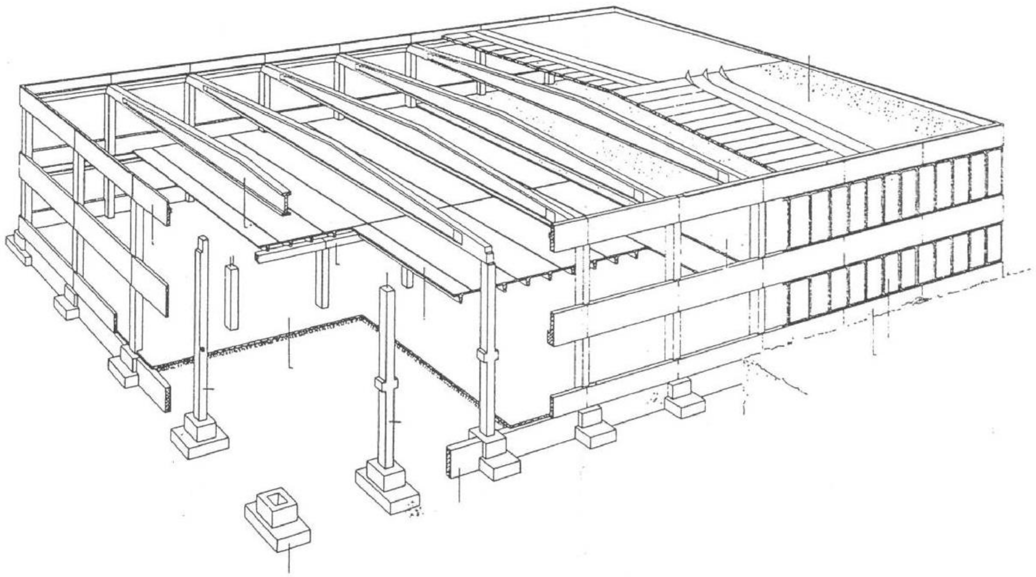
3.5 Large free space buildings

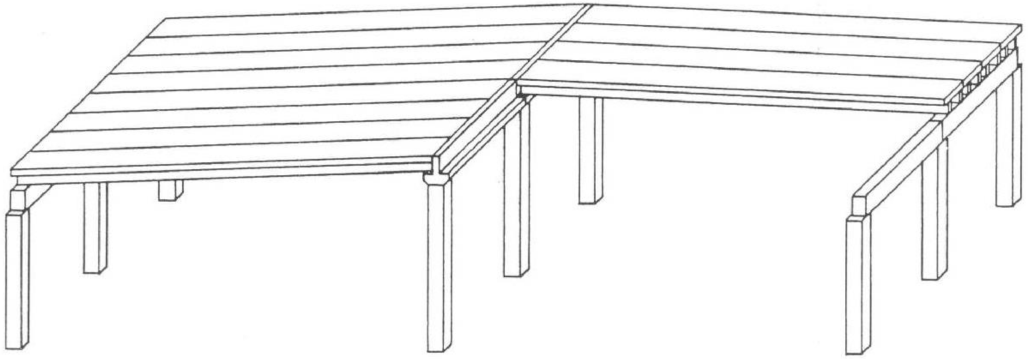
This type of building is used for:

- industrial buildings
- warehouses
- department stores, etc.

When large column-free areas are needed, the building is normally designed with precast frame systems or load-bearing facade walls.

Intermediate floors may be installed in the whole building or parts of it. Staircases and shafts are normally formed using bearing walls. Additional precast products are shown in Fig. 3.10.

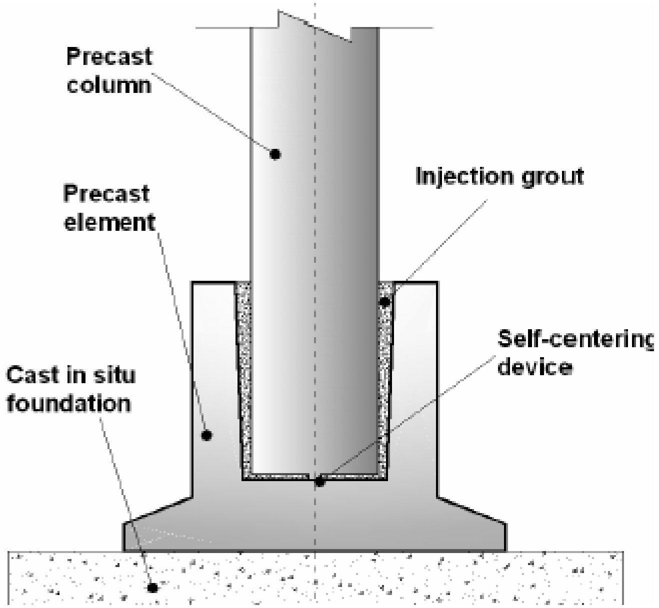


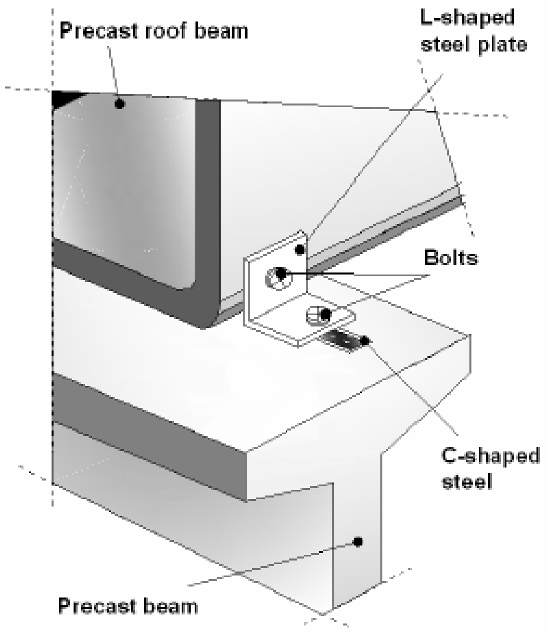


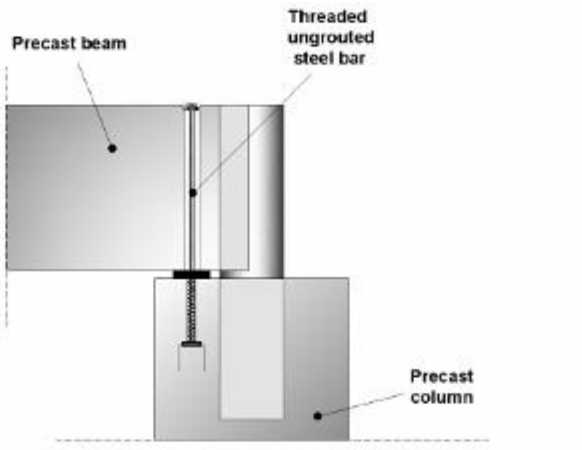
Straight

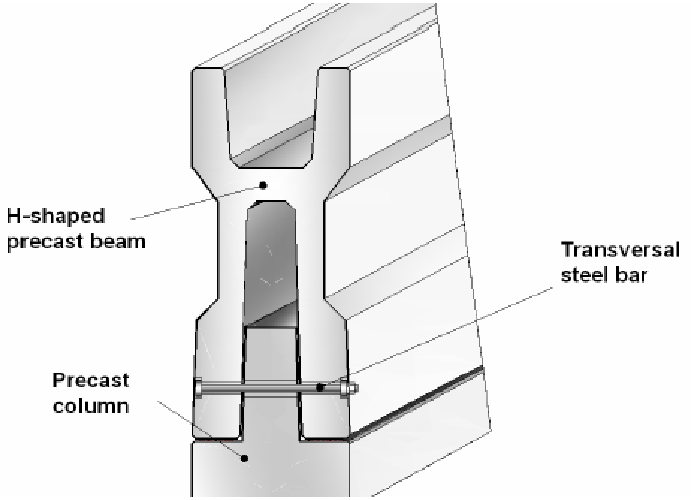
FIP Handbook on precast Building structures

Typical beam- column or column-foundation connections for industrial precast construction in the Mediterranean countries



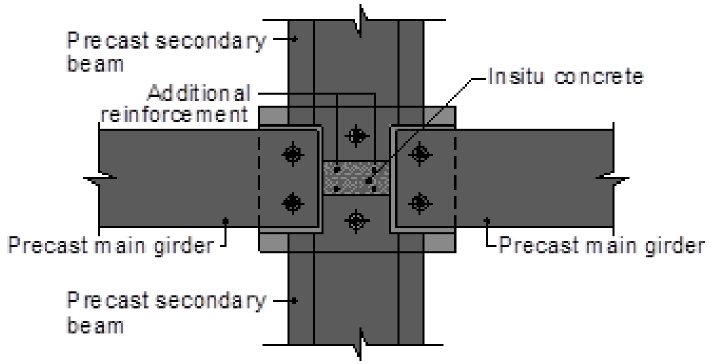




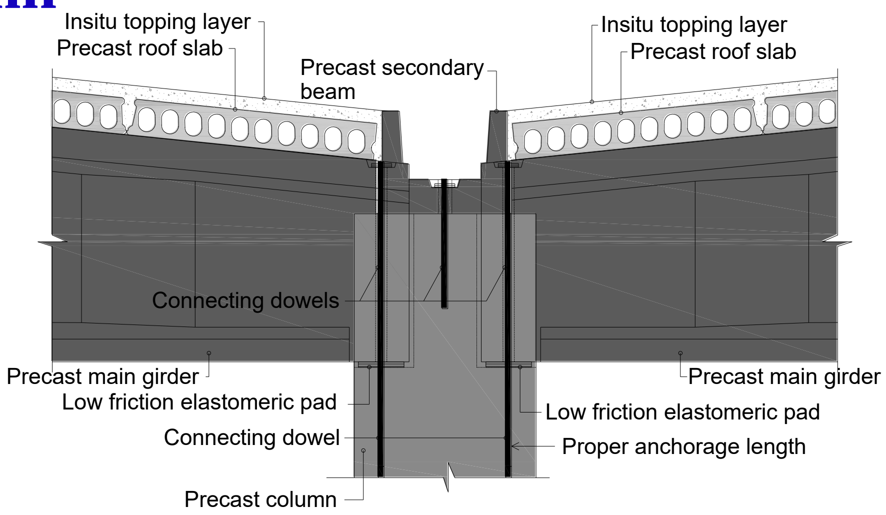


Figures from Calvi, Bolognini, Nascimbene (fib 2006)

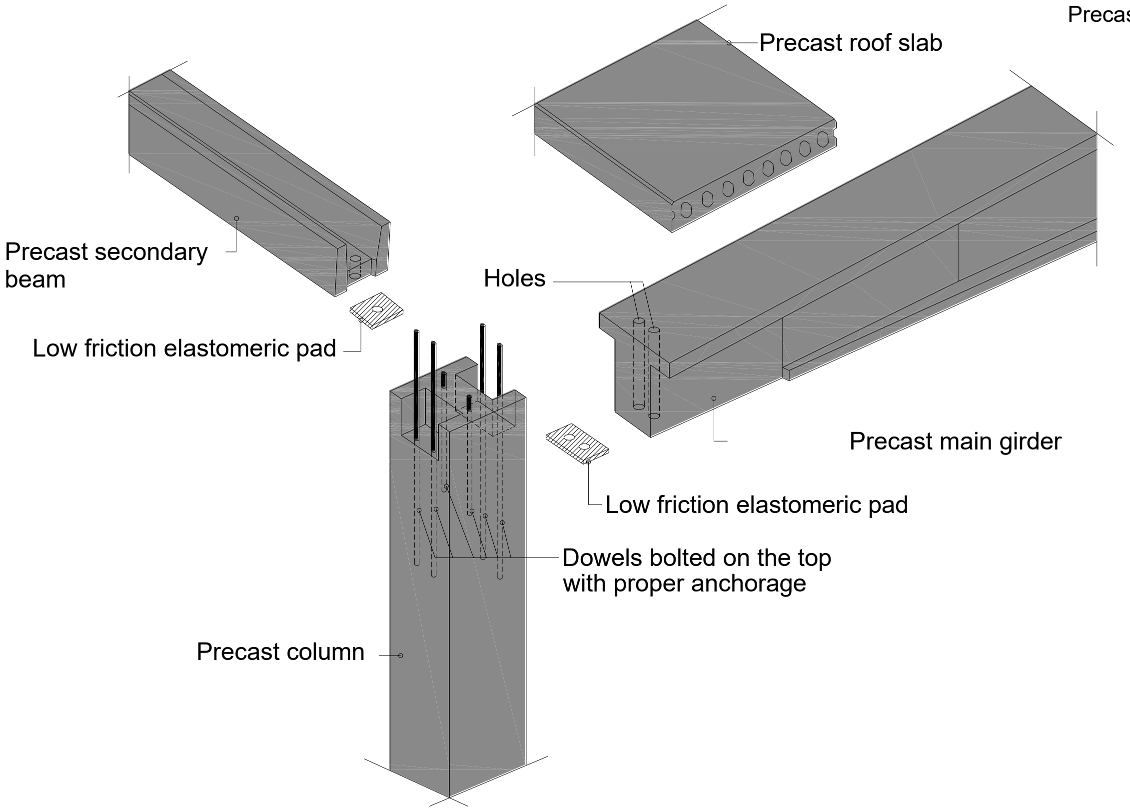
Typical European hinged beam-to-column connection on the top of a column



a) plan view



b) Elevation (vertical) view



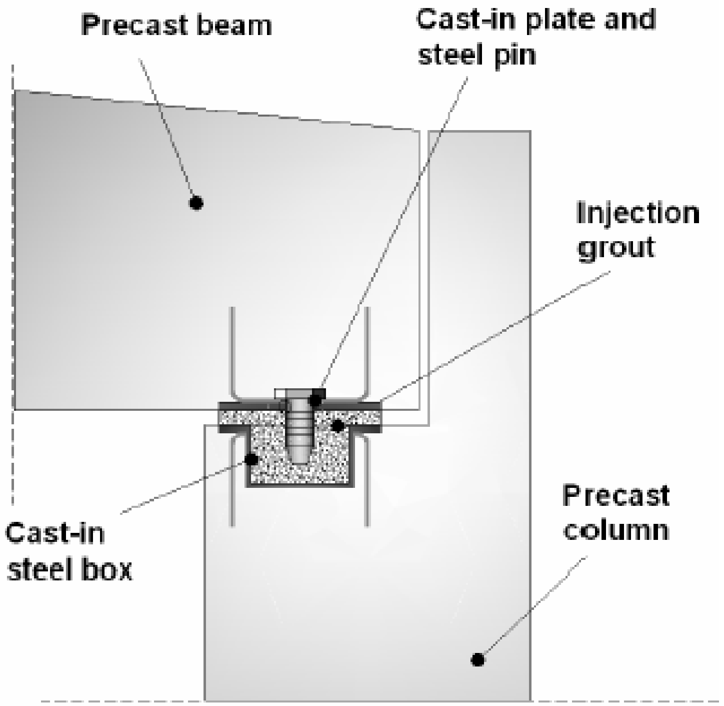
(Some) typical Advantages and structural Limits of precast structures

- **Advantage**: Quality control, speed of erection, dry construction

vs.

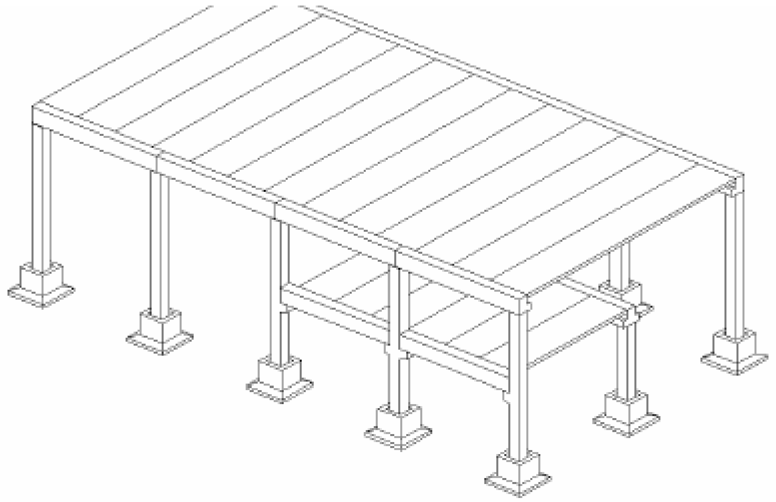
- **Limit**: inefficient <u>static schemes</u> (simple supports of beams, slabs). Oversizing of cantilever columns for lateral (wind & earthquake) loads

NEED for MOMENT RESISTING CONNECTIONS



Limitation to one-two storeys industrial buildings

(need for core walls or other lateral resisting systems)



•Significant limits due to the excessive deformability and high lateral displacement demand

•Second Order Effects (P-Delta)

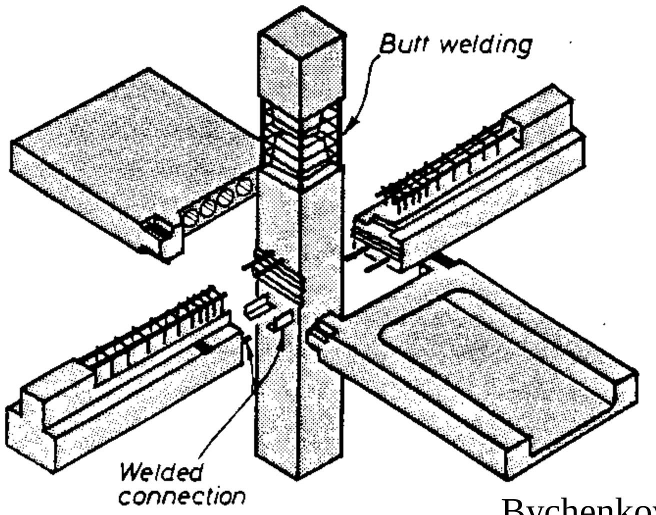
→ **NOT efficient** Static Structural Scheme

“EMULATION”

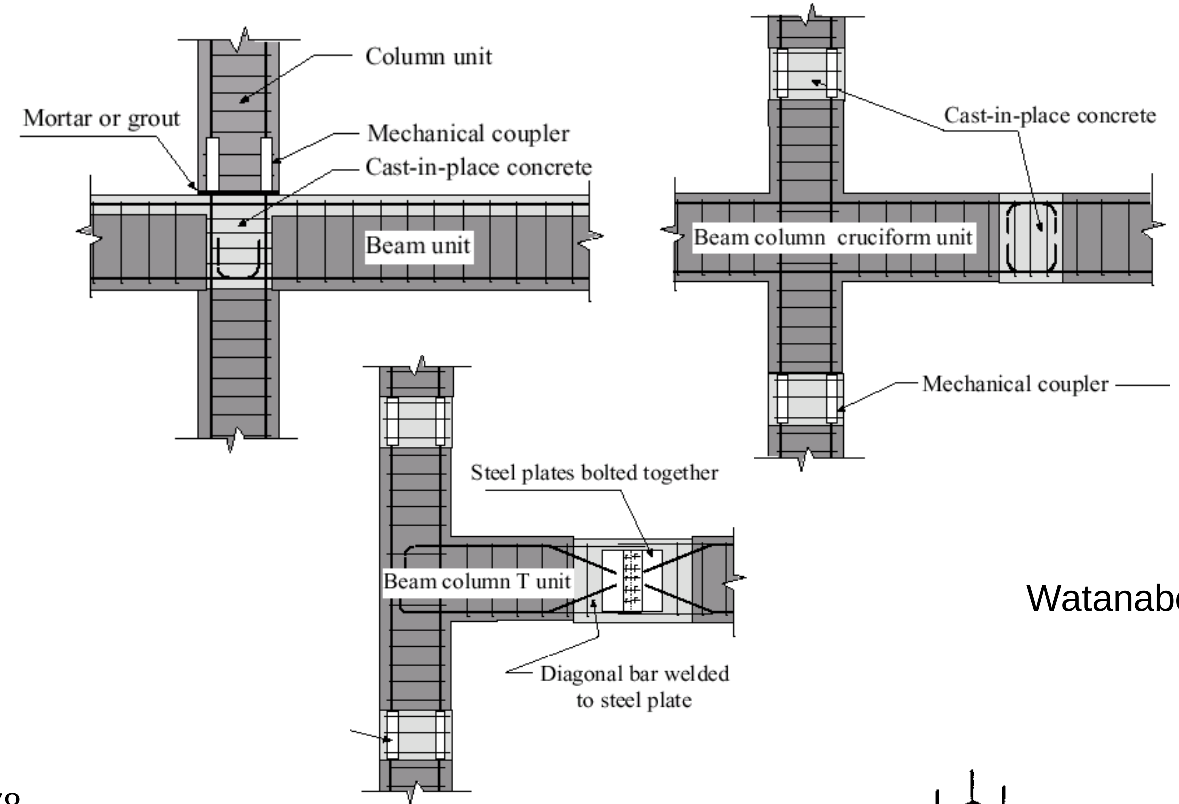
OF CAST-IN-SITU CONCRETE

CONNECTIONS

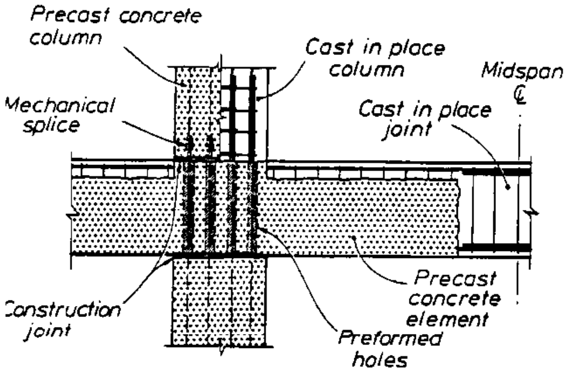
Traditional solutions
based on **"Emulation"**
of cast-in-place concrete



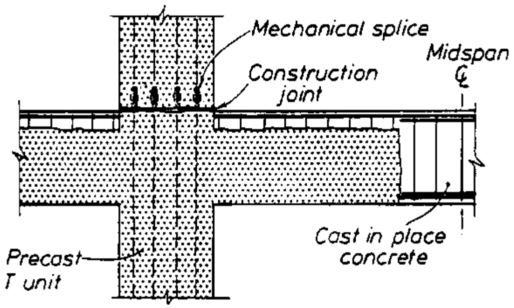
Bychenkov, 1978



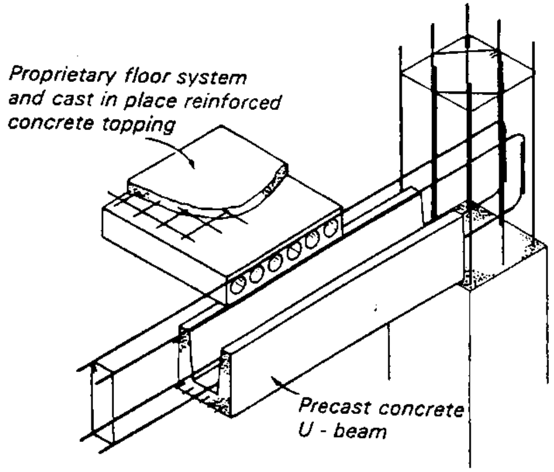
Watanabe, 2000



(b) System 2 - Precast Beam Units through Columns



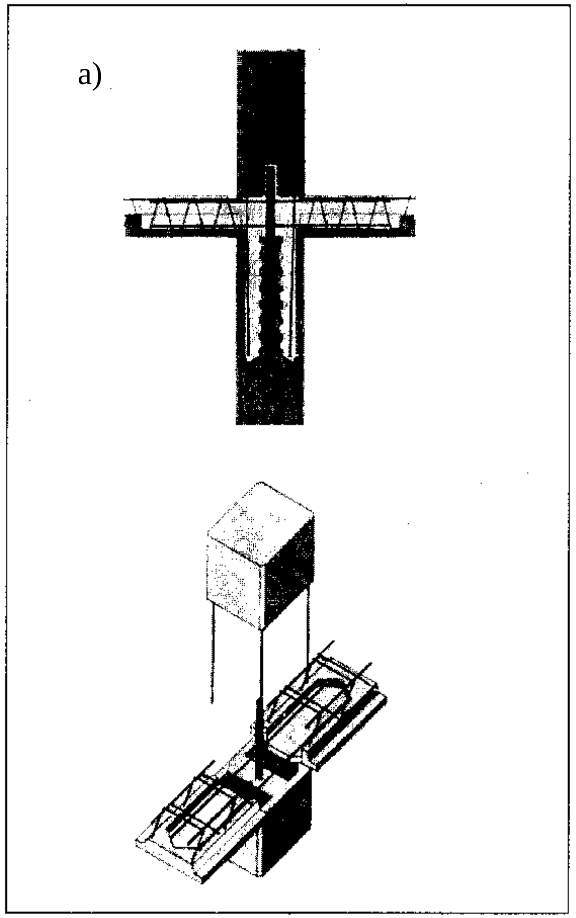
(c) System 3 - Precast T or Cruciform Units

