Seismic behaviour and design of modern masonry buildings: current status and future needs

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- UBC graduate students Dr. Brook Robazza, Nazli Azimikor, Dr. Jose Centeno, and Yu-Cheng Hsu
- BCIT undergraduate students (2010-2015)
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- Prof. Khaled Galal, Concordia University

Topics

1. Modern masonry buildings
2. Seismic design of reinforced masonry wall structures in Canada
3. Seismic behaviour and failure mechanisms
4. Future research needs

1. MODERN MASONRY BUILDINGS

Early Achievements:
Tall Masonry Buildings in the USA

- Monadnock Building, Chicago, USA
- Constructed in 1889
- 16-storey loadbearing masonry building
- Unreinforced masonry walls, 1.8 m thick at the base and 0.3 m at the top

Source: Klingner & The Masonry Society

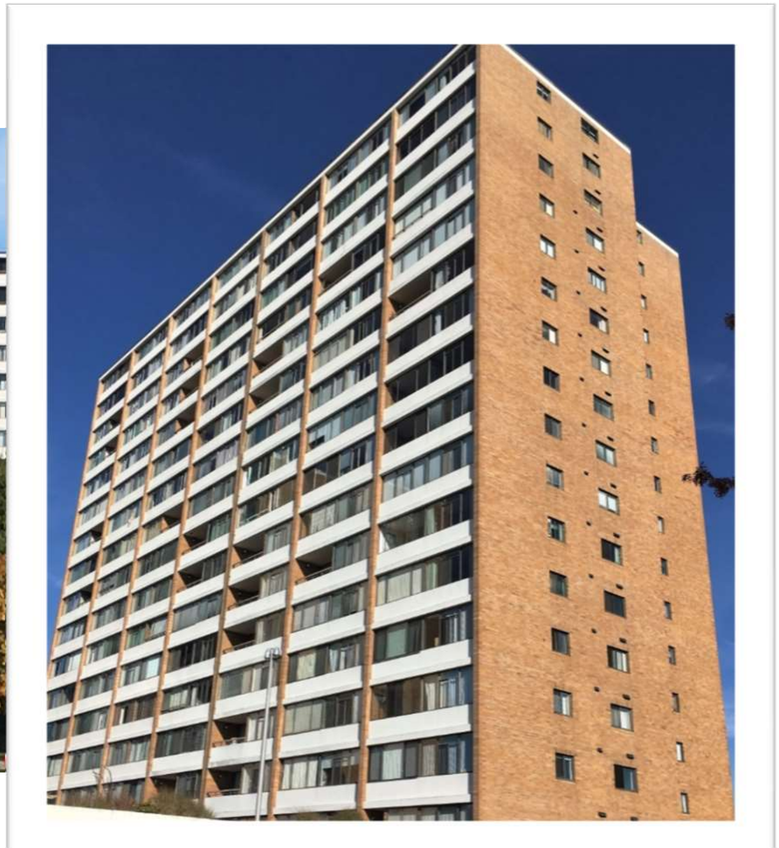
Tall Masonry Buildings in China

- 98 m tall office building in Harbin built in 2013
- 300 mm thick concrete block walls, vertical reinforcement with mechanical couplers
- Masonry construction competitive with RC shear walls - in terms of the overall cost (less steel), construction time (15 months), and reduced carbon emission

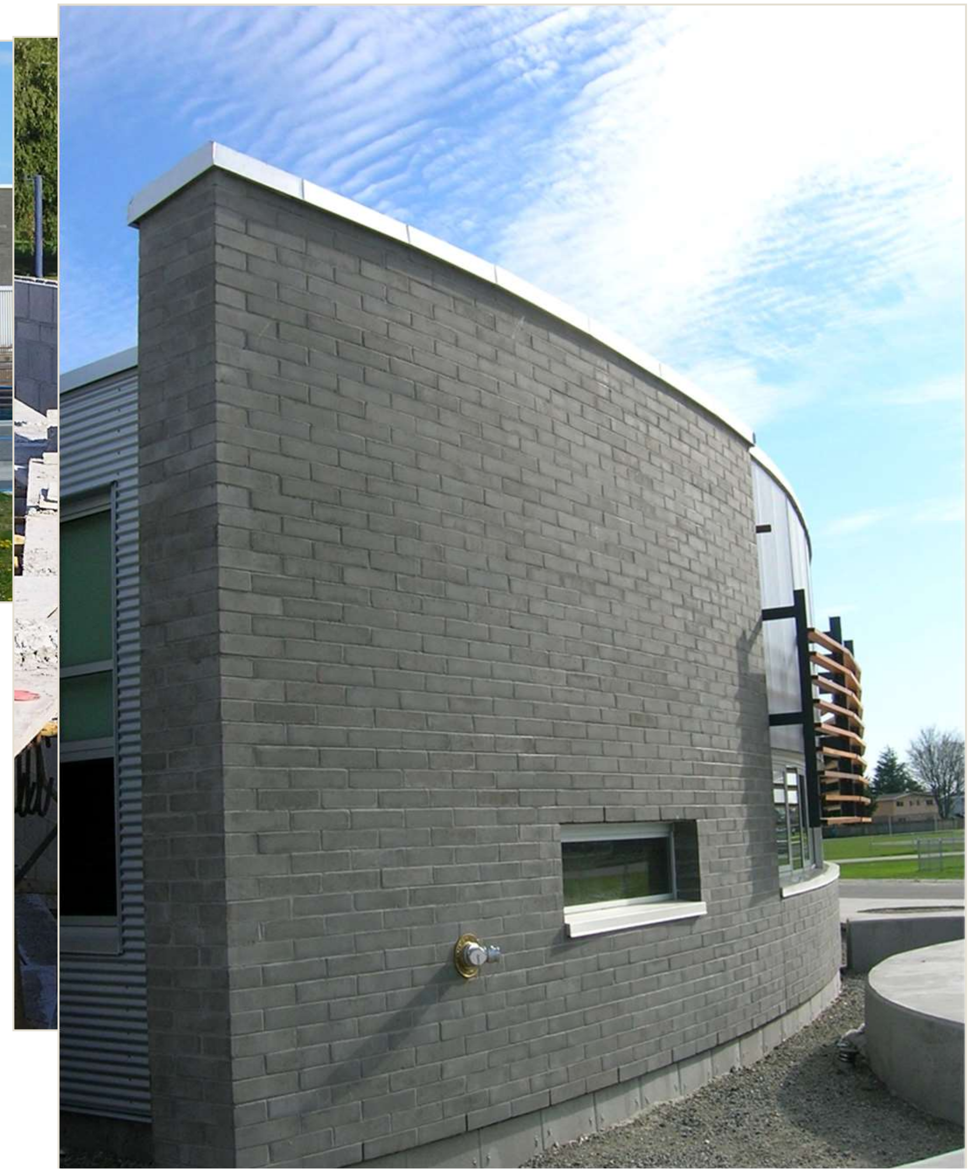
Wang, Zhang, and Zhu (2016)

Tall Masonry Buildings in Canada

- Very few examples, mostly in Eastern Canada
- Three 16-storey towers in Richmond (Vancouver), constructed in 1960s
- Exterior walls giant bricks - interior walls most likely concrete blocks



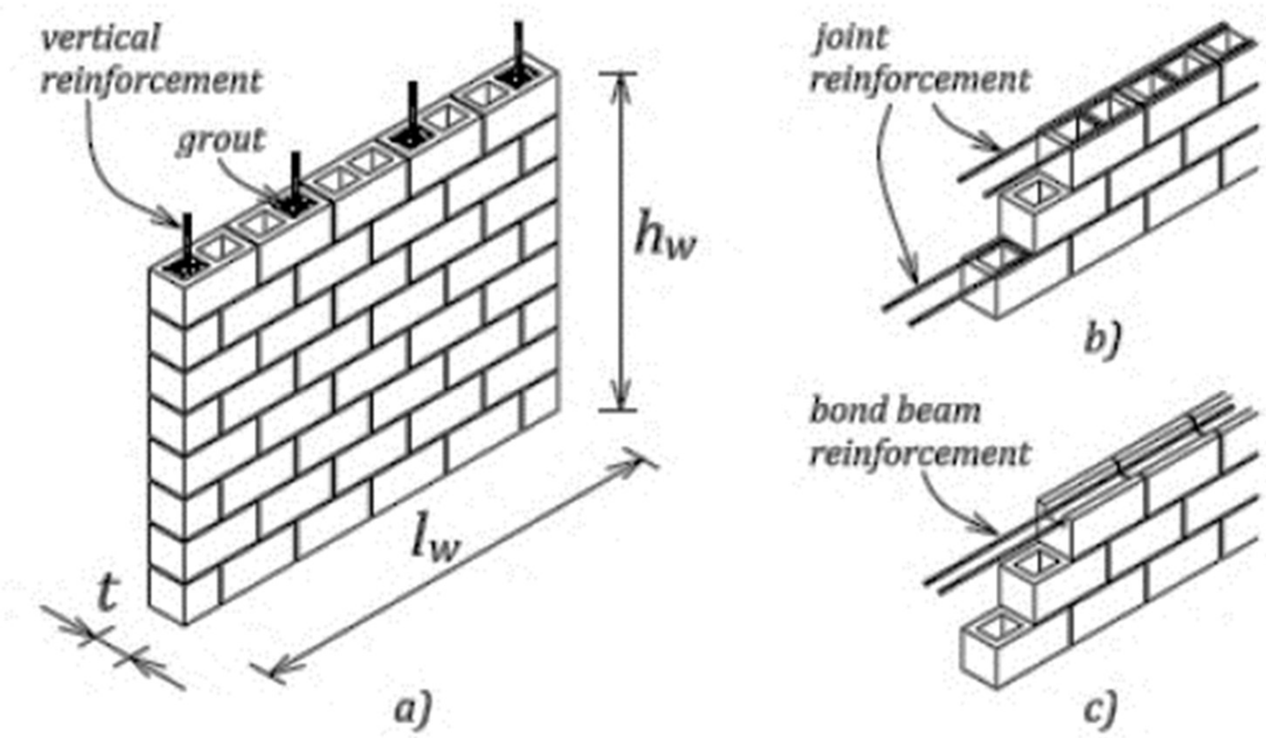
Common Masonry Construction Practice in Canada: Low-Rise Buildings



