TECHNICAL NOTE

INTERNATIONAL RESEARCH FRAMEWORK AND PRIORITIES FOR REINFORCED CONCRETE WALL BUILDINGS

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ABSTRACT

Recent earthquakes have highlighted discrepancies between the intended and observed performance of RC walls and significant research is in progress to improve the seismic performance of RC wall buildings. An international group of researchers and practitioners developed a research framework in order to conduct a project mapping and prioritisation exercise for RC wall research. The process by which this research framework and mapping exercise were conducted is described. The framework was used to identify research priorities that would provide a basis for the direction of future research. High priority topics included, shear demands and capacities, effect of load-rate and loading history, seismic assessment of older walls, residual capacity and repairability, non-rectangular and core walls, and whole of building response.

INTRODUCTION

Reinforced concrete (RC) walls are commonly used as lateral force resisting components in a wide range of building typologies worldwide. Despite providing an excellent seismic resisting system, recent earthquakes in Chile and New Zealand have highlighted discrepancies between the intended and observed performance of RC walls [1,2]. Extensive research is in progress worldwide to understand and improve the seismic behaviour of RC walls, with many countries facing similar challenges with respect to the design of new buildings and the assessment of existing building. The International Wall Institute was established in 2014 and brings together researchers and practitioners from a number of countries. During a recent workshop of the International Wall Institute, a research framework and prioritisation was developed. The objective was to provide a framework that would connect research that is being conducted by members of the International Wall Institute and identify gaps in the collective research programmes of participating nations. It was envisaged that the framework will assist in the identification of opportunities for funding in each country, leveraging opportunities for large scale testing at international facilities, and imitating international exchanges. A summary of the development of the research framework is presented along with outcomes from a prioritisation exercise that was conducted to align current and future projects.

INTERNATIONAL WALL INSTITUTE

The Virtual International Institute for Performance Assessment of Structural Wall Systems (or International Wall Institute) was initiated in 2014. The institute consists of researchers and practitioners from the US, NZ, Chile, Japan, and Europe. The primary goals of the Wall Institute are to share test plans and data, improve and validate numerical models, achieve consensus on critical design issues, prepare joint reports and papers, and develop collaborative research proposals. Given the extensive amount of RC wall research underway worldwide, the institute has played a vital role in synergising the efforts of individuals, leveraging opportunities and tests on other countries, and developing amendments to design standards/codes.

The International Wall Institute has functioned via workshops held every 8-10 months. The first two workshops were held in the US in Oct 2014 and Aug 2015, and the third workshop was held in Christchurch, New Zealand in April 2016. In addition to the workshops, several working groups on critical topics were initiated that meet regularly via web conferences. The working groups have enabling the sharing of data and the preparation of state-of-art reports.

Further details on the International Wall Institute and members can be found on the website: http://apedneault4.wix.com/wall-institute

DEVELOPMENT OF FRAMEWORK

The first two workshops provided an opportunity to present current research from each of the participating member institutions and to formulate working groups to address certain objectives of the institute. In order to move to towards a more collaborative research approach, a significant portion of the third workshop was set aside to develop the research framework and to conduct a project mapping and prioritisation exercise. The outline of the framework was initially drafted by a small group prior to the workshop and then presented for discussion and refinement. Consideration was given to the structure of the key topics in the framework, for instance grouping by member action or by member type. It was decided to arrange the framework by member type to be consistent with modern design standards, and to clearly identify topics that would align with expectations of research funders. The outline of the framework was agreed to by the workshop participants.

The agreed outline for the research framework is illustrated in Figure 1 and Figure 2. The key sections were grouped by wall

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typology with common tools that applied across typologies (such as modelling and design philosophies) separated out into separate sections. The framework was also built up to consider individual wall components through to building systems. RC wall topics included modelling, conventional walls (cantilever, squat, and irregular), existing walls, low-damage walls, and residual capacity and repair of damaged walls. Building systems included coupled walls, core walls, precast wall buildings, high wall-to-floor ratio buildings, and whole of building system aspects. Design philosophies that were considered included, reliability, capacity-based design, and performance-based design.