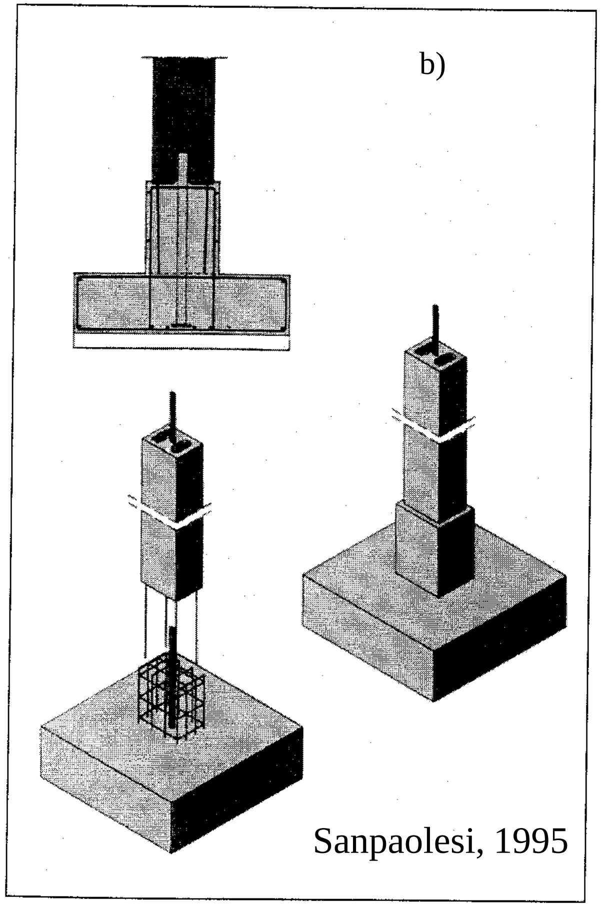


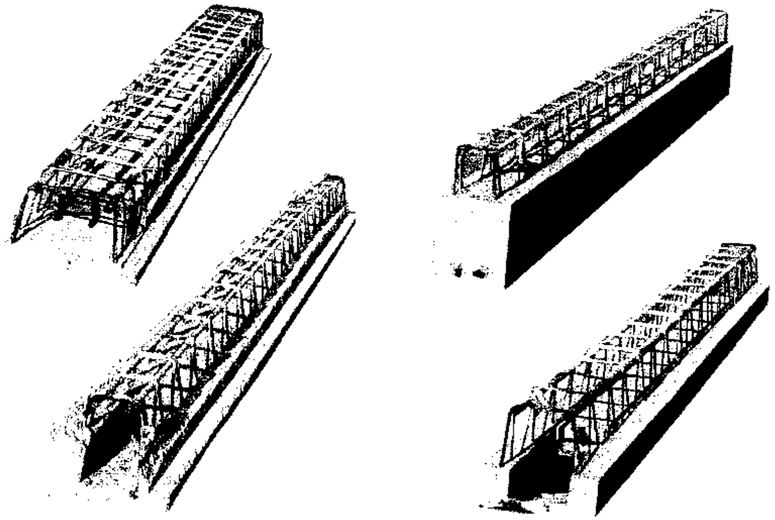
(d) Precast Concrete System Involving Shell Beams

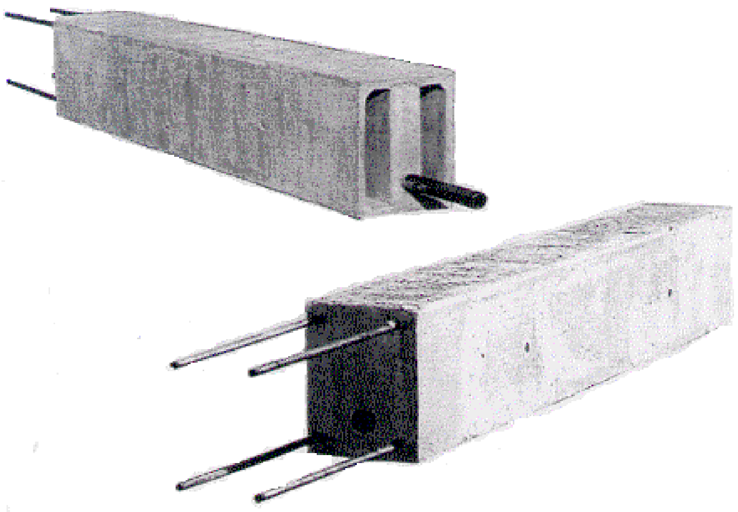
Park, 1990s

Traditional solutions
based on **”Emulation”**
of cast-in-place concrete



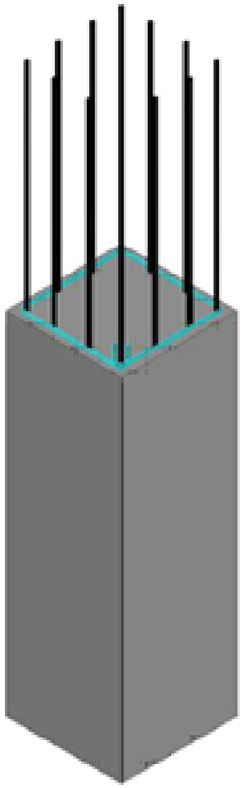




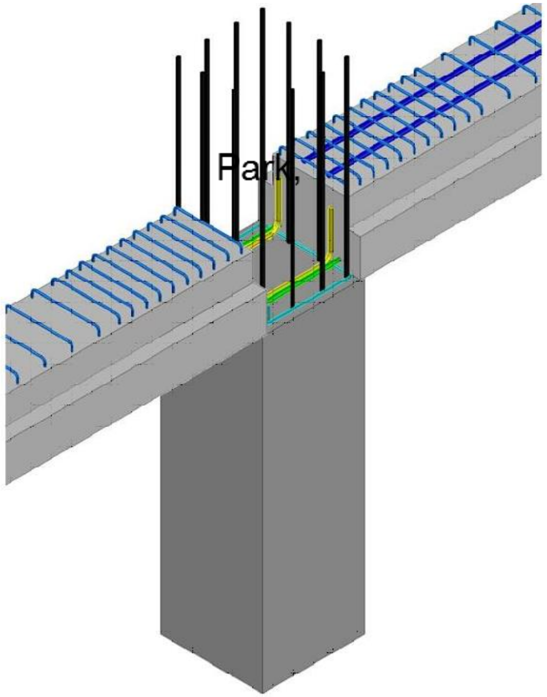


Construction Steps of emulative System S1

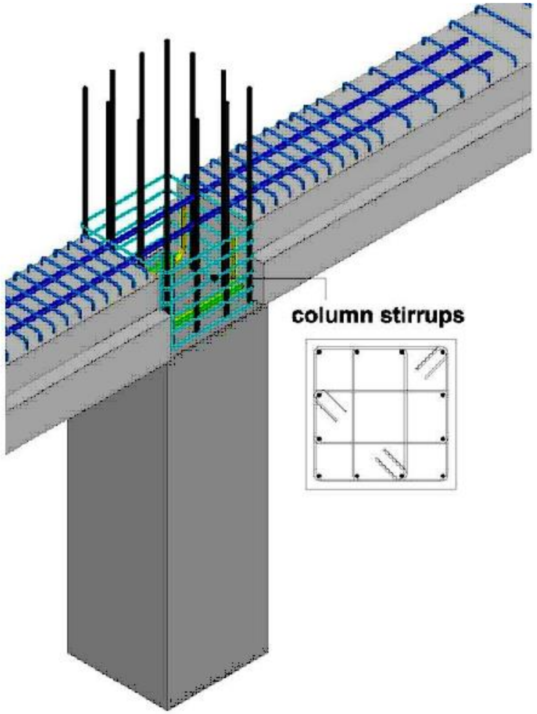
Step 1
Placement of the column



Steps 2-3
Placement of the two beams on the column



Step 4
Placement of column stirrups in the joint and top bar reinforcement



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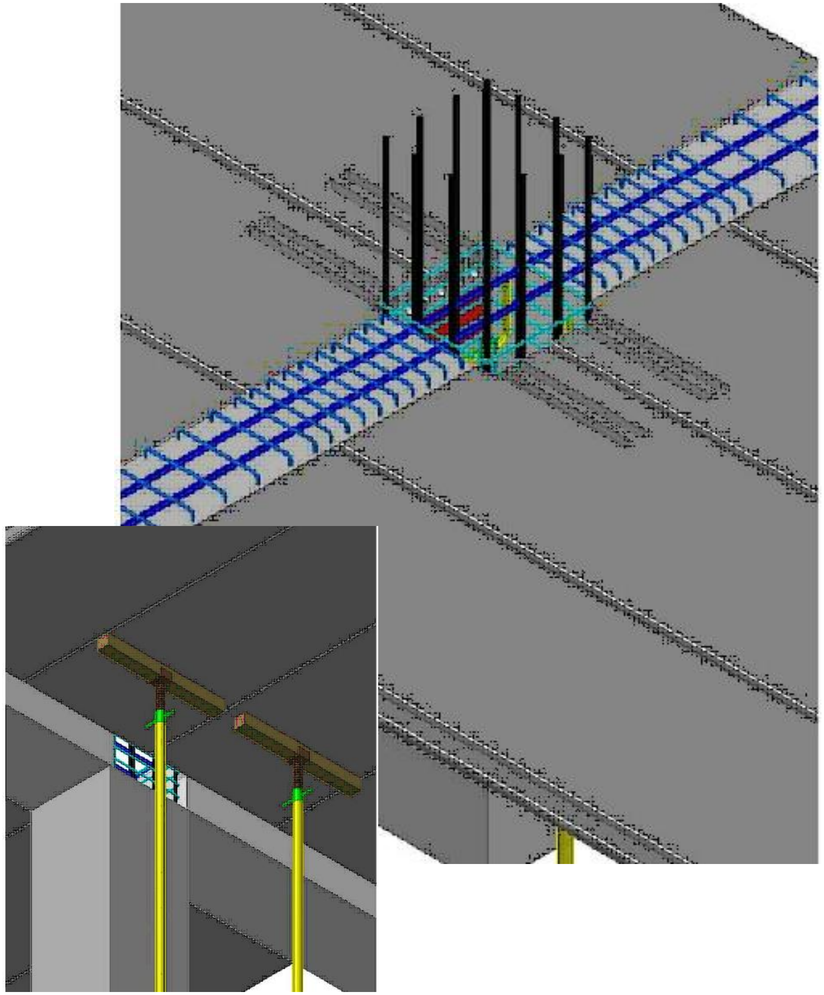
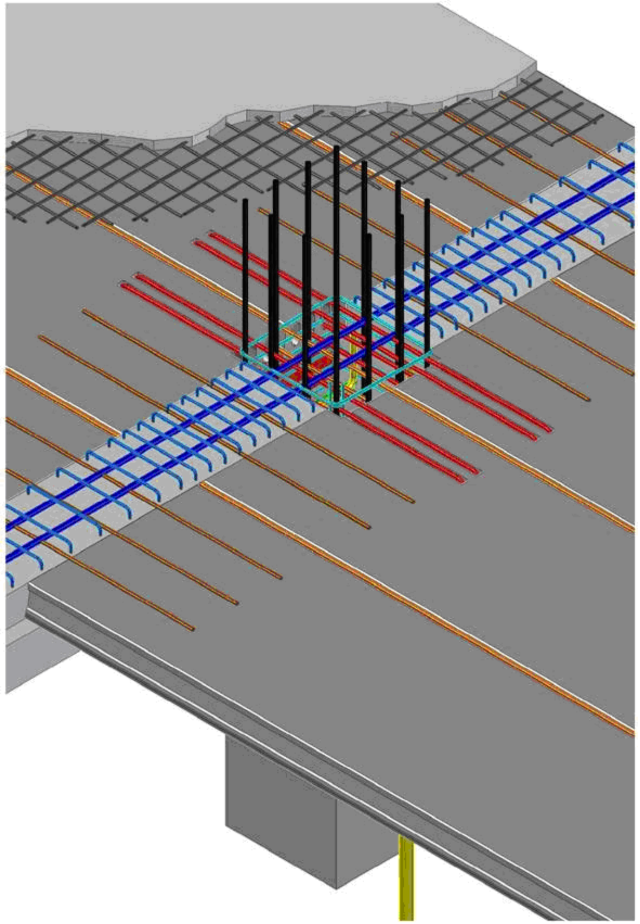
Step 5

Placement of Hollow-Core units (with propping underneath)



Step 6-7

Placement of all reinforcement including mesh and casting of concrete topping on the floor



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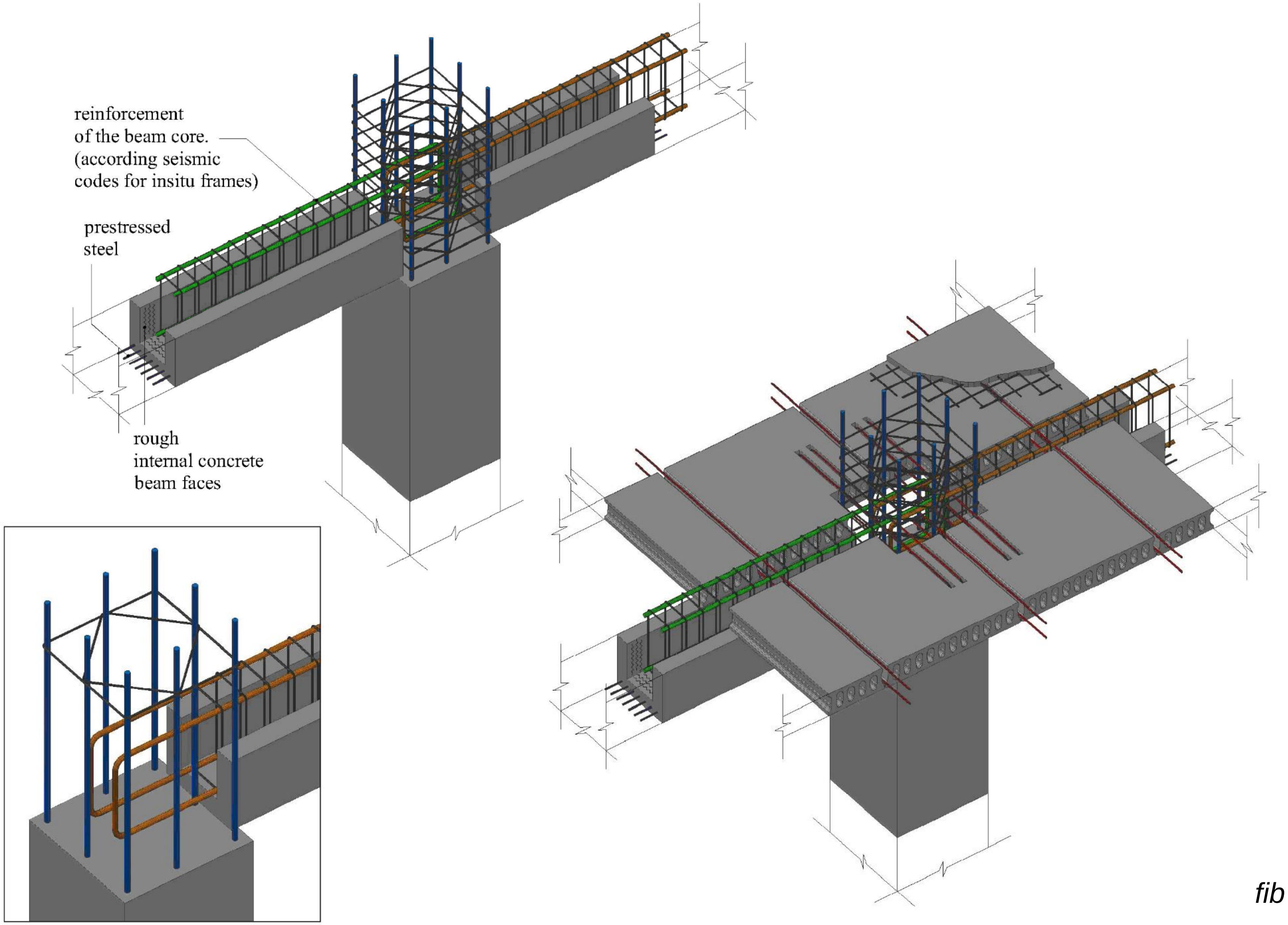
Construction Steps of emulative System S2

(U-shaped or shell beams)



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Example of on-site applications

Bazzano,

L’Aquila 2009


Bazzano,
L'Aquila 2009

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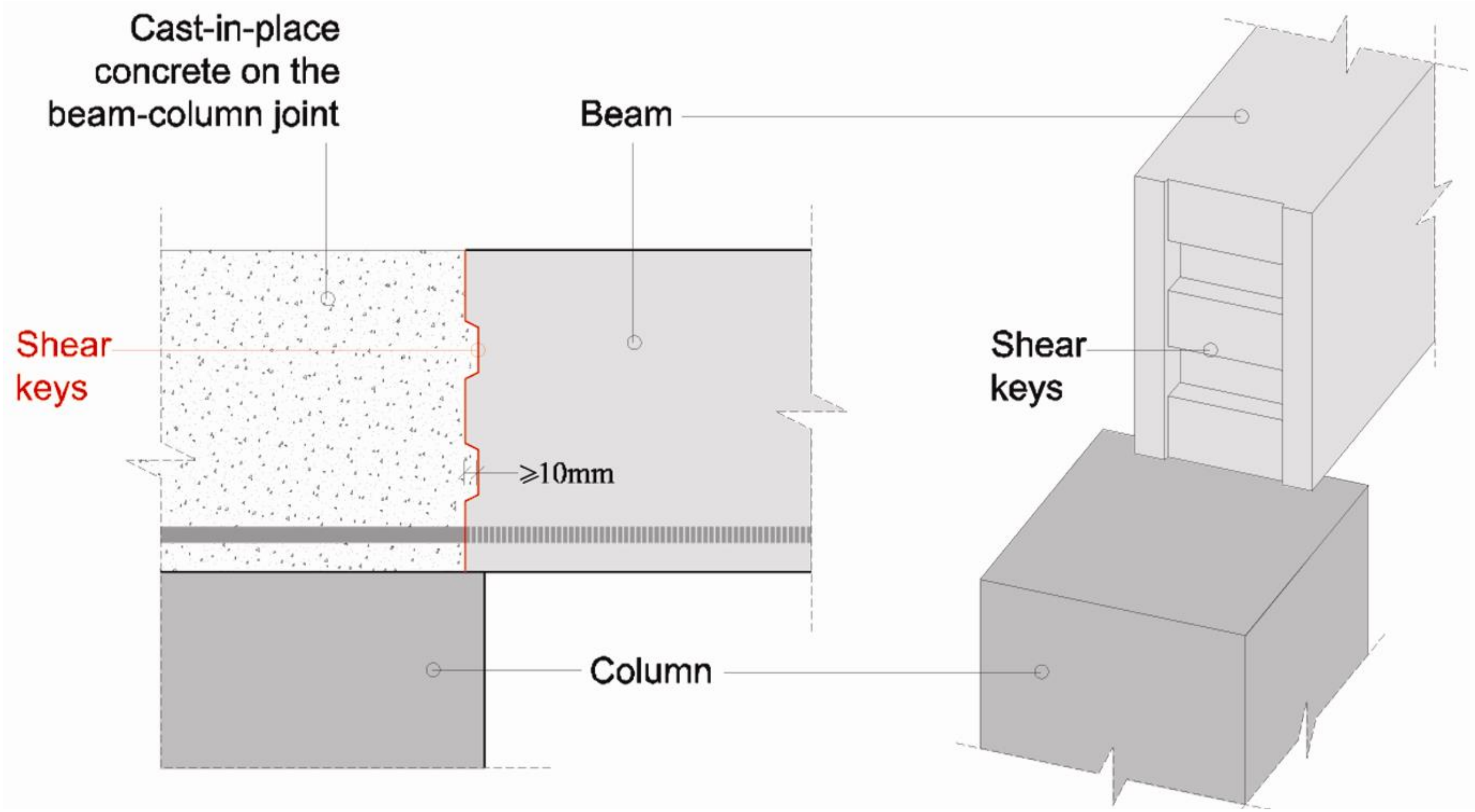
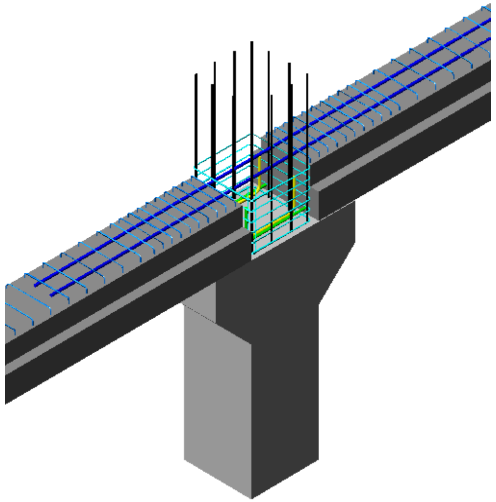
Bazzano, L'Aquila 2009



- **Note:** The **interface** between insitu concrete and beams in the beam-to-column joint cores should be made intentionally **rough** enough to accommodate shear.
- It is recommended that **mechanical shear keys** are created at the vertical ends of the precast beams during casting of precast beams.



Emulative System S1 with corbel

(minimum or no propping required)

Application of System S1 in Turkey
(Photo courtesy of Yapi Merkezi Prefabrication Inc. Istanbul)

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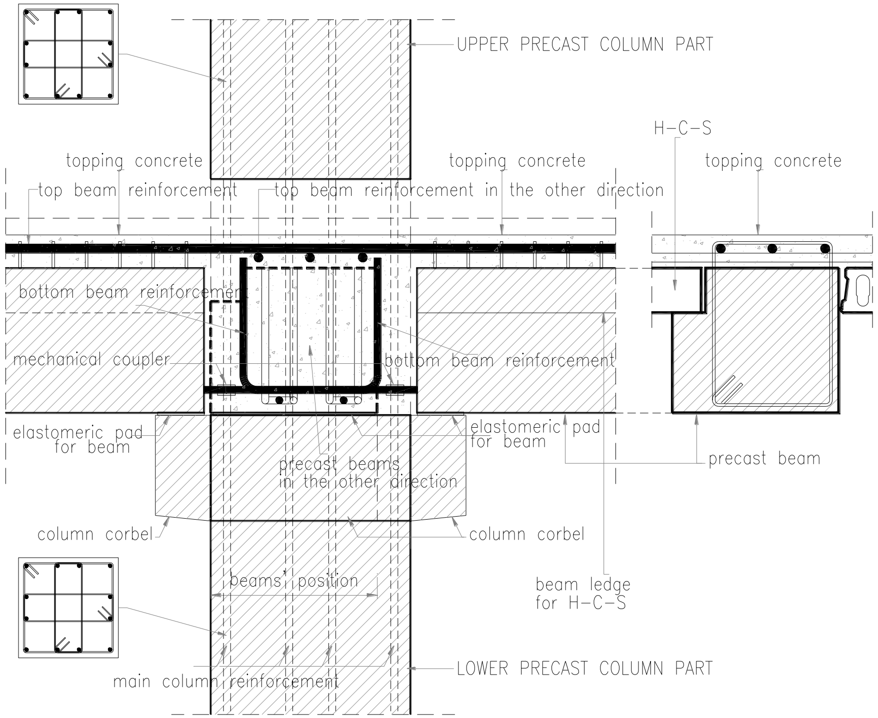
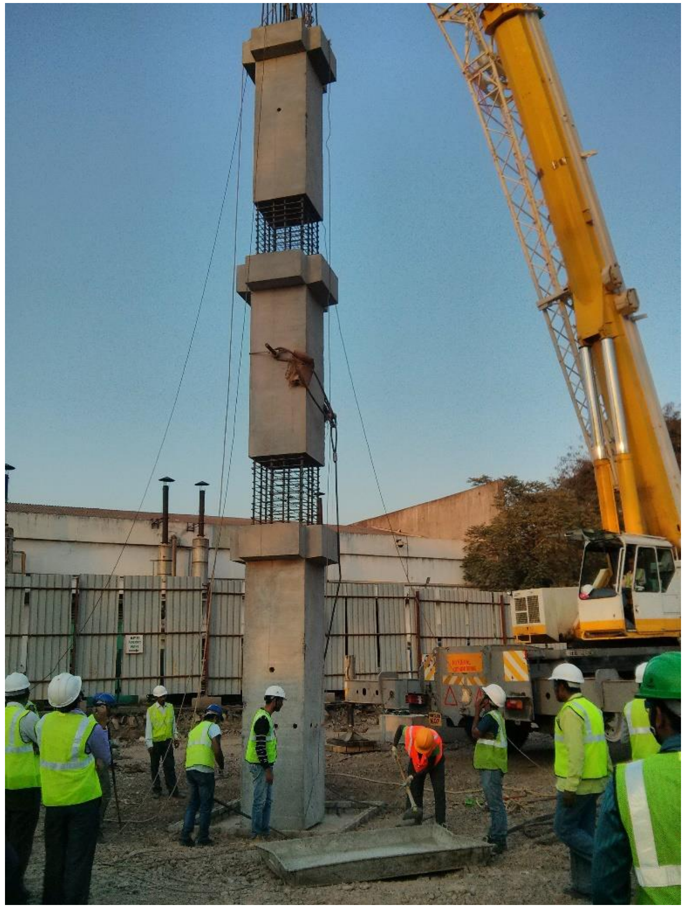
Application of Emulative System S7 (with continuous columns) in Pune-India (courtesy of Precast India Infrastructures PVT LTD - photo by Nagesh Kole)


