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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. Biaxial 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 additional 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-2: Shear resistance of RC walls.
- H-3: Influence of load-rate and history on the seismic response of 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-2: New low-damage 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.

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REFERENCES

1 Sritharan S, Beyer K, Henry RS, Chai YH, Kowalsky M and Bull D (2014). "Understanding poor seismic performance of concrete walls and design implications". *Earthquake Spectra*, **30**(1): 307-334.

2 Wallace JW, Massone LM, Bonelli P, Dragovich J, Lagos R, Lüders C and Moehle J (2012). "Damage and Implications for Seismic Design of RC Structural Wall Buildings". *Earthquake Spectra*, **28**(SUPPL.1): S281-S299.

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	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)*

World **(Chile, Japan, Europe)**	W1 PUC_Tests_of_thin_walls_with_single_layer_reinf W2 PUC_Seismic_demand_Chilean_RC_buildings W3 PUC_FEM of buildings inelastic frame elements - Hube W4 PUC_Epistemic_Uncertainty in modelling of building response W5 PUC_New 2 node elment to model wall behaviour W6 EPFL - Axially equilibrated DB beam element - Tarquini Almeida Beyer W7 EPFL - Lap_splice project - Tarquini Almeida Beyer W8 EPFL - RC core walls - Constantin & Beyer W9 EPFL - Thin Walls - Rosso Almeida Beyer W10 TokyoTech - PCaPC Walls - Kono W11 TokyoTech - Prism Test - Kono W12 TokyoTech - Beam element model with fibre sections - Kono W13 TokyoTech - Tests of lightly reinf layer single layer - Kono W14 TokyoTech - FEM analysis of lightly reinf layer single layer - Kono W15 TokyoTech -RC frames with RC infills Kono W16 UCH_Shell element analysis - Massone W17 UCH_Effective flange width - Massone W18 UCH_Walls_with_discontinuities - Massone W19 UCH_Tests_on_set_back_walls - Massone W20 UCH_Tests on shear amplification of walls with discontinuities - Massone W21 UCH_Tests on punched walls - Massone W22 UCH_Nonlinear system analysis - Massone W23 EPFL Vertical accelerations - Almeida & Beyer W24 UoL Shear demand and capacity - Fischinger W25 UoL Buildings with large wall to floor ratio - Fischinger W26 UoL Interaction between structural elements - Fischinger W27 UoL Macro-element modelling of walls (3D) - Fischinger W28 CEER- Thin wall project (collaboration with EPFL) - Arteta W29 TokyoTech - Tests on rectangular vs barbelled walls - Kono W30 CEER - Modelling nonlinear buckling of tied bars - Arteta W31 CEER - Confined concrete stress-strain relationship - Arteta W32 CEER - RC walls EDP risk assessment methodology

