Presentation to the

**Royal Commission on Canterbury Earthquakes**

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# Performance Based Seismic Design: Where to from here?

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# What did we observe in the recent earthquakes?

- Severe damage to non-structural components (ceilings, parapets, partitions, facades, windows, chimneys, canopies etc) than to structures
- Modern buildings suffered damage
- Older buildings severely damaged (and some collapsed)
- Ground response was very poor in many parts of the region (liquefaction, lateral spreading)
- Many buildings were rendered unusable due to ground/foundation damage

# Did we expect these?

**Remember: The imposed demand was similar to (in September) and higher than (in February) the current design level demand.**

- Damage to modern buildings → **Yes**
- Severe damage (and some collapse) to older buildings → **Yes** (Perhaps we were lucky that more did not collapse)
- Damage to non-structural components → We never thought about this
- Very poor ground response → Did we know this? If yes, why did we let buildings be built on these?

# What are we complaining about?

## Damage?

- Modern design expects (dare I say "attracts"?) damage even in moderate shakings
- The ground shakings generated by these earthquakes were not smaller than what we design for.

## Loss?

- The current design cares about life safety; but not other forms of loss.
- If loss hurts/matters, the design process should explicitly aim to control loss

# What are the things we need to do differently from hereon?

- Local soil characteristics to be checked thoroughly before buildings are planned to be built in an area
- Non-structural components (ceilings, partitions etc) to be systematically designed for seismic resistance
- Stricter regulations on retrofit of older buildings
- Communicate better (interact more)
  - Among ourselves (between architects, structural engineers and geotech engineers)
  - With the public ("designed for earthquake resistance" does not mean "earthquake proof")
- Adjust design target according to expectation
  - We cannot sow berry seeds and expect cherries to grow

# What are the research needs to enable us to do things differently?

Development and advancement of:

- Low-damage building technologies (Reinforced concrete, Steel, Timber)
- Damage resistant design for non-structural components
- Loss minimisation seismic design approach (including contents, downtime, injuries)
- Reliable ground assessment methods
- Ground damage mitigation strategies

# Performance vs. Loss: An Enigma

# Objectives of Seismic Design

Current seismic design approaches in the world have a combination of the following performance objectives:

- Immediate occupancy: No disruption of service after small *frequently occurring  earthquakes*
  - No closure of building (some damage?)
- Reusability: Repairable damage in *moderate-strong earthquakes*
  - Damage and closure of buildings
- Life-safety: Collapse prevention in *large and rare earthquakes*
  - Irreparable damage, building to be demolished

(Note: Design codes do not specify performance requirements in the way they are specified above; e.g. MCE is not used in NZS1170.5)

# How has the ongoing ductility based Capacity Design performed?

- Immediate occupancy in minor earthquakes: ACHIEVED, but minor *damage* needing repairs without disruption.

- Reusability in moderate-strong earthquakes: ACHIEVED, but moderate-severe *damage* resulting in injury and disruption of service (i.e. *downtime*) during the repair.

- Life-safety in very strong earthquakes: ACHIEVED, apart from a few exceptions resulting in *death*. Structures need to be demolished and rebuilt

# Where do we Stand?

- We achieved all design objectives we wanted from our design method, yet
  - **Financial loss due to the 3*D's* (*damage, downtime & death*) could not be avoided.**
  - **The total loss in some recent earthquakes was reported to be in tens of billions; e.g 1989 Loma Prieta ($11b), 1994 Northridge ($17-26b), 2010 Darfield (NZD6b); 2011 Christchurch (NZD20b).**

- Is this what we wanted?
  - **Probably NO**

- Where have we gone wrong?
  - **In setting the performance objectives for our structures.**

# Where to in Future?

- *Loss optimization seismic design* (LOSD)
  - **Performance objective 1: Life-safety (Collapse prevention)**
  - **Performance objective 2: Minimization of earthquake induced loss.**
- Design criteria: Expected loss < Acceptable loss
  - **We need to estimate the expected/probable loss**
  - **A probabilistic loss estimation methodology is needed**