UPPER PRECAST COLUMN PART
H-C-S
topping concrete
topping concrete
topping concrete
top beam reinforcement
top beam reinforcement in the other direction
bottom beam reinforcement
mechanical coupler
bottom beam reinforcement
elastomeric pad for beam
elastomeric pad for beam
precast beams in the other direction
precast beam
column corbel
column corbel
beams' position
beam ledge for H-C-S
main column reinforcement
LOWER PRECAST COLUMN PART



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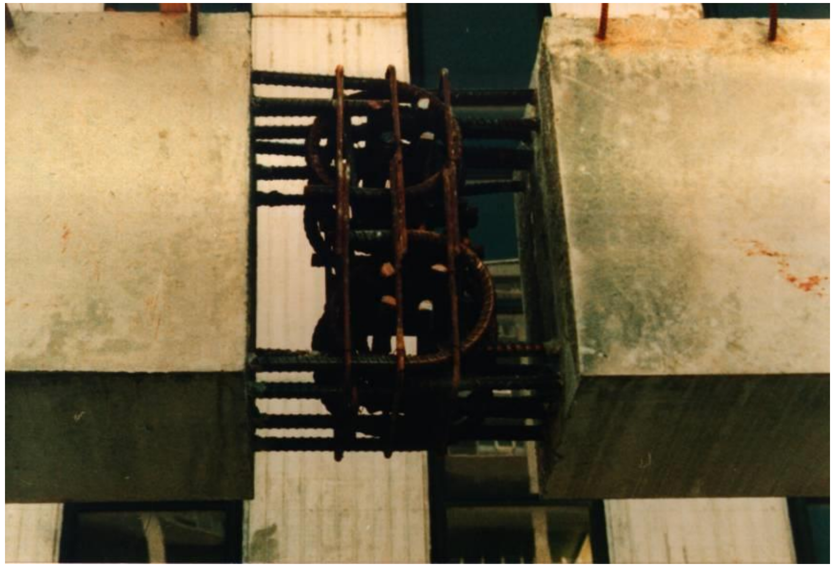
Application of ”Emulative” solutions in New Zealand



Unisys House, Wellington, New Zealand

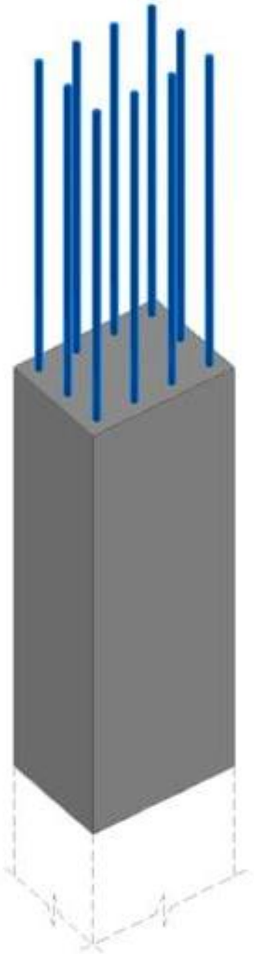
(Photo courtesy of A. O’Leary)

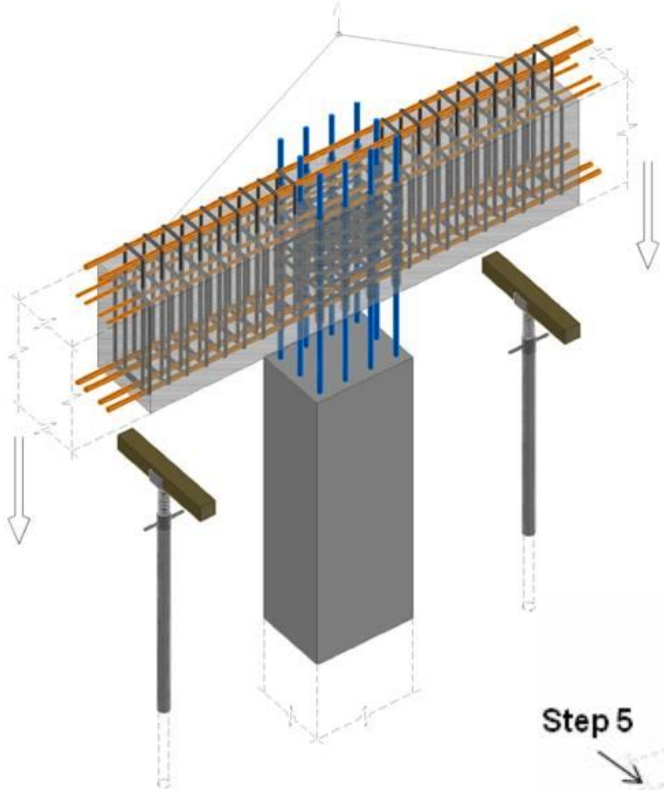
Double vertical cruciform joints

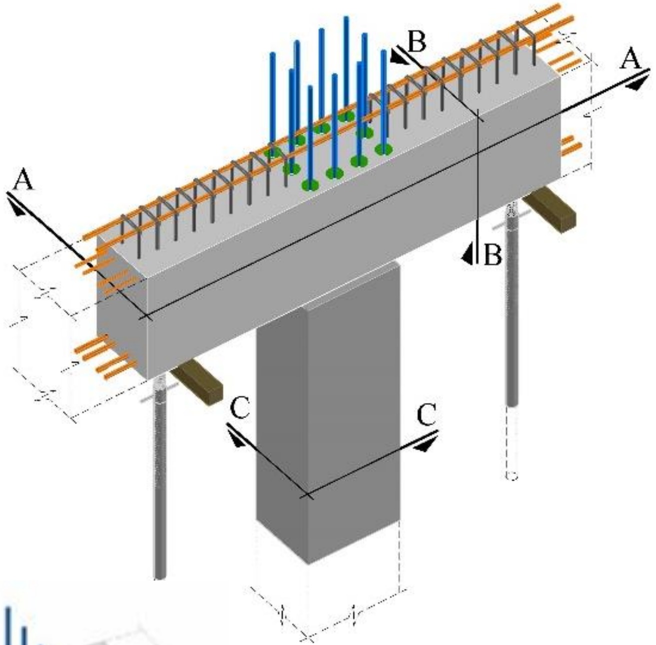
Unisys House, Wellington, New Zealand (Photo courtesy of A. O’Leary)

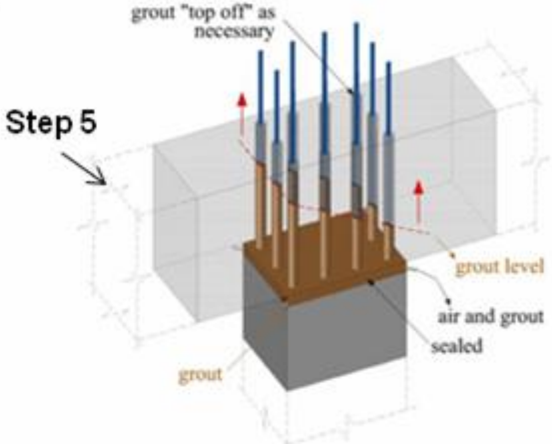
Construction Steps of emulative System S3

(top beam passing through)

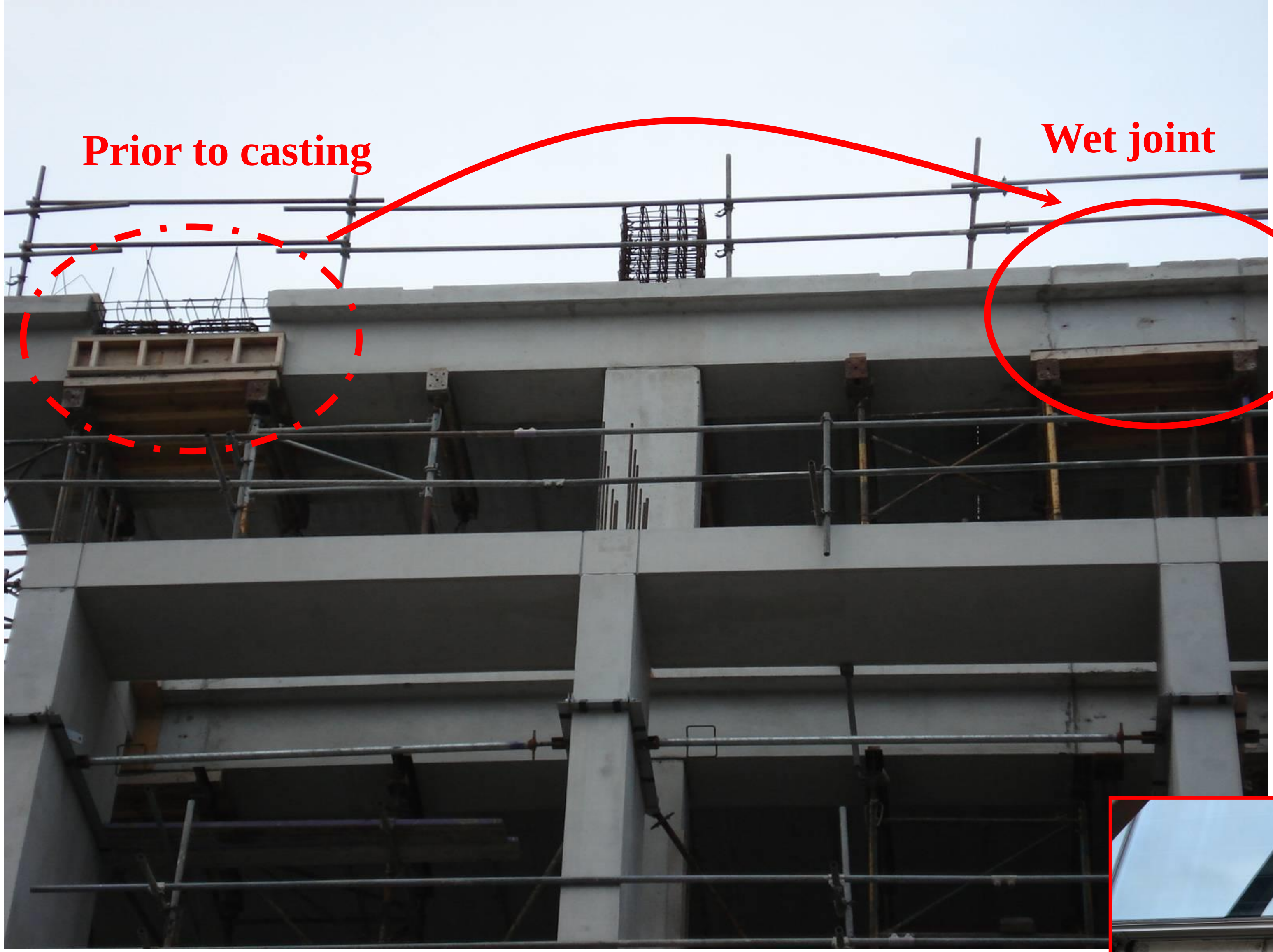








Application of ”Emulative” solutions in New Zealand



Application of
"Emulative" solutions

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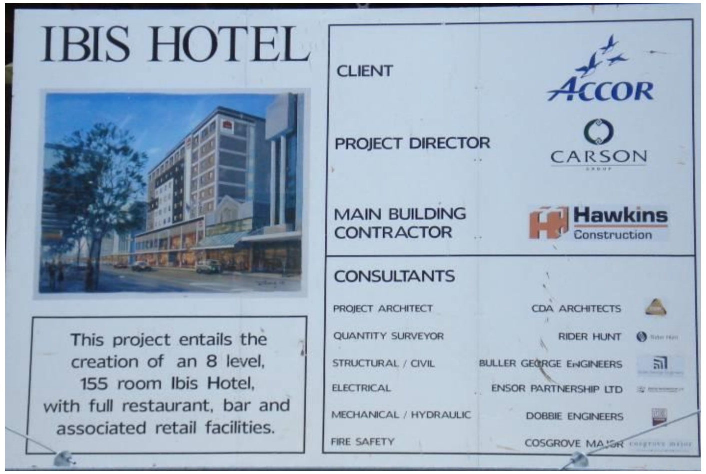
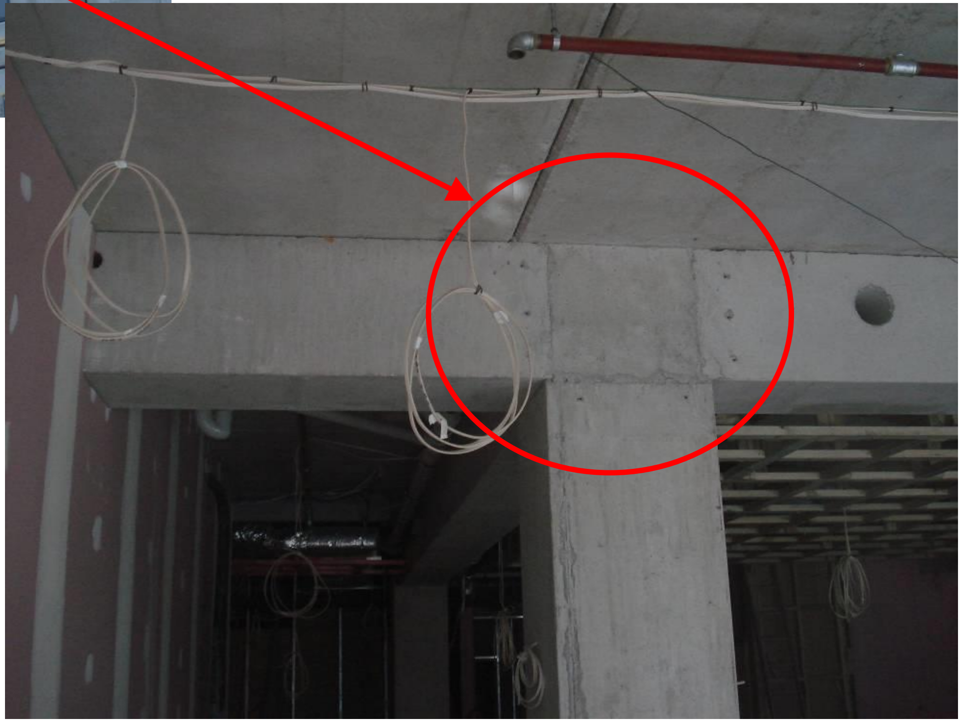
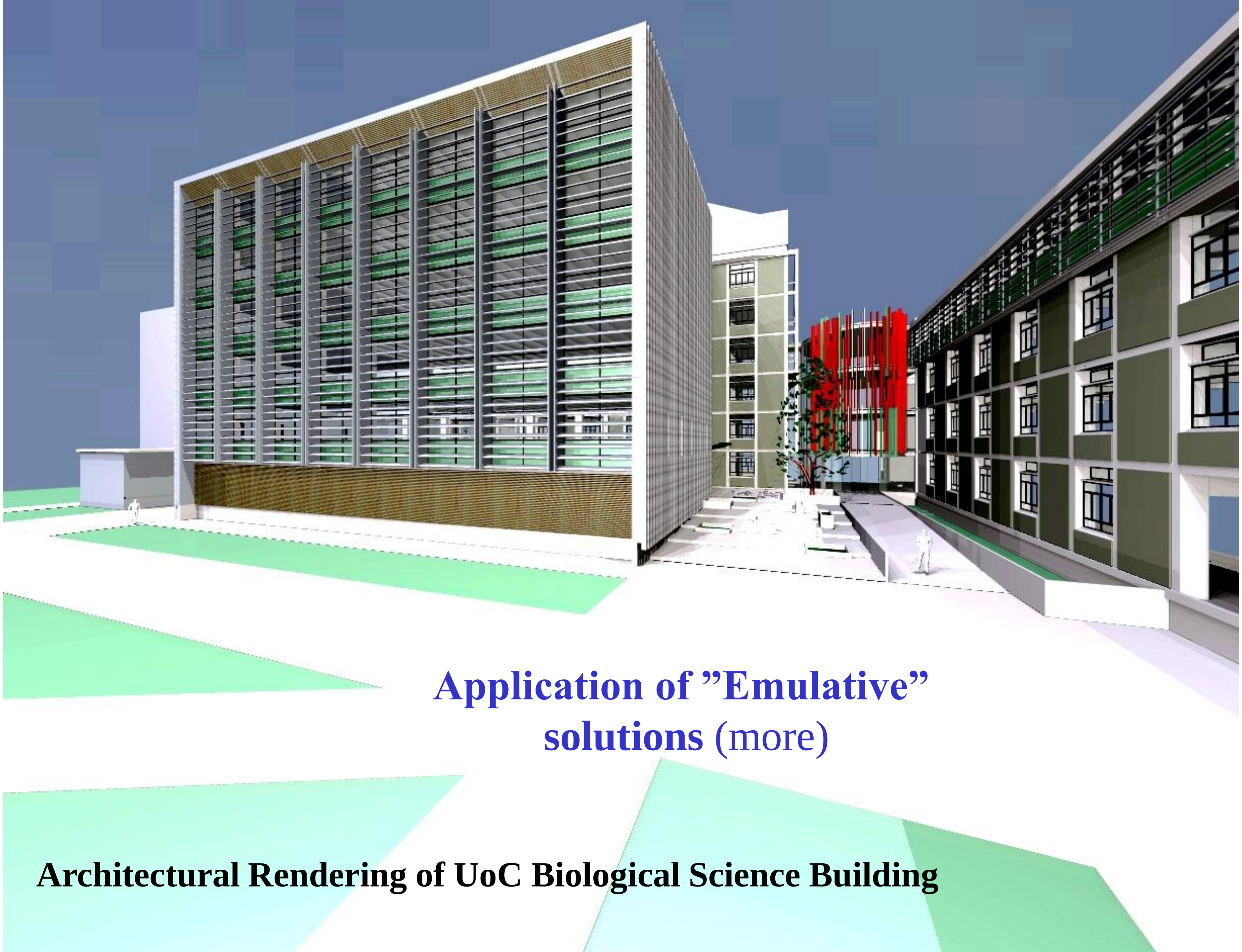
Application of ”Emulative” solutions







Application of ”Emulative” solutions (more)

Architectural Rendering of UoC Biological Science Building

UoC Biological Science Building,,
Christchurch, New Zealand

Double (horizontal) cruciform joints

Beam-to-column "wet" connection

Limits of the “Emulative” approach

- **Does not exploit** the advantages of precast concrete
- **Slow down** the erection speed **(higher costs)**
- **Complexity of connections** and of semi-precasting elements **(higher costs)**

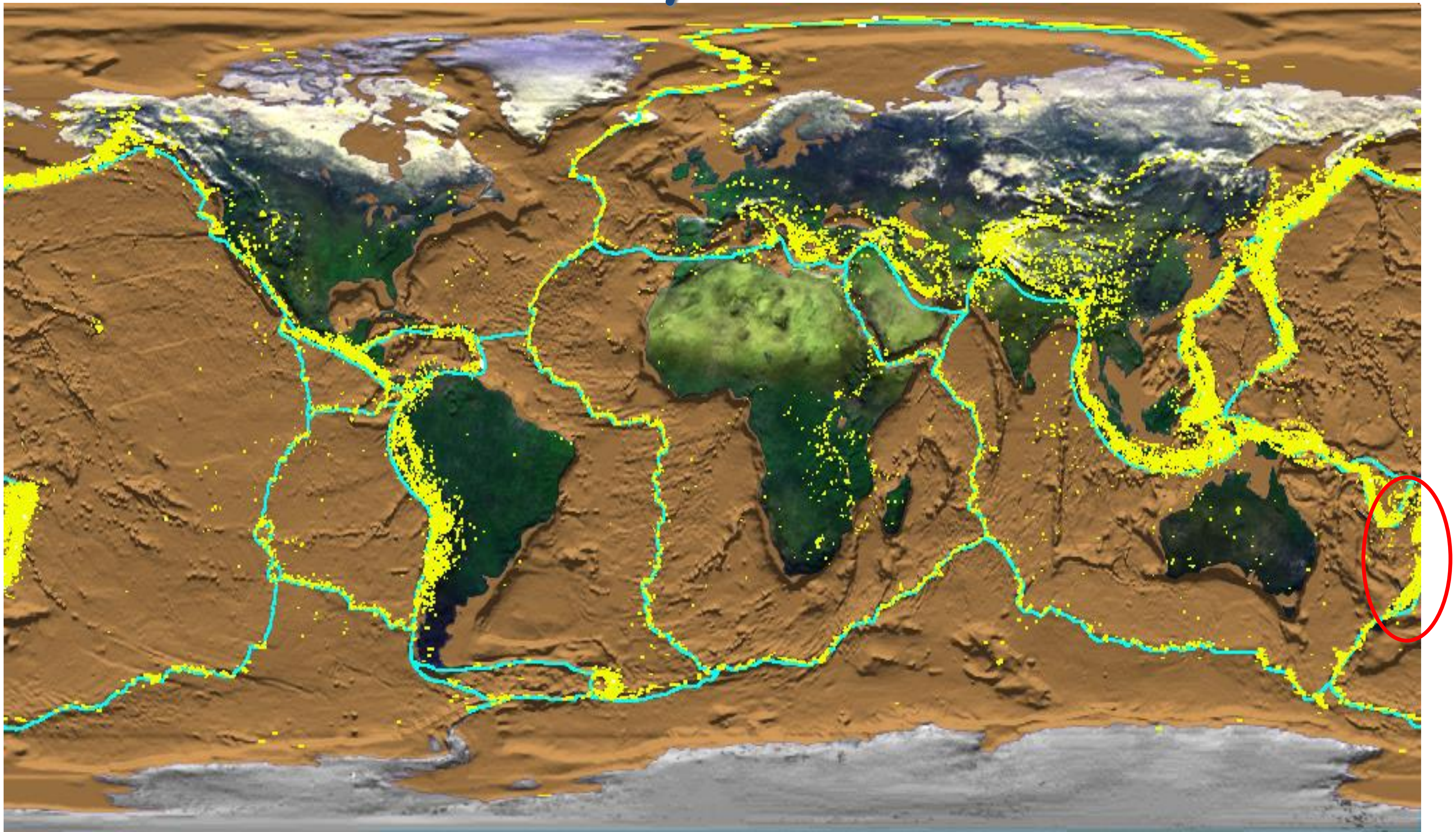
- **As typical of Traditional Ductile Systems**

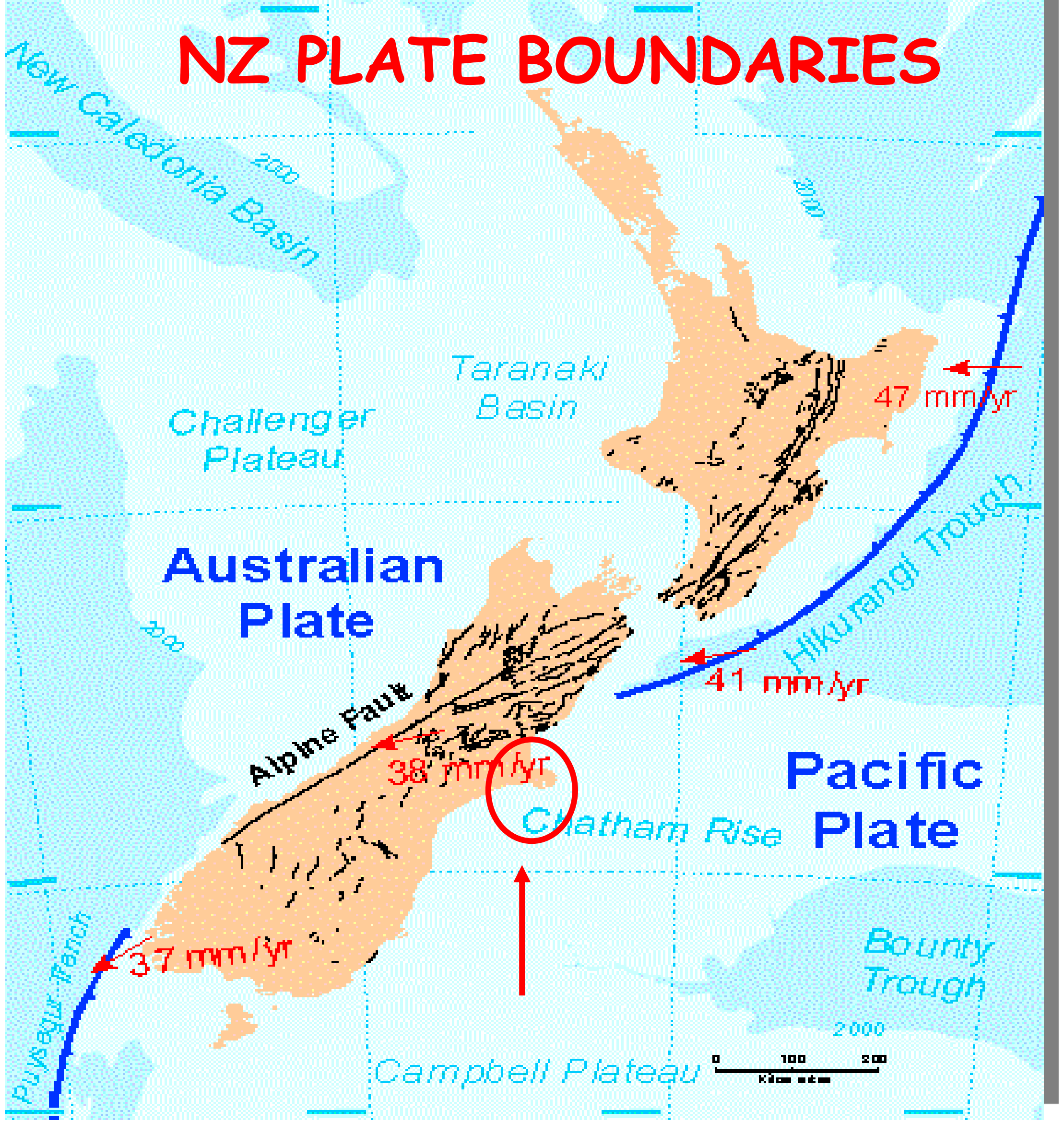
DUCTILITY= (Unavoidable?) DAMAGE

- **Permanent (Residual) Deformations after the earthquake**
- **High Costs of repairing (when feasible and convenient to repair)**

Seismic Performance of modern solutions

A Reality Check..





