New Insights into Whole Building Performance from the Christchurch Natural Laboratory

Presentation to UACEER 2012 Earthquake Engineering Research Symposium, by G Charles Clifton

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Scope of Talk

- Christchurch earthquake series
- Expected performance of buildings
- Insights into performance of:
  - Multi-storey buildings
  - Long span single storey buildings
  - Pallet racking systems
  - Domestic houses
- Fire following earthquake
- Conclusions

Christchurch is a full scale open air laboratory testing the structural response of buildings under very severe earthquakes

Christchurch Earthquake Series

Timing, Intensity, Expected Building Performance

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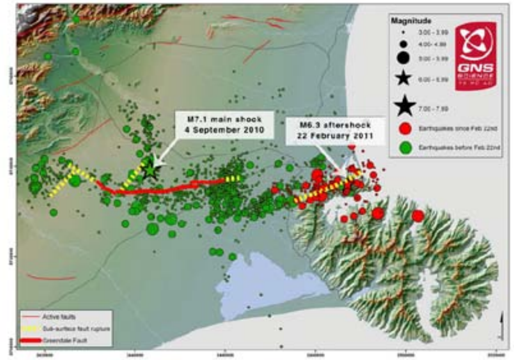


The Earthquake Sequence: Impact on Christchurch CBD

Magnitude and Intensity of damaging events to date:

4 Sept 2010: M 7.1, MM 7, ≈ 0.7 x DLE*

26 Dec 2010: M 5.5?, MM 7 to 8

22 Feb 2011: M 6.3, MM 9 to 10, ≈ 1.8 x DLE*

13 June, 2011: M 5.4?, MM 7 to 8

13 June 2011: M 6.3, MM 8 to 9, ≈ 0.9 x DLE*

23 December 2011: M 5.5, MM 6 to 7, ≈ 0.6 x DLE*

25 May 2012: M 5.2, MM 5 to 6, ≈ 0.5 x design*

DLE* = design level event for ultimate limit state (ie the design "big one")

Cumulative effect ≡ close to maximum considered event (step above DLE)

22 February Earthquake – Intensity of Shaking and Duration

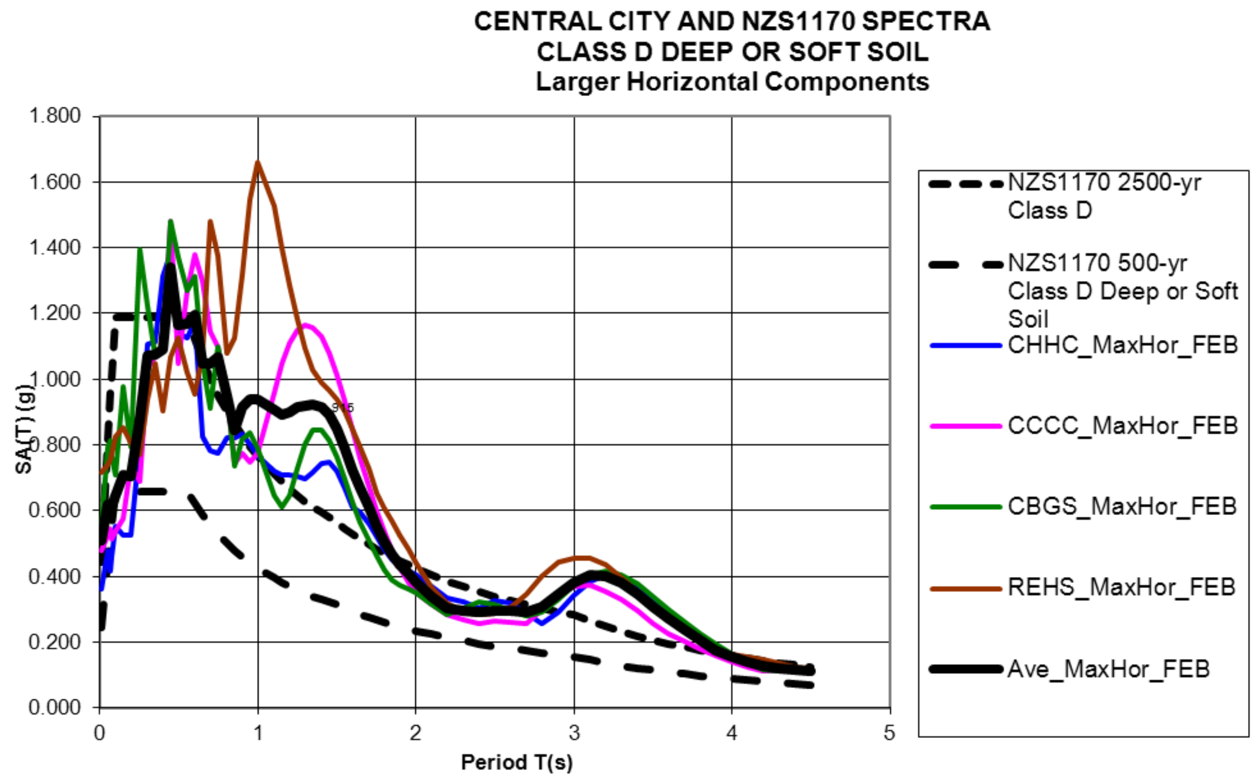
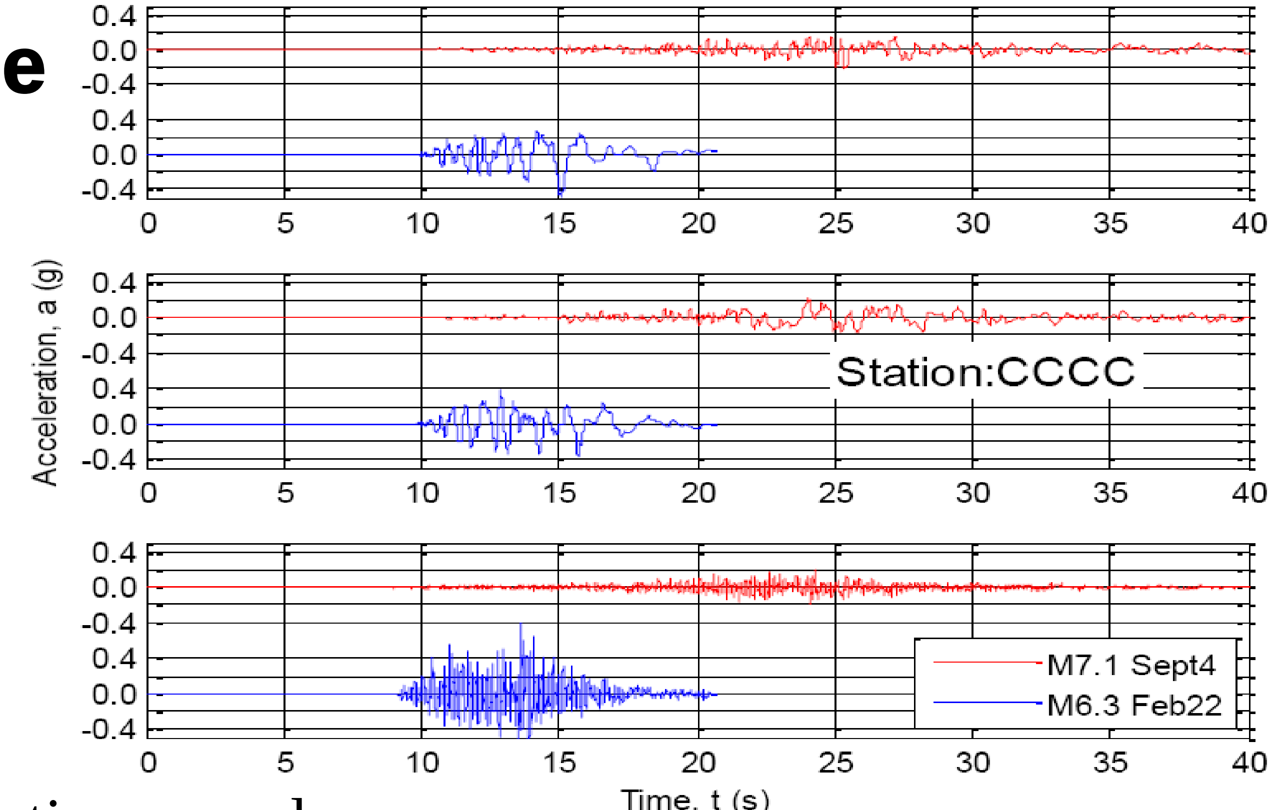