- Mostly low-rise buildings
- Example: a school building in Vancouver
- Concrete block masonry walls with concrete brick veneers

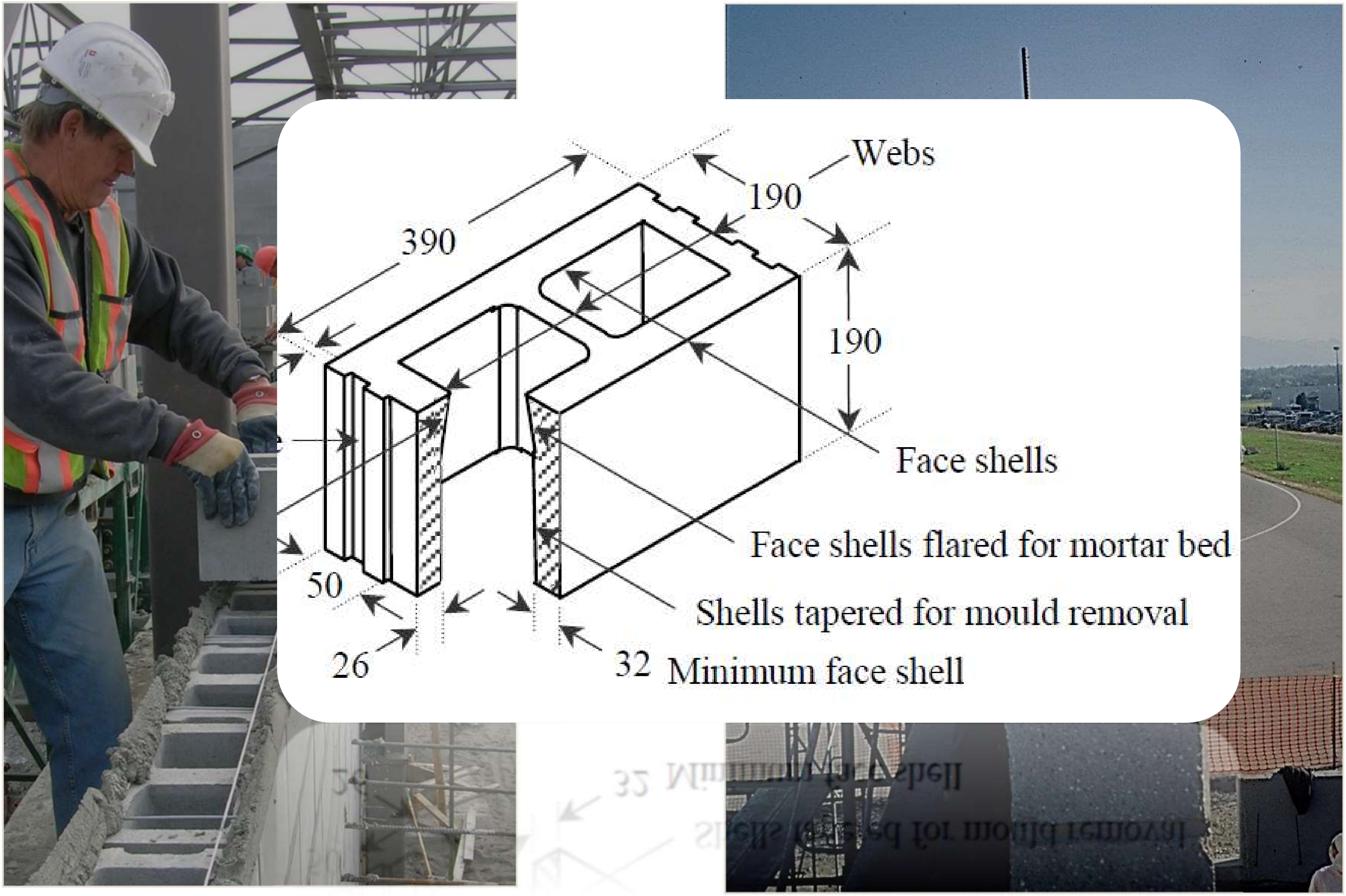
Reinforced Masonry (RM) Construction

- Hollow concrete blocks (with 2 holes/cores)
- Vertical reinforcement placed in hollow cores
- Horizontal reinforcement: joint reinforcement and/or bond beam reinforcement



Source: Brzev and Anderson (2018)

RM Wall Construction: Vertical Reinforcement



Laying blocks and mortar

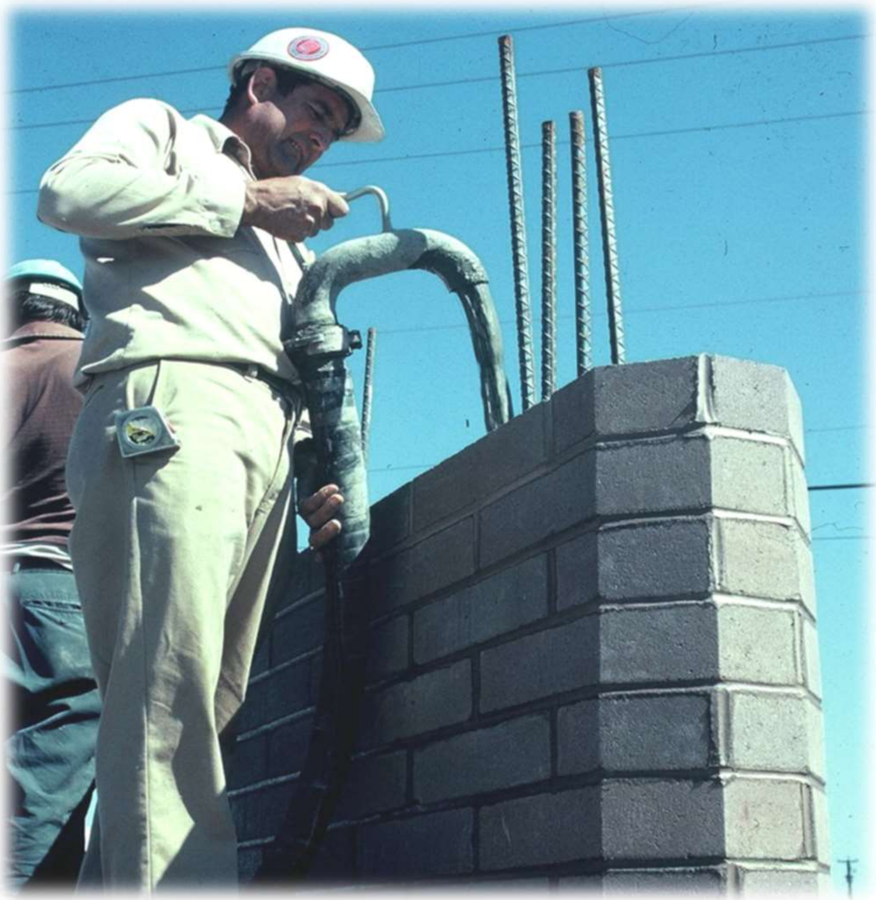
Placing vertical reinforcement

Horizontal Reinforcement

Bond beam reinforcement

Joint (ladder) reinforcement

Grouting



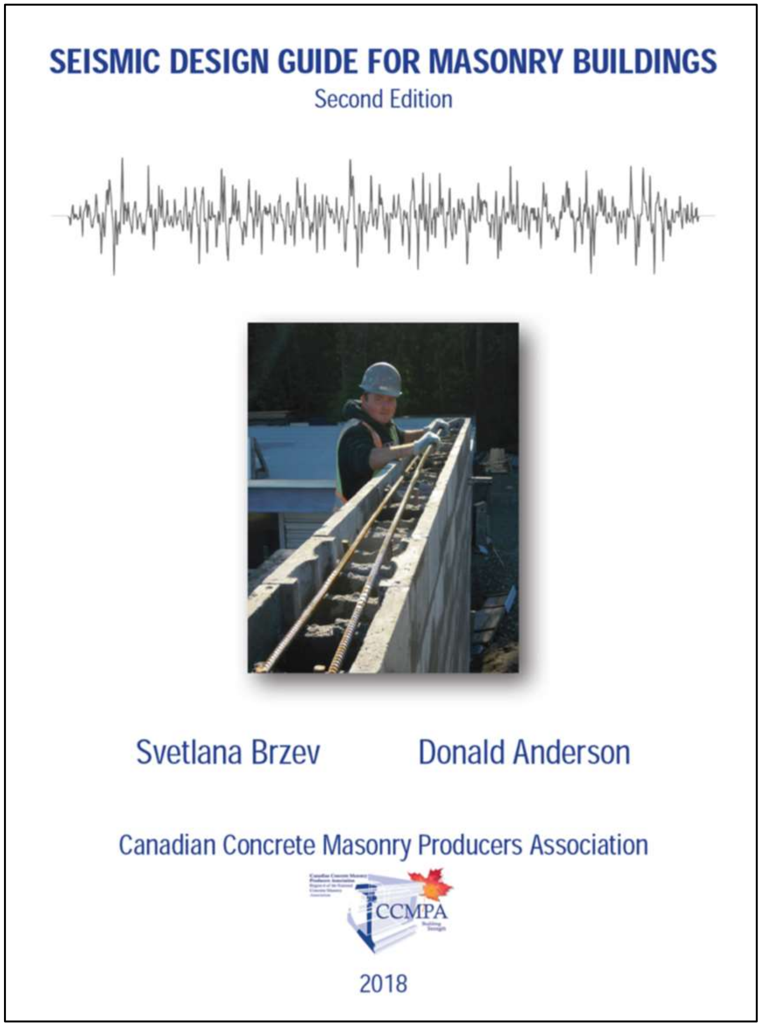
Grout is like micro-concrete: a mix of cement and sand (fine grout), and in some cases small-size aggregate (coarse grout)