Christchurch

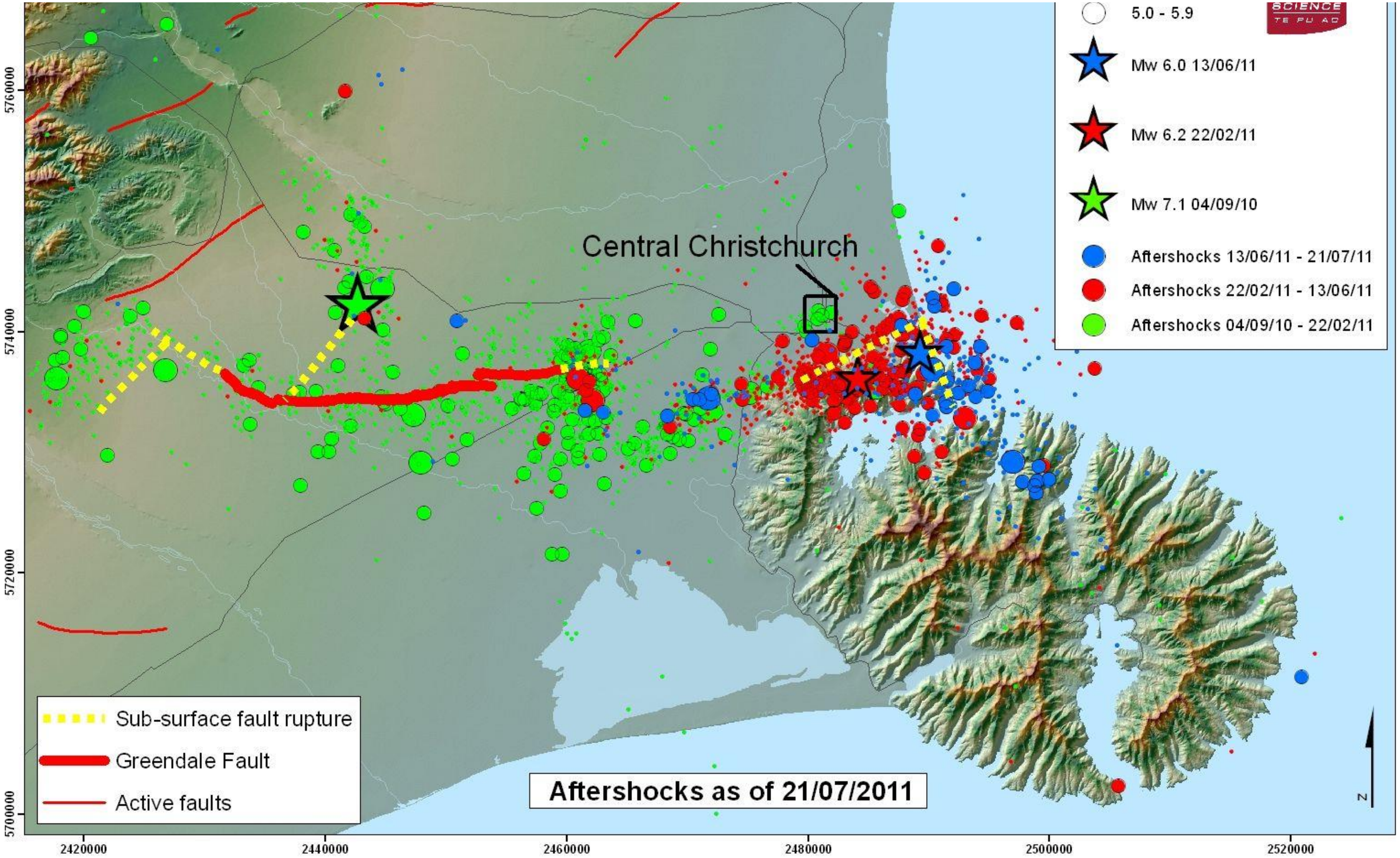
(PGA=0.22g)

“Shaky Islands”

The dramatic "experimental tests"

from the Christchurch Earthquake sequence

(4 Sept 210, 26 Dec 2010, 22 Feb 2011, 13 June 2011...)



12.51pm 22nd Feb 2011…

PGC- Collapsed Reinforced Concrete Building (1960s)

Issues:

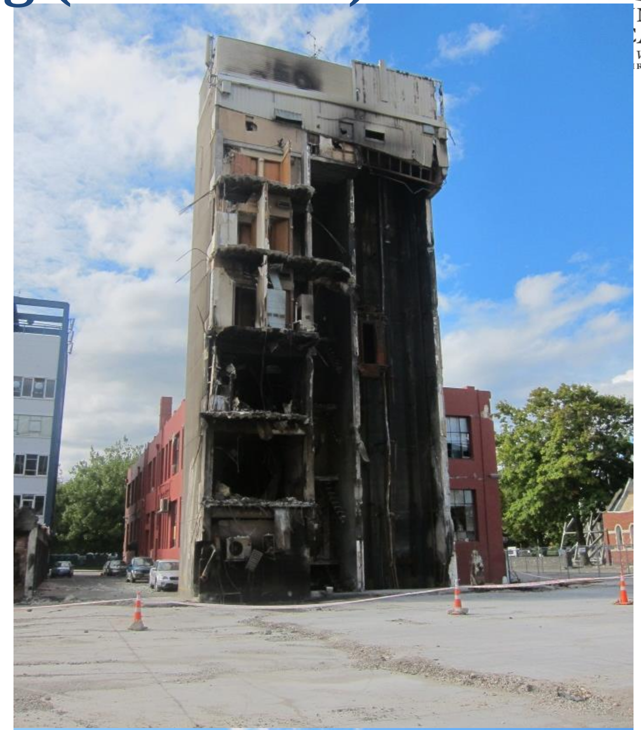
- Design methodology and assumptions (capacity design)
- Lack of Redundancy
- Detailing

PGC Building (Photo courtesy of Weng Y Kam)

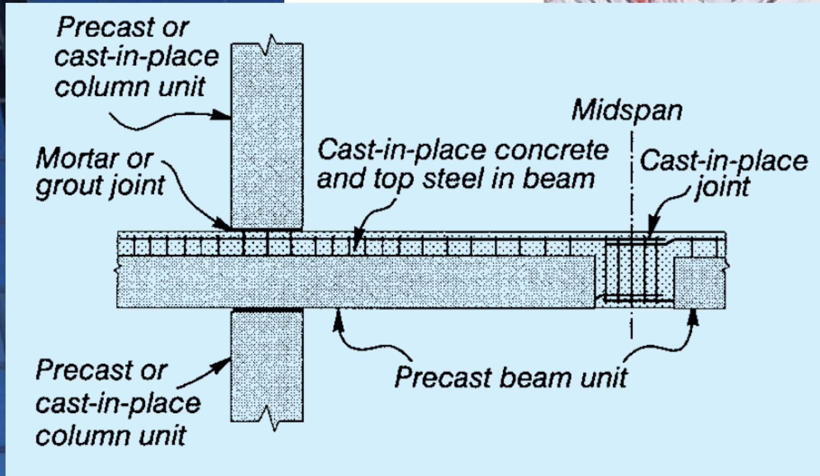
CTV - Collapsed Reinforced Concrete Building (mid 1980s)

Issues:

- Design methodology and assumptions (capacity design)
- Lack of Redundancy
- Detailing



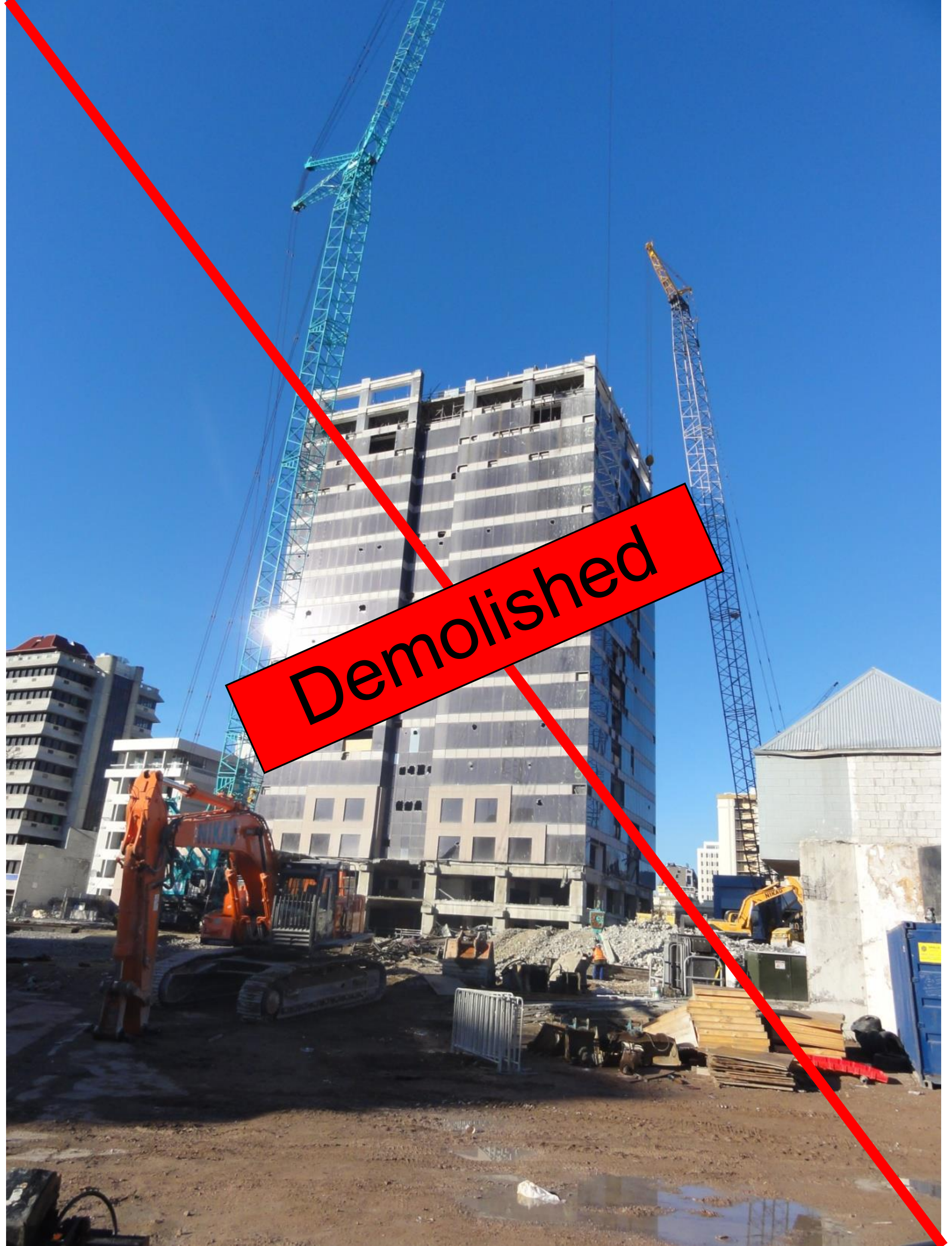
22-storey precast concrete (post-1980s)



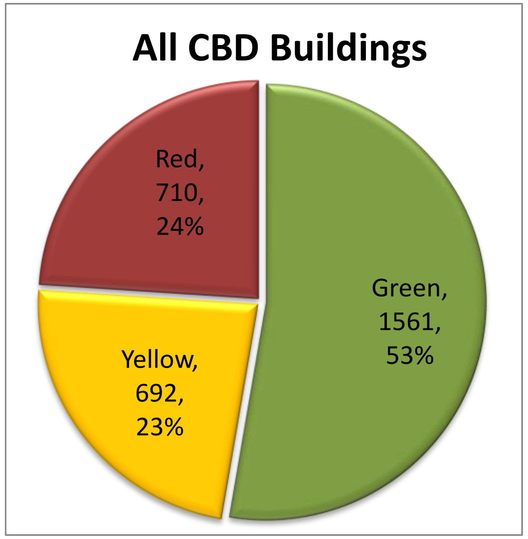
(b) System 2 - Precast Beam Units Through Columns

Extensive **damage (beyond** reparability) to modern Buildings

Typical plastic hinges in beams
(intended to act as sacrificial fuses)



A very common end : Man-made Demolition



As per 12 June 2011
Source: CCC Data
(Kam, Pampanin, Elwood, 2012)

"But they [buildings] did what they were meant to do"


CERA
Canterbury Earthquake
Recovery Authority
00:26
HD
vimeo


CERA
Canterbury Earthquake
Recovery Authority
LATER
SHARE
EMBED
SCALING IS ON
00:29
HD
vimeo

Rebuilding a SAFER and RESILIENT community

Photo courtesy of
Kam Yuen Weng and Umut Akguzel

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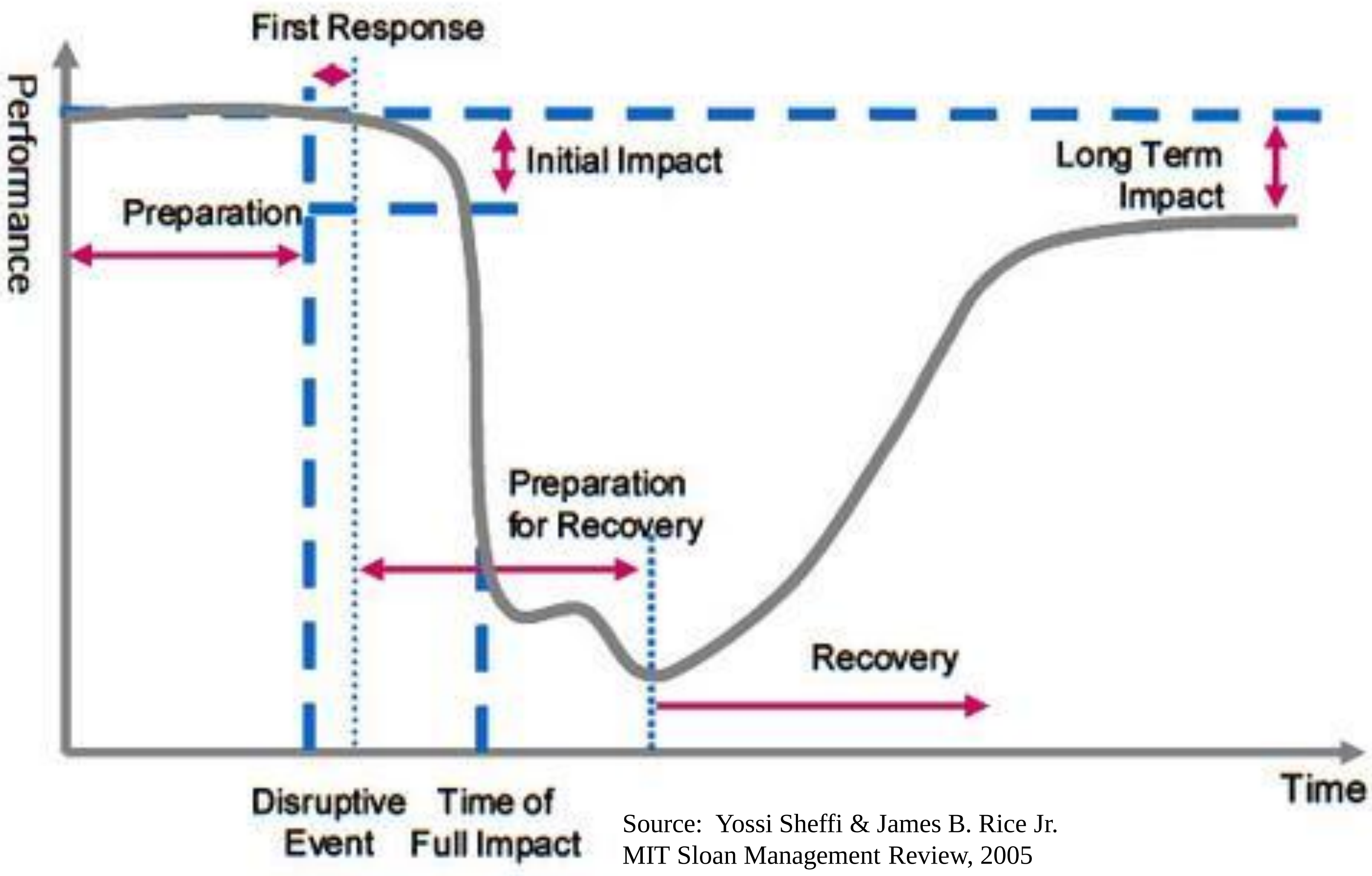
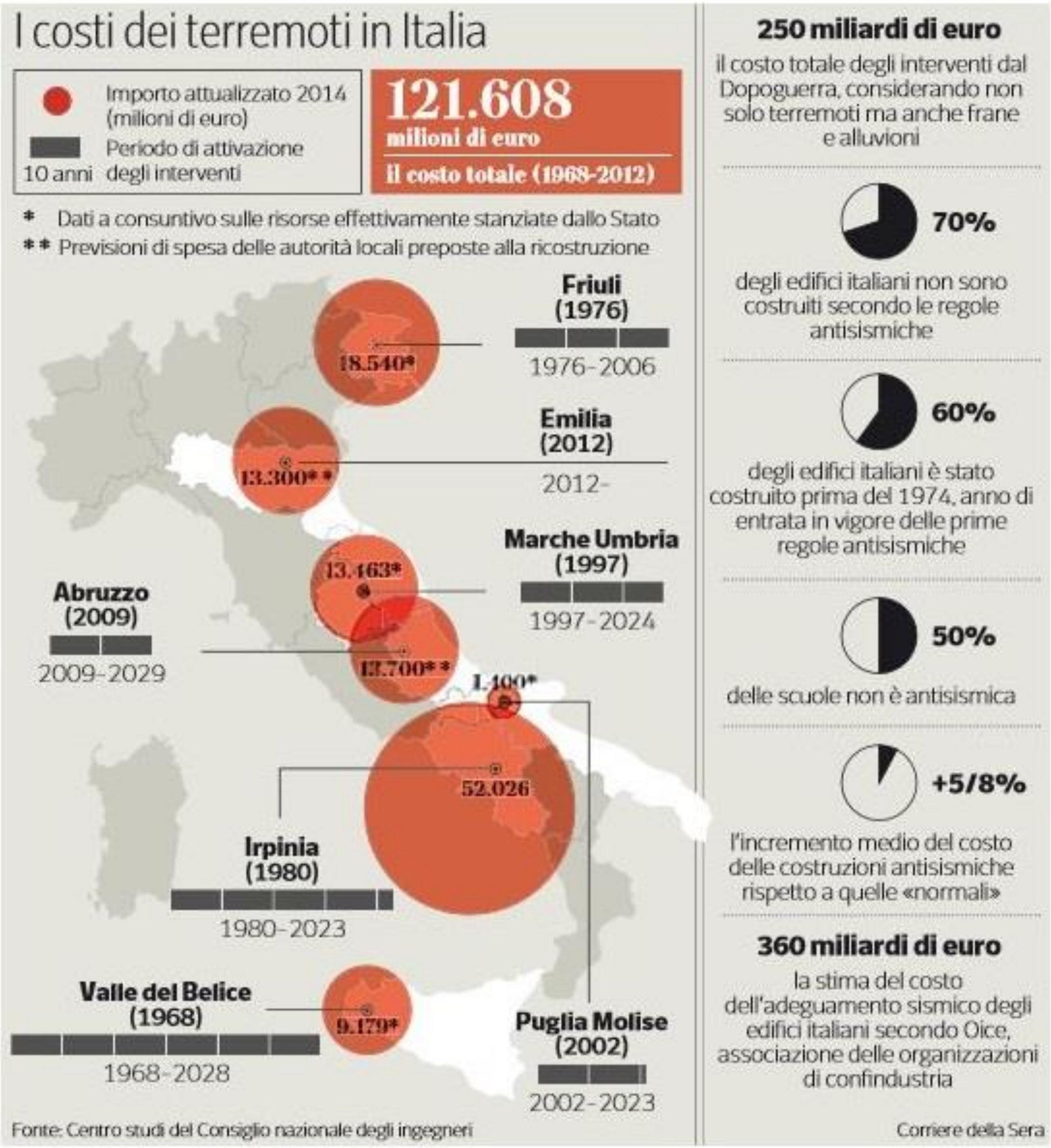
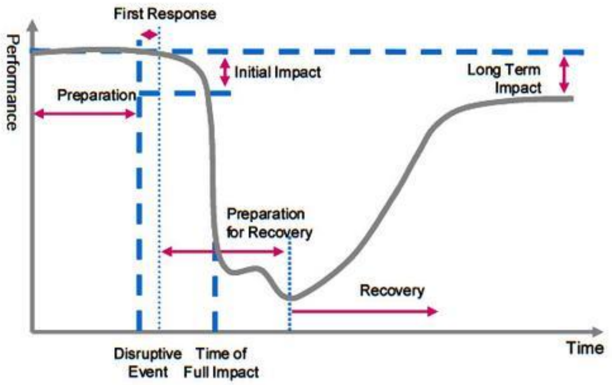
The Concept of Resilience



Source: Yossi Sheffi & James B. Rice Jr.
MIT Sloan Management Review, 2005



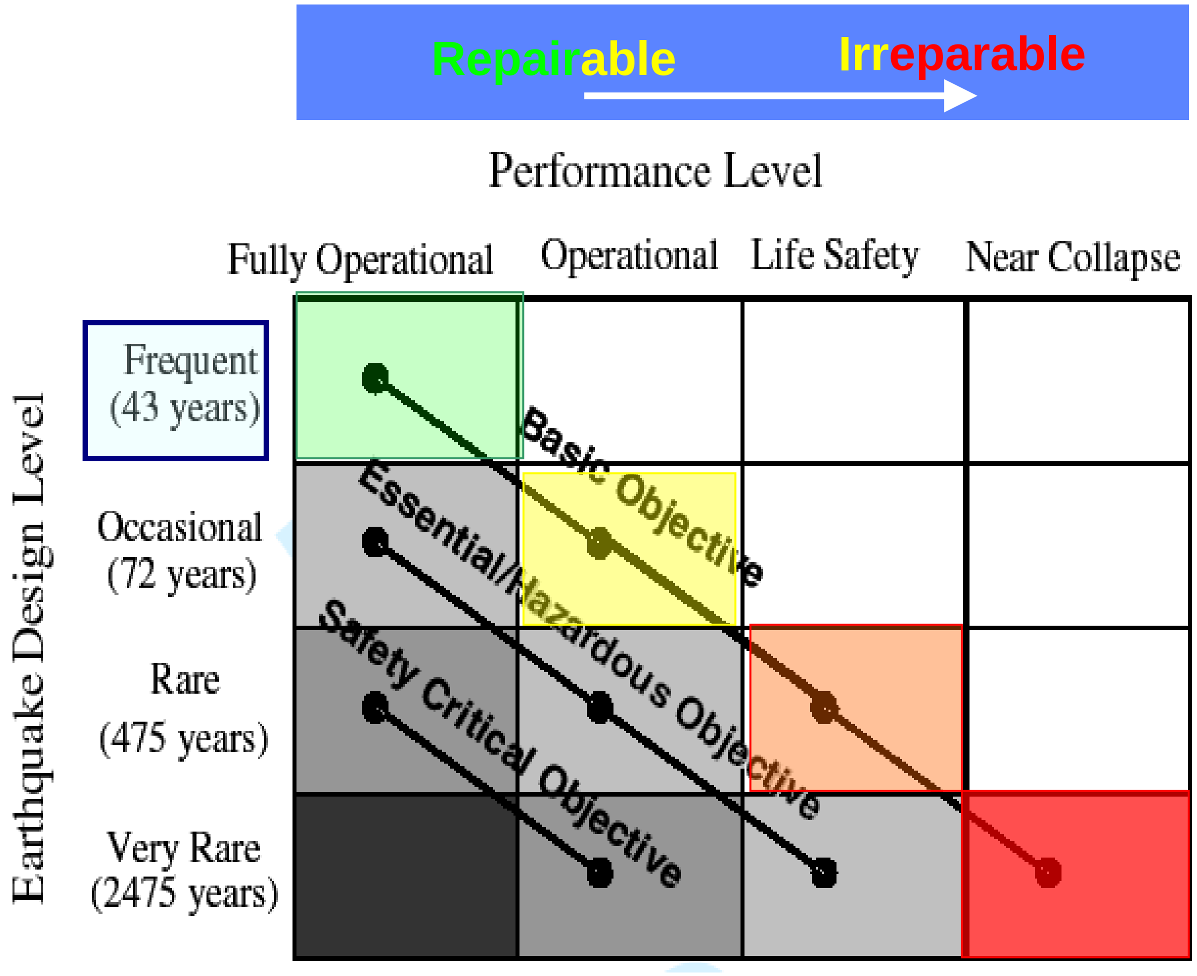


Costi indiretti?
Indirect Costs?