APPENDIX B: PROJECT MAPPING AND PRIORITISATION

RC Wall Research Framework	New Zealand	World	US	Priority	Comments
1. RC Walls					
1.1. Wall modelling and demands	NZ10	W12 W8 W5 W6 W17 W27 W14	US9 US11 US15 US21		
1.1.1. Stiffness		W26 W8	US3 US4 US6 US10 US12 US14	M	Important for code development
1.1.2. Displacement demands		W16			
1.1.3. Shear demands	NZ9	W24	US2	H	
1.1.3.1. Higher mode effects		W20			
1.1.4. Axial loads		W23			
1.1.5. Biaxial demands and behaviour	NZ3		US5 US8 US11		
1.1.6. Load rate and history	NZ3 NZ8			H	Refer to work on bridge columns
1.1.7. Torsion modelling		W8			Link with core wall and whole building
1.1.8. Shear resistance		W24	US11 US18	H	
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		W29 W25			
1.2.1.1.1.1. Boundary details	NZ1 NZ4a,b	W11 W25	US3 US4 US10 US11 US14 US17		
1.2.1.1.1.2. Web details and horz reinforcement	NZ1 NZ4b	W25	US3 US4 US10 US11	M	
1.2.1.1.1.3. Longitudinal reinforcement (incl splices)	NZ2a NZ4a,b	W7	US3 US4 US10 US11	M	
1.2.1.1.1.4. Deformation capacities	NZ1 NZ2a NZ4a,b	W8 W11 W30 W31	US3 US4 US11 US16		
1.2.1.1.1.5. Wall geometry	NZ4a	W8 W11	US3 US4 US11		
1.2.1.1.2. Limited ductile (intermediate/ordinary) wall		W1 W9 W25 W29	US19 US20		
1.2.1.1.2.1. Boundary details	NZ4b	W11 W25	US3 US4 US11		
1.2.1.1.2.2. Web details and horz reinforcement	NZ4b	W25	US4 US11		
1.2.1.1.2.3. Longitudinal reinforcement	NZ2a NZ4b		US3 US4 US11		
1.2.1.1.2.4. Deformation capacities	NZ2a NZ4b	W11	US3 US4 US11 US16		
1.2.1.1.2.5. Wall geometry		W11	US3 US4 US11		
1.2.1.1.3. Nominally ductile (essentially elastic) wall	NZ2c				
1.2.1.1.3.1. Boundary details	AU1				
1.2.1.1.3.2. Web details and horz reinforcement					
1.2.1.1.3.3. Longitudinal reinforcement	NZ2a AU1				
1.2.1.1.3.4. Deformation capacities	NZ2a NZ6 AU1				
1.2.1.1.3.5. Wall geometry	AU1				
1.2.2. Squat walls (need design primer/SOA paper)					Need for a primer
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		W18 W19 W20 W21 W25 W15	US12	M	
1.3. Existing RC walls	NZ11			H	Coordination needed and identify priorities
1.3.1. Thin walls, single layer reinforcement	NZ2b				
1.3.1.1. Flexural	AU1	W9 W13 W28 W20 W25	US13		
1.3.1.1.1. Crushing					
1.3.1.1.2. Bar fracture					
1.3.1.1.3. Buckling		W11			
1.3.1.2. Shear-controlled		W1 W13 W20			
1.3.1.3. Axial failure					
1.3.2. Other existing walls					
1.3.3. Retrofit					

1.4. New low-damage walls				M	SOA report needed - then identify where to go
1.4.1. Rocking walls		W10	US5 US8		
1.4.2. Energy dissipating devices			US5 US8		
1.4.3. High-performance materials					
1.4.4. Modification of conventional systems	NZ7	W10			
1.4.4.1. Bar debonding			US10		
1.4.4.2. Slotted beam					
1.5. Residual capacity and reparability of walls (post-earthquake)	NZ7			H	Contributes to a lot of basic mechanics
2. Building systems					
2.1. Coupled walls		W25 W27			
2.1.1. Design and acceptance criteria					
2.1.1.1. Coupling beam detailing					
2.1.2. Demands and modelling		W2 W5		M	
2.1.2.1. Slab restraint on coupling beam			US1		
2.1.2.1.1. Cast-in place slabs	NZ8				
2.1.2.1.2. Pre-cast slabs	NZ8				
2.1.2.2. Coupling beam shears					
2.1.2.3. Wall axial and shear loads	NZ1 NZ4a NZ8				
2.2. Core walls					
2.2.1. Design and acceptance criteria					
2.2.1.1. Corners				H	
2.2.1.2. Coupling beam – edge detailing					
2.2.2. Demands and modelling (and behaviour)		W8 W4		H	
2.2.2.1. Biaxial demands			US11		
2.2.2.2. Torsion/shear flow post-yield					
2.2.2.3. Effective flange width (incl coupling beams)		W17	US11		
2.3. Tilt-up and precast wall systems	NZ6			M	Guidance on connections
2.3.1. Connections	NZ2c NZ6 AU1		US8		
2.3.2. Diaphragm-wall interaction			US5 US8		
2.4. High wall-to-floor ratio buildings		W25			
2.5. Whole-of-Building aspects		W26 W27 W3		H	Models for system response
2.5.1. Diaphragm behaviour and design			US22		element interaction
2.5.1.1. Design for inertial and transfer loads	NZ5				torsional/bidirectional response
2.5.1.2. Diaphragm stiffness	NZ5				
2.5.1.3. Influence on demands in vertical system					
2.5.2. Podium response					
2.5.3. System Interaction (incl Floor - wall interaction)	NZ3 NZ8 NZ9		US2 US8		
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	NZ9				
2.5.4.1. Deformations					
2.5.4.2. Accelerations					
2.5.5. Building instrumentation/monitoring		W22	US7		
2.5.6 Irregular buildings		W22 W3 W15	US5 US12	M	
2.5.7 Structural redundancy		W22			
3. Design philosophies			US2		
3.1. Reliability					
3.2. Capacity-based design		W33 W2 W24 W25			
3.3. Performance-based design					