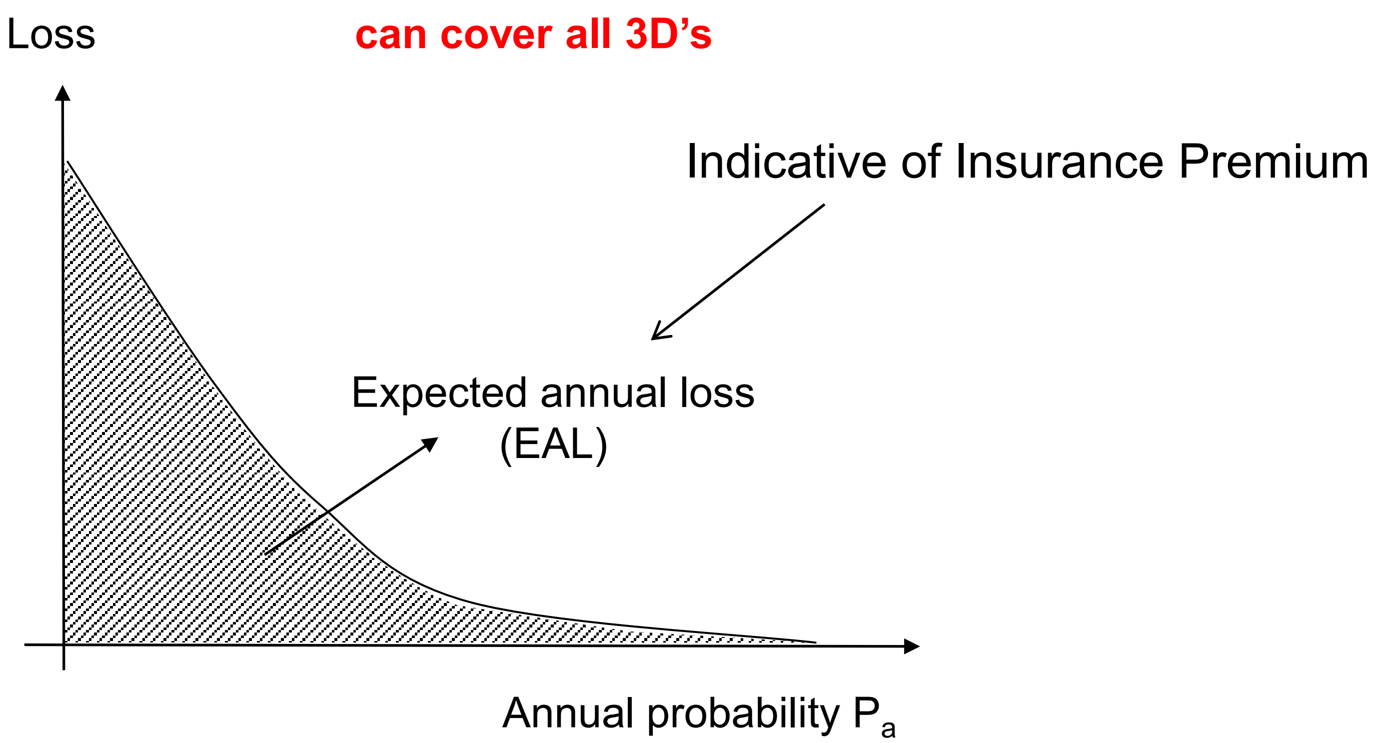
# LOSD design criteria

| Performance measures |
|---|
| Repair ($R$): Expected cost for component/content repair/replacement, $\mu_R$ (percentage of building value including contents)<br>Downtime ($D$): Expected closure of the building for repair/replacement, $\mu_D$ (days)<br>Injury ($I$): Expected likelihood of injury/casualty, $\mu_I$ (probability of minor/major injury and death) |

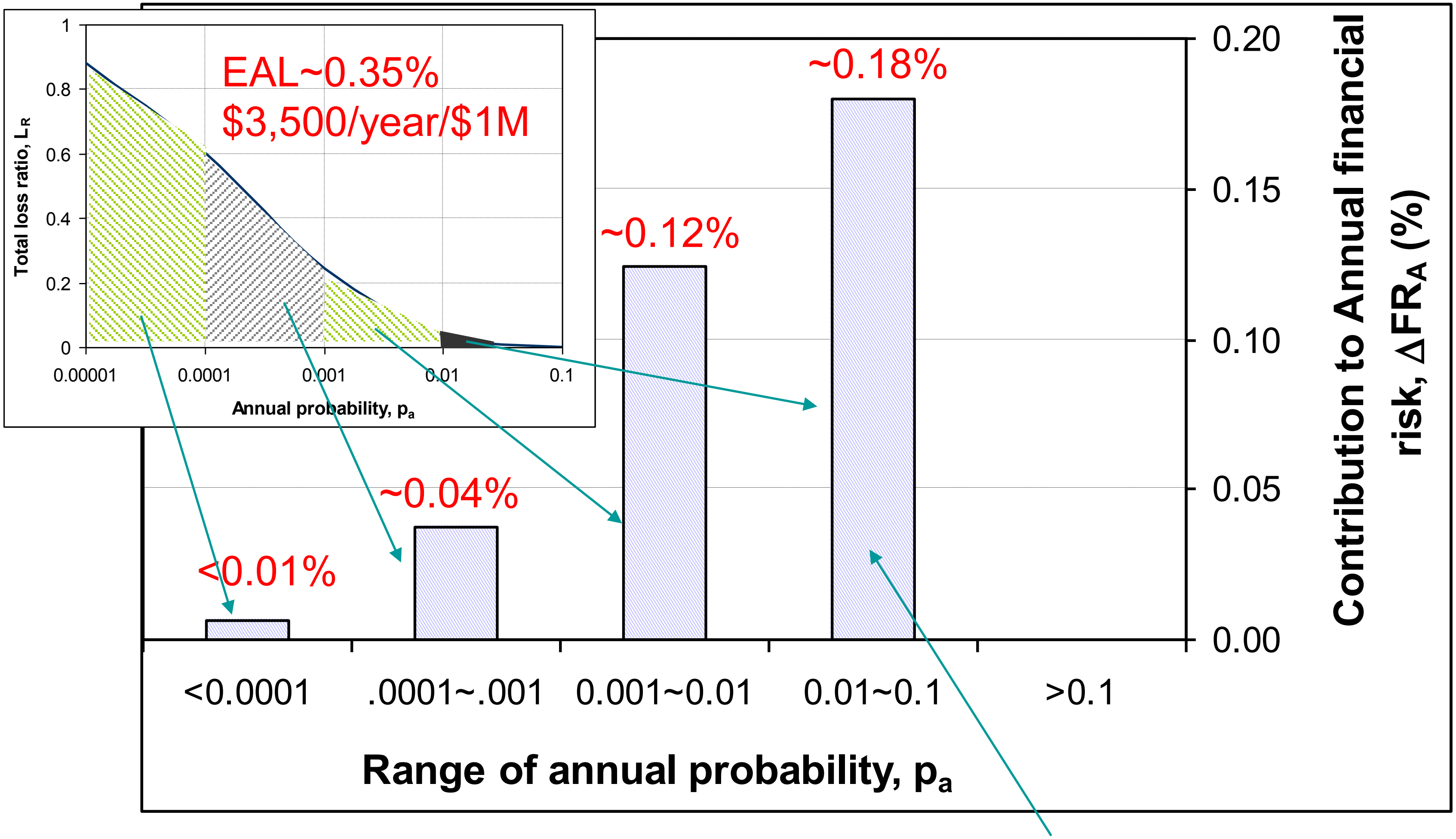
| | | Allowable loss (Capacity) | | |
|---|---|---|---|---|
| Ground motion intensity corresponding to | Expected loss (Demand) | Residential buildings | Commercial and office buildings | Emergency facilities |
| Frequently occurring earthquake (FOE), 50% in 50 yrs | Repair: $\mu_R$ | 0.1% | 0.01% | 0.001% |
| | Downtime: $\mu_D$ | 0.1 day | 0.01 day | 0.001 day |
| | Injury: $\mu_I$ (%) | 0.1,0.01,0.001 | 0.01,0.001,0.001 | 0.001,0.001,0.001 |
| Design basis earthquakes (DBE), 10% in 50 yrs | Repair: $\mu_R$ | 10% | 1% | 0.01% |
| | Downtime: $\mu_D$ | 10 days | 1 day | 0.01 day |
| | Injury: $\mu_I$ (%) | 10,1,0.01 | 1,0.1,0.001 | 0.1,0.01,0.001 |
| Maximum considered earthquake (MCE), 2% in 50 yrs | Repair: $\mu_R$ | No limit | 10% | 0.1% |
| | Downtime: $\mu_D$ | No limit | 10 days | 0.1 day |
| | Injury: $\mu_I$ (%) | 50,10,0.1 | 10,1,0.01 | 1,0.1,0.001 |