c.a. 1500-2000 miliardi (billions) in 40 anni (years)

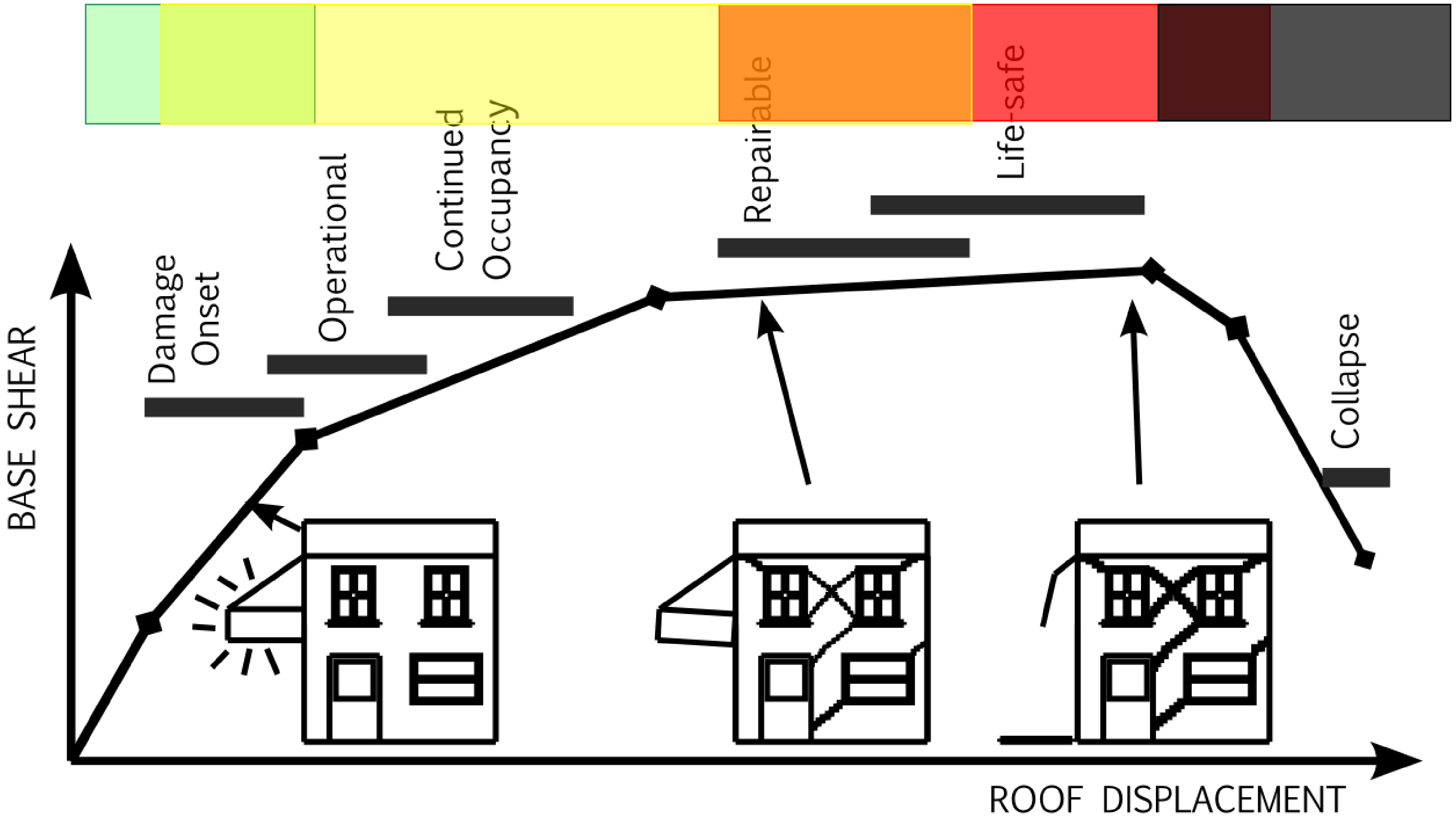
=40 miliardi all'anno (billions/year)

“Our” understading of Earthquake-Resistant



From SEAOC Vision 2000 (1995)

Which means.....



Modified after Hamburger and Mohele, 2000

Fallacy

*The Code-Standard is **NOT** meant to be used as a Target or Ultimate Goal but as a minimum by law*

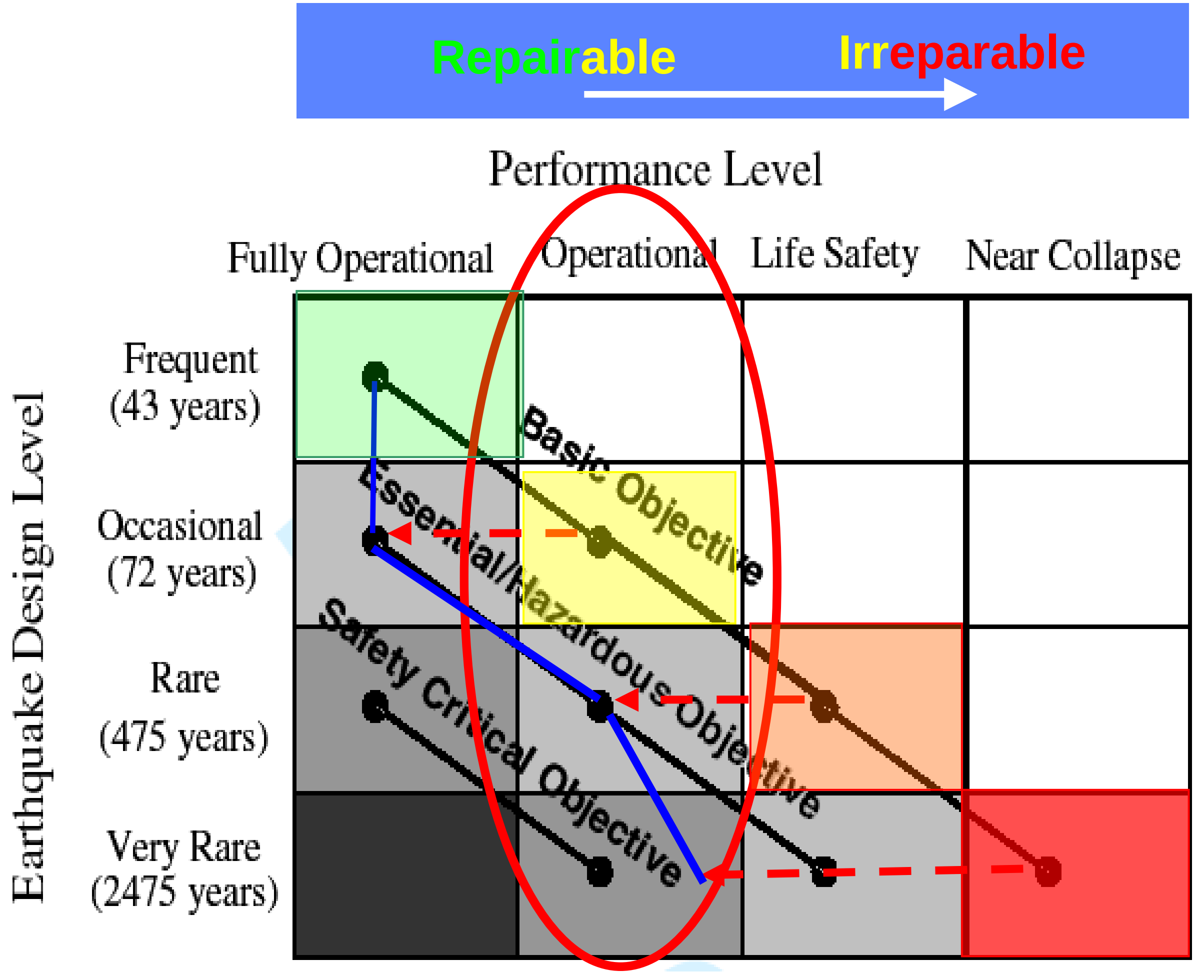
Corollary

Earthquake-Resistant ≠ *Earthquake-Proof*

(earthquake engineering community's view)

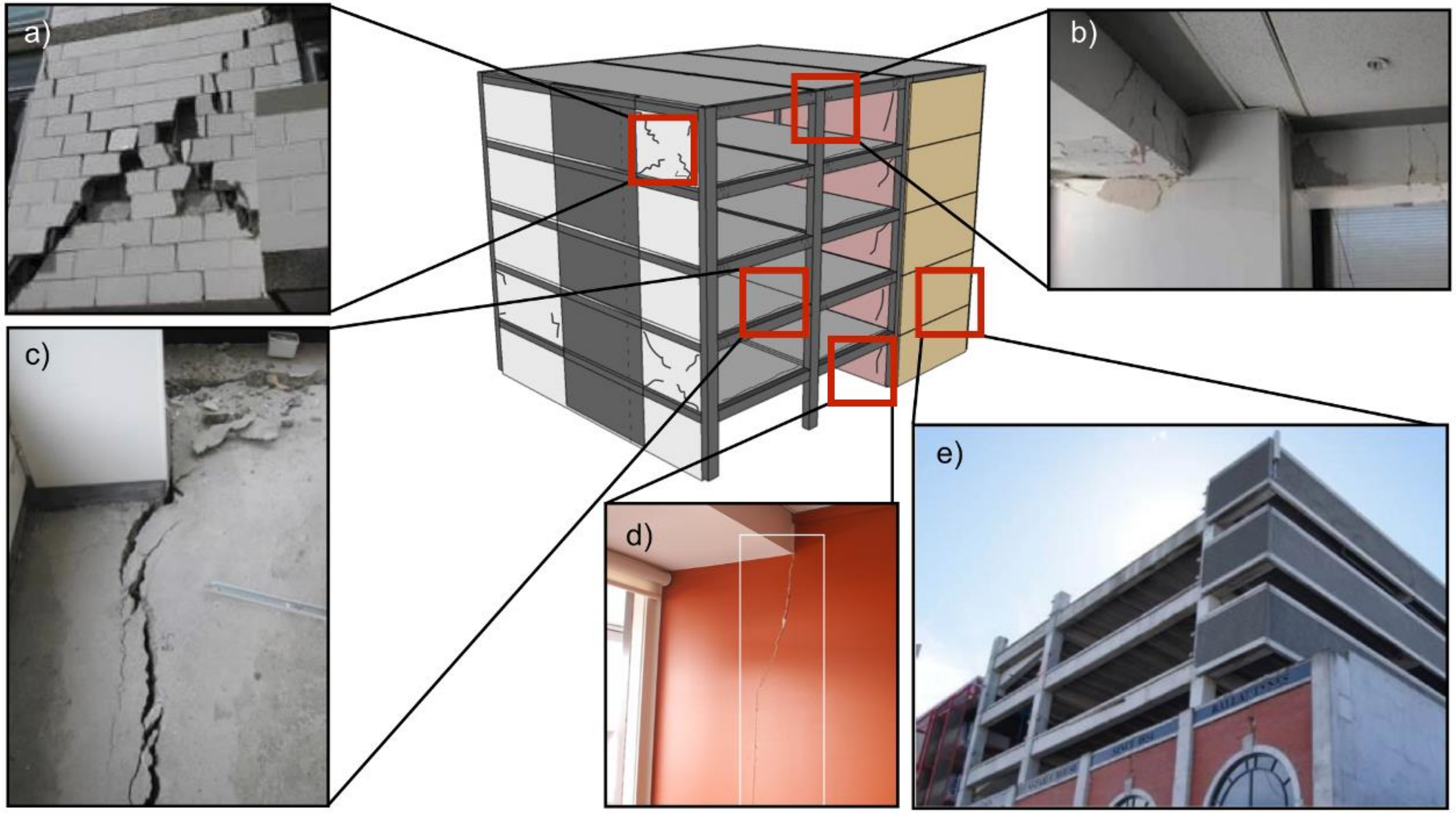
(everyone else's view)

The Renewed Challenge of Eartquake Engineering: Raising the bar to meet Society's Expectations



Towards the "Ultimate Earthquake Proof-building"
Shake-table testing of an integrated low-damage system

from Johnston, Watson, Pampanin, Palermo (2013, 2014)



Typical damage to structural and non-structural components in New BUILDINGS (Traditional Emulation of Cast-in-situ approach)

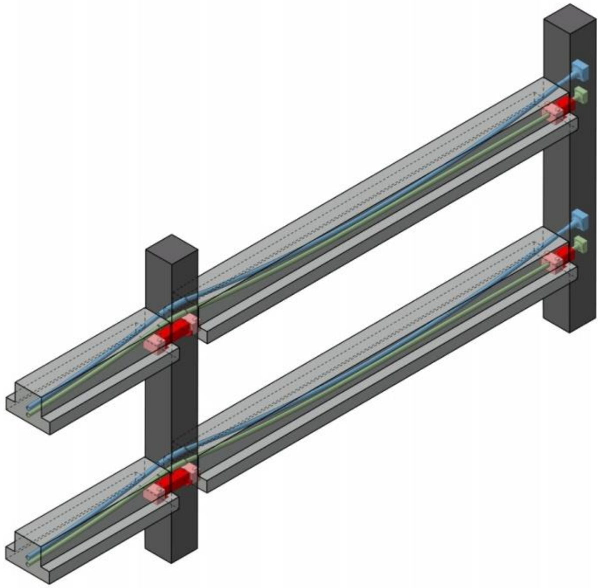
“JOINTED DUCTILE”

CONNECTIONS

(Low-Damage Technology)

New Generation of Seismic Resisting Systems
Introduction to PRESSS-technology

Prof. Ing. Stefano PAMPANIN



PRESSS-Technology
(PREcast Seismic Structural System)

Five-Storey Test-Building (UC San Diego, Aug 1999, coordinator Prof. M.J.N. Priestley)

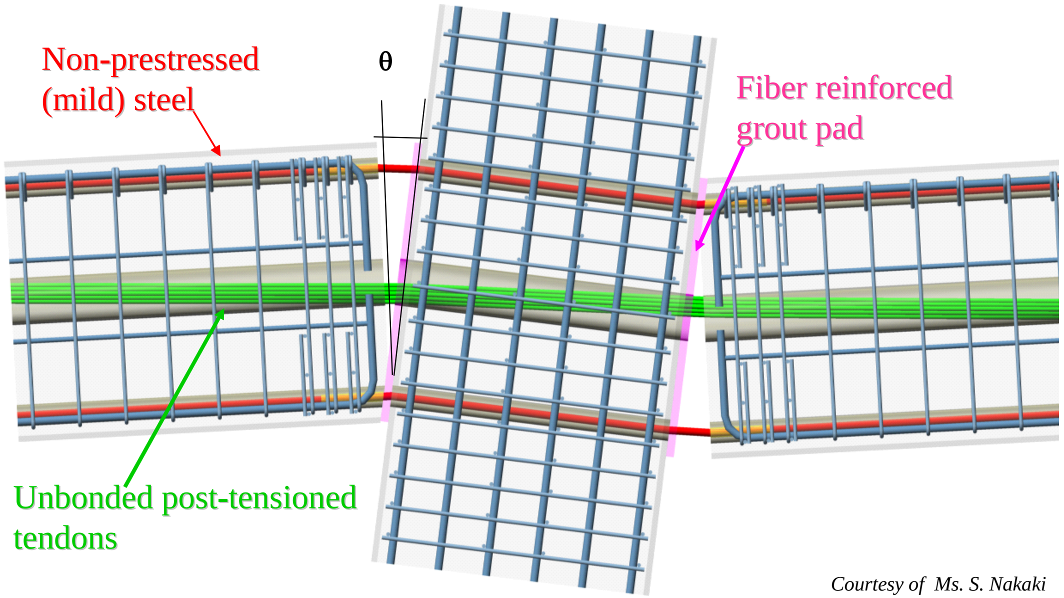
New Generation of Damage-Resisting systems

- **Jointed Ductile** DRY connections assembled by post-tensioning techniques
- inelastic demand accomodated within the connection

- **Hybrid systems** : combination of unbonded post-tensioning AND dissipaters

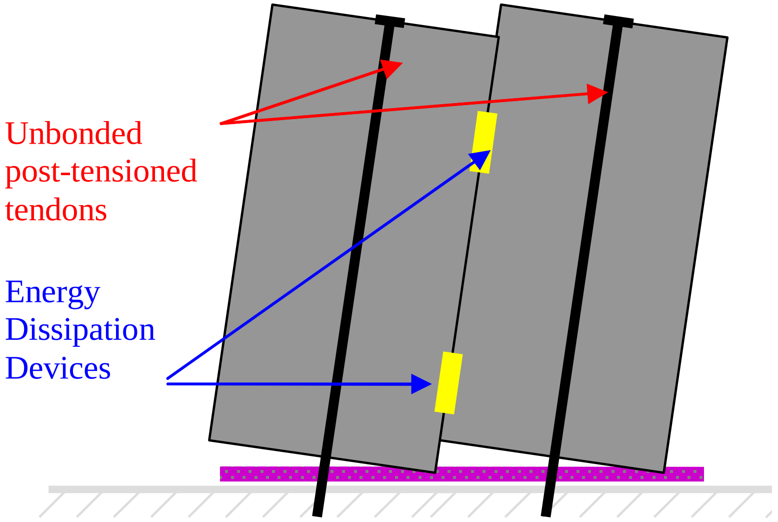
- **"Controlled Rocking"** :
  - Reduced *level of damage*
  - Negligible *residual (permanent) deformations* (recentering)

FRAMES

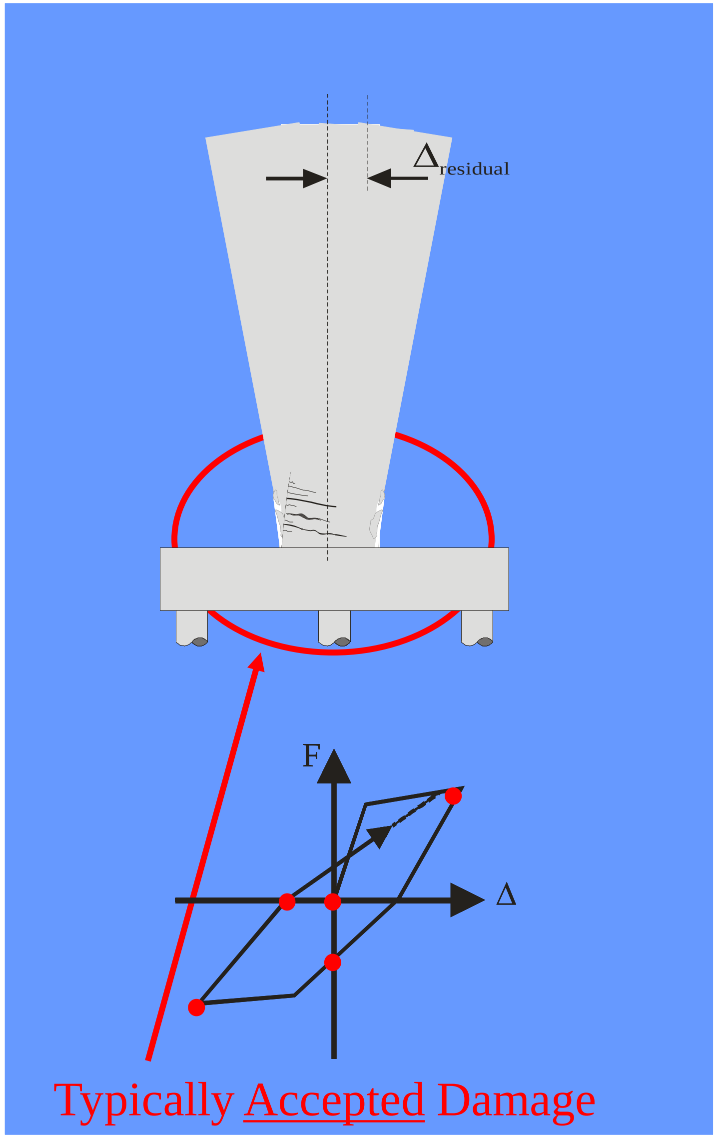


Courtesy of Ms. S. Nakaki

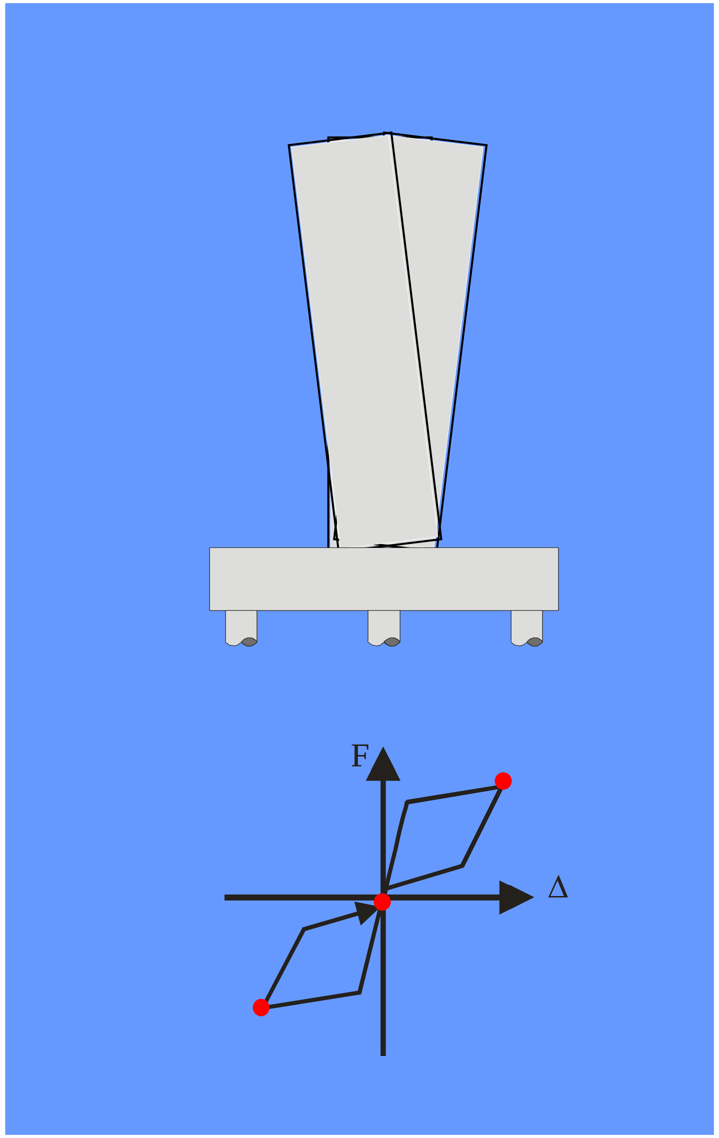
WALLS



Traditional (monolithic)

