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

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

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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)
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.
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

PhD student: Yasuto Nakamura

bnhcrc.com.au
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
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

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

![Graph showing equivalent lateral acceleration vs. displacement for retrofitted walls.](image-url)
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
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
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)
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)
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
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
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
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

Structures with RC Walls
- Collapse Behaviour:
- (i) Out-of plane buckling (left)
- (ii) Local bar buckling (right)

Tension-compression tests by PhD student, Scott Menegon
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
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

Scenario Ground Motion
X of n

Unmitigated Building Fragility Model

Contents Fragility Model

Casualty Model

Recovery Prognosis for Community of Businesses

Building Damage State

Contents Damage

Casualties

Business Interruption Loss Model

Total Unmitigated Precinct Loss for Scenario X =
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 vent 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)

• 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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