Figure 1 NZS 1170.5 Spectra and Largest Horizontal Direction Recorded from the CBD Strong Motion Records

Notes:

1. **The long dotted black line is the ULS design spectrum for normal importance buildings for the soft soil type, Class D, generally considered in the CBD, Z = 0.22**
2. **The short dotted black line is the Maximum Considered Event design spectrum for normal importance buildings for Class D soil in the CBD, Z = 0.22**
3. **The solid thick black line is the average from the 4 recording stations all of which are within 1km of the CBD and in similar ground conditions**

Aftershocks more intense than main event



Very good strong motion records

- Large number and good quality

PGA from February earthquake very intense

- 0.5g to 1.2g Hor PGA within CBD (cf: 0.22g for ULS DLE)
- Up to 1.8g Hor and Ver PGA in hill suburbs

Performance requirements of modern buildings in this level of event (>DLE)

For normal importance buildings to conventional ductile design, they:

- Shall remain standing under DLE, should also under MCE
- Structural and non structural damage will occur
- Building will probably require replacement

What Types of Damage Occurred?

All possible types, singularly and in combination:

- Structural damage or collapse
- Ground instability: liquefaction, lateral spreading
- Damage to external cladding and internal wall linings
- Collapsed suspended ceilings , shelving and contents
- Damage from landslides, slope instability and rockfalls

Building Performance

- Houses performed well for life safety
- Multi-storey buildings did not collapse
- Old buildings did not kill occupants but rather those outside
- Newer buildings that collapsed killed occupants
- Fire suppression systems worked extremely well

Insights into Multi-Storey Building Performance

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Strength and Stiffness: Actual versus Predicted

- Steel buildings typically 2 to 2.5 times stronger and stiffer than the models predicted: why: we are working on reasons – slab, non structural elements, SFSI
- This determined from extent of observed response versus predicted response from model
- Most steel buildings effectively self-centred without need for specific devices to ensure this

HSBC Tower:

- Open plan office building
- Design drift 1.3% under DLE
- Actual drift ≅ 1% under 1.8 DLE
- Ratio of stiffness real/model = 2.3

Source: measurement of scuff marks on stairs; details from Design Engineer

Contribution of Composite Floor Slab to Steel Concrete Buildings Strength and Stiffness

- Excellent diaphragm action
- Ability to resist beam elongation
- Out of plane resistance of some 20 kN/mm and 25mm elastic threshold
- Assists with self centering
- Increases shear strength of active links, therefore
- Increases demand on system

Theoretical Comparison Floor Slab Contribution: Te Puni Village

- Floor is Unispan+topping on steel beams
- Modelling of floor slab as shell element representation compared with floor diaphragm
- Out of plane strength and stiffness modelled