2. SEISMIC DESIGN OF REINFORCED MASONRY WALL STRUCTURES IN CANADA

Seismic Design of Masonry Shear Wall Structures in Canada

- Design to meet the requirements of Canadian masonry design standard CSA S304-14 (published in 2014) and the National Building Code of Canada 2015 (or 2020)
- Seismic design considerations similar to RC shear walls: capacity design, shear resistance restrictions, wall height-to-thickness ratio restrictions
- Seismic detailing requirements related to the extent of grouting, amount and distribution of reinforcement, spacing of reinforcement, hooks for horizontal reinforcement

Resource: Seismic Design Guide for Masonry Buildings (Brzev and Anderson 2018)



Explains seismic design provisions of CSA S304-14 and presents design examples

Electronic version available free of charge - see link below

https://ccmpa.ca/download/seismic-design-guide-for-masonry-buildings/

Masonry Wall Classes for Seismic Design per the National Building Code of Canada 2015

Referred to as **Ductile RM shear walls** by CSA S304-14

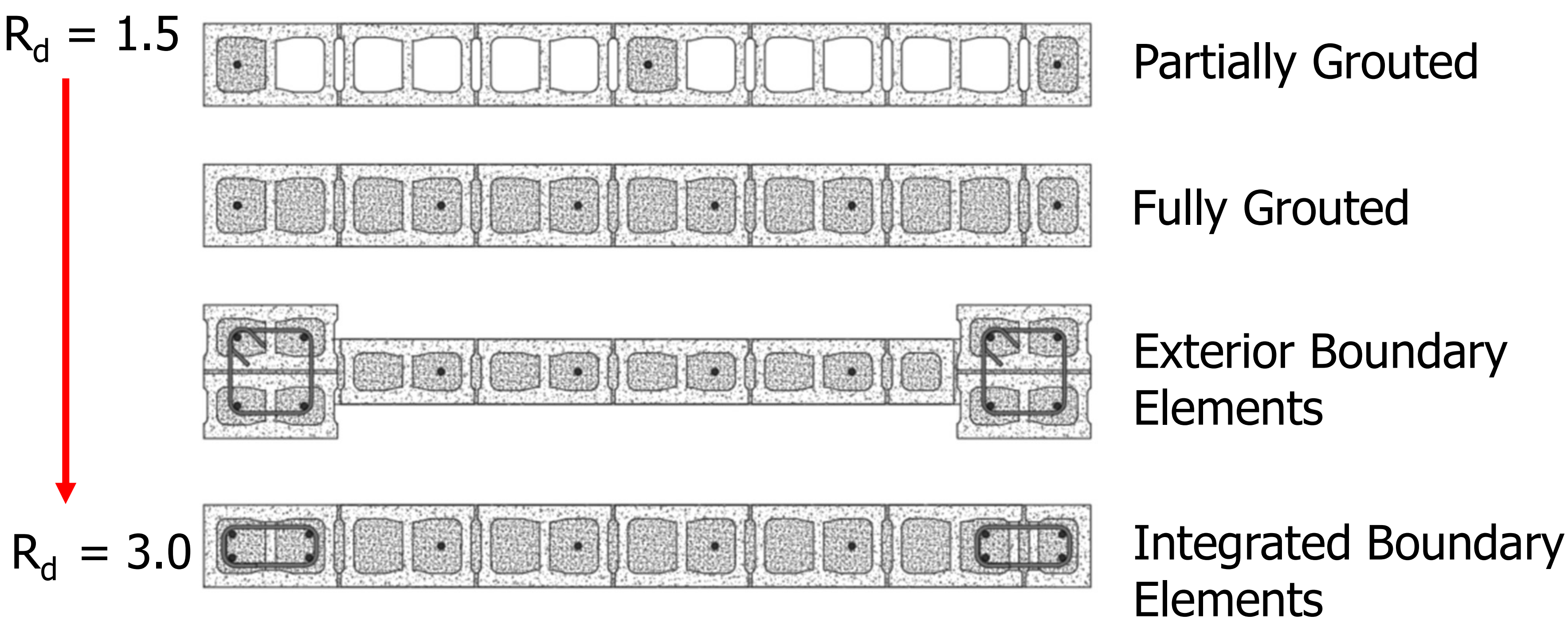
1. Unreinforced $R_d = 1.0$
2. Conventional Construction $R_d = 1.5$
3. Moderately Ductile $R_d = 2.0$
4. Moderately Ductile Squat $R_d = 2.0$
5. Ductile $R_d = 3.0$

R_d is ductility force reduction factor: 1.0 indicates elastic (non-ductile) performance

R_o is overstrength factor - equal to 1.5 for all masonry classes

Product $R_d \times R_o$ - used for seismic design

Types of Ductile RM Shear Walls: Difference in Grouting and End Zones

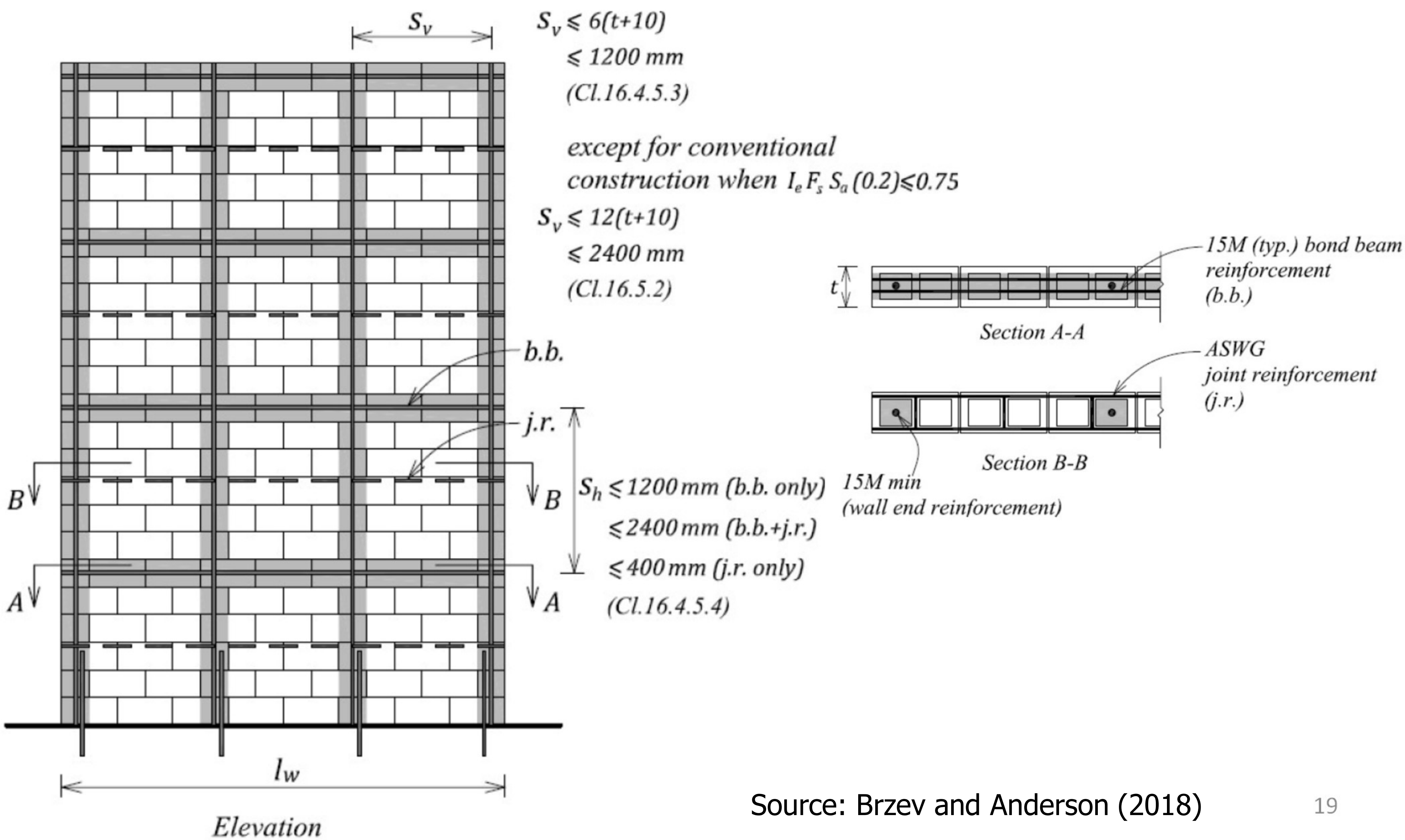


Note: horizontal reinforcement was omitted from the diagram

Conventional Construction (R_d= 1.5)

