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**HAZARDS**CRC

# RESILIENCE & MITIGATION THROUGH HARDENING THE BUILT ENVIRONMENT (BUILDINGS & INFRASTRUCTURE)

A9: Cost-effective mitigation strategy development for building related earthquake risk

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School of Civil, Environmental & Mining Engineering, The University of Adelaide



An Australian Government Initiative



# **A9: COST EFFECTIVE MITIGATION STRATEGY FOR BUILDING-RELATED EARTHQUAKE RISK**

## **Project Participants**

### **Univ of Adelaide:**

**MC Griffith, M Jaksa, P Visintin, H Derakhshan**

### **Univ of Melbourne:**

**NTK Lam, H Goldsworthy, E Lumantarna**

### **Swinburne University:**

**JL Wilson, E Gad, HH Tsang**

### **Geoscience Australia:**

**M Edwards, H Ryu, M Wehner**

# MOTIVATION - Lessons from Christchurch



Christchurch corner shops



Adelaide corner shops



Christchurch theatre



Adelaide arcade

# **CHRISTCHURCH, NZ - Seconds After the 22 February 2011 Earthquake (Mw6.3, Depth 10km)**



# FAILURE OF OLDER UNREINFORCED MASONRY BUILDINGS



Out-of-plane wall bending failures in Unreinforced Masonry (URM) buildings in Christchurch (42 fatalities)

# FAILURE OF REINFORCED CONCRETE BUILDINGS IN CHRISTCHURCH



PGC – 18 fatalities



CTV – 115 fatalities

# Aims: To develop evidence base to inform decision making for earthquake risk mitigation

- ✓ Establish seismic vulnerability classes for representative building types in Australia
- ✓ Survey existing retrofit techniques for known performance in recent earthquakes
- ✓ Develop cost-effective Australia-specific retrofit solutions
- Develop economic loss models that include business interruption and casualty costs
- Develop decision-support and earthquake risk tools to support asset managers for retrofit.





# EXPOSURE: Australian building stock vulnerability classification (completed)

## Building classification parameters

- Usage,
- Construction Period,
- Proximity to Coast,
- Primary Lateral Load Resisting System,
- Storey Height Range,
- Wall Type,
- Wall Material,
- Roof Material.

Cost-Effective Mitigation Strategy  
Development for Building Related  
Earthquake Risk

Preliminary Building Schema

GEOSCIENCE AUSTRALIA

Prof. H. Edwards, M. and Z. Wilson, M.

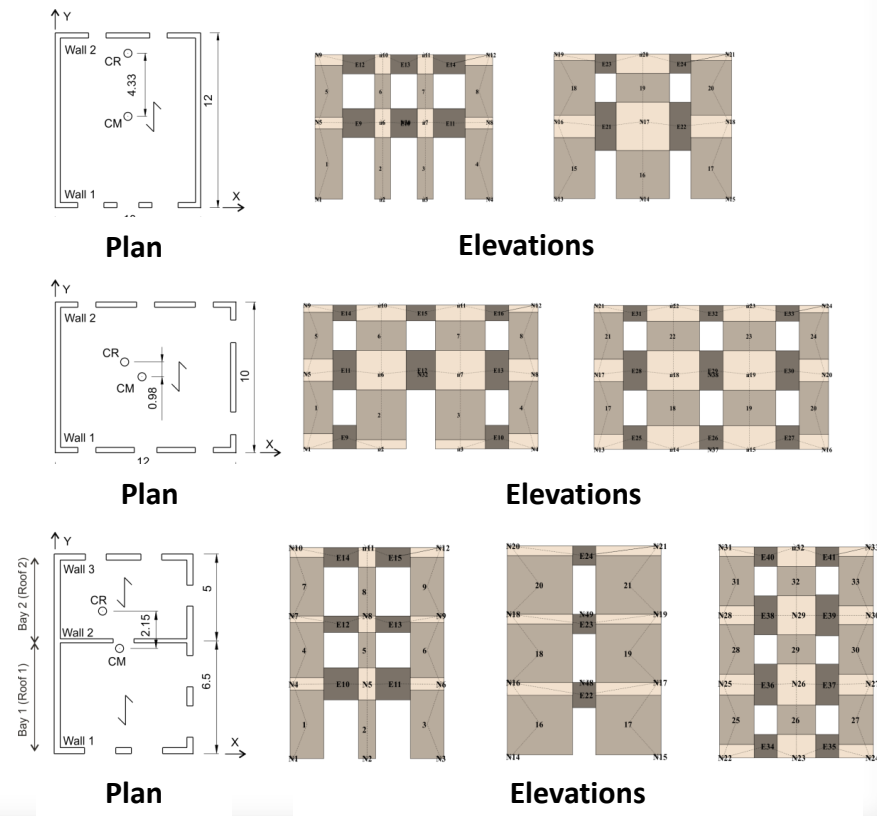
Australian Government  
Geoscience Australia  
Geoscience Australia

# URM BUILDINGS: Progress

Analysis techniques pre-requisite to cost-effective retrofit

- Push-over method developed for “main” building with flexible floors (ARC DP120100848, 2012-15)

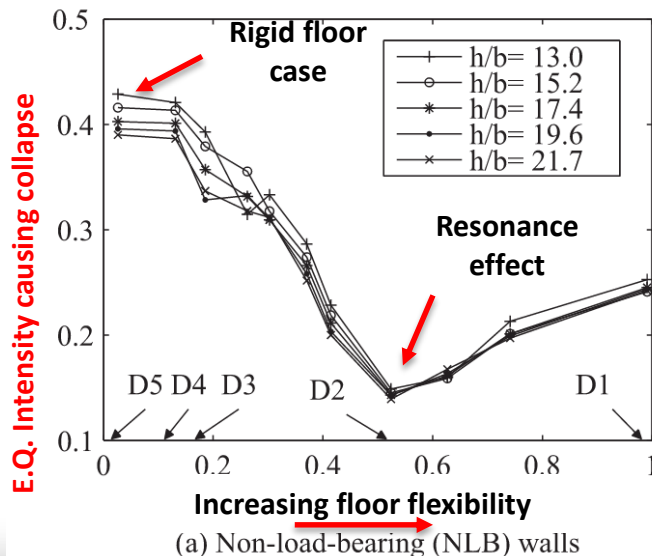
- 3 building types
- Choices of method, e.g. single-mode vs. modal pushover evaluated
- Reasonably conservative method identified