# Loss Assessment Process

Methods do exist for probabilistic seismic loss assessment



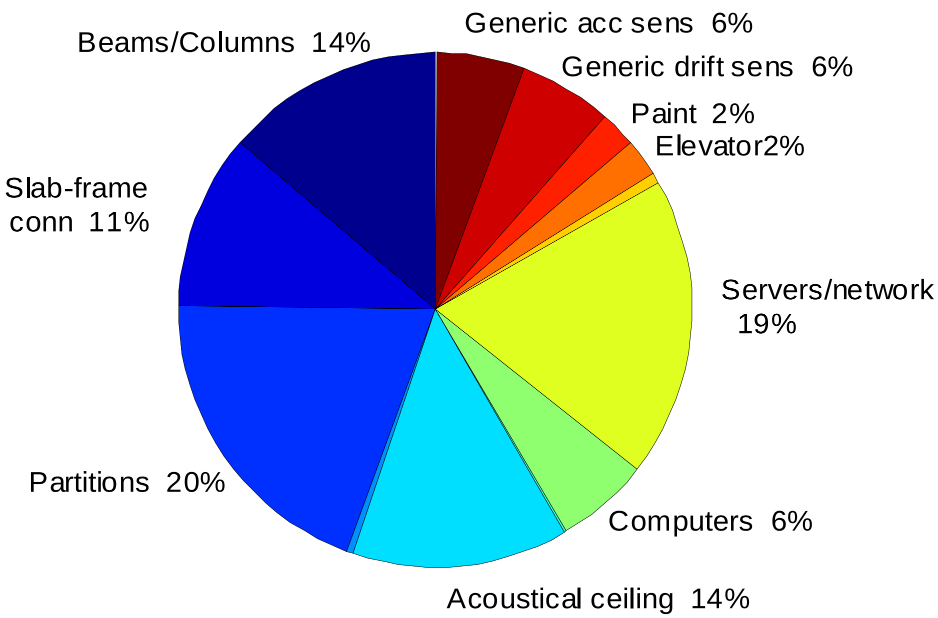
# Expected annual loss (EAL)