1 RC Walls

1.1 Wall modelling (micro, macro, interaction) and demands (nonlinear models)

1.1.1  Stiffness
1.1.2  Displacement demands
1.1.3  Shear demands
   1.1.3.1  Higher mode effects
1.1.4  Axial loads
1.1.5  Bi axial demands and behaviour
1.1.6  Load rate and history
1.1.7  Torsion modelling
1.1.8  Shear resistance

1.2 Conventional modern walls (CIP and precast)

1.2.1  Cantilever walls (planar and asymmetric)
   1.2.1.1  Wall design and acceptance criteria
      1.2.1.1.1  Ductile (special) walls
         a. Boundary details
         b. Web details and horizontal reinforcement
         c. Longitudinal reinforcement (incl. splices)
         d. Deformation capacities
         e. Wall geometry
      1.2.1.1.2  Limited ductile (intermediate/ordinary) wall
         a. Boundary details
         b. Web details and horizontal reinforcement
         c. Longitudinal reinforcement (incl. splices)
         d. Deformation capacities
         e. Wall geometry
      1.2.1.1.3  Nominally ductile (essentially elastic) wall
         a. Boundary details
         b. Web details and horizontal reinforcement
         c. Longitudinal reinforcement (incl. splices)
         d. Deformation capacities
         e. Wall geometry

1.2.2  Squat walls
   1.2.2.1  Wall design and acceptance criteria
   1.2.2.2  Modelling
      1.2.2.2.1  Strut and tie approaches
      1.2.2.2.2  Stiffness
      1.2.2.2.3  Boundary conditions (fixed base appropriate?)
   1.2.3  Irregular walls - punched, discontinuous, setback, flag shaped

1.3 Existing RC walls

1.3.1  Thin walls, single layer reinforcement
   1.3.1.1  Flexural
      1.3.1.1.1  Crushing
      1.3.1.1.2  Bar fracture
      1.3.1.1.3  Buckling
   1.3.1.2  Shear-controlled
      1.3.1.3  Axial failure
   1.3.2  Other existing walls
   1.3.3  Retrofit

1.4 New low-damage walls

1.4.1  Rocking walls
1.4.2  Energy dissipating devices
1.4.3  High-performance materials
1.4.4  Modification of conventional systems
   1.4.4.1  Bar debonding
   1.4.4.2  Slotted beam

1.5 Residual capacity and reparability of walls (post-earthquake)

Figure 1: Research framework – Part 1 (RC walls).
2 Building systems

2.1 Coupled walls
2.1.1. Design and acceptance criteria
2.1.1.1 Coupling beam detailing
2.1.2. Demands and modelling
2.1.2.1 Slab restraint on coupling beam
2.1.2.1.1 Cast-in place slabs
2.1.2.1.2 Pre-cast slabs
2.1.2.2 Coupling beam shears
2.1.2.3 Wall axial and shear loads

2.2 Core walls
2.2.1. Design and acceptance criteria
2.2.1.1 Corners
2.2.1.2 Coupling beam – edge detailing
2.2.2. Demands and modelling (and behaviour)
2.2.2.1 Biaxial demands
2.2.2.2 Torsion/shear flow post-yield
2.2.2.3 Effective flange width (incl. coupling beams)

2.3 Tilt-up and precast wall systems
2.3.1. Connections
2.3.2. Diaphragm-wall interaction

2.4 High wall-to-floor ratio buildings

2.5 Whole-of-Building aspects
2.5.1. Diaphragm behaviour and design
2.5.1.1 Design for inertial and transfer loads
2.5.1.2 Diaphragm stiffness
2.5.1.3 Influence on demands in vertical system
2.5.2. Podium response
2.5.3. System Interaction (incl. Floor - wall interaction)
2.5.3.1 Outrigger column effects
2.5.3.2 Wall-slab and slab-column connections
2.5.4. Demands on non-structural components
2.5.4.1 Deformations
2.5.4.2 Accelerations
2.5.5. Building instrumentation/monitoring
2.5.6. Irregular buildings
2.5.7. Structural redundancy

3 Design philosophies

3.1 Reliability
3.2 Capacity-based design
3.3 Performance-based design

Figure 2: Research framework – Part 2 (Building systems & Design philosophy).

MAPPING CURRENT RESEARCH PROJECTS
Following the development of the framework structure, current research projects were mapped alongside these topics. This mapping exercise was conducted at the Christchurch workshop within regional groups that consisted of New Zealand, United States, and Chile-Japan-Europe (World). The projects were listed by workshop attendees with additional communication to Wall Institute members that could not attend. A total of 66 current projects were identified, and the project listings for each region are summarised in Appendix A.

The mapped projects are shown within the research framework in Appendix B. Projects were listed against all topics that they directly addressed and so appeared multiple times within the framework. It should be noted that many projects may indirectly contribute to other topics as well, and the research framework would help to make those connections as projects proceeded.

The mapped projects highlighted significant cross-over between projects in each region. Significant groupings of projects occurred in the wall modelling and ductile/limited ductile conventional cantilever wall design. Projects were also generally well covered across the identified topics, but a few areas were identified where gaps existed with no current research. These gaps were either the result of an emerging priority (discussed below), or areas that had been extensively addressed by past research.

RESEARCH PRIORITISATION
In addition to mapping current projects, each region identified the key priority areas where additional research was required. These were highlighted in yellow within each
regions project listings within the spreadsheet in Appendix B. Discussion as a full group resulted in final identification of research priorities that were classified as high (H) and medium (M).