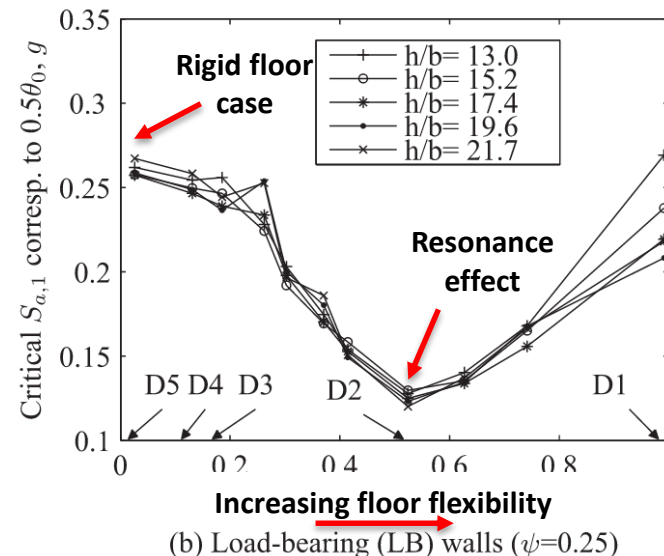
# URM BUILDINGS: Progress

Analysis techniques pre-requisite to cost-effective retrofit

- Effects of diaphragm flexibility on out-of-plane wall stability (ARC DP120100848, 2012-15)
  - Resonance between floor period and building found to reduce wall stability
  - To be incorporated in OOP wall assessment



(a) Non-load-bearing (NLB) walls



(b) Load-bearing (LB) walls ( $\psi=0.25$ )

# URM BUILDINGS: Progress

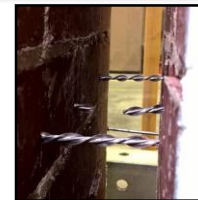
## Retrofit techniques for cavity walls

- Strategy: Combination of FRP only on the external faces of each leaf + anchors or foam inside cavity; no FRP inside the narrow gap due to limited access

#	Cavity structure	Notes
1	N/A (Single-leaf)	Control specimen
2	Standard ties @ 516 mm	no FRP retrofit
3	Standard ties @ 516 mm	FRP retrofit
4	Standard ties @ 260 mm	FRP retrofit
5	8 mm dia. Helifix anchors @ 430 mm alternate sides of FRP	Retest of Wall 3 (standard ties cut)
6	8 mm dia. Helifix anchors @ 430 mm both sides of FRP	Retest of Walls 3&5
7	Expanding foam infill	Retest of Wall 4 (FRP retrofit; ties cut)
8	2 x 50 mm wide foam channels	New wall, FRP retrofit
9	2 x 50 mm wide foam channels	New wall, no FRP retrofit



Standard ties



Helifix anchors



Foam infill/strips

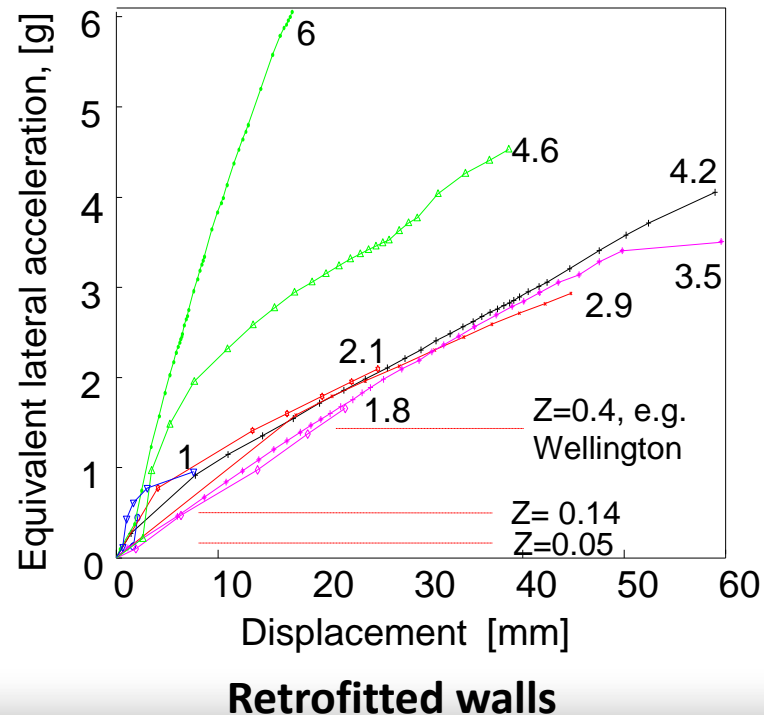


Typical test setup

# URM BUILDINGS: Progress

## Retrofit techniques for cavity walls - Results

- Un-retrofitted walls unsatisfactory, particularly with flexible floor diaphragms.
- Retrofit scenarios improve wall strength to resist loads up to high seismic regions ( $z=0.4$ ).