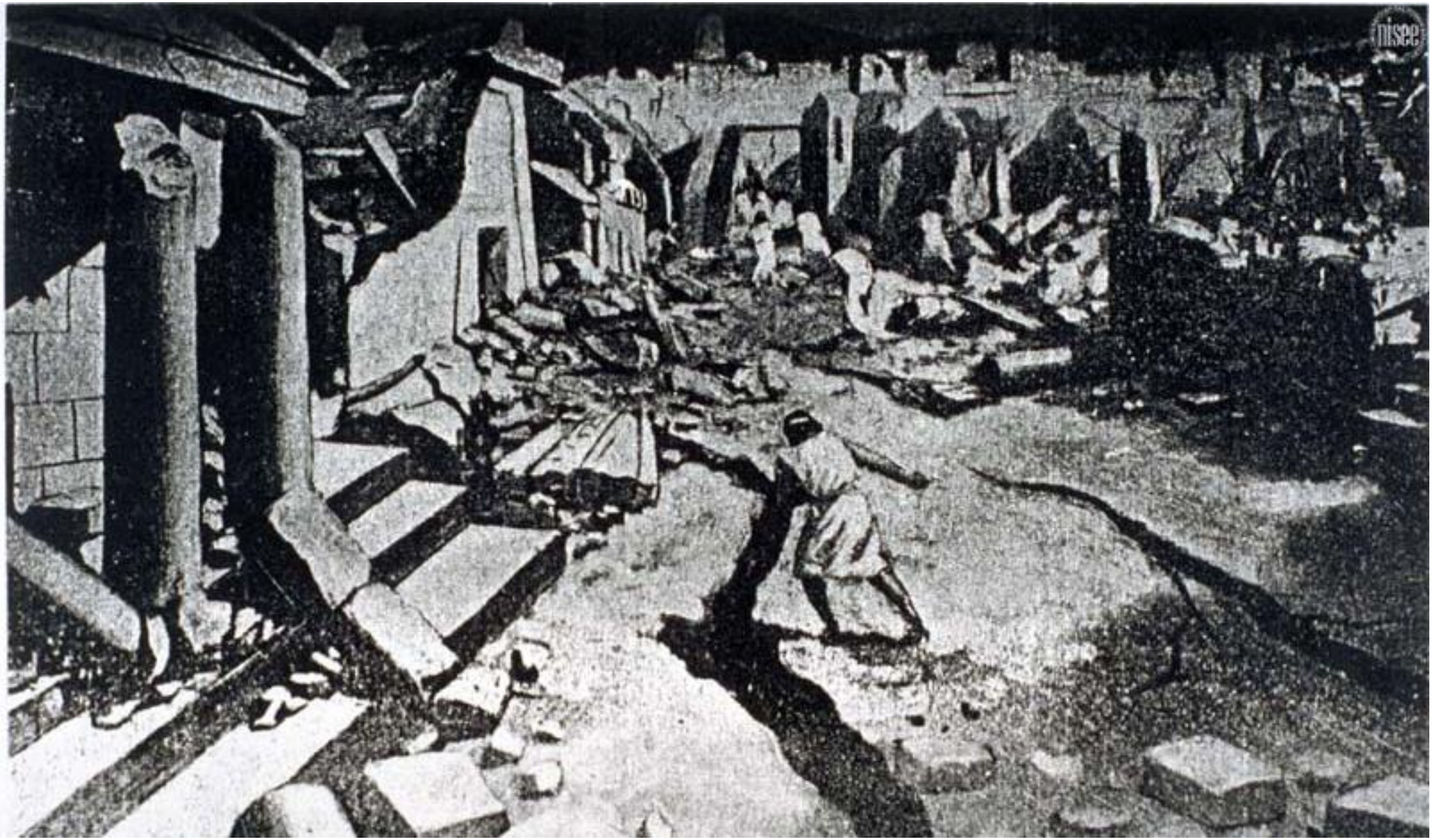


New generation (jointed ductile)



courtesy of Dion Marriott

Learning from our ancestors

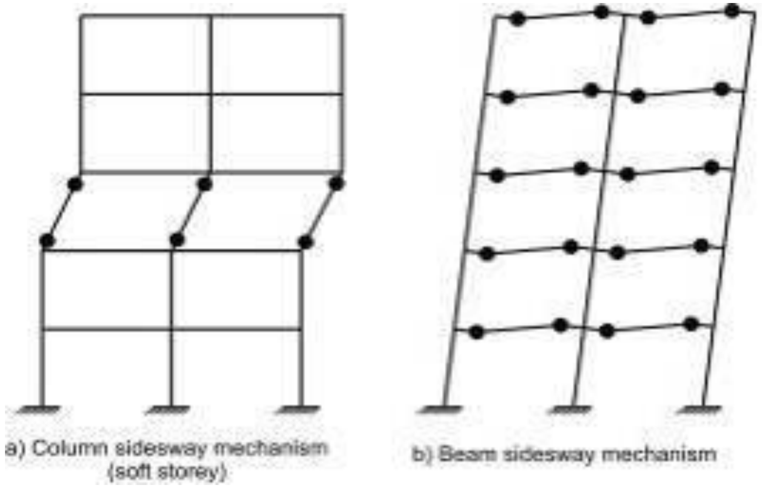


What a brilliant legacy from our Ancestors

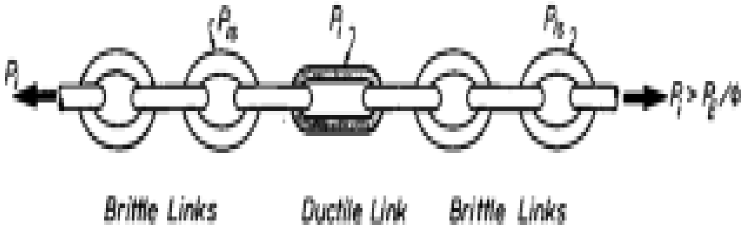
Temple of Haephestus, Ancient Agora’, Athens

A paradigm shift

❑ Changing the way of thinking at "plastic hinges"



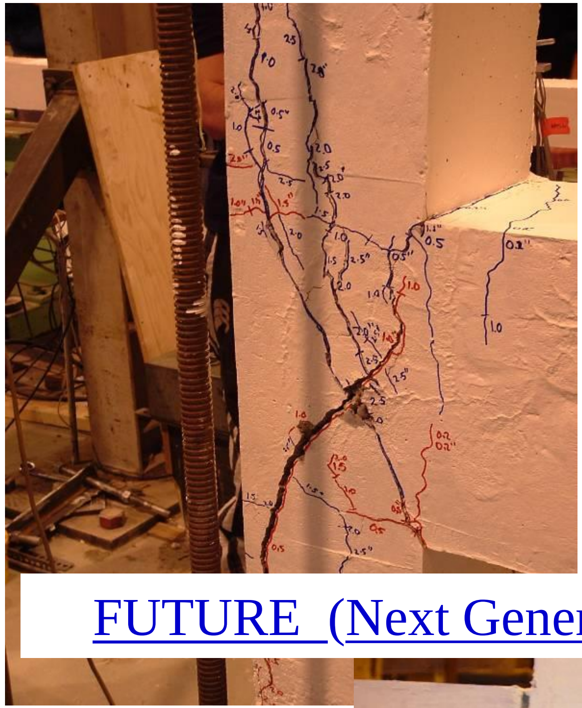
❑ Fully exploiting the concept of Capacity Design



❑ Ductility NOT anymore = damage

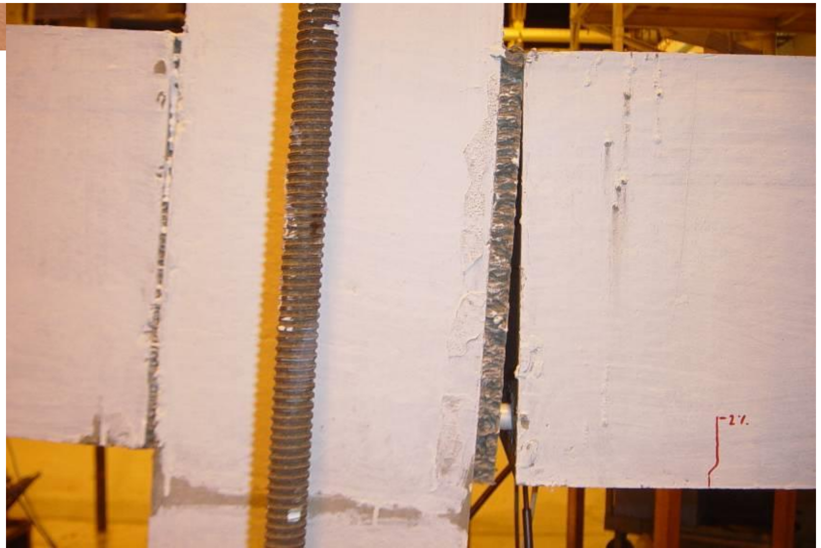
Historical Developments in Seismic Design Philosophy

PAST (pre-1970s codes)



PRESENT (post-1970s codes)

FUTURE (Next Generation of codes: NZ 3101:2006 (Appendix B)



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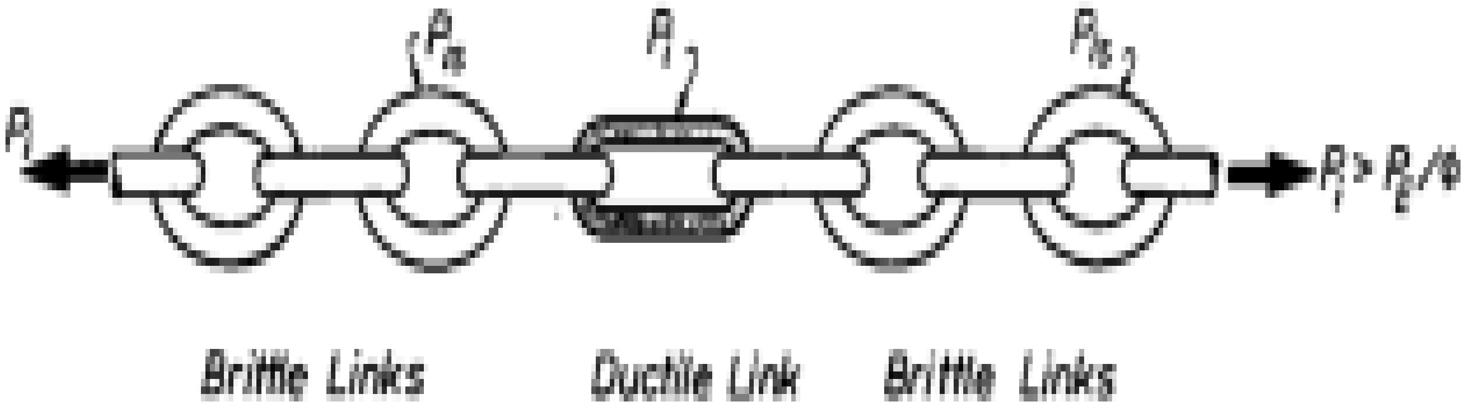
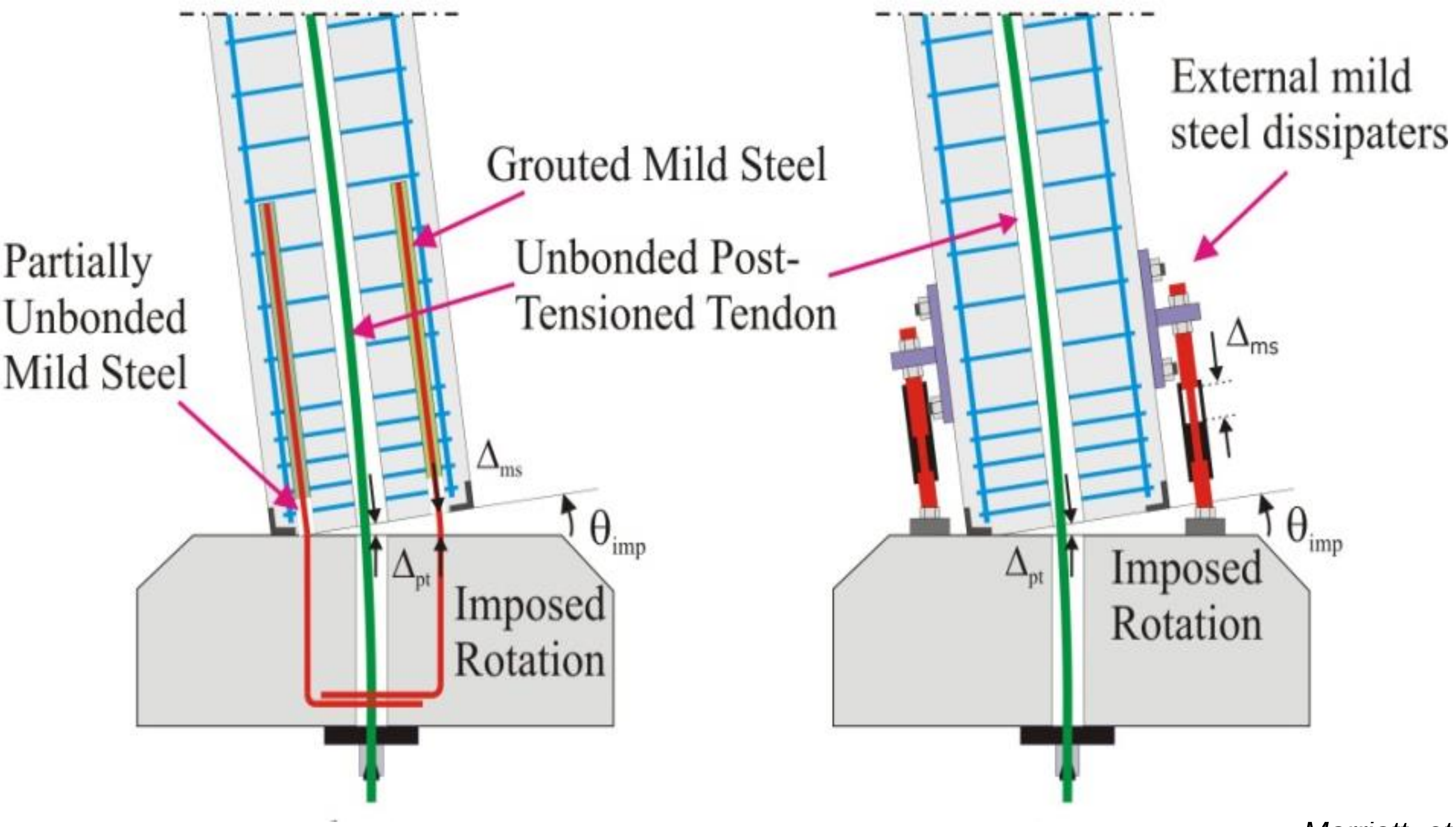
One Further Step Ahead:

Repairability of the Weakest Link of the chain

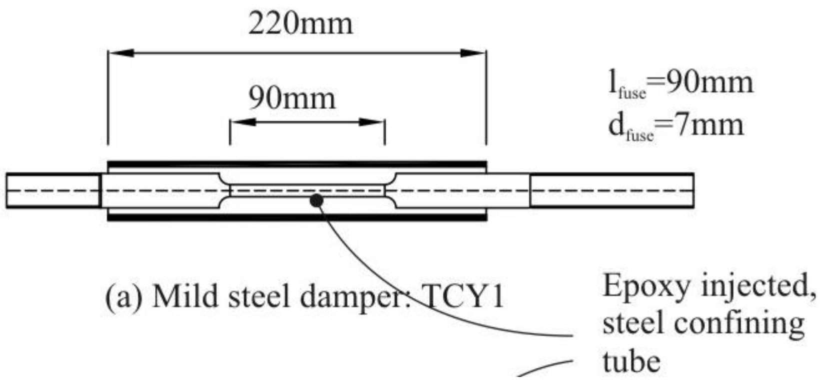


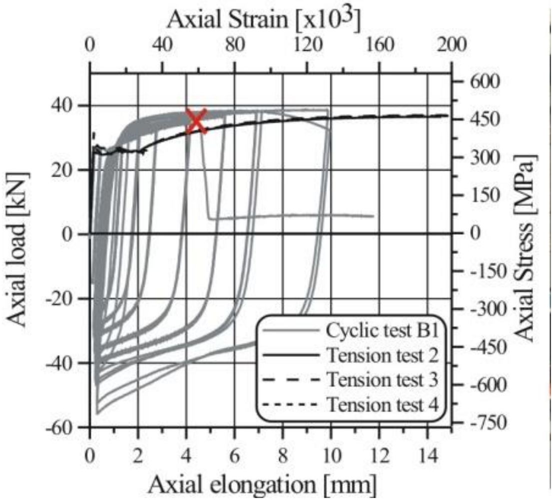
External &Repleacable Dissipaters
("Plug & Play")



Marriott et al., 2008

The "Plug & Play" dissipater





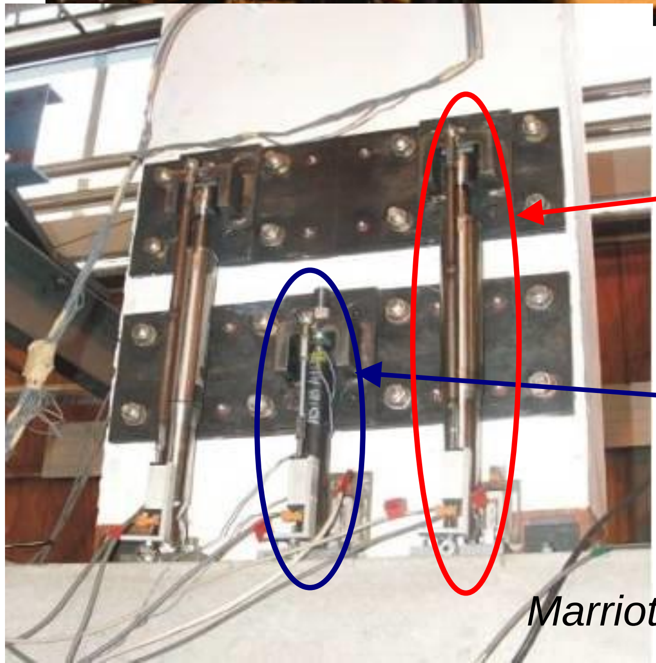
Pampanin et al., 2005

Earthquake Event or Aftershock?

(you can simply check and replace
the Plug&Play fuses)

Alternative “architecture” Configurations

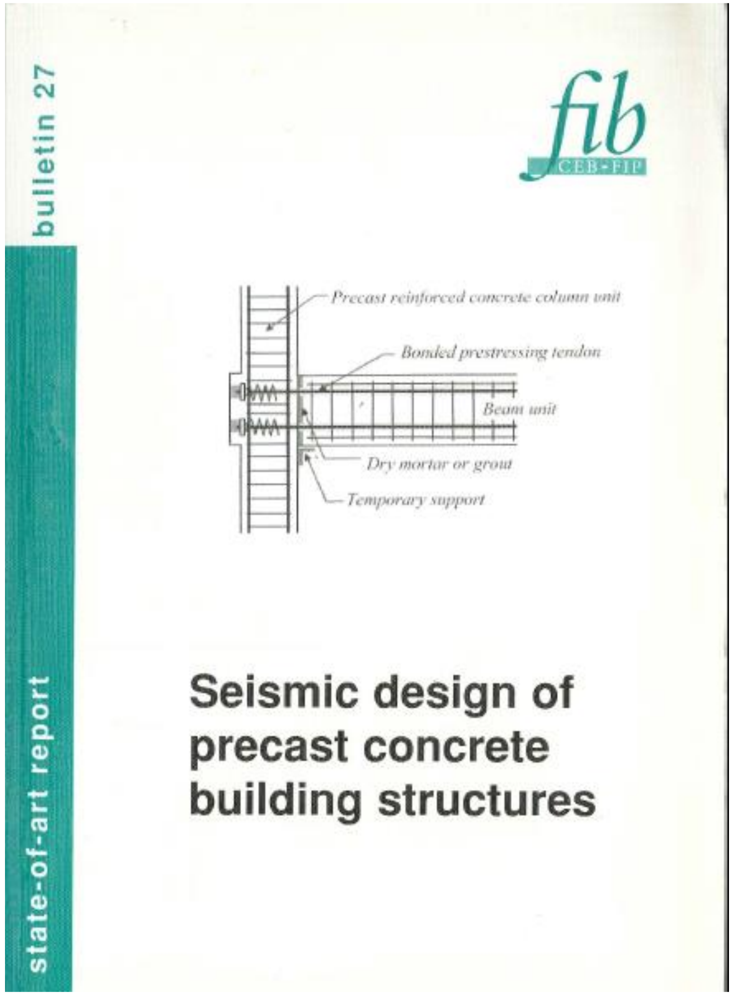
Amaris et al. 2006



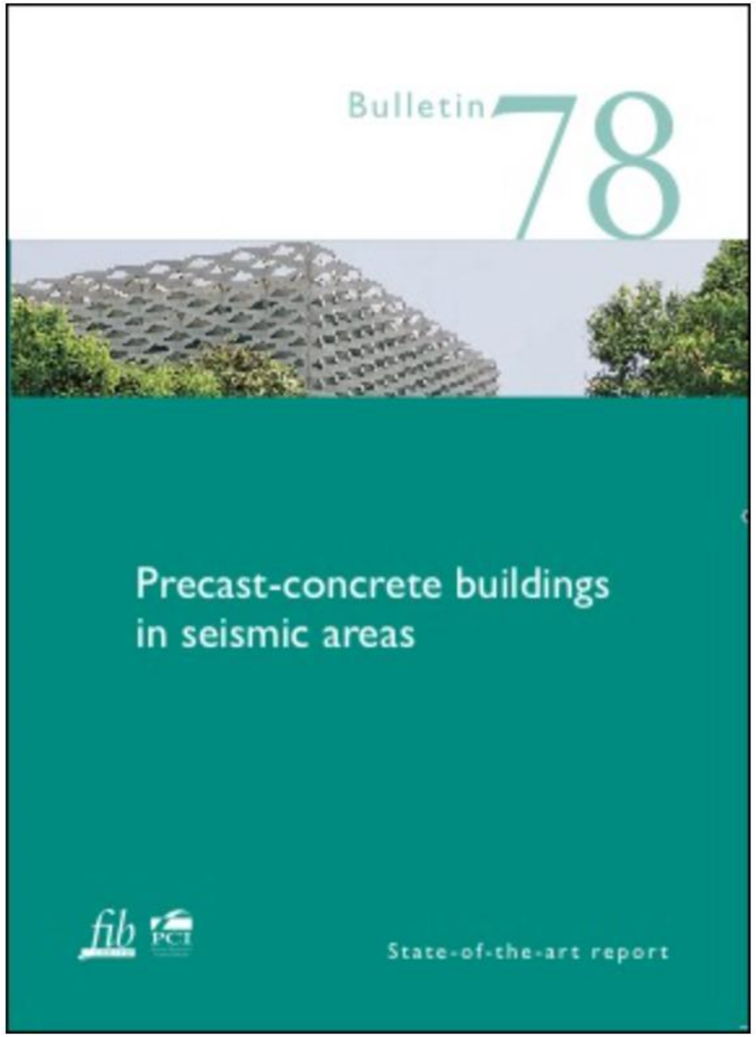
Marriott et al., 2007

Design Code Implementation

Design guidelines are available



fib, 2004



fib, 2016

Code/Standards are available

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New Zealand Standard

CONCRETE STRUCTURES STANDARD

Part 1 –
The Design of Concrete Structures

NZS3101:2006

APPENDIX B – SPECIAL PROVISIONS FOR THE SEISMIC DESIGN OF DUCTILE JOINTED PRECAST CONCRETE STRUCTURAL SYSTEMS (Normative)

NZS 3101:Part 1:2006

B2 Definitions

B2.1 *Jointed systems*

Jointed systems are structural systems in which the connections between the precast concrete elements are weaker than the elements themselves. Jointed systems do not emulate cast-in-place concrete construction. The connections of jointed systems can be of limited ductility or ductile.

B2.2 *Hybrid systems*

Hybrid systems are jointed structural systems in which the self-centering capability is provided by post-tensioning and/or axial compressive load, and energy dissipation is provided by yielding non-prestressed steel reinforcement or other special devices. Hybrid systems are ductile.

B2.3 *Equivalent monolithic systems*

Equivalent monolithic systems are structural systems in which the connections between the precast concrete elements are designed to emulate the performance of cast-in-place concrete construction. The connections can be of limited ductility or ductile.

B3 Scope and limitations

This Appendix applies to ductile jointed and hybrid precast concrete structural systems. The systems may be moment resisting frames, structural walls or dual systems, in which the precast concrete elements are joined together by post-tensioning techniques with or without the presence of non-prestressed steel reinforcement or other energy dissipating devices.

B4 General design approach

B4.1 *General*

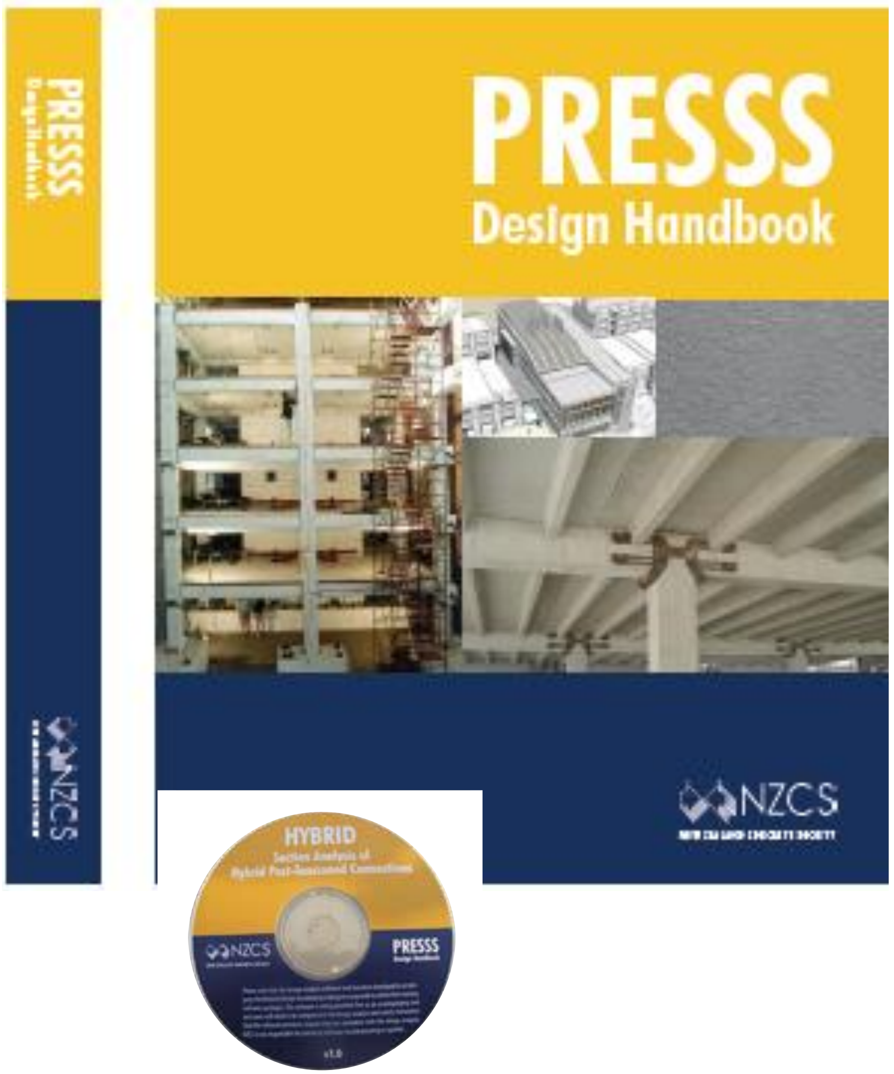
Either a force-based or a displacement-based design approach shall be used for the seismic design of jointed and hybrid structural systems. Modifications to the inter-storey drift limits used in design shall be made in accordance with B4.2.