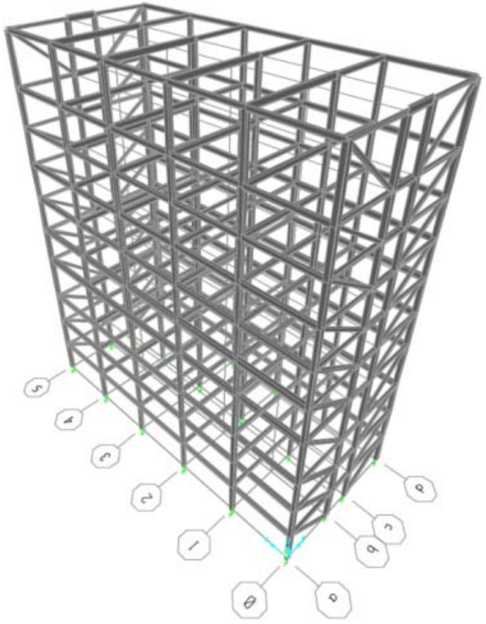

Figure 3-42: 3D model using the Diaphragm Constraint

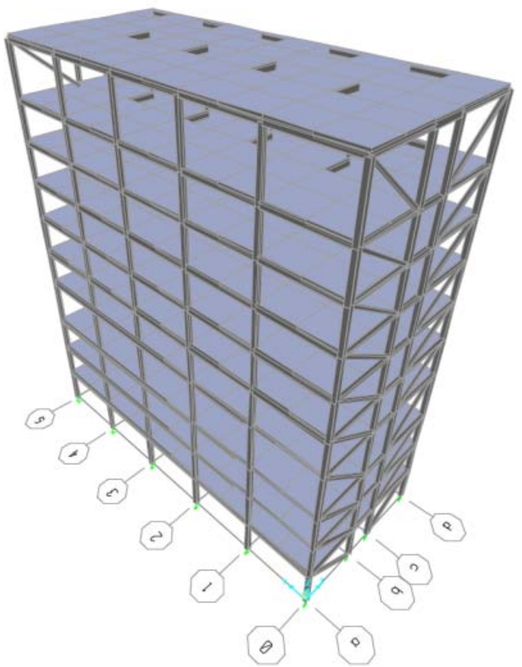

Figure 3-43: 3D model using shell elements

Theoretical Comparison Floor Slab Contribution: Te Puni Village

- Drift envelope from 7 strong motion earthquake records at DLE
- Transverse direction modelled
- Periods given by:
  - Diaphragm T_1 = 1.6 secs
  - Shell T_1 = 1.09 secs
  - Actual T_1 = 0.8 secs

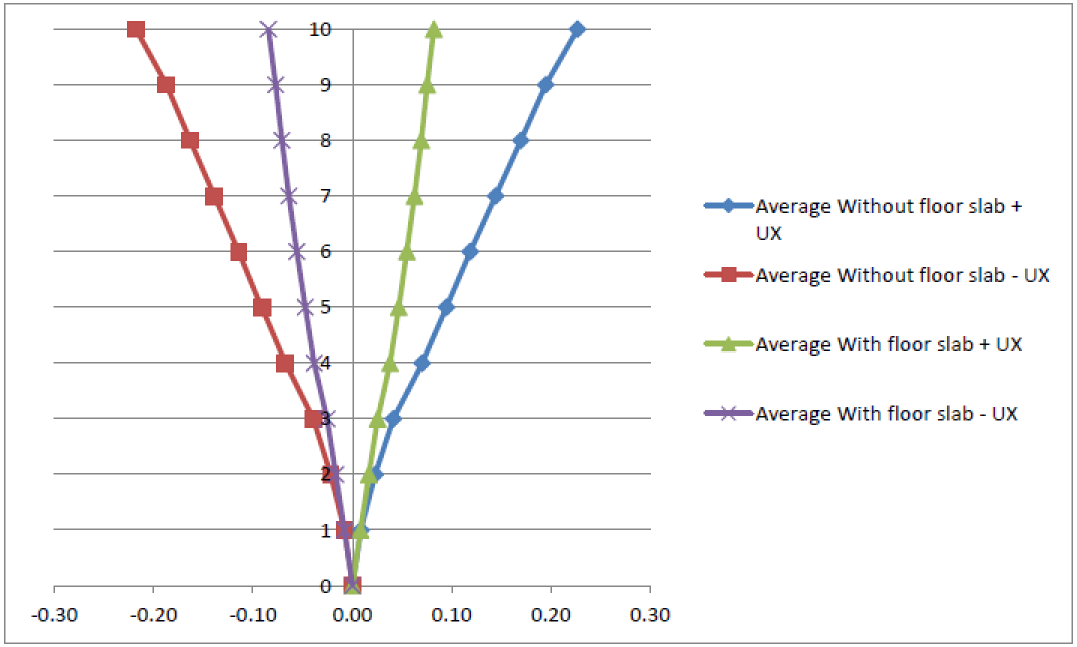

Figure 4-5: Average Inter-Storey drift envelope

Lao, Yin Pok; ME thesis 2011/2012

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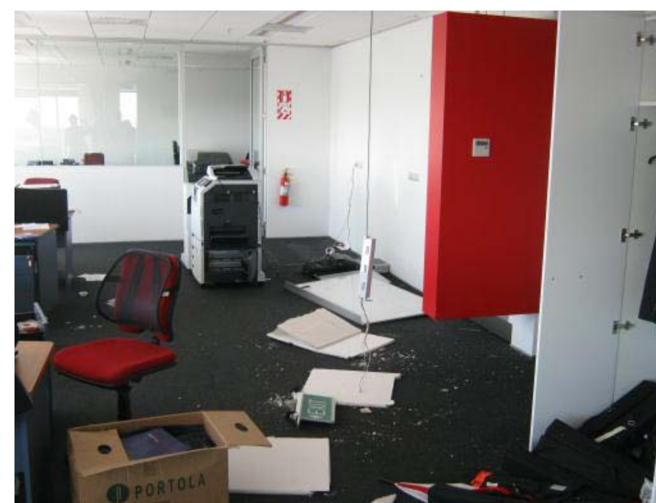
Damage and Disruption to Contents and Non-Structural Components

- Minimal in buildings that performed well
  - most contents still in place
- Proportional to observed drift
  - more effects in buildings with higher drift (compare PWC and HSBC tower)
- EBFs showed less damage than MRFs
- Some effects of vertical acceleration seen, eg
  - doors off hinges