# URM BUILDINGS: Progress

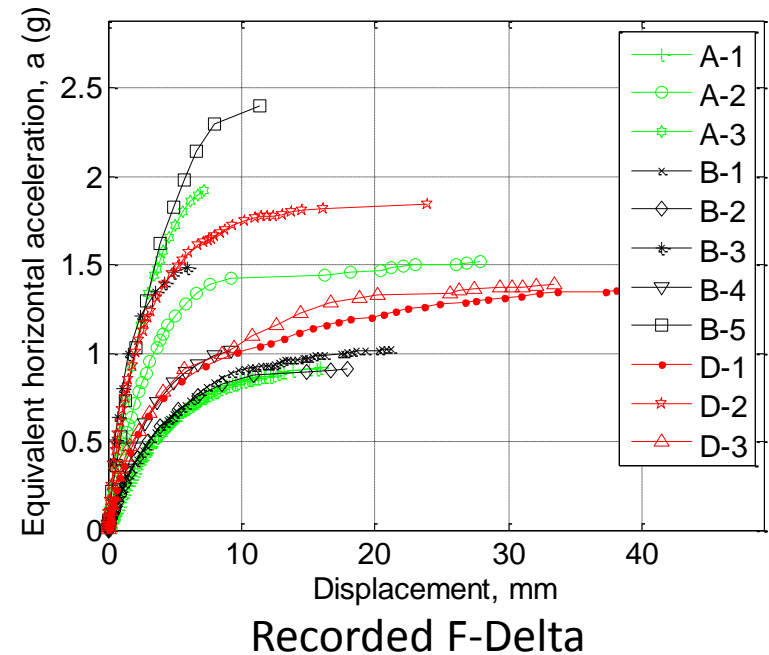
Retrofit techniques and FRP to masonry bond

- Long-term durability of FRP retrofit for Australian conditions:-
  - 6x 2.3m tall retrofitted 'walls'
  - 72x 5-brick stacks compression and stiffness
  - 105x 5-brick stacks for FRP bond strength
  - 84x 2-brick stacks for masonry tensile bond
  - Subject to temperature cycles and humidity cycles over 18 months (started late 2015 to finish mid-2017)
  - Effects to be formulated into already established FRP retrofit design procedures

# URM BUILDINGS: Progress

## In-situ testing

- 11 walls tested in 3 buildings
- 3 chimneys tested in 2 buildings
- Material testing done in-situ and in lab
- To be continued with in-situ retrofit as opportunity arises



Wall airbag testing



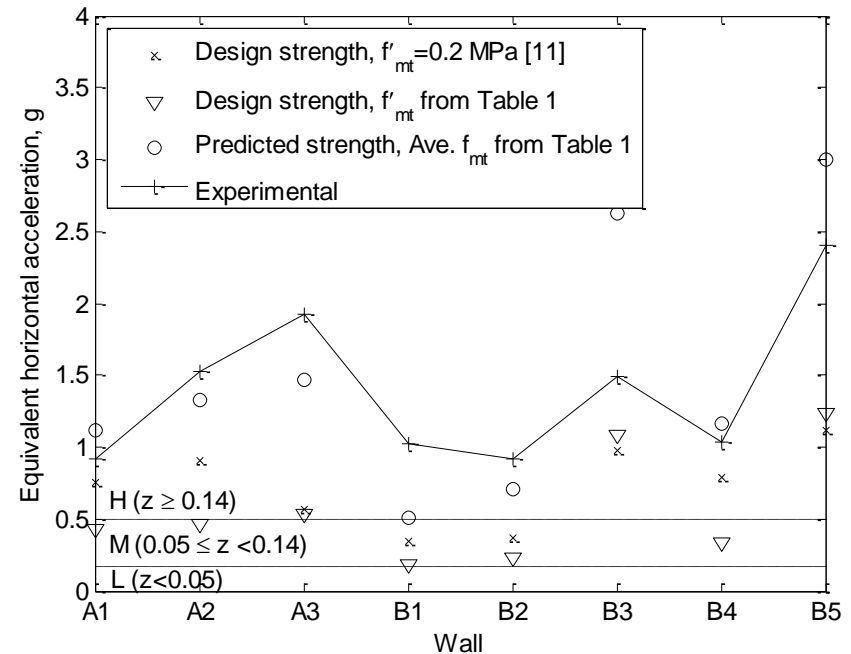
A chimney cross section



Chimney testing

# URM BUILDINGS: Progress

- Characteristic masonry bond strength was 0.04 MPa (only 20% of code-allowed value of 0.2 MPa)
- Still, the code formulae for wall strength is conservative due to ignoring/idealizing boundary conditions
- Found that chimneys in buildings other than single-storey located in regions with  $Z > 0.07$  need to be retrofitted



**Experimentally measured peak strength envelopes almost all calculation scenarios**



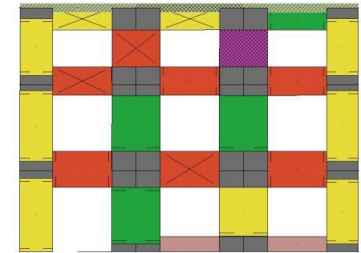
# URM BUILDINGS: Progress

Whole building analysis – international collaborators

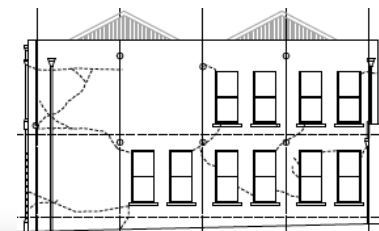
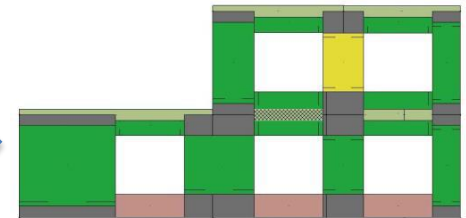
- Simulation of building earthquake damage done in Universities of Auckland, Pavia, Genoa
- The validated building models including several others are being used in Adelaide to defined seismic input to URM components, e.g. chimneys



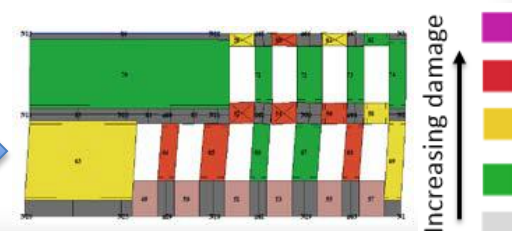
Royal Hotel, Christchurch



Avonmore House,  
Christchurch



Lancaster House, Gisborne



Pushover results

# URM BUILDINGS: Near Future

## Fragility curves for non-structural URM components

- Use new method to calculate seismic input (as per previous slide)
- Damage threshold for toppling non-structural parts are vague in literature and needs to be verified