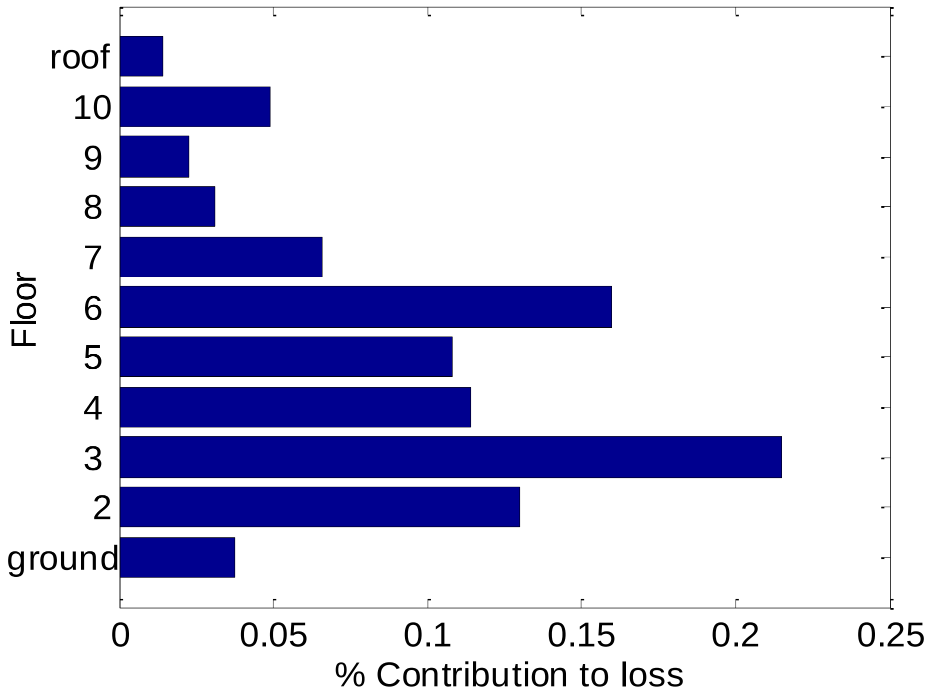

**A part or whole of this is insurance deductible**

# Informed Decision Making

**Loss at $S_a$ = 0.5g**




By components

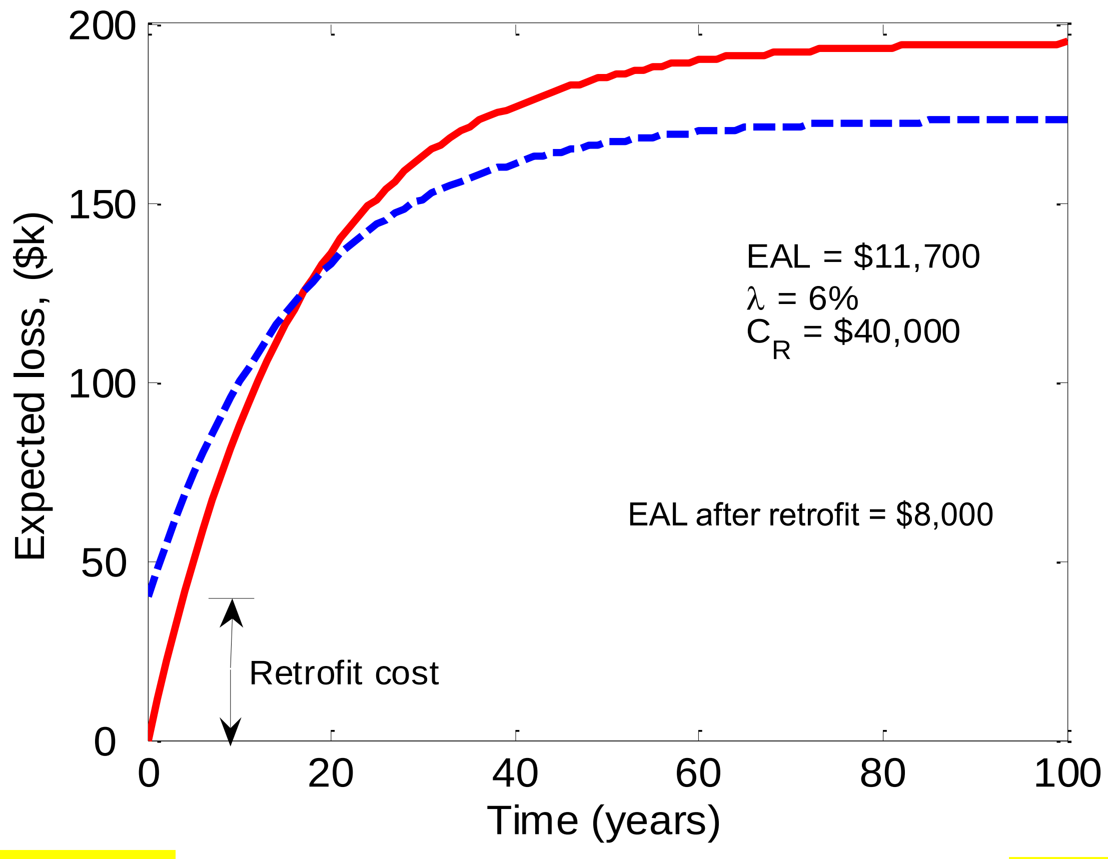



By floor

Example: for a 10-storey RC office building

# Efficient Decision Making

## Is a retrofit economically feasible?



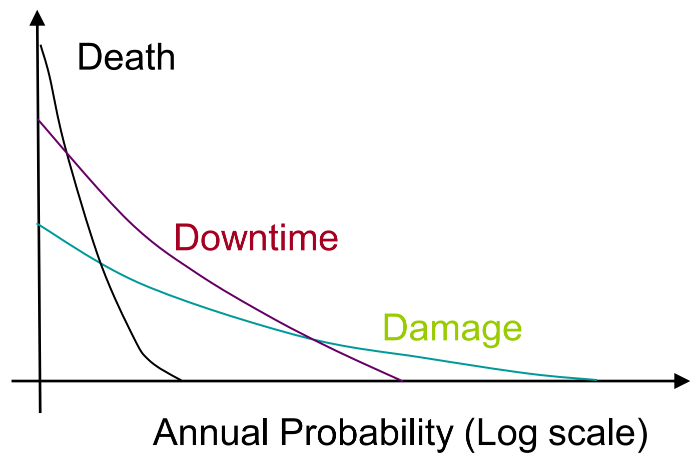

$$E_L = \frac{(1 - e^{-\lambda t})}{\lambda} EAL + C_R$$

$$t_{cr} = \frac{-1}{\lambda} \ln\left(1 - \frac{\lambda}{(1-\alpha)} \frac{C_R}{EAL}\right)$$

# How to optimize the 3 D's?

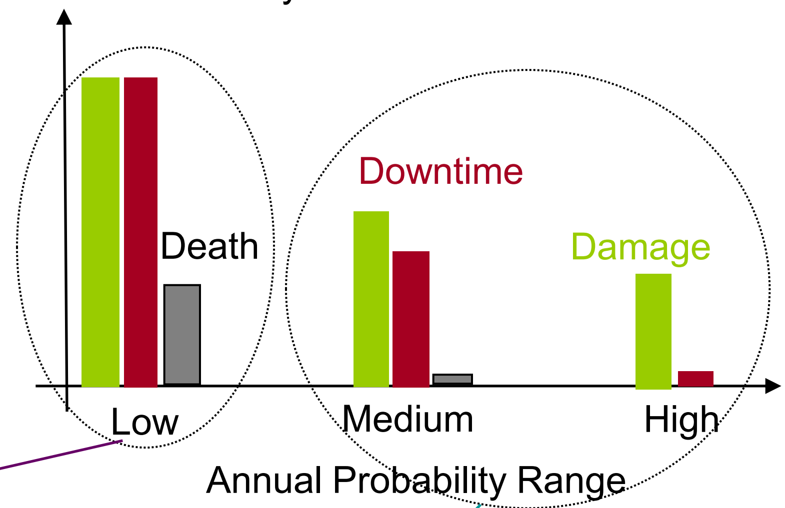
## Probable Loss

Probable Loss = Consequence




## Financial Risk

Risk = Consequence x Probability




Low risk but high consequence
Important for Life-safety criteria
Must be avoided

**IDEA: AVOID/REDUCE DAMAGE IN MINOR-MODERATE SHAKINGS**

Low consequence to individual owners
High financial risk ➔ Big blow to the economy
Mainly contributed by
minor-moderate damage
and the resulting downtime

# How can we reduce damage?

- **Provide very high capacity** (economically viable?)
- **Low-damage Technologies**
  - Base Isolation
  - External Braces/dampers
  - Damage avoidance design

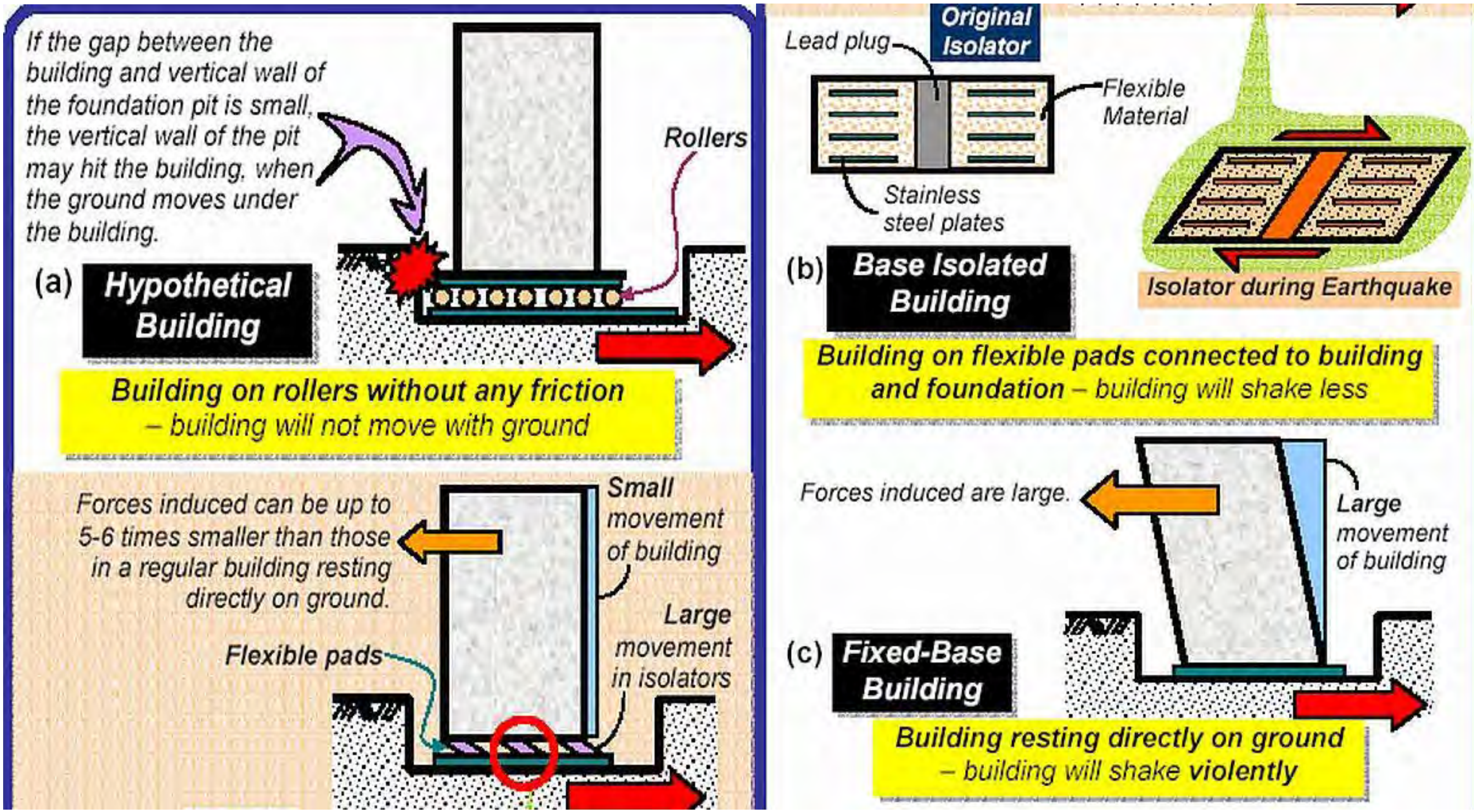
# Base Isolation

- Passive control technique to decouple a building from its foundations (by using isolators)