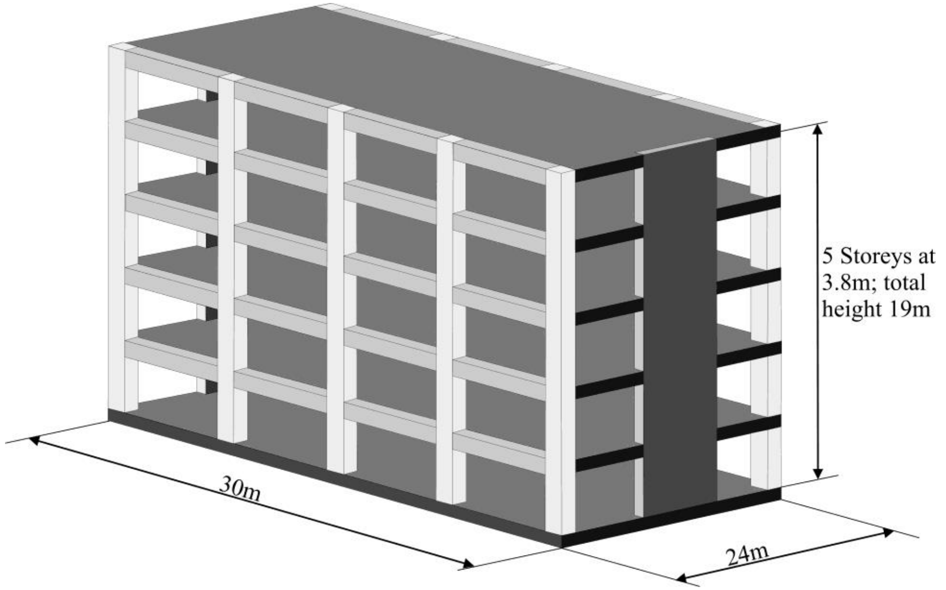
B4.2 *Drift limits*

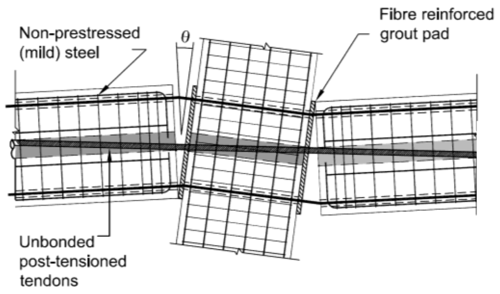
Inter-storey drift limits as defined in NZS 1170.5 shall be adopted for jointed structures, except that drift limits corresponding to a damage control, or the serviceability limit state may be increased by up to 50 %, provided analytical calculations and/or experimental validation demonstrates a reduced level of damage, (both structural and non-structural), when compared to an equivalent monolithic structure. No increase in drift limit corresponding to the ultimate limit state shall be allowed where high inelastic demand and P-delta effects can govern the response.

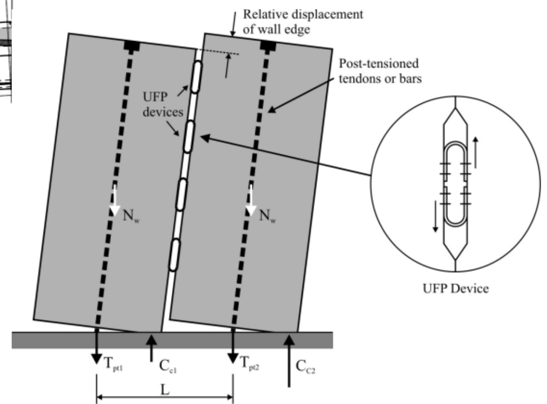
NZCS PRESSS Design Handbook (2010)

With **Displacement Based Design Examples** of **Frames and Walls**
(According to NZS3101:2006)





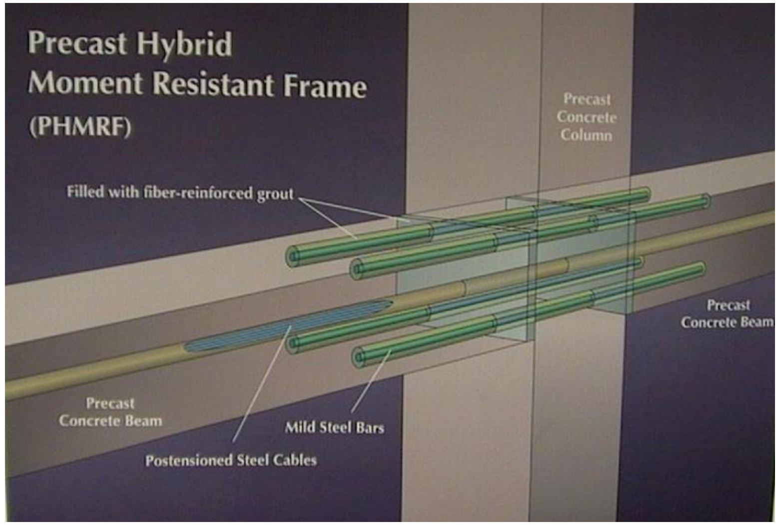




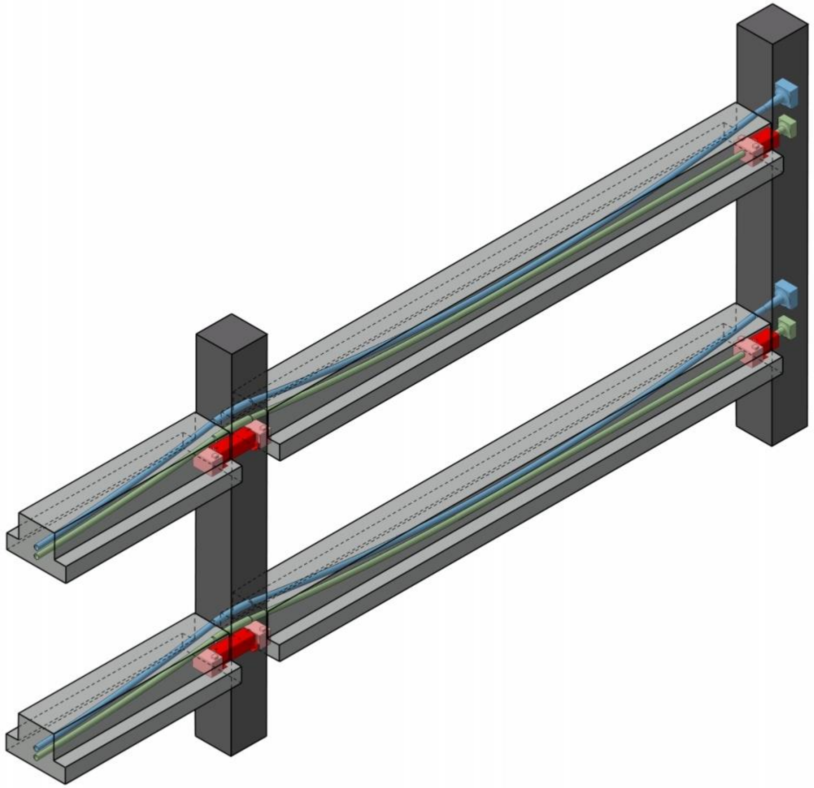
From theory…
to Practice

On-site Applications

Paramount Tower, San Francisco (Englekirk, 2002)



On-site Applications



Brooklyn System – Italy
(Pampanin, Pagani, Zambelli, 2004)

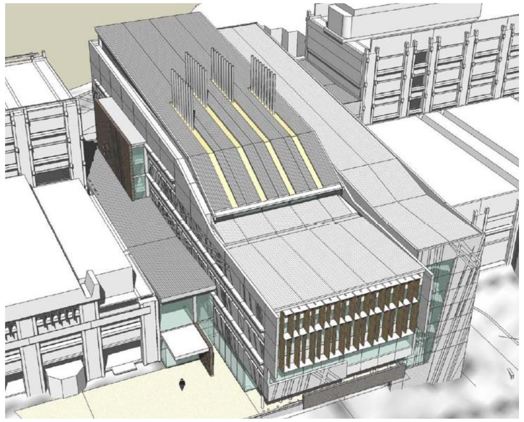
On-site Applications

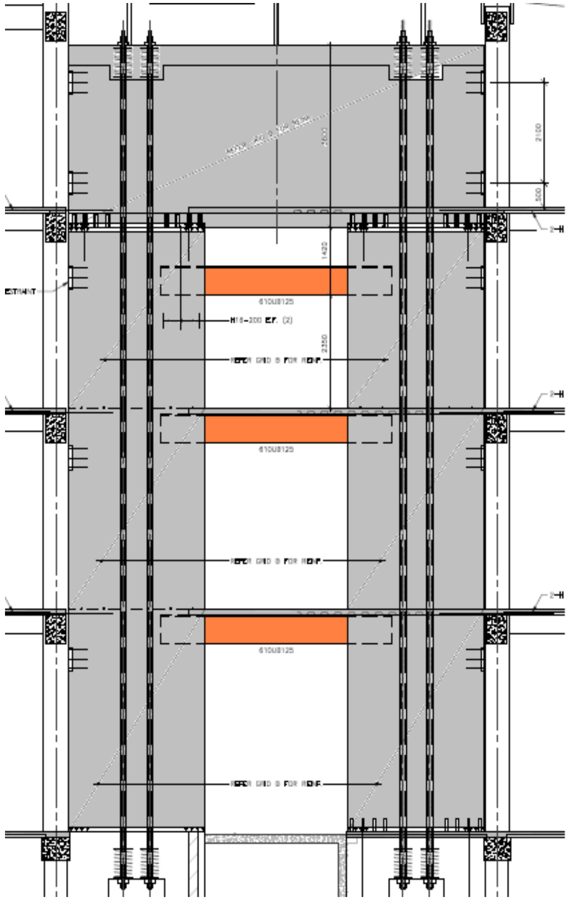
Hotel Virgo
(Mendoza, Argentina)
courtesy Pretensados Argentinos

On-site Applications

Zona Franca America, Costarica, Holcim Producto de Concreto

On-site Applications





Alan MacDiarmid Building, Victoria University, **Wellington**

Cattanach and Pampanin, 2008

Dunning Thornton consultants

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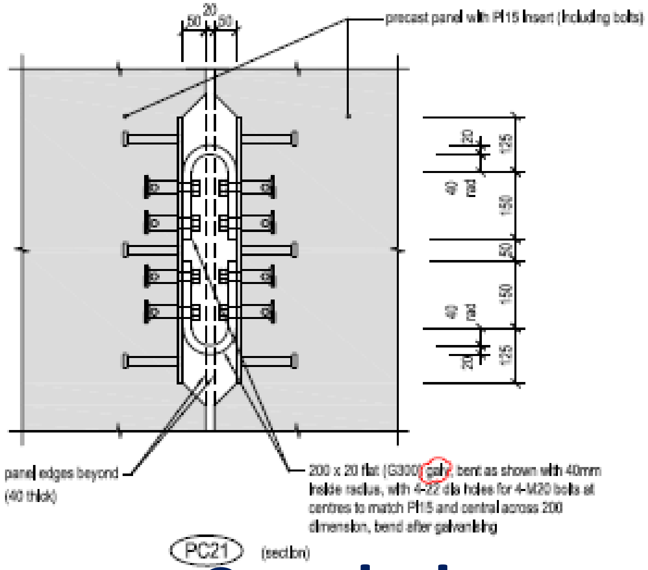
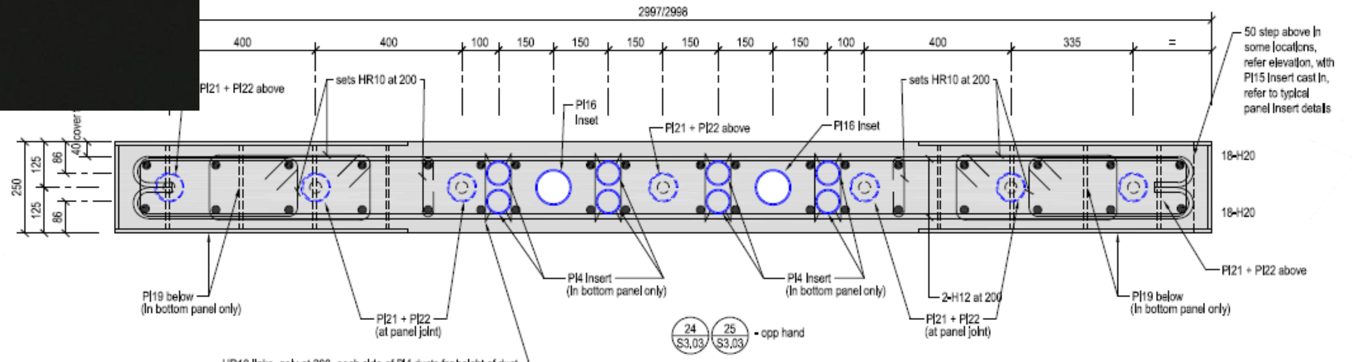
NZ's second PRESSS Building (6)

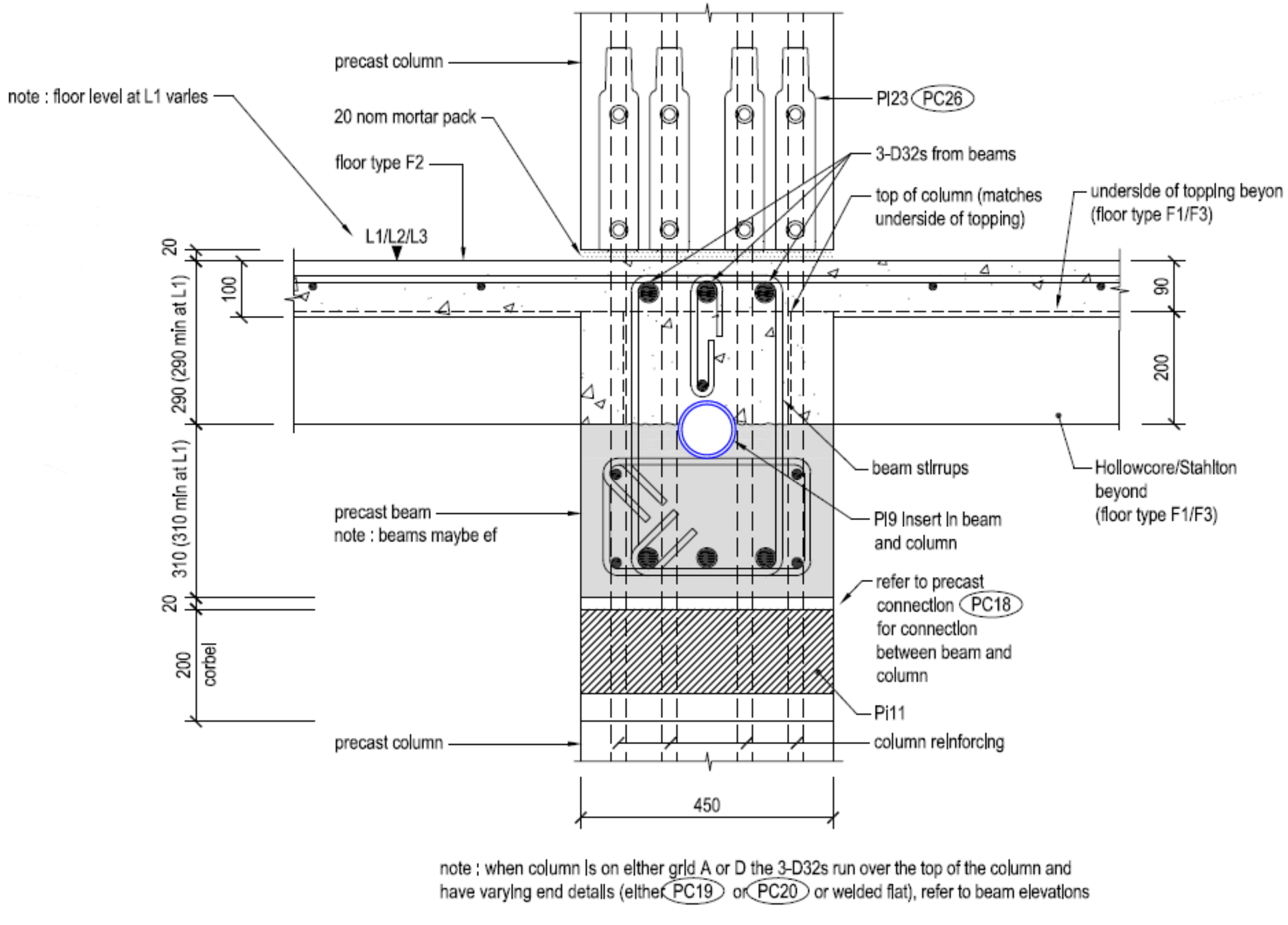
Pampanin, Haverland, Kam, 2010



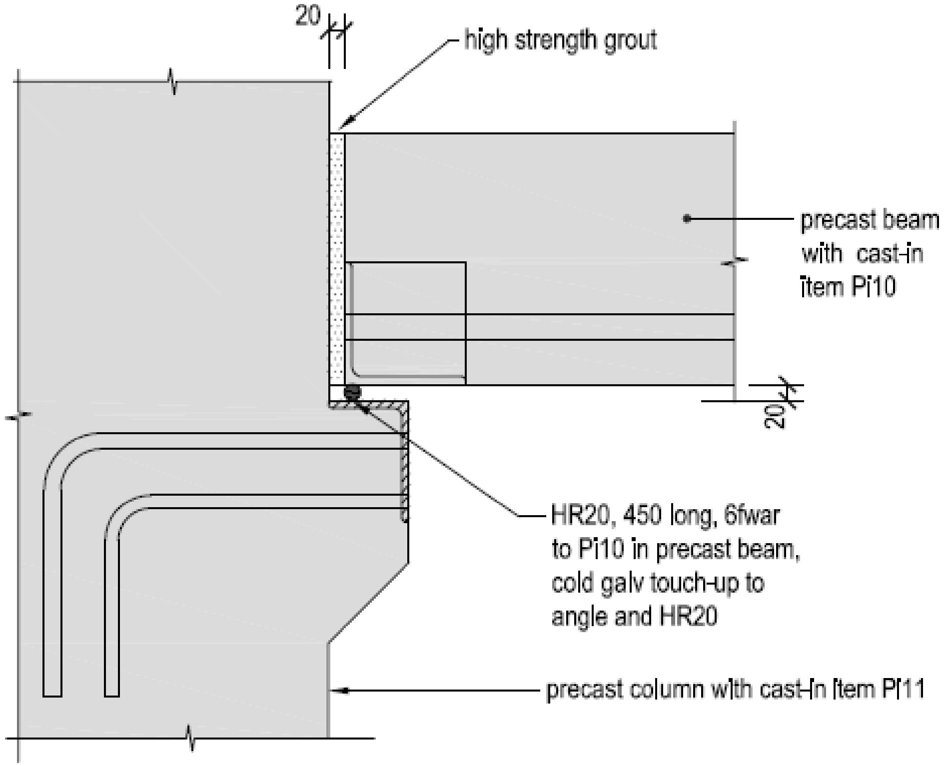
Coupled PRESSS walls



Beam- Column Connection



column joint
(insitu beams not shown)



PC18 (section)

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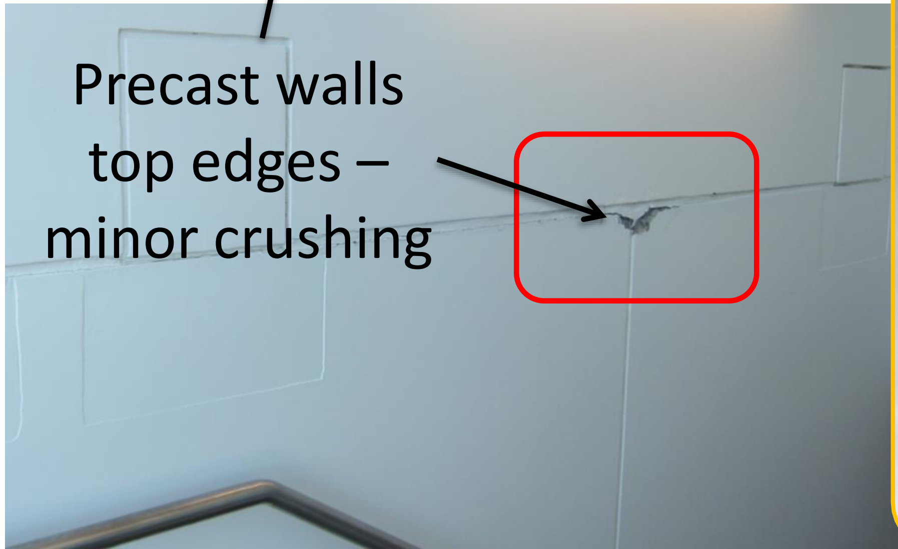
Christchurch EQ (22 Feb 2011) performance



Precast walls top edges – minor crushing

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Continuous functionality and immediate re-occupancy

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Isn’t this the GOOD NEWS that our Society deserves to receive?