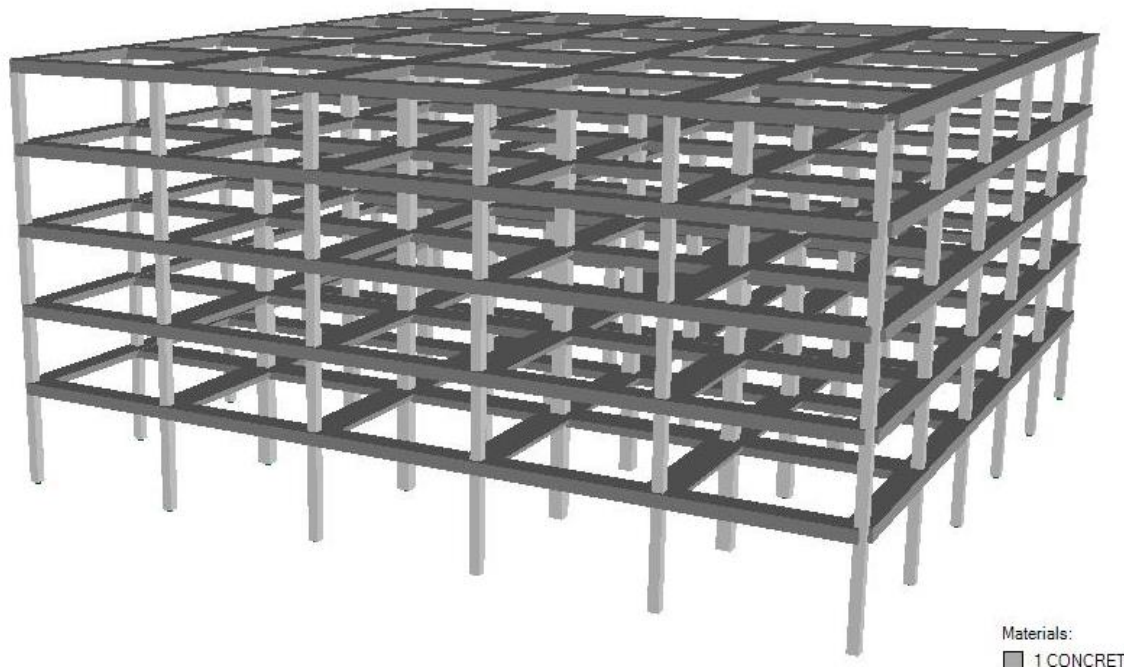
## Fragility curves for main building

- Damage levels identified in literature verified/re-defined using the improved pushover method
- Existing fragility curves verified/re-produced
- Stone masonry specifics to be considered (being studied in a parallel ARC discovery project 2016-19 in University of Adelaide; collaboration with Auckland)

# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Development of Fragility Curves based on:
  - (i) Quasi-Static Test, & (ii) Hybrid Simulation

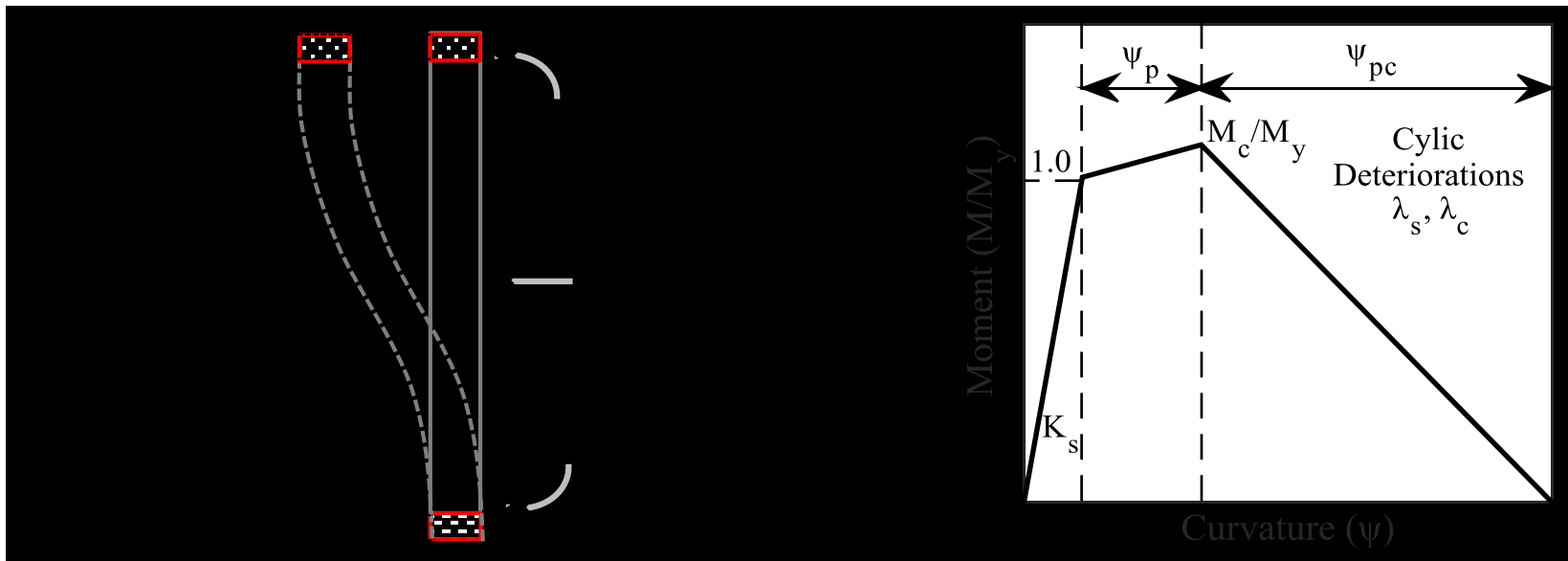


5-story Ordinary Moment Frame designed to Melbourne conditions (by PhD student, Scott Menegon)

# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Collapse Modelling is governed by the choice of modelling parameters

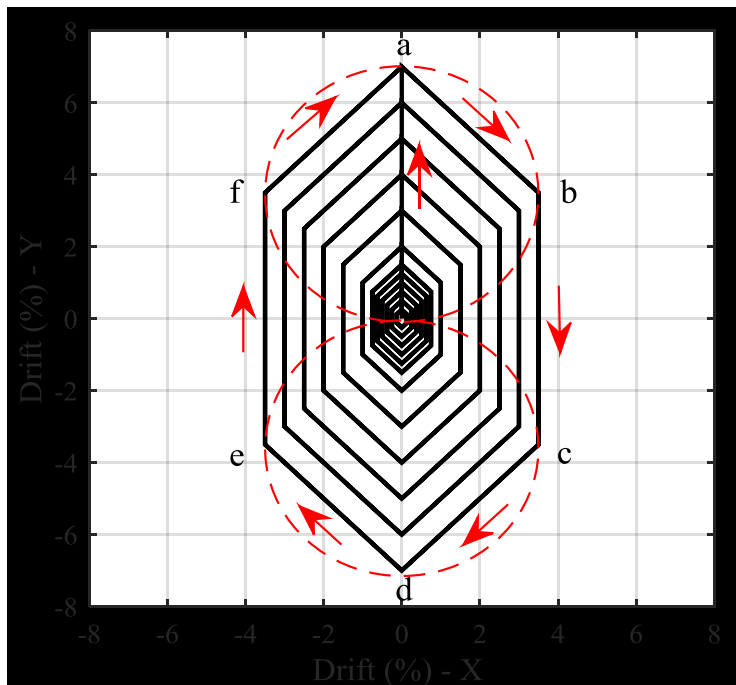


The modified Ibarra-Medina-Krawinkler (IMK) nonlinear analytical model for flexural behaviour of RC beams and columns

# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Obtaining modelling parameters from Quasi-Static Cyclic Test



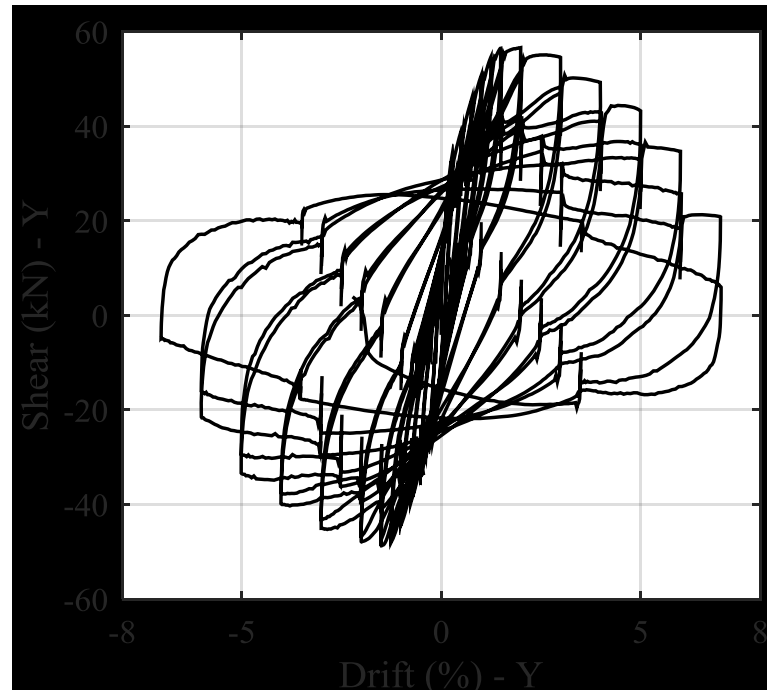
Hexagonal orbital pattern for bidirectional lateral deformation reversals (FEMA 461, implemented by research fellow, Javad Hashemi)



# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

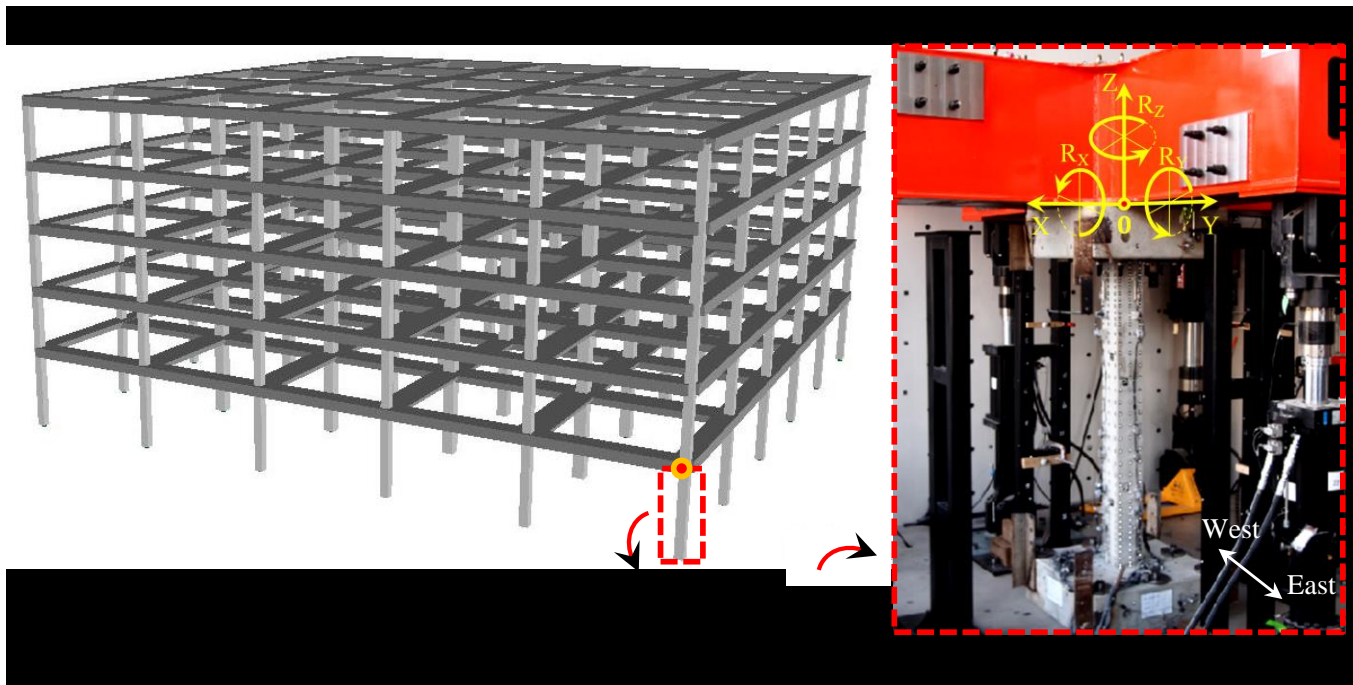
- Obtaining modelling parameters from Quasi-Static Cyclic Test



# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Obtaining modelling parameters from 6-DOF Hybrid Simulation Test

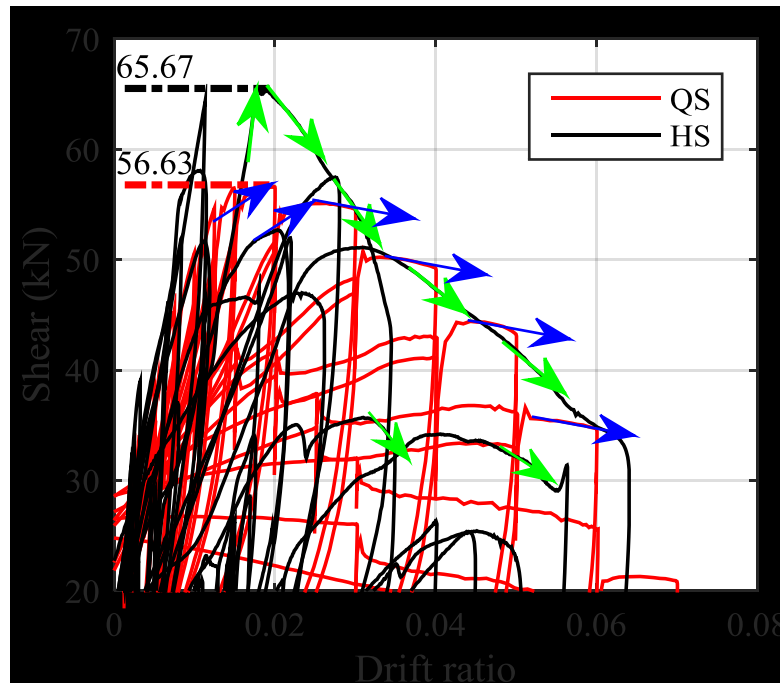


Implemented by  
research fellow,  
Javad Hashemi, and  
PhD student,  
Yassamin Al-Ogaidi

# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Differences in flexural strength and in-cycle negative stiffness between QS & HS

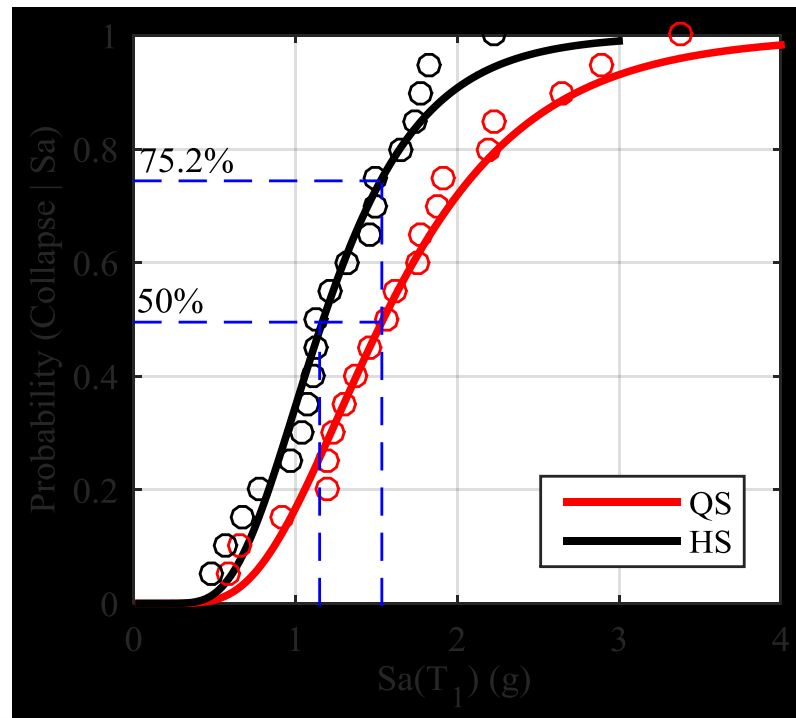




# REINFORCED CONCRETE BUILDINGS: Progress

## Moment Frame Structures with In-situ RC Columns

- Comparison of fragility curves based on results from QS & HS tests
- Low collapse probability due to the definition of collapse at **7%** drift

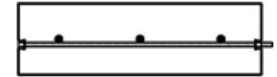


# REINFORCED CONCRETE BUILDINGS: Progress

$p_v = 1.2\%$



$p_v = 0.6\%$



## Structures with RC Walls

- Collapse Behaviour:
- (i) Out-of plane buckling (*left*)
- (ii) Local bar buckling (*right*)



(i)



(ii)