- Base isolation does not make a building earthquake proof; it just enhances the earthquake resistance

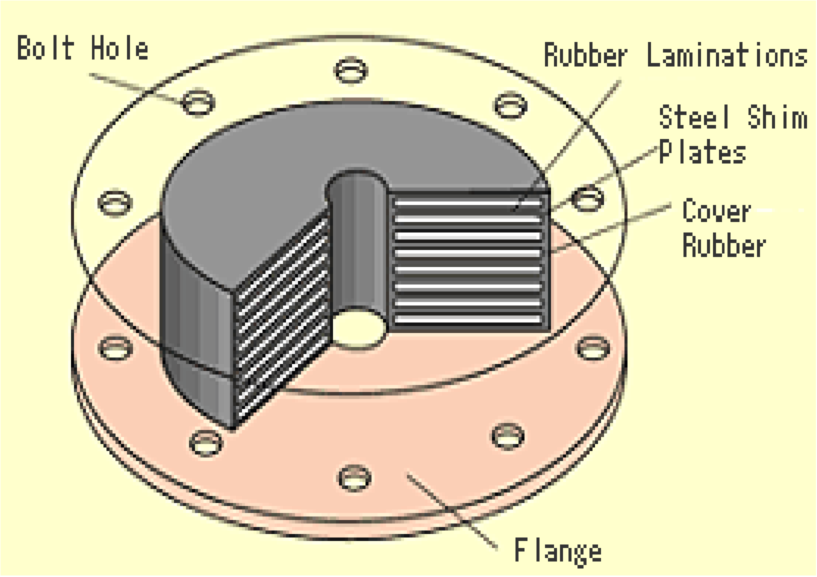
- Not suitable for all buildings; most effective for short or medium rise buildings on hard soil.

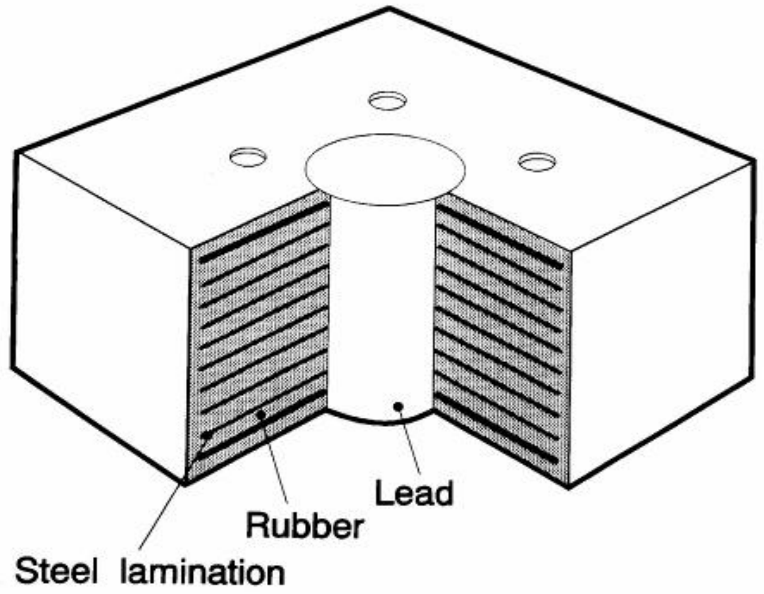
# Concept of Base Isolation

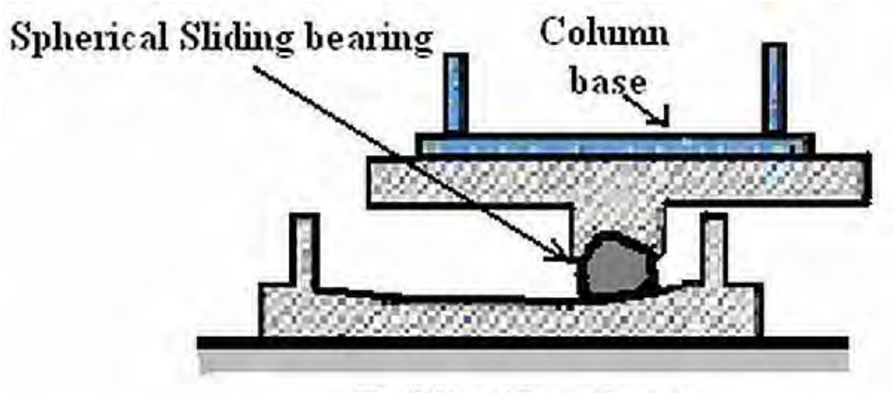



Source: http://www.iitk.ac.in/nicee/EQTips/

# Base Isolation Bearings




Spherical Sliding Isolation Bearing

# Cost Implication of Base Isolation

## LOWERING THE INITIAL AND LIFETIME COSTS OF ISOLATION IN BUILDINGS

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Saint Martin's University

REU Site: University of California, Berkeley
PI: Stephen Mahin
Graduate Student Advisors: Tracy Becker and Charlotte Wong