High priority areas included:
- H-1: Shear demands and higher-mode effects in RC walls.
- H-4: Existing RC walls: Coordination needed to identify priorities for assessing and strengthen existing buildings.
- H-5: Residual capacity and reparability of walls (post-earthquake).
- H-6: Corner detailing in core walls.
- H-7: Demands and modelling of core wall systems.
- H-8: Whole of building aspects: System level considerations across all types of walls/buildings.

Medium priority areas included:
- M-1: Guidance on effective stiffness of RC walls (elastic modelling input and code provisions).
- M-2: Longitudinal reinforcement requirements in ductile walls.
- M-3: Web cross-ties and horizontal reinforcement detailing in ductile walls.
- M-4: Irregular walls with penetrations, discontinuities, set-backs, etc.
- M-5: New low-damage wall systems.
- M-6: Demands and modelling of coupled wall systems.
- M-7: Guidance on connections in precast concrete wall buildings (e.g. tilt-up).
- M-8: Response of design of irregular wall buildings.

In addition to the research priorities, several areas were identified as requiring a state-of-art report:
- SOA-1: Squat walls.
- SOA-3: Connections in precast wall buildings.

It was considered that these state-of-art reports would help to summarised the past research in each of these areas and identify further research requirements that would address practice issues related to these topics. In many cases, amendments to design standards may be required and would also be identified by the state-of-art reports.

ACKNOWLEDGEMENTS

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REFERENCES


## APPENDIX A: PROJECT LISTINGS

### New Zealand and Australia

| NZ1 | Elwood - Ductile Wall Details (MBIE) |
| NZ2a | Henry - Lightly-reinforced Walls - New (MBIE) |
| NZ2b | Henry - Lightly-reinforced Walls - Existing (MBIE) |
| NZ2c | Henry - Lightly-reinforced Walls - Precast (MBIE) |
| NZ3 | Pampanin - Bidirectional response of rectangular walls (MBIE) |
| NZ4a | Dhakal - Wall Buckling - global (MBIE) |
| NZ4b | Dhakal - Wall Buckling - bar (MBIE) |
| NZ5 | Bull - Diaphragm demands (MBIE) |
| NZ6 | Hogan - Precast walls (QuakeCoRE) |
| NZ7 | Motter - Repair of damaged RC walls (QuakeCoRE) |
| NZ8 | Henry - System interaction (NHRP) |
| NZ9 | Dhakal - 3D behaviour of regular wall buildings (UC) |
| NZ10 | Lee - Wall nonlinear modelling (UC) |
| NZ11 | Pampanin - Cataloguing of Older RC NZ shear wall buildings (UC/EPFL) |
| AU1 | Wilson - Nominally ductile walls - CIP and Precast (ARC) |

### United States

<p>| US1 | Wallace - Coupled Walls (BRI) |
| US2 | Wallace - Wall Shear Reliability Design |
| US3 | Wallace - Wall Boundary Detailing (NSF) |
| US4 | Wallace - Flexural Wall Database (NSF) |
| US5 | Wallace - Rocking Walls |
| US6 | Wallace - 4 story Conventional Shake Table (NSF)* |
| US7 | Wallace - Tall Building Instrumentation Resilience (NSF)* |
| US8 | Sritharan - Rocking Walls with Floor Interaction (NSF) |
| US9 | Sritharan and Cho - Micro Scale Modeling/ Statistical Evaluation (ISU)* |
| US10 | Sritharan - Rectangular Wall Detailing* |
| US11 | Lowes - Non-linear Continuum Analysis of Walls |
| US12 | Lowes - Behavior of Irregular Walls and Walled Buildings (ATC) |
| US13 | Pujol - Minimum Reinforcement in Walls with Regular and High-Strength Steel* |
| US14 | Lepage - High-Strength Rebar in Cantilever Walls (Pankow)* |
| US15 | Moehle - ATC 78 Rapid Wall Building Assessment* |
| US16 | Moehle - Modeling of Lateral Instability* |
| US17 | Moehle - Wall Boundary Confinement* |
| US18 | Pujol - Wall Shear Behavior/ Strength* |
| US19 | Kurama - Tests of Walls for Nuclear Industry* |
| US20 | Varma - Nuclear Wall Modeling and Tests* |
| US21 | Kolozvari - Shear Wall Modeling (NSF)* |
| US22 | Fleishman - Precast Diaphragm (NSF)* |</p>
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<td>PUC.New 2 node element to model wall behaviour</td>
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## APPENDIX B: PROJECT MAPPING AND PRIORITISATION

### RC Wall Research Framework

1. **RC Walls**
   
   1.1. Wall modelling and demands
     
     1.1.1. Stiffness
     1.1.2. Displacement demands
     1.1.3. Shear demands
       
       1.1.3.1. Higher mode effects
     1.1.4. Axial loads
     1.1.5. Biaxial demands and behaviour
     1.1.6. Load rate and history
     1.1.7. Tension modelling
     1.1.8. Shear resistance
     