Column Base Fixity

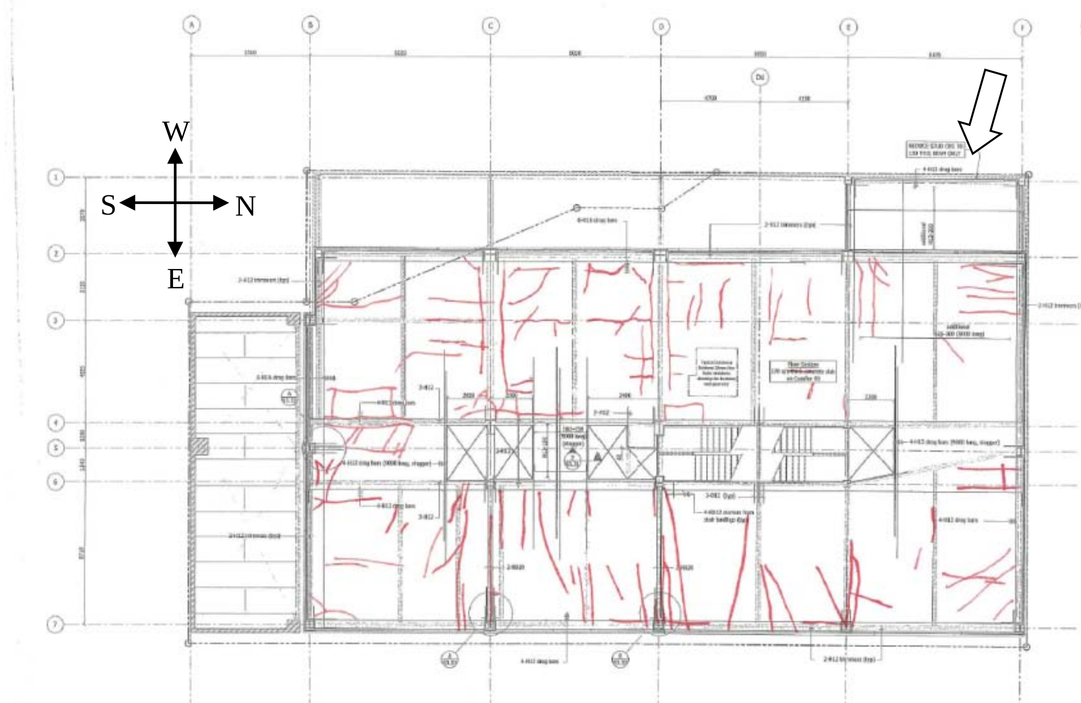
- Moment resisting and braced frame columns typically designed as pinned
- Expected to form base plastic hinges when superstructure becomes inelastic.
- No examples seen in practice, therefore
- Need to realistically model foundation flexibility

Case Study: Pacific Tower

22 storey mixed EBF and MRF, composite floors, transfer diaphragms levels 2, 6, 11, 20

- Building over 2x stiffer than model
- Building has effectively self centred:
  - 60 mm out of plumb midheight
  - 30 mm out of plumb at top
  - under 0.1% residual deflection most floors
- Repairs required
  - Significant inelastic demand levels 2 to 7; most active links in those levels will be replaced (42 in total)
  - Some active link steel does not meet the new specification which post-dates this building; if had less repair required
  - Cracking in composite floors; all cracks over 0.5mm wide being epoxy grouted
  - Requires realignment of lift guide rails
  - Plan to reopen February 2013

Pacific Tower Floor Slab Cracking: Level 6



Floor cracking shows:

- Evidence of torsional response?
- Slab elongation NS ≈ 3-4 mm; EW 1-2 mm
- Maybe cracking due to vertical motion
- Minimal damage around EBFs

Pacific Tower Influence of Non Structural Components and Layout

Levels 2 – 6 open plan carpark

Levels 6 – 15 hotel

Levels 15 – 22 apartments

Non structural contributions:

- Hotel approx 1 – 5 kN/mm length of internal walls; up to 500 kN per floor
- Levels 6 to 22 much stiffer and stronger than SRS
- Inelastic demand levels 2 – 6
- None at the top

Performance of Modern Concrete Moment Resisting Frames

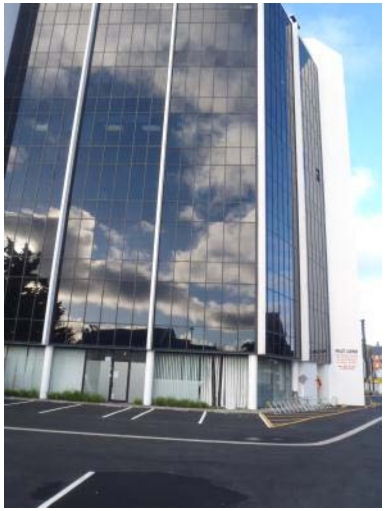
- Capacity design procedure has worked as expected
- No visible damage to columns or beam column joints of MRCFs
- Problem is plastic hinge cracking in beams:
  - Expect large number of small cracks
  - Seen small number large cracks
  - Loss of reinforcement strain?
  - Threshold for leave in place?
  - Strategy for repair?

Floor Slab Response in Reinforced Concrete Frames with Precast Floors

- Floors pulling away from frames, shear walls
- Beam elongation in frames
- Reinforcing bar strains and fracture
- Enhanced torsional response
- How to repair??

Shear Wall Performance

- Single major transverse crack in many cases
- Fractured rebar
- Transverse splitting of walls and compression failure
- Progressive deterioration in successive earthquakes
- Reasons for failures to be determined
  - evidence of high compression along full length of walls
- How to repair?