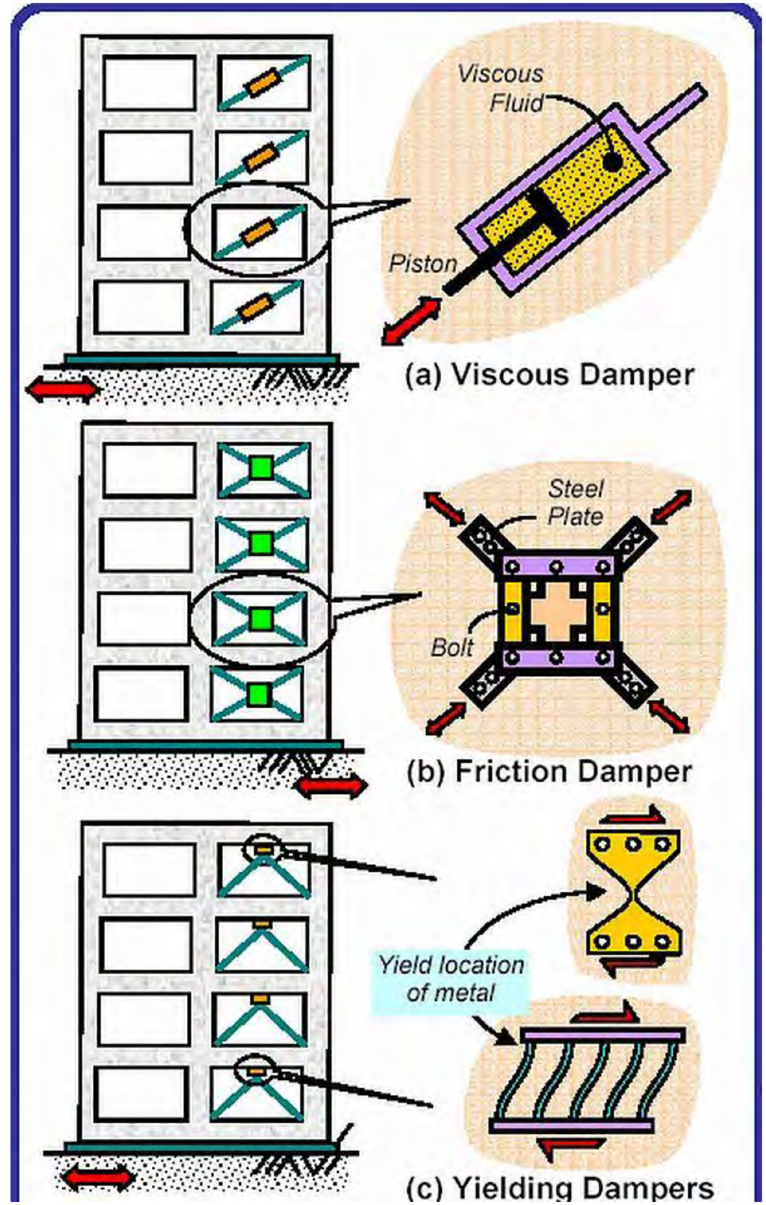
### Earthquake Economics

Base isolation has a higher initial cost than conventional construction. The cost increase comes from isolators, excavation, construction of an extra level that provides no additional usable or rentable space, stiffening of the superstructure, and a moat that surrounds the isolated layer. This leads to an additional cost of $50 per square foot [Enscoe, 2010]. Building owners and developers are reluctant to pay this additional cost. However, the benefits of isolation far exceed the initial cost of installing isolation, especially in today's society.

# Damping Devices

- absorb energy and add damping to buildings, in order to reduce seismic response
- especially suitable for tall buildings which cannot be effectively base-isolated
- retrofitting existing buildings is often easier with dampers than with base isolators
- example: viscous/fluid (lead extrusion) dampers, friction dampers, hysteretic dampers etc

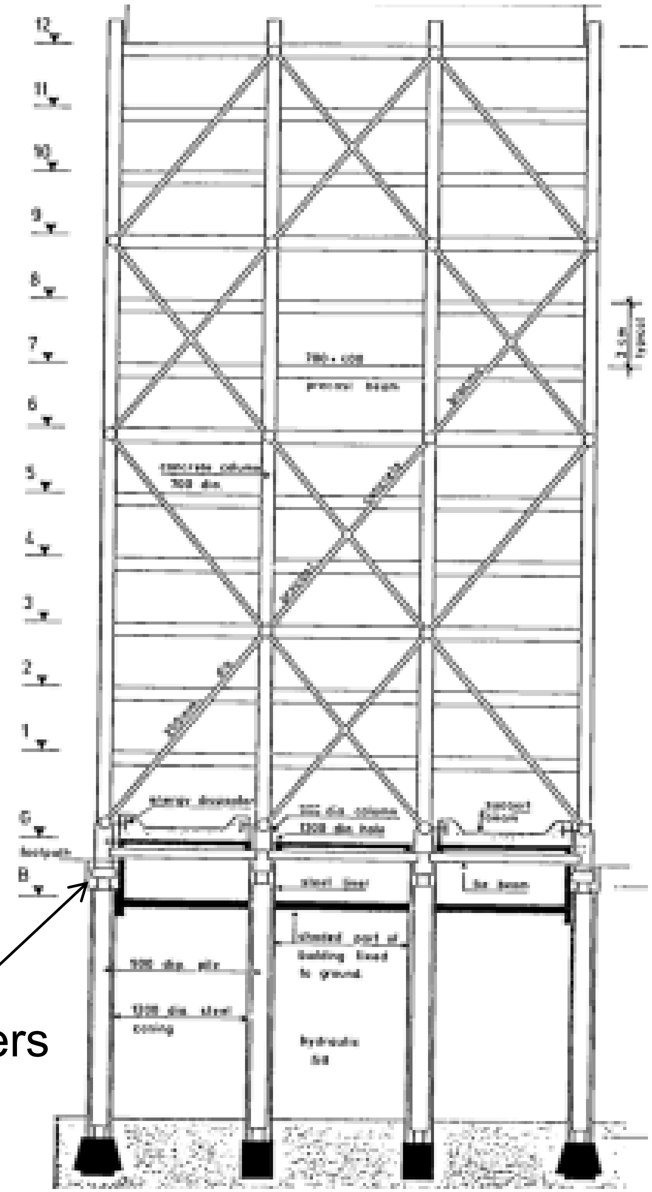
# Typical Use of Damping Devices




Source: http://www.iitk.ac.in/nicee/EQTips/

# Applications in NZ

Union House, Auckland



Steel dissipaters

# Applications in NZ

Te Papa, Wellington


# Applications in NZ

Christchurch Women's Hospital (40 lead rubber bearings)

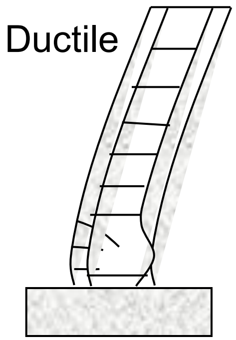
# Damage Avoidance Design (DAD)

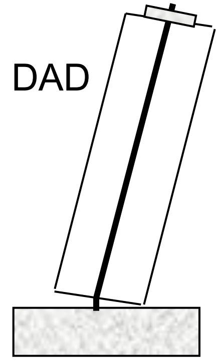
- Different names used by different researchers
  - Hybrid system: Stone et al 1995
  - PRESSS system Priestley et al 1999
  - Rocking system
  - Damage Resistant Design