   1.2. Conventional modern walls (CIP and precast)
     
     1.2.1. Conventional walls (planar and asymmetric)
       
       1.2.1.1. Wall design and acceptance criteria
         
         1.2.1.1.1. Ductile (special) walls
         1.2.1.1.1. Boundary details
         1.2.1.1.1.2. Web details and horizontal reinforcement
         1.2.1.1.1.3. Longitudinal reinforcement (incl. splices)
         1.2.1.1.1.4. Deformation capacities
         1.2.1.1.1.5. Wall geometry
         1.2.1.1.2. Limited ductile (intermediate/ordinary) wall
           
           1.2.1.1.2.1. Boundary details
           1.2.1.1.2.2. Web details and horizontal reinforcement
           1.2.1.1.2.3. Longitudinal reinforcement
           1.2.1.1.2.4. Deformation capacities
           1.2.1.1.2.5. Wall geometry
         1.2.1.1.3. Nominal ductile (essentially elastic) wall
           
           1.2.1.1.3.1. Boundary details
           1.2.1.1.3.2. Web details and horizontal reinforcement
           1.2.1.1.3.3. Longitudinal reinforcement
           1.2.1.1.3.4. Deformation capacities
           1.2.1.1.3.5. Wall geometry
         1.2.1.1.4. Squat walls (need design primer/SAW paper)
           
           1.2.1.1.4.1. Wall design and acceptance criteria
           1.2.1.1.4.2. Modelling
           1.2.1.1.4.3. Strut and tie approaches
           1.2.1.1.4.4. Stiffness
           1.2.1.1.4.5. Boundary conditions (fixed base appropriate?)
         1.2.1.2. Irregular walls - punched, discontinuous, setback, flag shaped
           
           1.2.1.2.1. Wall design and acceptance criteria
           1.2.1.2.2. Modelling
           1.2.1.2.3. Strut and tie approaches
           1.2.1.2.4. Stiffness
           1.2.1.2.5. Boundary conditions (fixed base appropriate?)

   1.3. Existing RC walls
     
     1.3.1. Thin walls, single layer reinforcement
       
       1.3.1.1. Flexural
         
         1.3.1.1.1. Crushing
         1.3.1.1.2. Bar fracture
         1.3.1.1.3. Buckling
       1.3.1.2. Shear-controlled
       1.3.1.3. Axial failure
       1.3.2. Other existing walls
     
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**Notes:**
- Important for code development
- Refer to work on bridge columns
- Link with core wall and whole building
- Need for a primer
- Coordination needed and identify priorities
1.4. New low-damage walls
   1.4.1. Rocking walls
   1.4.2. Energy dissipating devices
   1.4.3. High-performance materials
   1.4.4. Modification of conventional systems
   1.4.4.1. Bar debonding
   1.4.4.2. Slotted beam

1.5. Residual capacity and repairability of walls (post-earthquake)

2. Building systems
   2.1. Coupled walls
      2.1.1. Design and acceptance criteria
      2.1.1.1. Coupling beam detailing
      2.1.2. Demands and modelling
      2.1.2.1. Slab restraint on coupling beam
      2.1.2.1.1. Cast-in place slabs
      2.1.2.1.2. Pre-cast slabs
      2.1.2.2. Coupling beam shear
      2.1.2.3. Wall axial and shear loads

   2.2. Core walls
      2.2.1. Design and acceptance criteria
      2.2.1.1. Column
      2.2.1.2. Coupling beam – edge detailing
      2.2.2. Demands and modelling (and behaviour)
      2.2.2.1. Biaxial demands
      2.2.2.2. Torsion/shear flow post-yield
      2.2.2.3. Effective flange width (incl. coupling beams)

   2.3. Tilt-up and precast wall systems
      2.3.1. Connections
      2.3.2. Diaphragm-wall interaction

2.4. High wall-to-floor ratio buildings

2.5. Whole-of-Building aspects
   2.5.1. Diaphragm behaviour and design
   2.5.1.1. Design for inertial and transfer loads
   2.5.1.2. Diaphragm stiffness
   2.5.1.3. Influence on demands in vertical system
   2.5.2. Pseudodynamic response
   2.5.3. System interaction (incl. floor - wall interaction)
   2.5.3.1. Outrigger column effects
   2.5.3.2. Wall-slab and slab-column connections
   2.5.4. Demands on non-structural components
   2.5.4.1. Deformations
   2.5.4.2. Accelerations
   2.5.6. Building instrumentation/monitoring

3. Design philosophies
   3.1. Reliability
   3.2. Capacity-based design
   3.3. Performance-based design

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