- Most widely used RM wall category in Canada
- Less ductile performance expected than other wall classes
- Simple design and detailing – similar to design for wind effects
- Capacity design approach needs to be followed to avoid shear failure

Conventional Construction (R_d = 1.5): Detailing Requirements

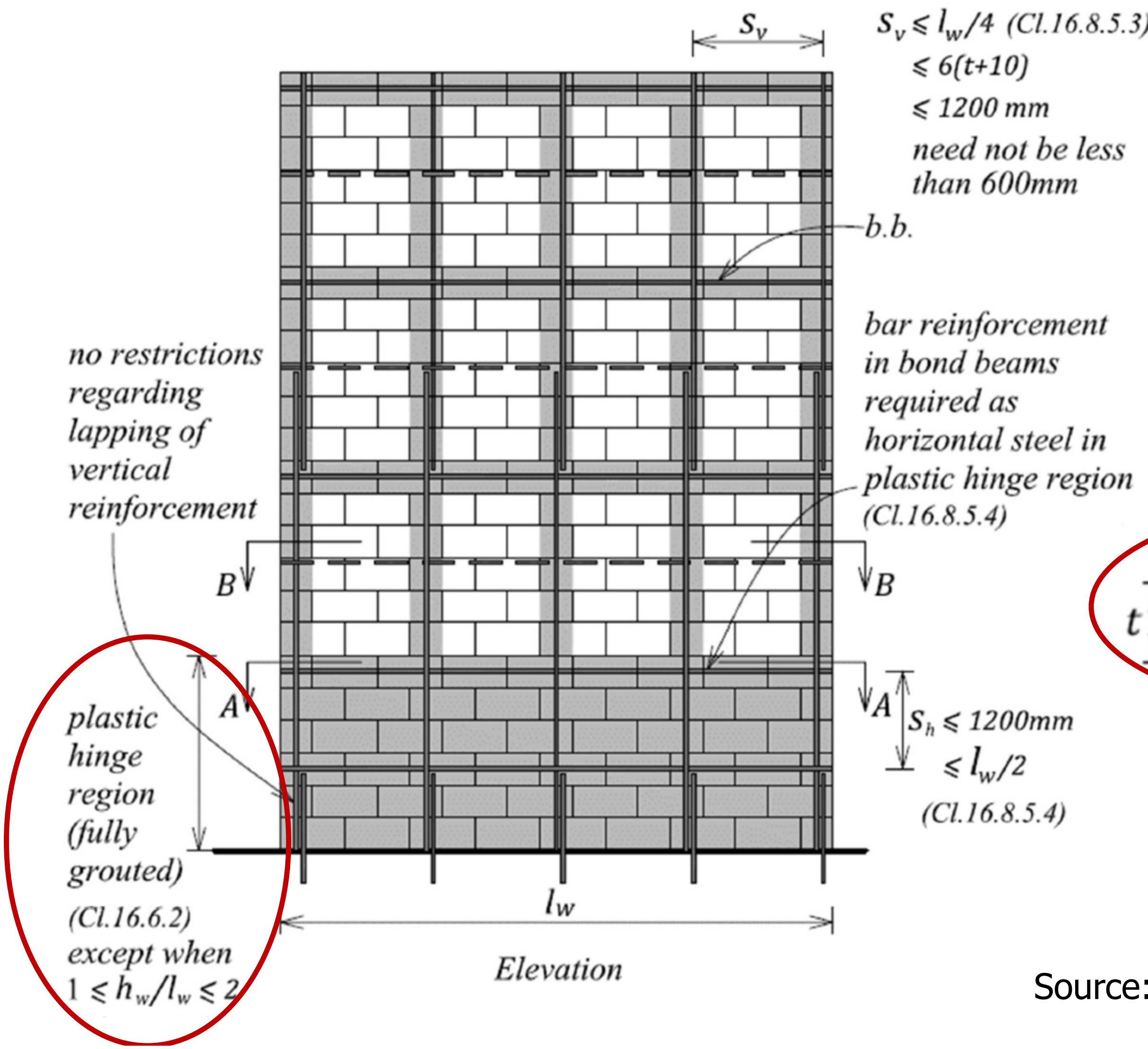


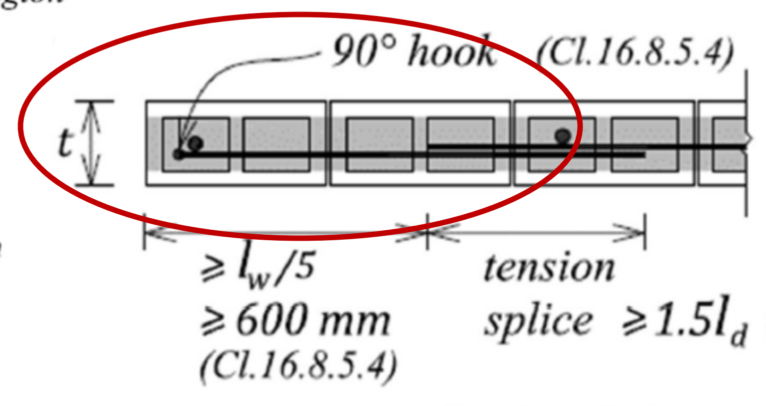
Source: Brzev and Anderson (2018)

Moderately Ductile Shear Walls (R_d= 2.0)

- Mandatory for post-disaster buildings irrespective of seismic hazard level
- Plastic hinge zone either partially or fully grouted
- Partially grouted walls intended for post-disaster buildings at low seismic hazard sites

Moderately Ductile Shear Walls (R_d = 2.0): Detailing Requirements



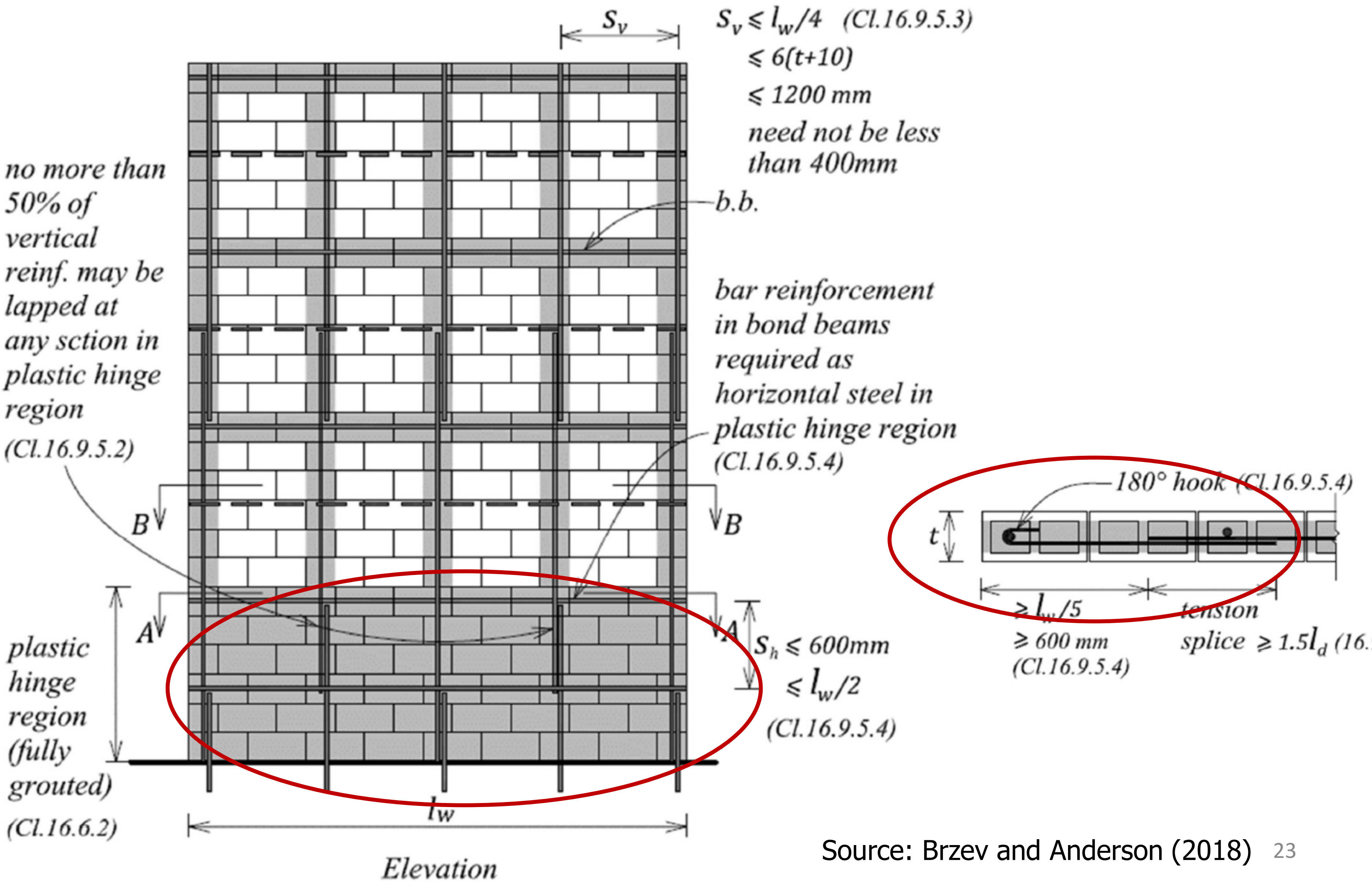


Source: Brzev and Anderson (2018)