- Common principles
  - Precast components assembled at site
  - Tied using unbonded post-tensioning, which provides the strength
  - External dampers used for energy dissipation
  - Self-centring system; i.e. no residual displacement

# Damage Avoidance Design (DAD)

- Structural damage: associated with inelastic deformation
- Avoid inelastic deformation of members
- Members behave elastically like rigid bodies.
- Accommodate the displacement demand by rocking at interfaces (e.g. beam-column)
- Interfaces designed (armoured) specially to avoid damage due to stress concentration
- Strength from unbonded post-tensioning
- External dampers provided for energy dissipation

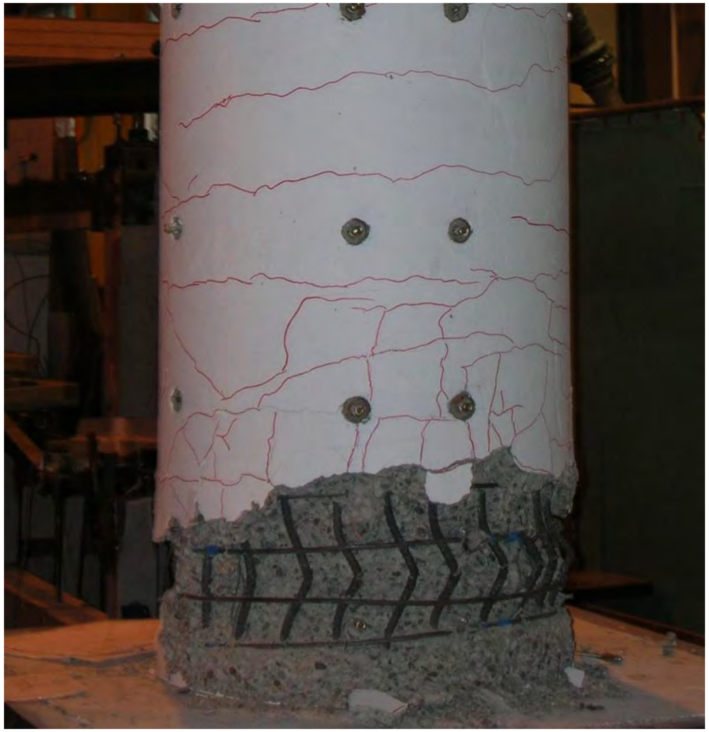


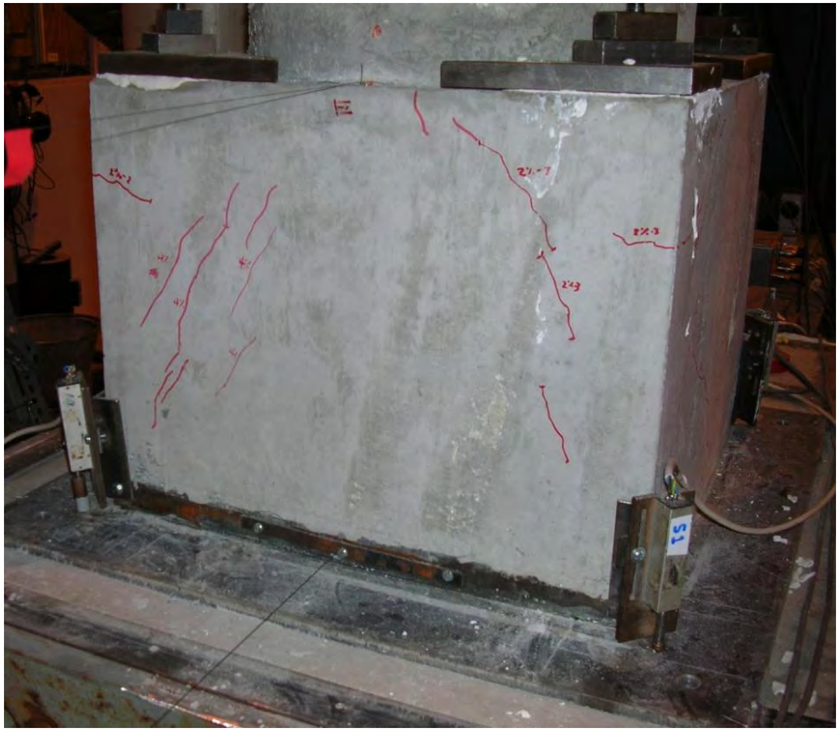
# Bridge Pier: Conventional vs. Damage Avoidance Design


(b)