Effects of Vertical Acceleration

Generally relatively minor, eg:

- Permanent deformation in long span floors (HSBC Tower)
- Cracking of cantilever bay windows (HSBC Tower)
- Cracking pattern in composite floors

Sometimes much more serious, eg:

- Transfer beams end compression failure (Crowne Plaza Hotel)
- Contribution to shear wall and column compression failures

Pounding of Buildings

- Increasingly significant cause of damage in older buildings
- Not significant in modern buildings

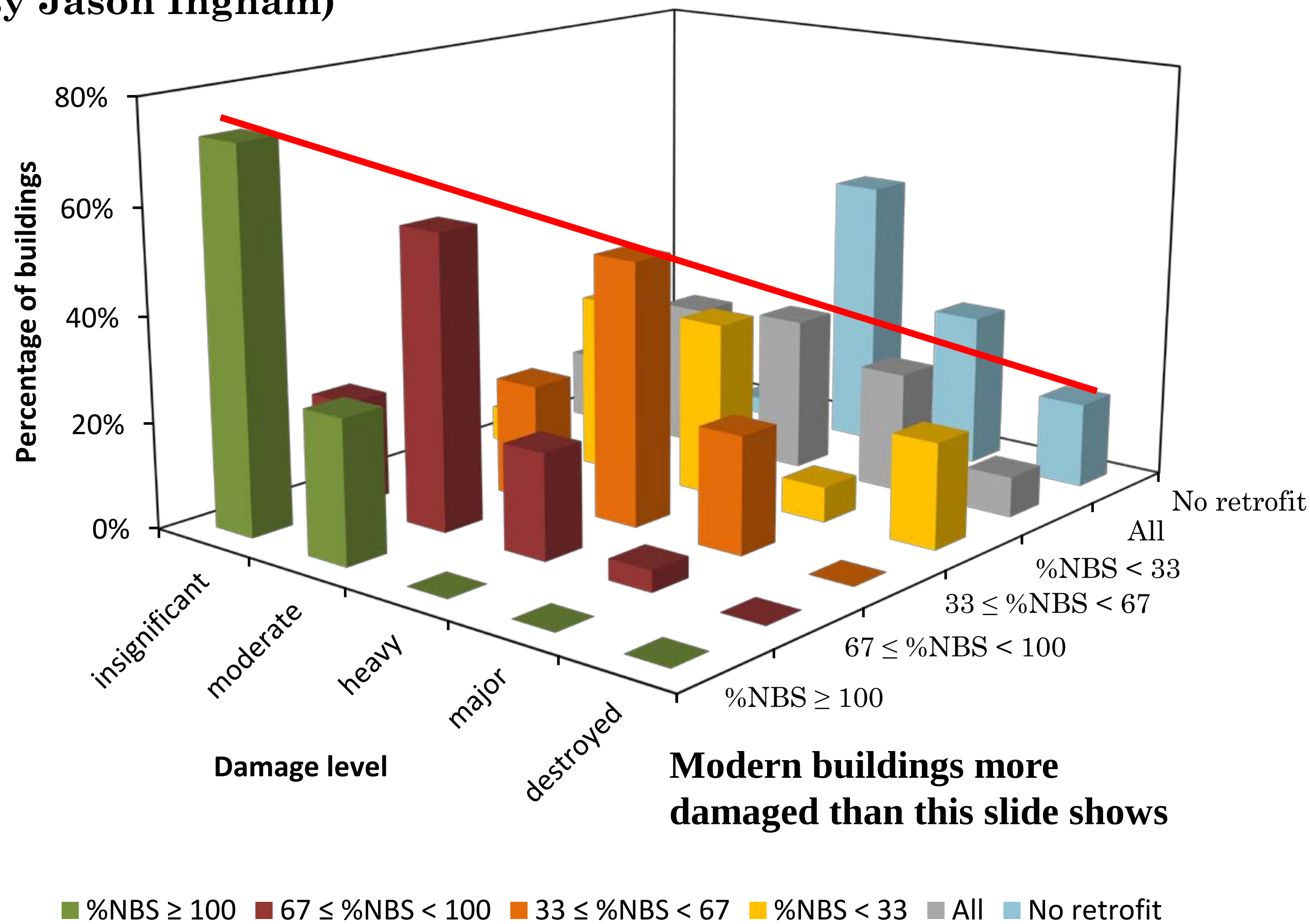
Effects of Poor Detailing and Below Specification Materials

Poor details or below specification material performed badly, some examples shown:

- Braces not lined up with stiffeners
- Frames not connected into the floors
- Inadequate welds
- Steel with very low notch toughness

Damage levels for different levels of %NBS earthquake (survey following 22nd Feb 2011)

(courtesy Jason Ingham)



Modern buildings more damaged than this slide shows

Long Span Single Storey Building Performance

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Steel Portal Framed Buildings

- Generally performed very well despite ground instability sometimes major
- Some collapse of precast concrete wall boundary elements
- Failure of roof bracing system due to:
  - Ductile overload brace systems
  - Fracture some roof bracing systems and components

Engineered timber buildings

Most performed very well

Despite lateral spreading of portal bases

Slide from Andy Buchanan

Pallet Racking Systems

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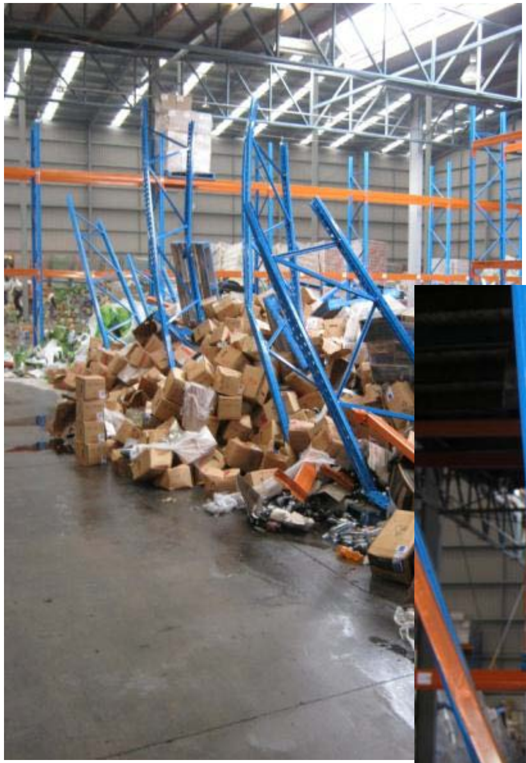
What went wrong?