Ductile Shear Walls (R_d= 3.0)

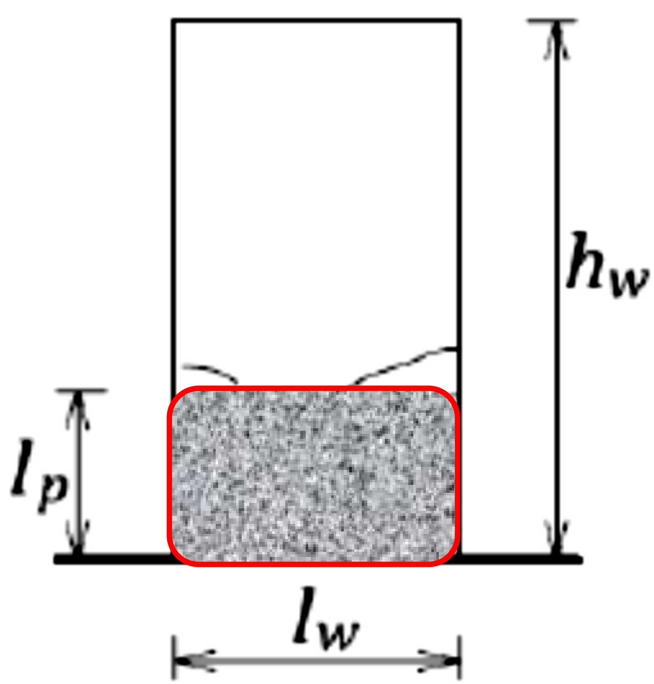
- This class was first introduced in 2014 (CSA S304-14)
- Based on several experimental studies on RM shear walls from Canada, USA and New Zealand performed since 2004.
- The results indicated that RM shear walls have a significant ductility potential, and that the maximum permitted R_d = 2.0 value per the 2004 masonry standard was overly conservative.
- Higher R_d value for ductile walls in line with the provisions of other international standards (e.g. USA and New Zealand)

Ductile Shear Walls (R_d = 3.0): Detailing requirements



Source: Brzev and Anderson (2018)

Plastic Hinge Region: A Detailing Requirement

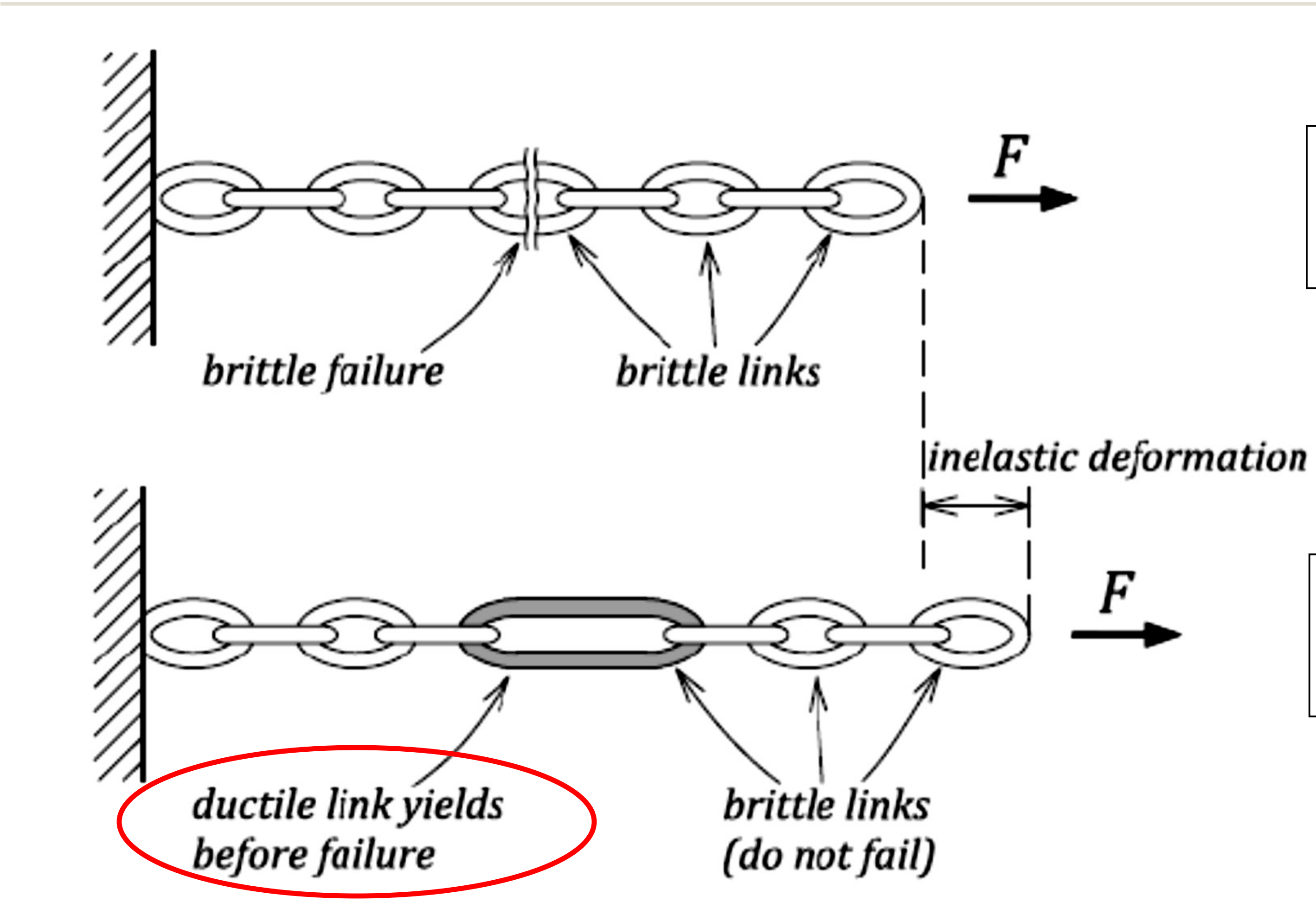


- Plastic hinge is a region of the member where inelastic deformations and damage are expected to occur <-> plastic hinge length l_p
- It is important to ensure full grouting of ductile RM walls within the plastic hinge region (grouted RM walls have significantly higher masonry shear resistance)
- CSA S304 prescribes l_p value depending on the wall class

CSA S304-14 Key Seismic Design Requirements for RM Shear Walls

1. Capacity design approach (to avoid shear failure)
2. Shear resistance limits
3. Ductility check (to ensure ductile flexural behaviour)
4. Wall height/thickness limits (to avoid instability)

Capacity Design Approach - Required for Ductile Seismic Behaviour

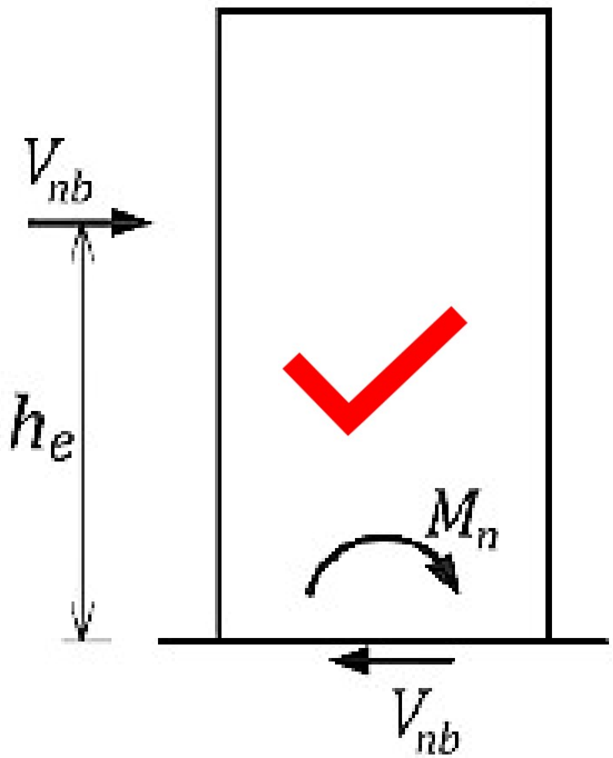


Brittle behaviour

Ductile behaviour

Source: Brzev and Anderson (2018)

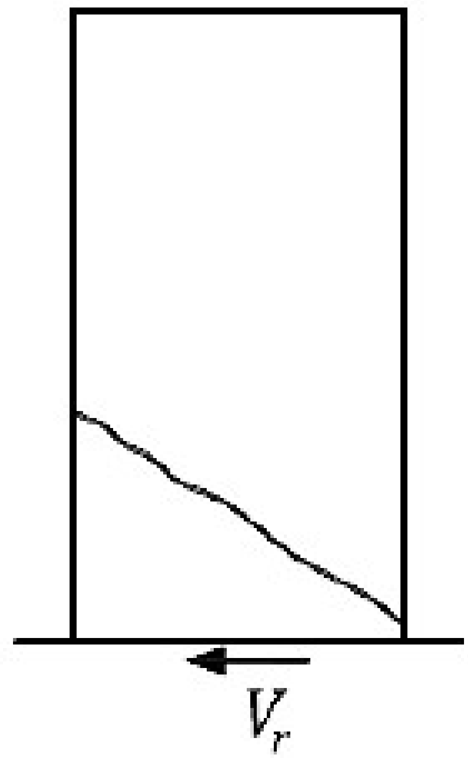
Capacity Design Approach: Shear Failure to be Avoided!



$$\boxed{V_f \le V_r}$$

and

$$\boxed{V_{nb} < V_r}$$



Flexural failure mechanism

Shear failure mechanism

Use M_n for Moderately Ductile (R_d= 2.0)!