# Bridge Pier: Conventional vs. Damage Avoidance Design

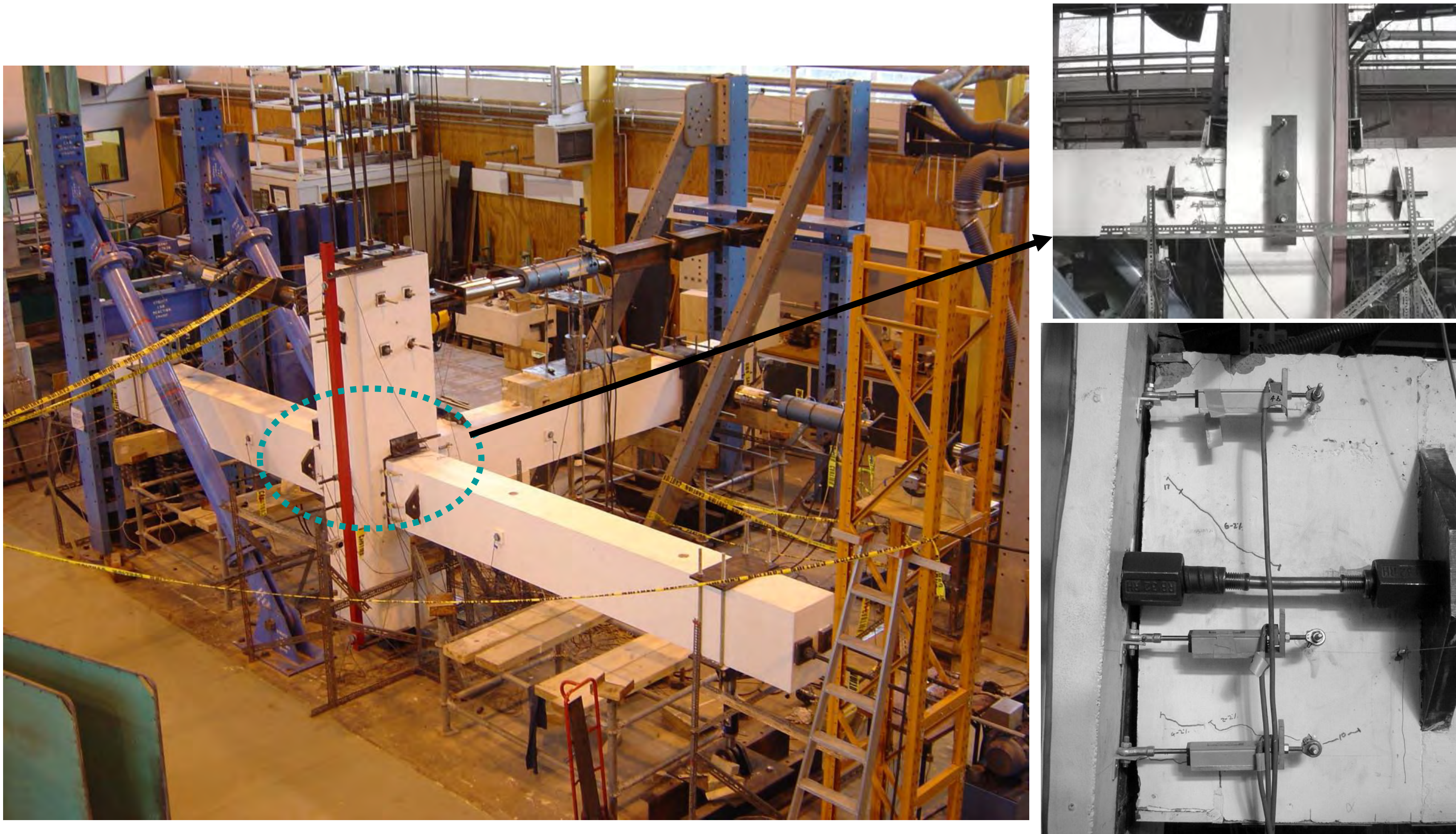


Ductile pier after testing



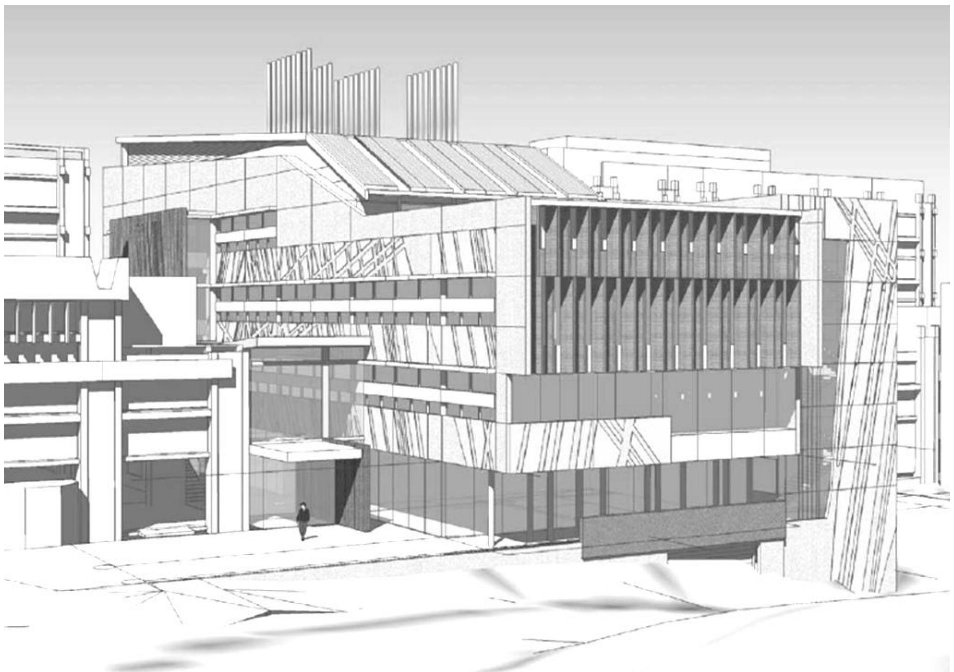
DAD pier after testing

# Damage Avoidance Design of Building Frames

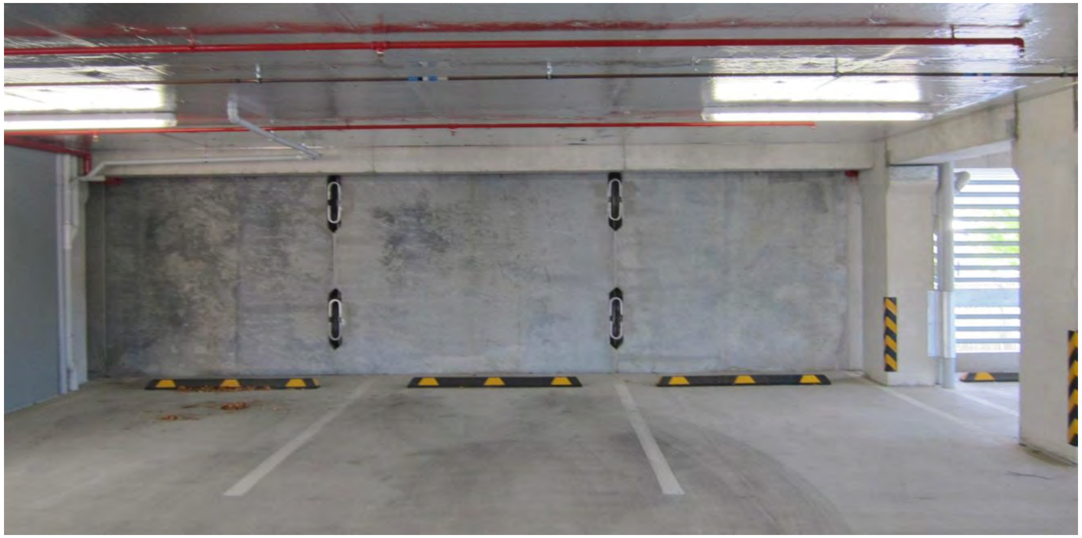


# Applications in NZ

Victoria University Wellington: First multi-storey PRESSS Building in New Zealand



# Applications in NZ



Second multi-storey PRESSS-Building in New Zealand (first in South Island): Endoscopy Consultants' Building for Southern Cross Hospital Ltd, Christchurch

Reportedly performed very well in recent Christchurch earthquakes

# Closing Remark

- **Rajesh, the Engineer**
  - In general, the performance of buildings in Canterbury earthquakes exceeded the adjusted expectations
- **Rajesh, the Citizen**
  - Really? The earthquakes have cost us 30 billion dollars (15% of our GDP); did we expect to lose more than this? Do we need to go completely broke for you to say that we haven't done well?

- Let's give up our "resistance to change" attitude, and work towards an approach that will require structures to meet the expectations of both Rajesh, the engineer, and Rajesh, the citizen, in future earthquakes.

# Thank You!