- September 4th, 2010 Darfield earthquake
- February 21st, 2011earthquake

- Substantial damage to racking systems in both events and failure of many systems
- Failure has the potential for loss of human life, and substantial economic consequences.

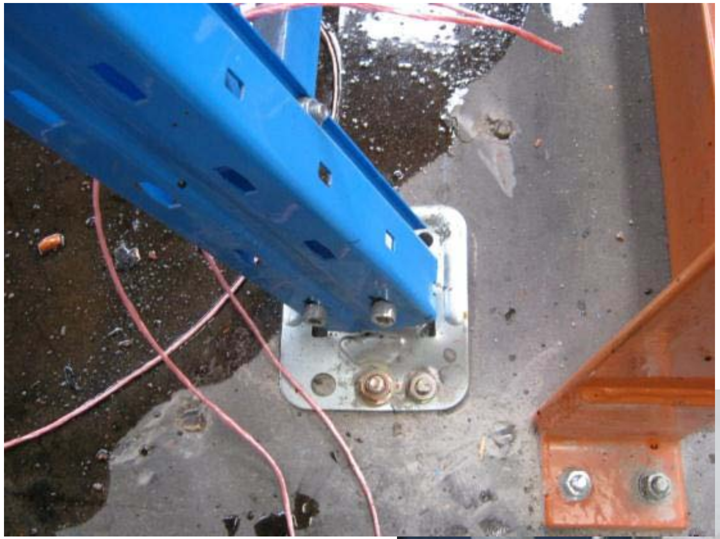
Failure Modes: Down-aisle direction

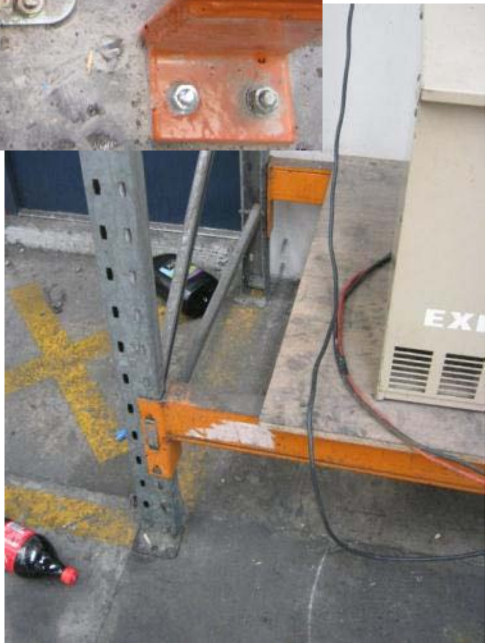
- Yielding of the beam to column connection
- Column crippling followed by soft storey



Failure Modes: Transverse direction

- Fracture of baseplate
- Pull-out of baseplate from slab





Study to Determine Reserve of Strength

- Down-aisle direction only
- Experimental testing of semi-rigid joint
- Characterisation of joint stiffness, strength
- NITH of representative internal frames with semi-rigid connections

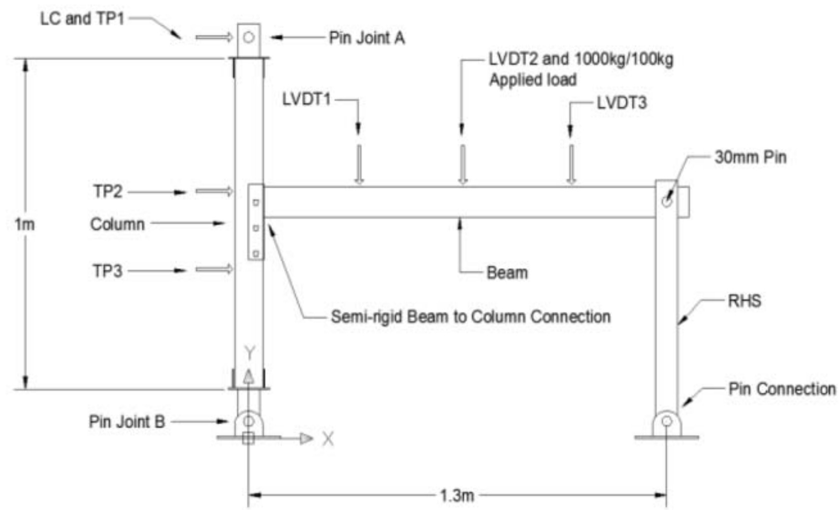


Figure 3: Beam to column stiffness test setup

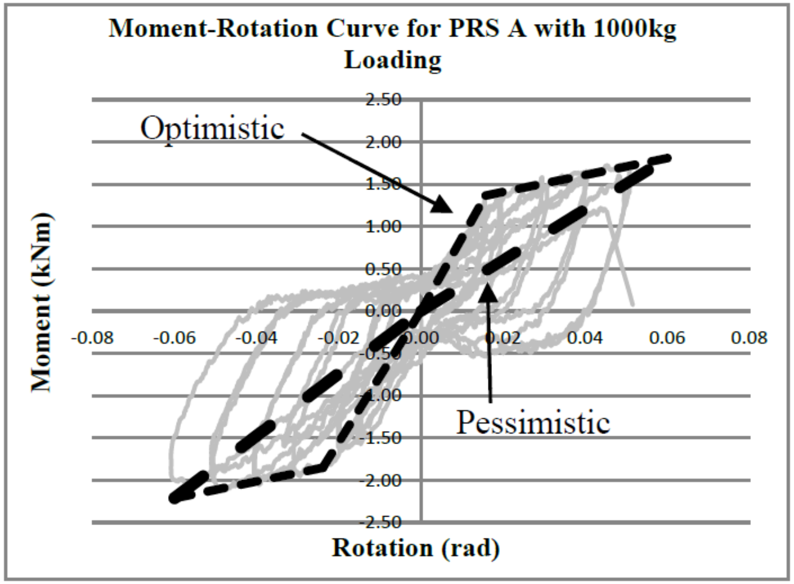


Figure 6: Optimistic and pessimistic stiffness curves

Dean Hoogeveen 4th year project 2011

Results Show:

Variable	Value for PRS A	Value for PRS B
$(PGA_{beginning\ damage}/PGA_{design})_{min}$	1.1	0.8
$(PGA_{beginning\ damage}/PGA_{design})_{average}$	1.5	1.2
$(PGA_{collapse}/PGA_{design})_{min}$	2.8	2.3
$(PGA_{collapse}/PGA_{design})_{average}$	3.1	2.3

PRS A and PRS B are the two NZ rack manufacturers

- Threshold is rack dependent
- Ratio up to 6 in Chch eqs
- Issue with non complying racks

Insights into Domestic House Performance

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Domestic Houses: Key Points

- Most are timber framed on concrete slab or piles with the older houses
- Roofs are long run steel or concrete tile
- Generally performed well where ground remained stable
- Houses at least 2x stiffer and stronger than design level:
  - lot of redundancy
  - minor cracking only
  - steel framed performed slightly better than timber framed; less lining cracking and brick veneer loss

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Concrete Tiled Roofs

Roof shaken off

Chimneys through roofs

Timber house structurally safe

Slide from Andy Buchanan

Solid wood houses

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Good performance despite differential slab movement

Slide from Andy Buchanan

Slide from Andy Buchanan

Internal linings

Gypsum plasterboard

Provided bracing for most houses

Cracking and some dislodging

Slide from Andy Buchanan

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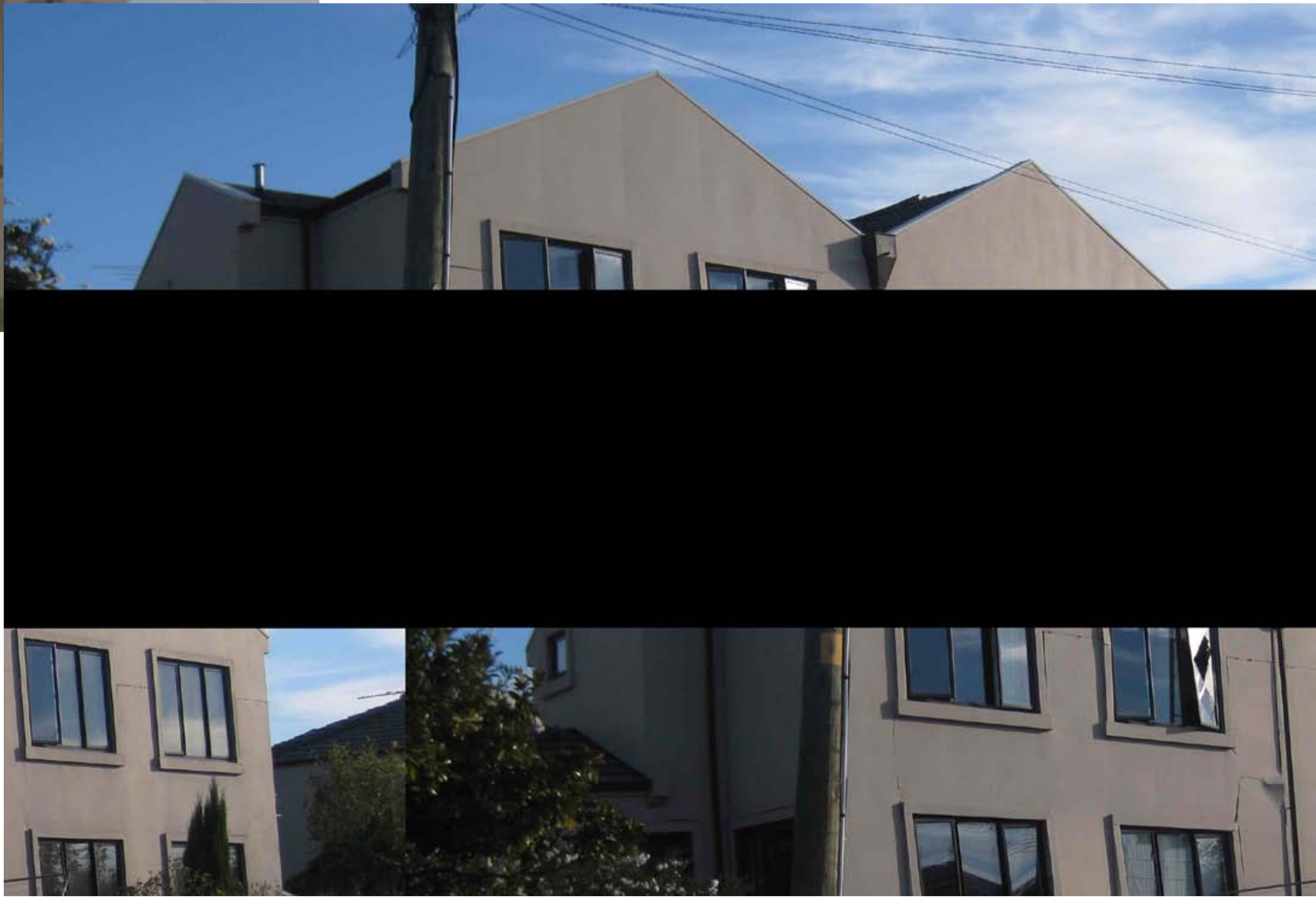
Soft storey collapse