Source: Brzev and Anderson (2018)

CSA S304-14 Capacity Minimum Shear Resistance

Capacity design

For the design of RM shear walls, the factored shear resistance, V_r , should be greater than the shear due to effects of factored loads, but not less than the smaller of

1. the shear corresponding to the development of moment resistance, as follows:
   a. the shear corresponding to the development of *factored moment resistance*, M_r , of the wall system at its plastic hinge location for Conventional Construction (Cl.16.5.4) or Moderately Ductile Squat (Cl.16.7.3.2) shear walls,
   b. the shear corresponding to the development of *nominal moment capacity*, M_n, for Moderately Ductile shear walls (Cl.16.8.9.2),
   c. the shear corresponding to the development of *probable moment capacity*, M_p , for Ductile shear walls (Cl.16.9.8.3) and walls with boundary elements (Cl.16.10.4.3), and
2. the shear corresponding to the lateral seismic load (base shear) where earthquake effects were calculated using R_dR_o=1.3.

"Almost elastic"

Shear Resistance for Ductile RM Walls

$$V_r = V_m + V_s$$

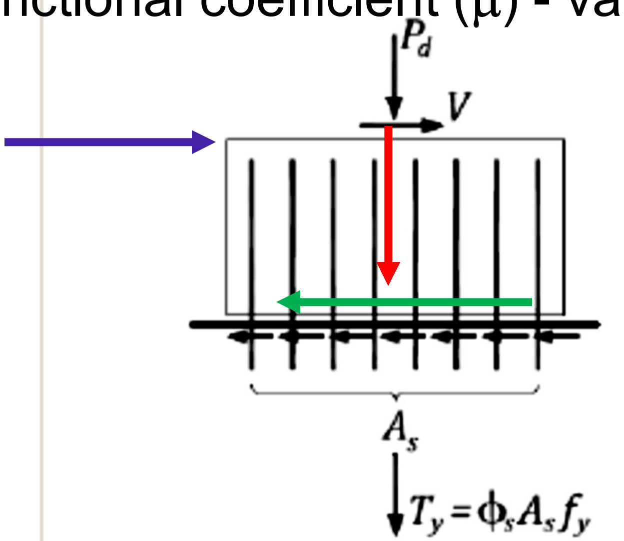
- V_m = masonry shear resistance (diagonal tension)
- Ductile RM shear walls: 25% and 50% reduction in V_m value for Moderately Ductile and Ductile walls respectively
- Conventional Construction RM walls: no V_m reduction

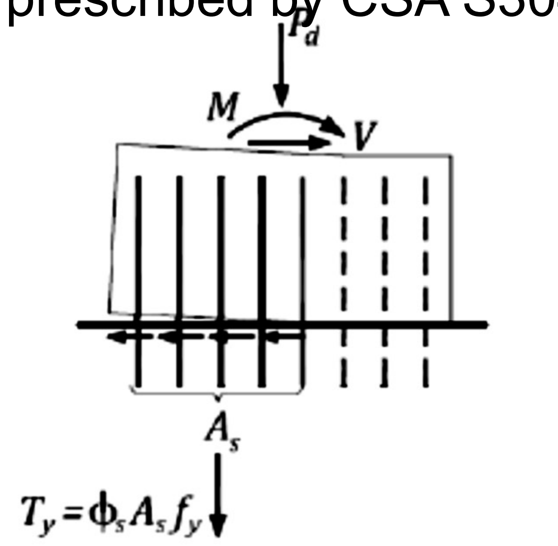
Sliding Shear Resistance

- May govern in low-rise buildings due to low axial compression level
- Sliding shear resistance $\mathbf{V_r}$ determined based on the Coulomb's Law

$$\boxed{V_r = \phi_m \mu C} \qquad \boxed{C = P_d + T_y}$$

- Vertical component **C** depends on self-weight $\mathbf{P_d}$ and shear friction resistance $\mathbf{T_y}$ provided by vertical reinforcing bars yielding in tension
- Frictional coefficient (μ) - values prescribed by CSA S304





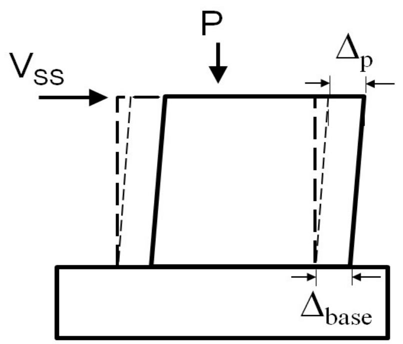
$\mathbf{T_y}$ <-> all vertical reinforcing bars
Conventional Construction and Moderately Ductile
(same as non-seismic provision)

$\mathbf{T_y}$ <-> only reinforcing bars in tension
Ductile Shear Walls

Source: Brzev and Anderson (2018)

Sliding Shear Displacements?

- Approaches for estimating sliding displacements not currently available in design codes
- Sliding Shear Behavior (SSB) Method developed by Jose Centeno
- Three different sliding mechanisms (2 for reinforced masonry and one for unreinforced masonry)
- The objective is to estimate sliding displacement at the base (Δ_{base}) due to sliding shear resistance V_{SS}