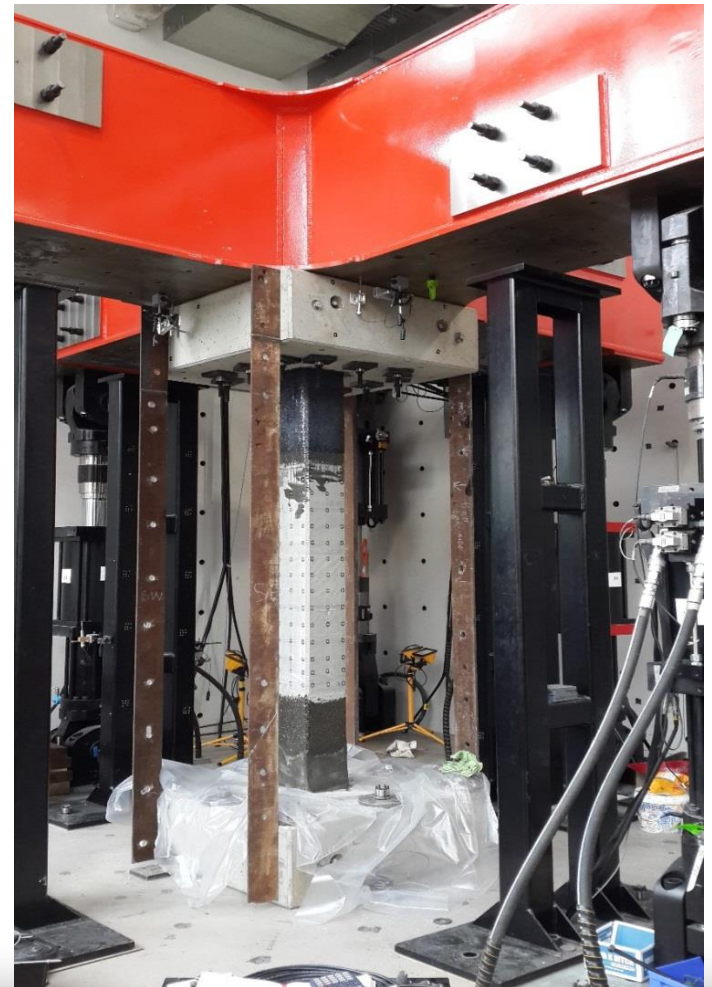
Tension-compression tests by PhD student, Scott Menegon

# REINFORCED CONCRETE BUILDINGS: Progress

## Seismic Retrofit Techniques

### CFRP Confinement

Implemented by  
research fellow,  
Robin Kalfat



# REINFORCED CONCRETE BUILDINGS: Progress

## Seismic Retrofit Techniques

- Poor detailing at beam-column joints
- Option 1: FRP Reinforcement
- Option 2: Metallic Haunch Element

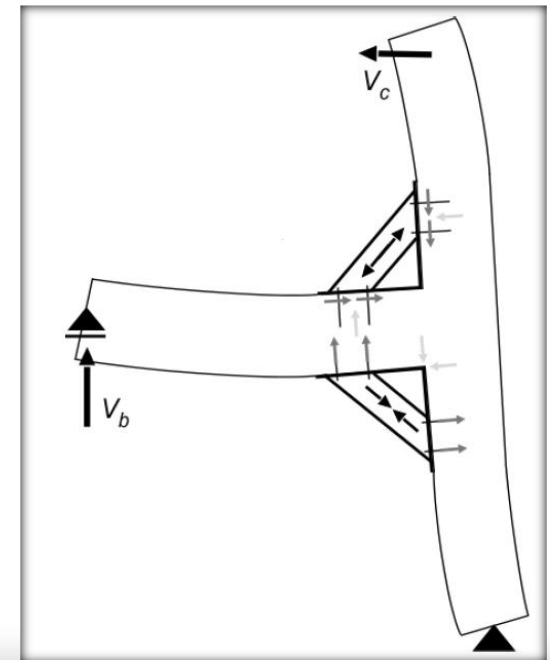
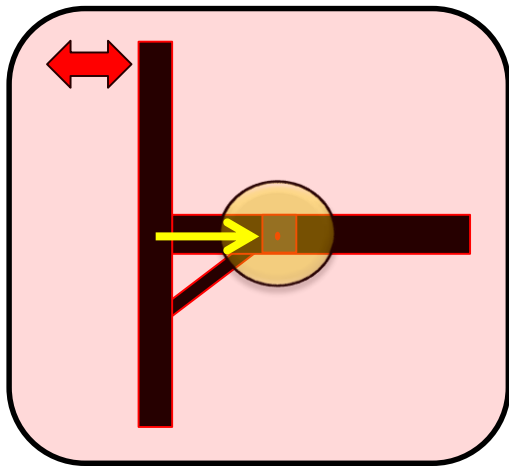