Rotorua Police Station

PRESSS Walls with “Plug&Play” dissipaters

spiire

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CHRISTCHURCH NEW ZEALAND

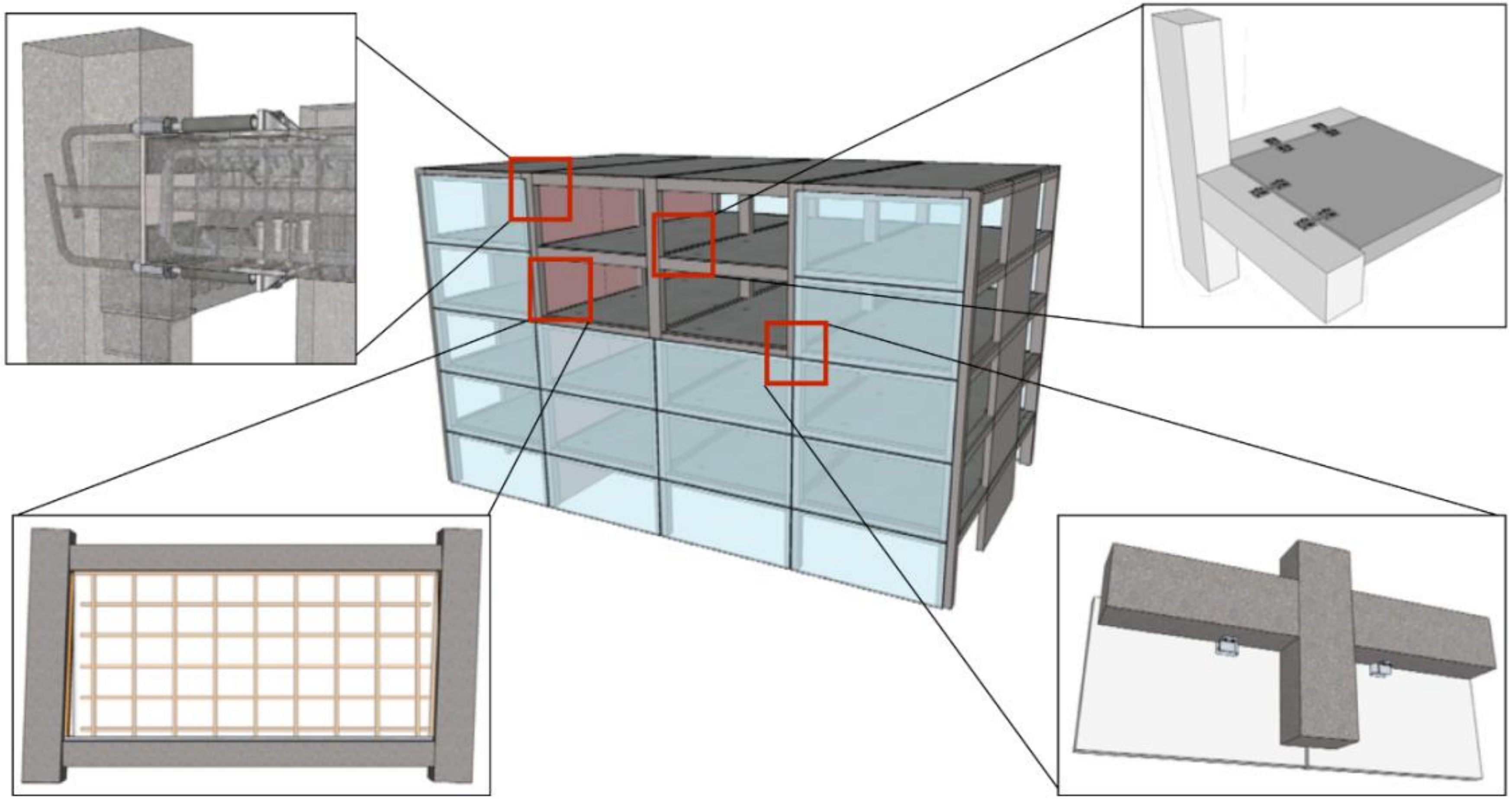
PRESSS Walls

with external and replaceable

“Plug&Play” dissipaters

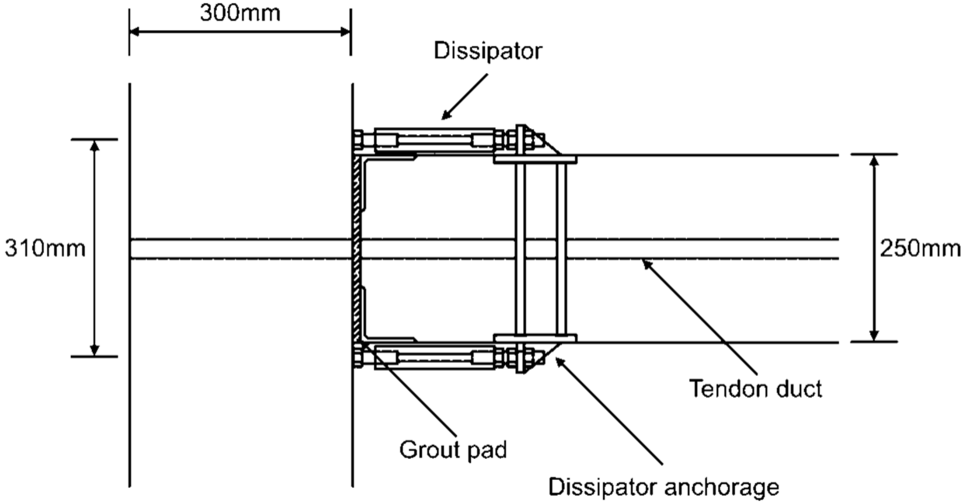
Towards the "Ultimate Earthquake Proof-building"
Shake-table testing of an integrated low-damage system

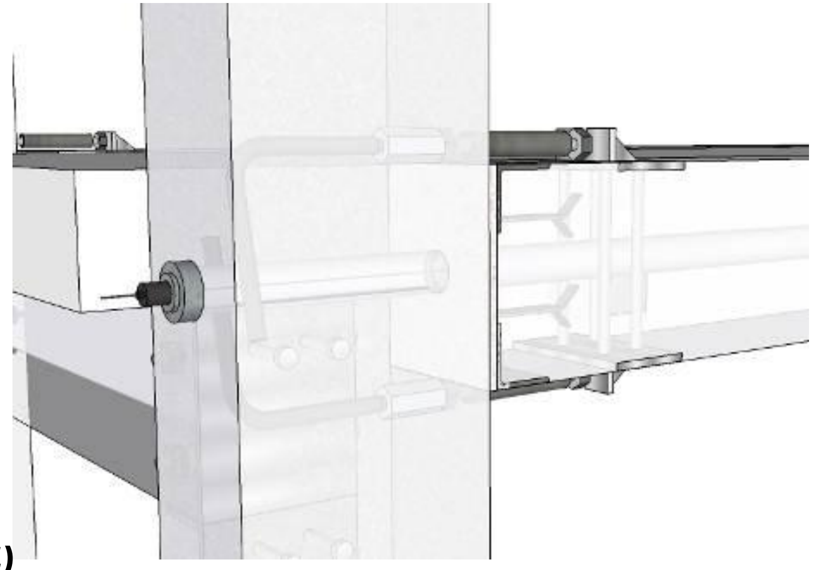
Johnston, Watson, Pampanin, Palermo (2013, 2014)



Next Generation of Integrated Low-Damage Building
- precast concrete with dry jointed ductile connections -

The Frame System



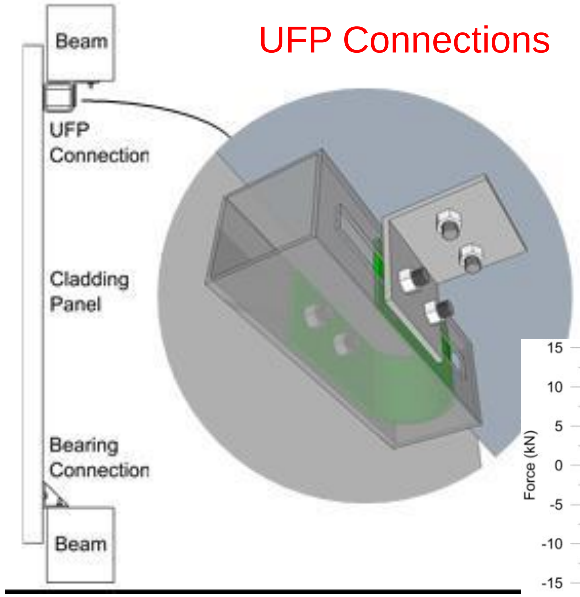


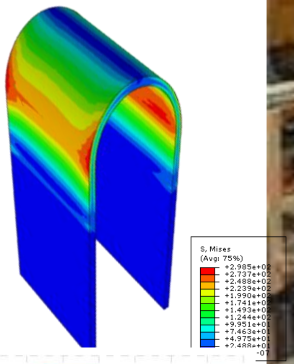
from Johnston, Watson, Pampanin, Palermo (2013, 2014)

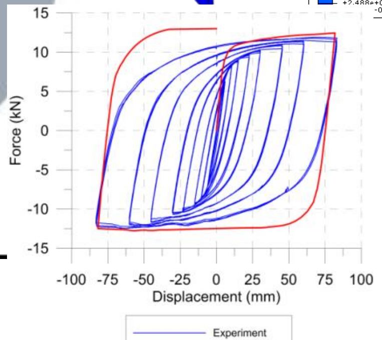
Low-damage façades

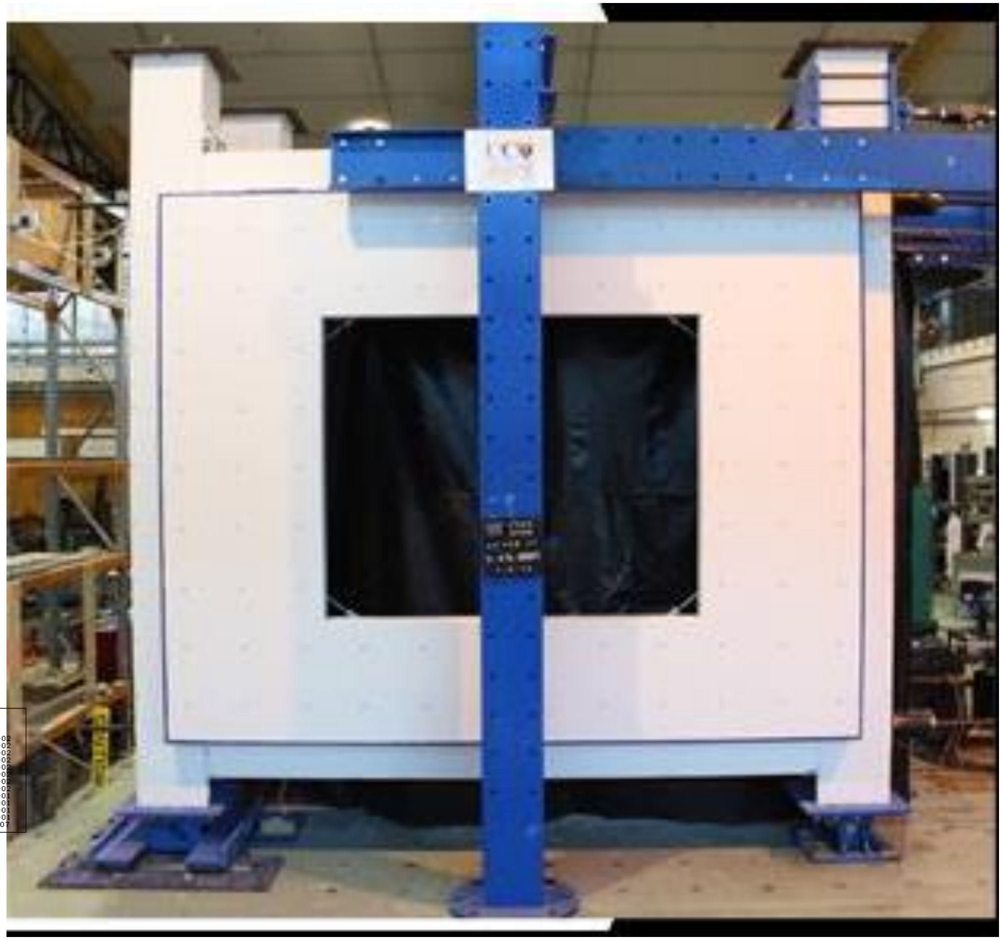
(Baird, Palermo, Pampanin, 2010-2014)

UFP Connections



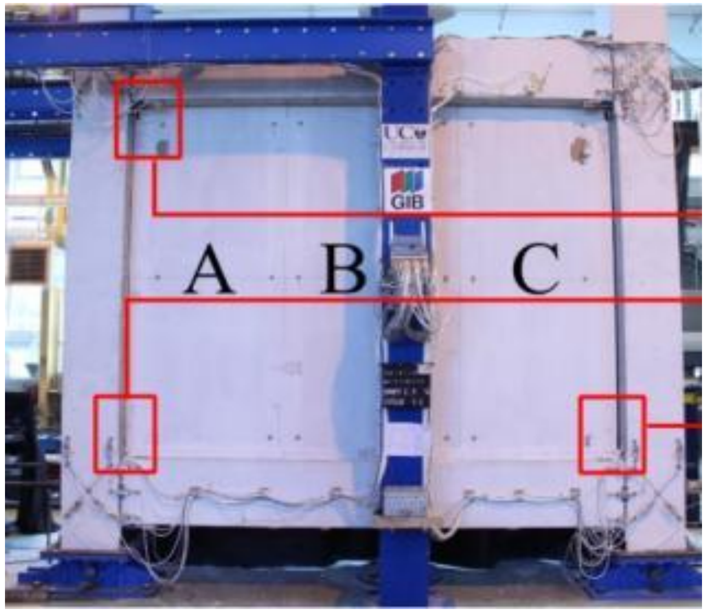


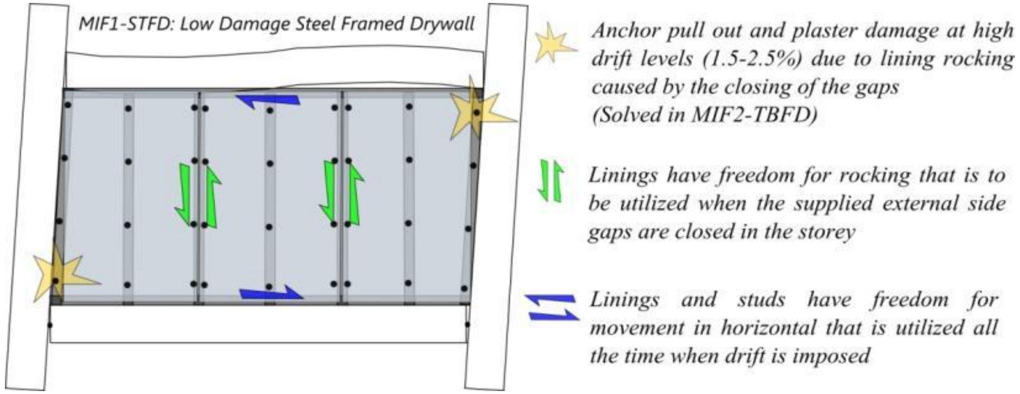


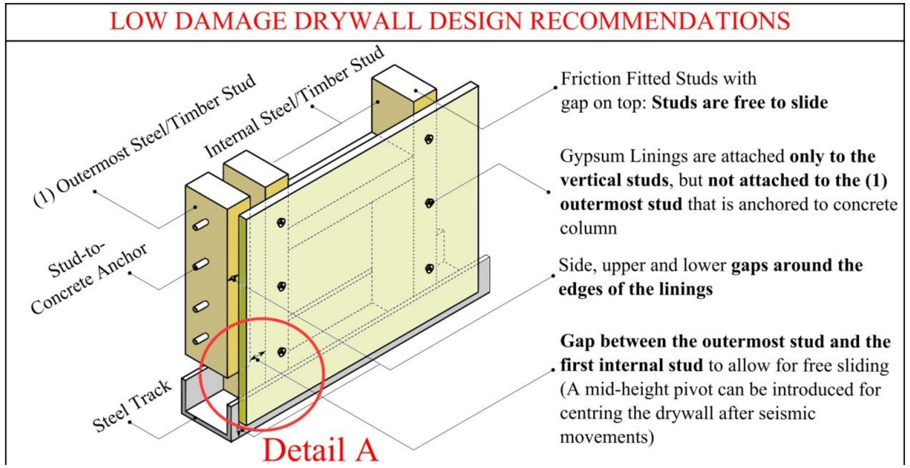


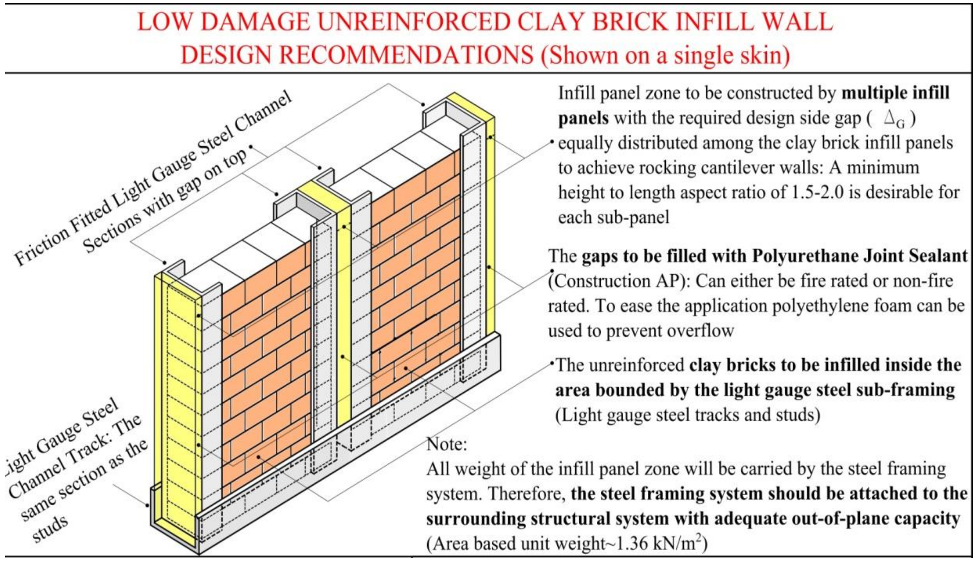
Low-damage infills

(Tasligedik, Pampanin, Palermo, 2010-2014)







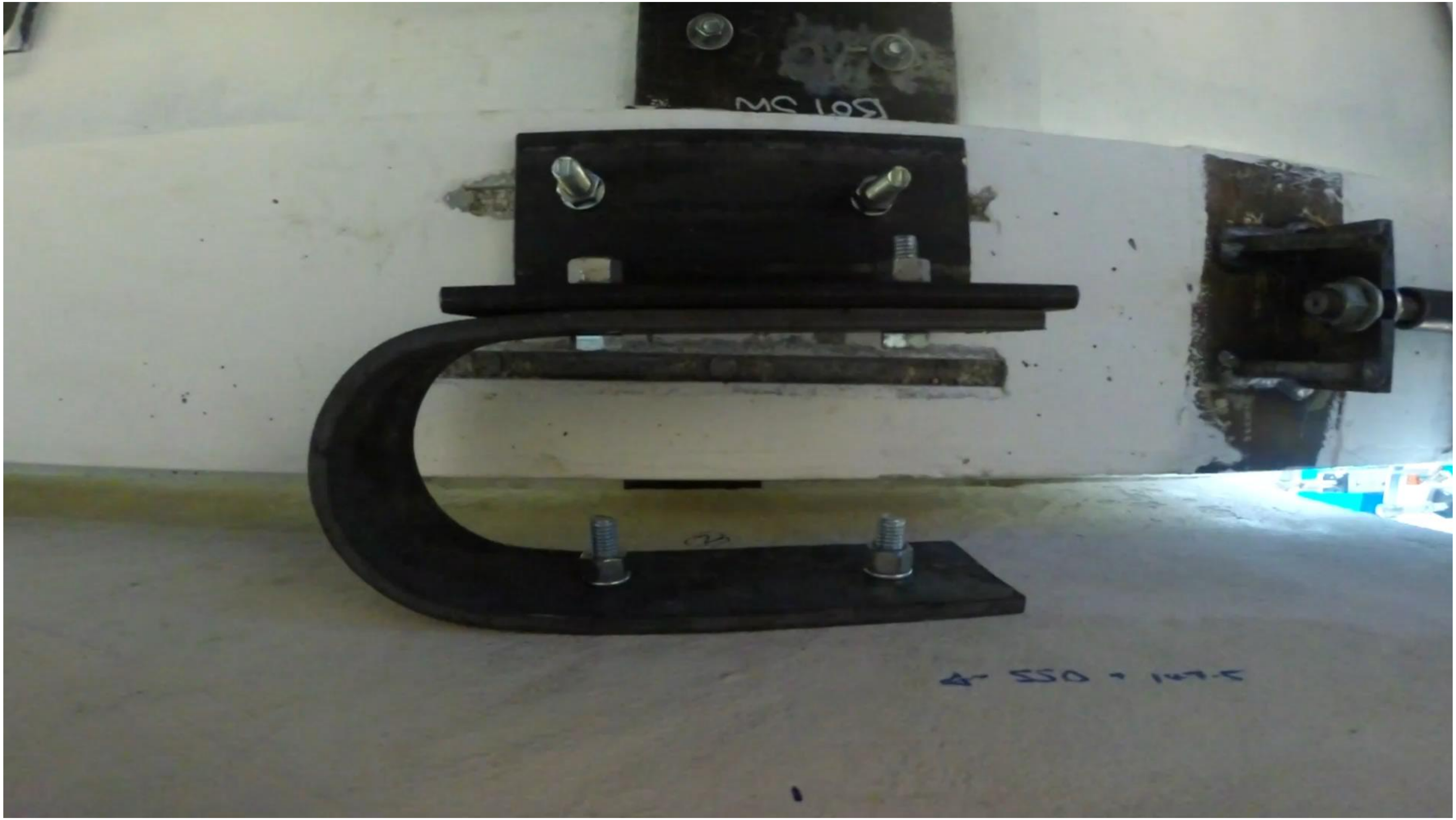


Johnston, Watson, Pampanin, Palermo, 2014

Johnston, Watson, Pampanin, Palermo, 2014

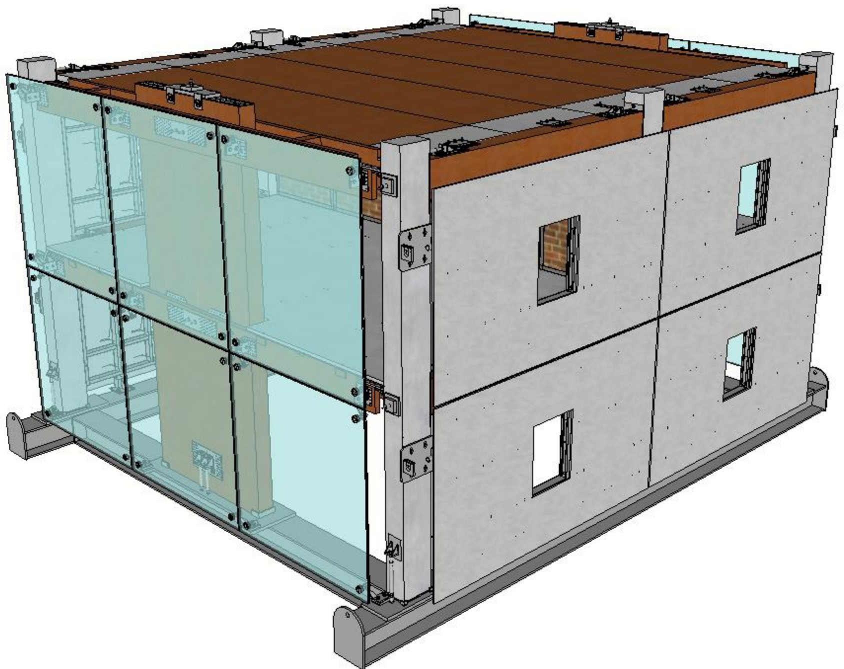
Johnston, Watson, Pampanin, Palermo, 2014

Johnston, Watson, Pampanin, Palermo, 2014

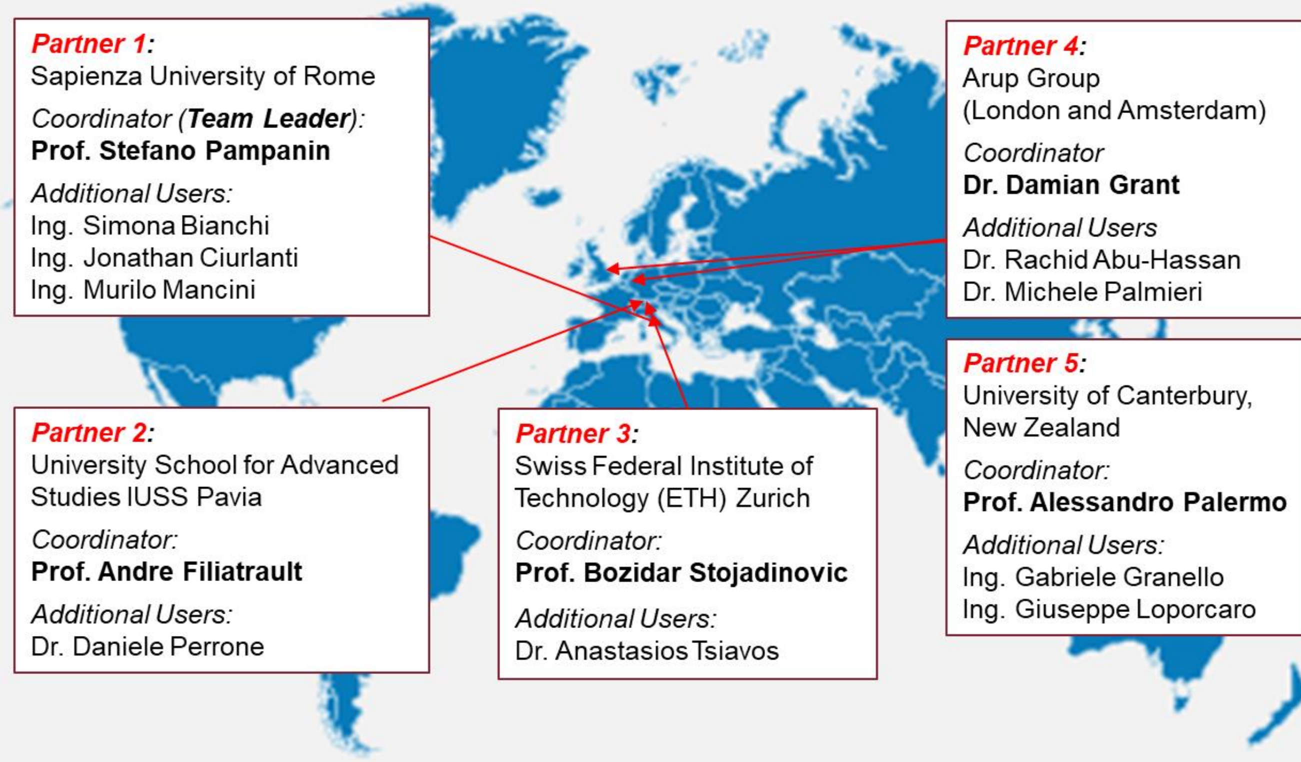


SERA Project (2017-2019)

Towards the Ultimate Earthquake proof Building System: development and testing of integrated low-damage technologies for structural and non-structural elements



https://www.youtube.com/watch?v=RHczItvneug



Stefano Pampanin (PI),,
Jonathan Ciurlanti, Simona Bianchi,
Gabriele Granello, Daniele Perrone,
Michele Palmieri, Damian Grant,
Alessandro Palermo, Andre Filiatrault,
Alfredo Campos Costa, Antonio Correia

1 August 2019
Laboratório Nacional de Engenharia Civil (LNEC) - Lisbon (Portugal)

TRIDIRECTIONAL TEST XYZ - LIMIT STATE 4

Christchurch (NZ) February 22, 2011
Mw = 6.3, Station = CCCC

Scaling Factor = 1.2
PGA = 0.58 g

Maximum inter-storey drift = 1.00 %
Peak floor acceleration = 1.28g

Towards a “S3 Design”
SAFER, SUSTAINABLE, SMART
Building Systems

(Pampanin et al., 2016-)

How much would it cost (vs. performance)?

The bar has been set to very high level

but the International Earthquake Engineering community is going to get there, <u>together</u>!

International Collaborators/Teams:
EERI (US), AIJ/JAEE (Japan), EEFIT (UK), NCEER (Taiwan), European Universities


Kia Ora
Thanks for your attention
Grazie per l’attenzione
stefano.pampanin@uniroma1.it