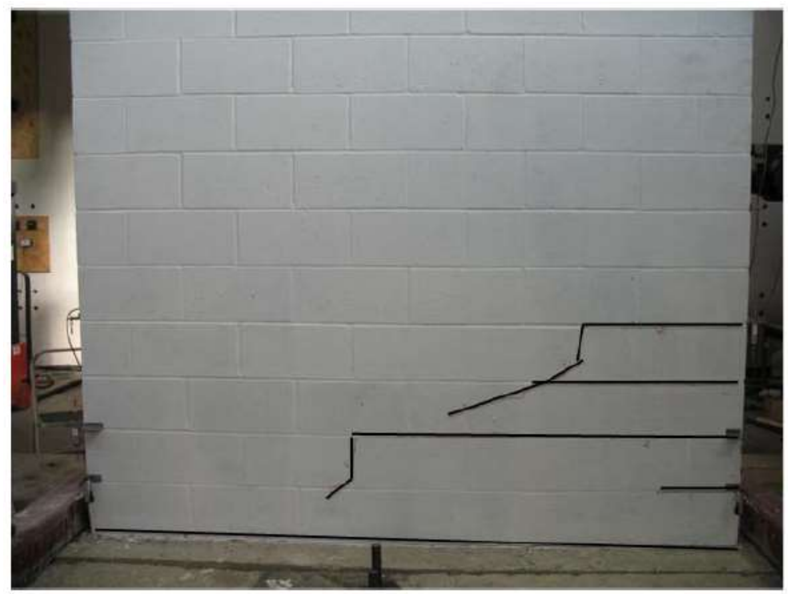
$$V_{SS} = Fr_A + Fr_{Fl} + DA_y$$

Fr_A : Friction due to Axial Compression

Fr_{Fl} : Friction due to Flexure-Compression

DA_y : Dowel Action Yield Resistance

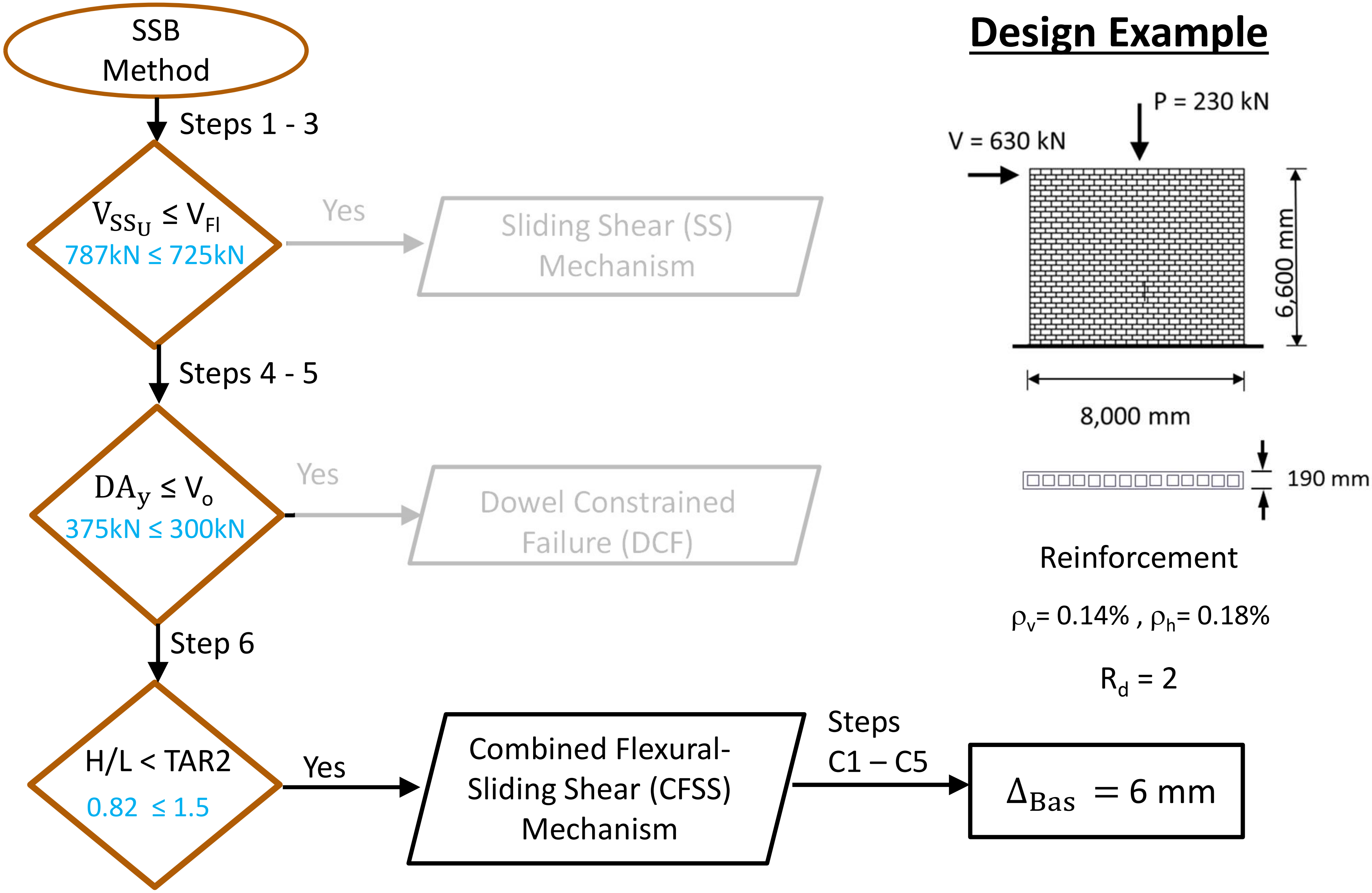
Jose Centeno, UBC (2015)



Sliding behaviour at displacement $2\Delta_y$
$H/L = 1.0$, $P/A_g f'_m = 0\%$, $\rho_v = 0.18\%$

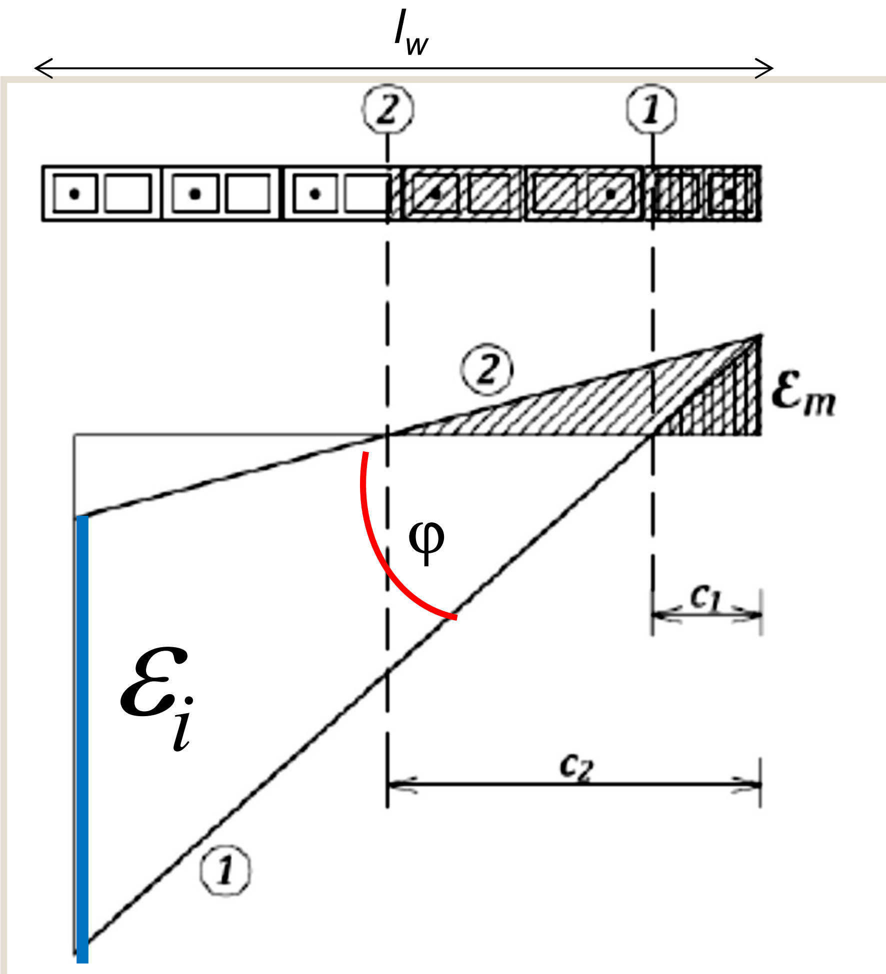
Experimental study by Hernandez (2012)

Sliding Shear Behavior (SSB) Method: Flowchart



Jose Centeno (2015)

Ductility Check



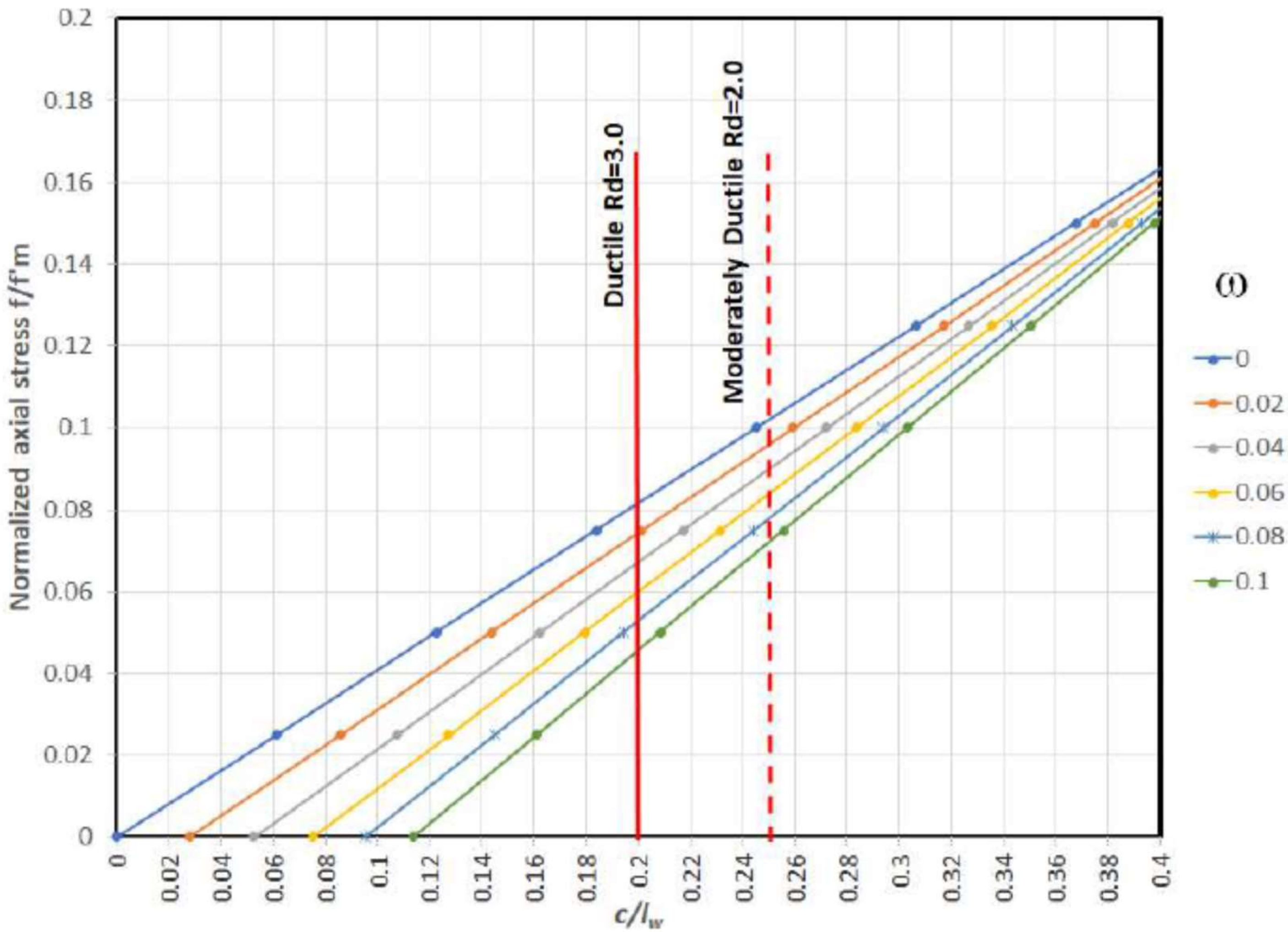
- Intended to verify whether ductility capacity of a RM shear wall is in line with the assumed wall class (R_d value)