# REINFORCED CONCRETE BUILDINGS: Progress

## Seismic Retrofit Techniques

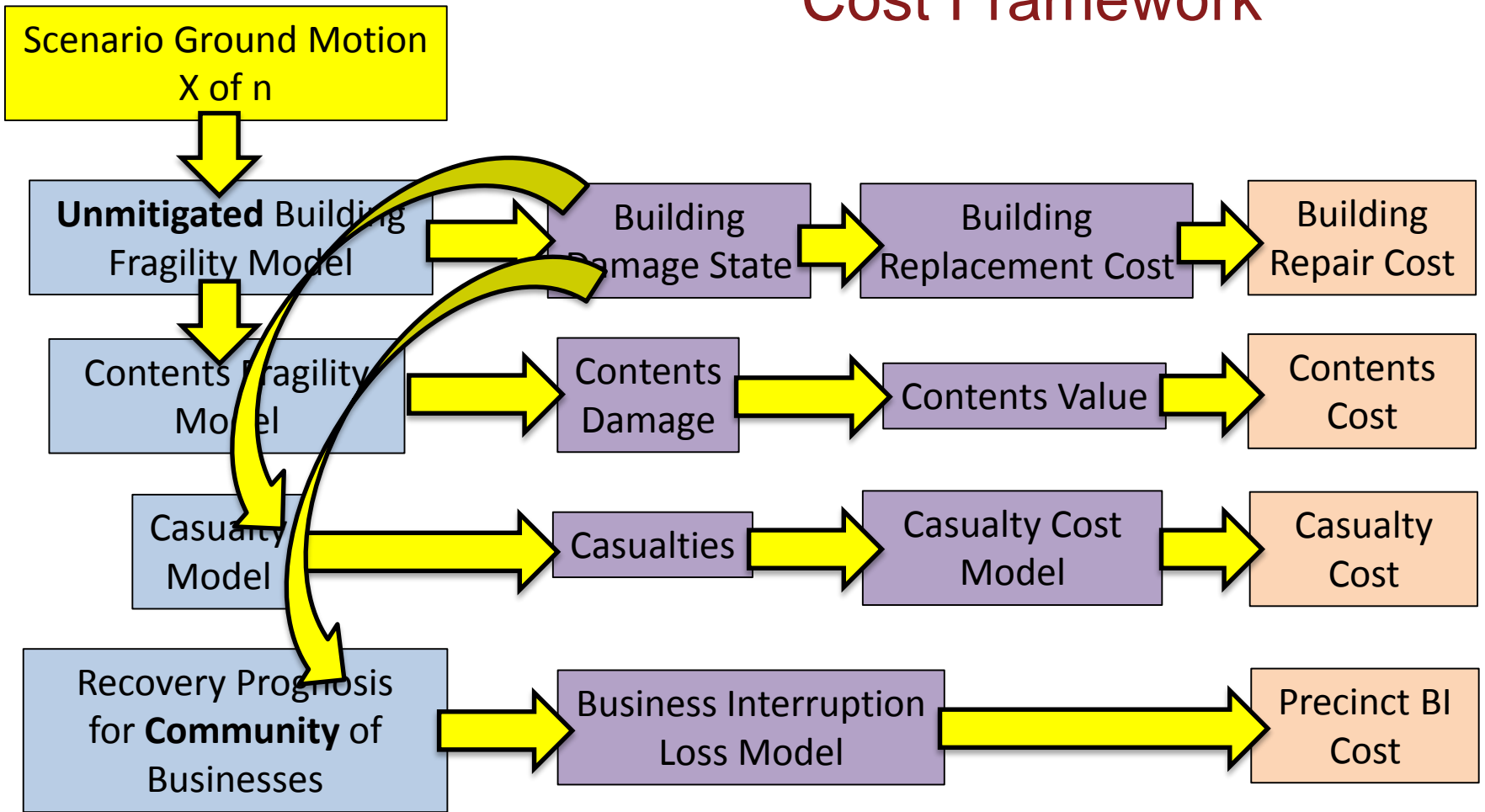
### Metallic Haunch Element

- Less invasive with post-installed anchoring system
- Load redistribution & relocating plastic hinge



Prepared by PhD student, Alireza Zabihi

# ECONOMIC MODELLING: Precinct Level Economic Cost Framework



Total Unmitigated Precinct Loss for Scenario X =

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# ECONOMIC EVALUATION

## Annualised Long Term Loss for Hazard Exposure:-

- Integrate total unmitigated losses for all likelihoods to determine annualised loss without action.
- Integrate total mitigated losses for all likelihoods to determine annualised loss with mitigation action.

## Annual Benefit of Mitigation:-

- Subtract annualised unmitigated loss from mitigated case to determine benefit

## Benefit Versus Investment Cost of Mitigation:-

- Discount the annual savings realised through mitigation to PV
- Divide PV of savings by retrofit cost to obtain B/C

# ECONOMIC MODELLING: Casualty Likelihood Modules

- Earthquake casualties are strongly correlated to the performance of buildings and so are influenced by the vulnerability of buildings and where people are located in time when an earthquake event occurs.
- Research will be adapting a population dynamics model to place people at the time of a rapid onset event such as an earthquake.
- This research recommends the adoption of the HAZUS-MH (FEMA 2003) casualty module due to its specific relevance to Australia.



# ECONOMIC MODELLING: Casualty Cost Modules

- Following the international practice and OBPR (2014), this research will adopt the values of:-
  - Value of Statistical Life (VSL) and
  - Value of Statistical Life Year (VLY)estimated by Abelson (2008) for estimating the monetary cost of casualties.
- Following the OBPR (2014) this research will adjust the value of statistical life year (which could be interpreted as the value of a year of life free of injury, disease and disability) by a factor that accounts for the type of injury, disease or disability.
- The research will use the AIHW published disability weights for diseases and injuries to adjust the VSLY (Mathers et al 1999).

# ECONOMIC MODELLING: Future Work

- Finalise cost models for injury associated with building damage in earthquakes.
- Development of business interruption model.
- Development of proposed framework/methodology and tools for assessing precinct level economic activity disruption. This is expected to include utilization of research undertaken in NZ on the recovery following the 2011 Christchurch Earthquake (Elwood et al, 2015)

# **FUTURE END USER PROJECTS**

## **Economic Evaluation of Design Hazard Changes to AS 1170.4 (End User ABCB):-**

- Apply CRC research to assessing the economic implications of adjusting the design hazard to Australian buildings.
- Apply CRC research to assessing the economic effectiveness of designing for high earthquake initially.
- Assessing the adequacy of design provisions for preventing catastrophic collapse in a rare earthquake.

## **Earthquake Mitigation Case Studies for WA Regional Towns (End User WA DFES):-**

- Many towns have older URM building stock some of which may be heritage listed.
- Project will work with State and local government and local EM to apply the CRC research to a virtual retrofit of town

## SUMMARY

- Progressing well against high level deliverables.
- Effective collaborations outside of the CRC.
- Experimental programs, both in the laboratory and in the field are proving very useful in capturing real behaviour.
- Economic framework advanced with the adaptation of models for likelihood of injury and the direction for adaptation of the value of human life and cost of injury for Australia.
- End user projects emerging that will utilise the research to mitigate current and future earthquake risk.

# THANK YOU

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