Before



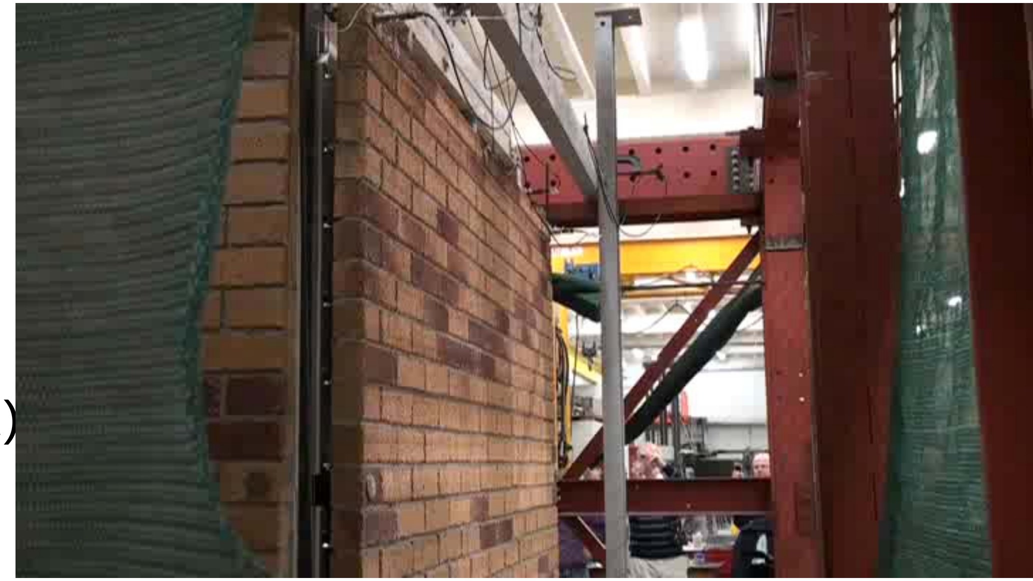
After

Light Steel Framing: Excellent performance

- Around 50 houses in strongly shaken areas
- New construction (most within last 10 to 15 years)
- Typical LSF frame on concrete slab with brick veneer
- No to minimal damage on sites with good ground

Seismic Performance of Light Steel Framing With Brick Veneer

- Excellent performance observed from tests
  - no damage under SLS
  - hairline cracking under ULS
  - no loss of bricks at MCE
  - some brick loss at 1.6xMCE (2.7x El Centro or 0.95g PGA)



- Performance in Darfield earthquake consistent with these tests
  - minor cracking and few bricks loose worst damage
  - most houses show no damage including no damage at corners

But worse was to come...

2 Storey House on 22 Feb Fault Line

- PGA_H and PGA_V = 1.8g
- Oamaru stone veneer damaged
  - Stones slid on mortar lines
  - Up to 8 stones dislodged
- Minor cracking internal gypsum board linings in places
  - Longest 1m crack
- Minor misalignment of one internal wall
  - Foundation bolt may have partially pulled out
- Client is very pleased
  - His house is repairable; stone veneer only significant damage
  - Similar houses close by destroyed




Fire Following Earthquake

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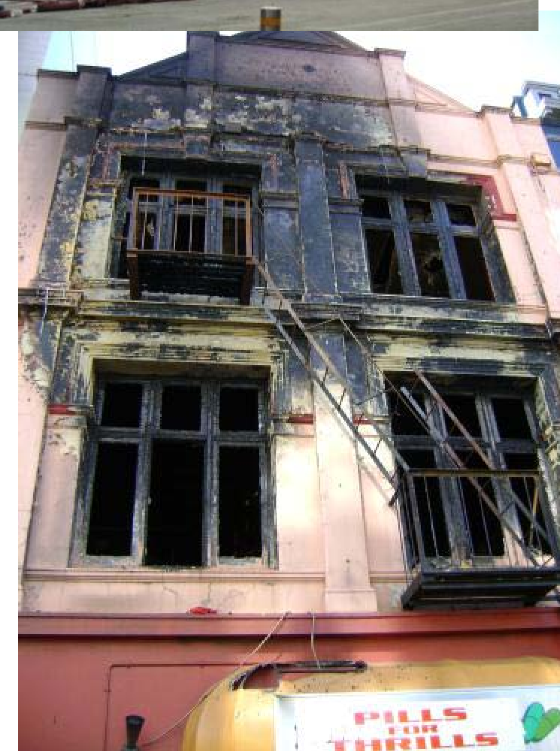
Fire Following Earthquake

- Major cause of loss of life in some earthquakes
  - Kobe, Japan, 1995, most recent example
- Major causes of fire damage and spread
  - Damage to buildings exposing combustible contents
  - Loss of water supply and Fire Service access
- How to mitigate loss of life
  - Provision of adequate earthquake and fire resistance
  - Non combustible claddings in closely spaced buildings
  - Reliability of egress and access
  - Restore water before electricity and gas restored
  - Systems in Christchurch earthquake series worked almost 100% - no significant fires

Fire Following Earthquake: Kobe 1995

Fire Following Earthquake: Christchurch 2010 and 2011

- Only 1 fire in each of the two biggest earthquakes
- 22 Feb occurred at worst possible time for fire to occur
  - many parts of city similar construction to Napier and greater damage, but no fire
- Gas and electricity cut-off systems worked very well
- Sprinkler systems did not discharge due to earthquake



Conclusions

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Conclusions

- Christchurch earthquake series uniquely severe due to intensity and duration of 6 damaging earthquakes
- Buildings typically >2x stiffer and stronger than models
- Capacity design procedure worked well for life safety
- Failure modes in concrete plastic hinges not what is expected; issues of repair and modification of new construction details being worked through
- Fire suppression systems worked 100% in buildings that remained standing

New Research Needs from Christchurch

- Christchurch earthquakes have shown the need to undertake research into:
- Whole structure behaviour under realistic conditions
    - Floor systems not just individual beams and columns
    - Earthquake rates of loading
- New UofA labs will facilitate this (operational 2015?)
    - Strong wall/strong floor and actuator capability will allow up to three storey full scale testing
    - Dynamic rates of loading
    - Full size building bay assemblage
    - Academic staff includes experts in all structural materials
    - We have excellent links with industry and other researchers