Alternatives:

1) Simplified check: if neutral axis depth-to-wall length ratio (c/l_w) is within the prescribed limits
2) Detailed: required to find inelastic strain ε_i, curvature φ, and rotation θ

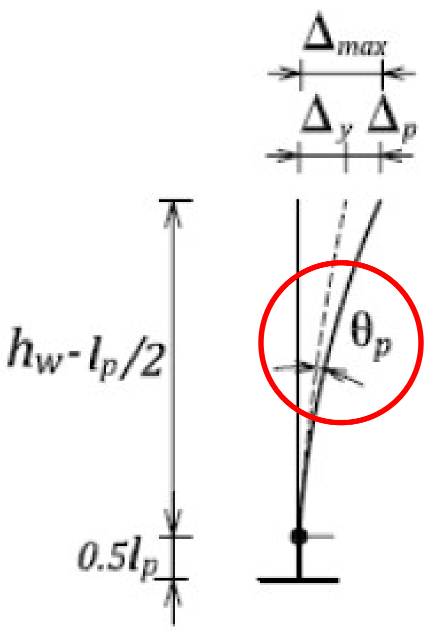
Source: Brzev and Anderson (2018)

Simplified Ductility Check
c/l_w ratio obtained from the M_r calculation

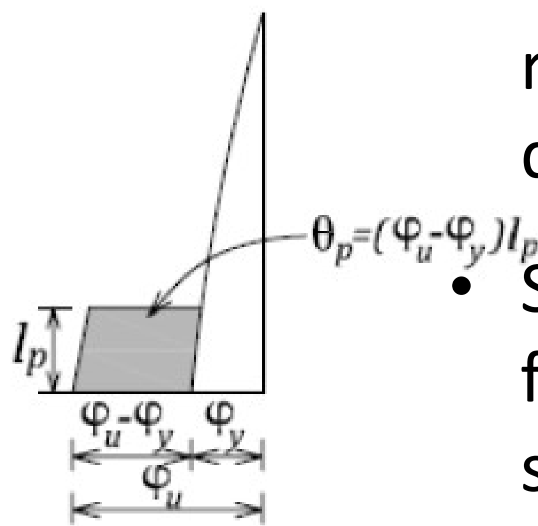


Source: Brzev and Anderson (2018)

Detailed Ductility Check



Inelastic rotational demand θ_{id}



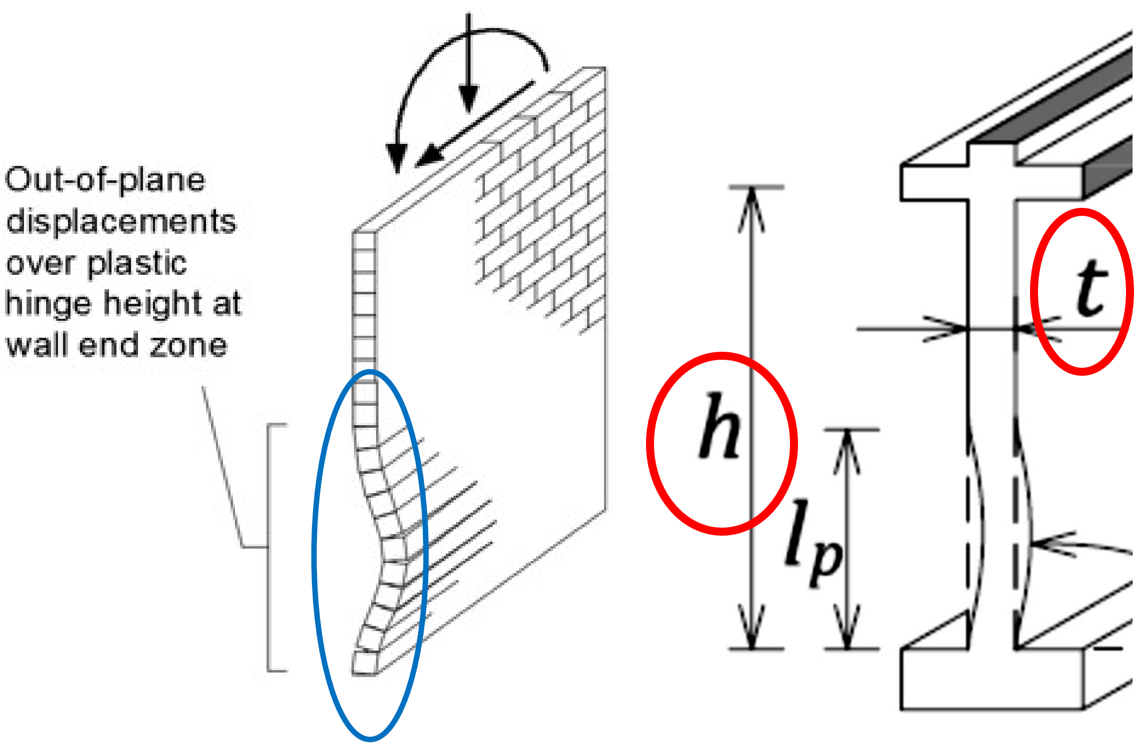
Inelastic rotational capacity θ_{ic}

- Requirement: inelastic rotational capacity θ_{ic} must exceed the rotational demand θ_{id} due to seismic excitation
- Similar to ductility check for reinforced concrete shear walls according to CSA A23.3-04

Source: Brzev and Anderson (2018)

Wall Height/Thickness Ratio: Restrictions

(not applicable to "Conventional Construction")



- Intended to prevent instability (buckling) of compression zone in ductile RM shear walls under in-plane seismic loading
- h/t limit ranges from 12 to 20 (with exceptions)

3. SEISMIC BEHAVIOUR OF DUCTILE RM SHEAR WALLS: FINDINGS OF SELECTED RESEARCH STUDIES

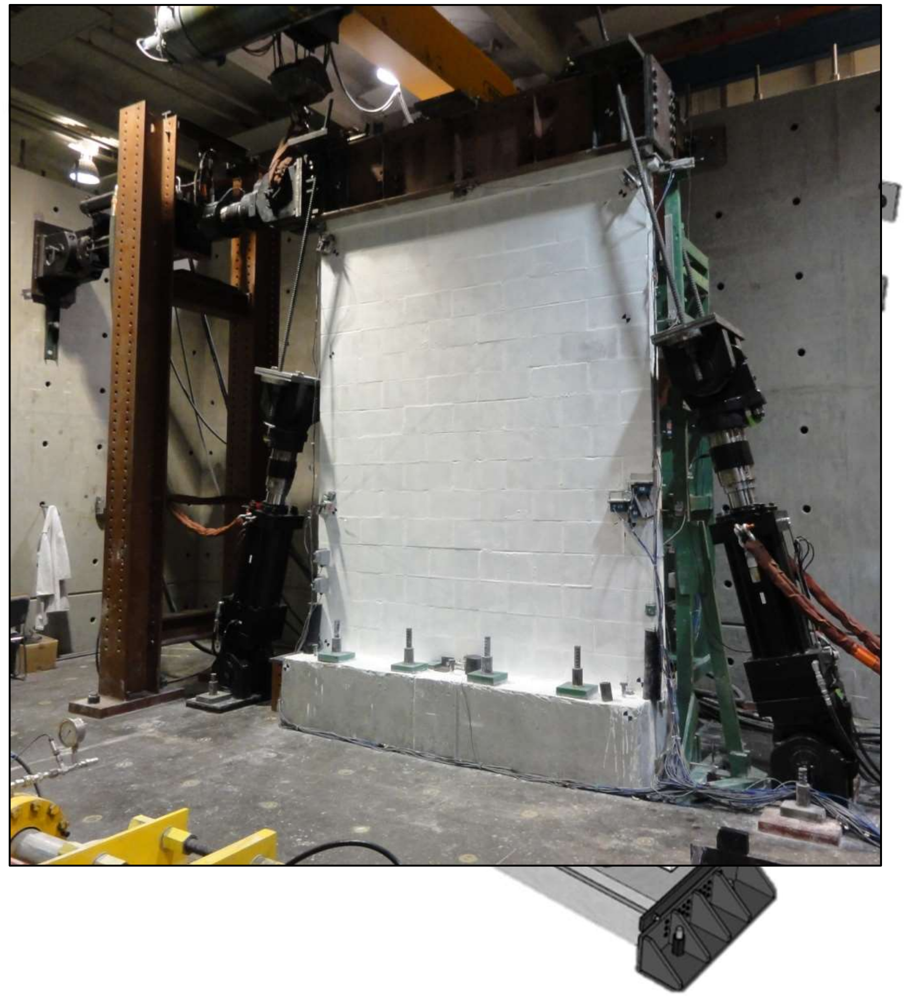
UBC Research Program on Seismic Behaviour of Ductile RM Shear Walls

Funded by the NSERC CRD and masonry industry (2011-2018) PI: Ken Elwood Co-PI: Svetlana Brzev

- Phase 1: Testing of 5 full-scale uniaxial specimens simulating wall end zone under reversed cyclic loading (Nazli Azimikor, MASc 2012)
- Phase 2: Testing of 8 full-scale wall specimens under reversed cyclic loading (Brook Robazza MASc and PhD, 2019)

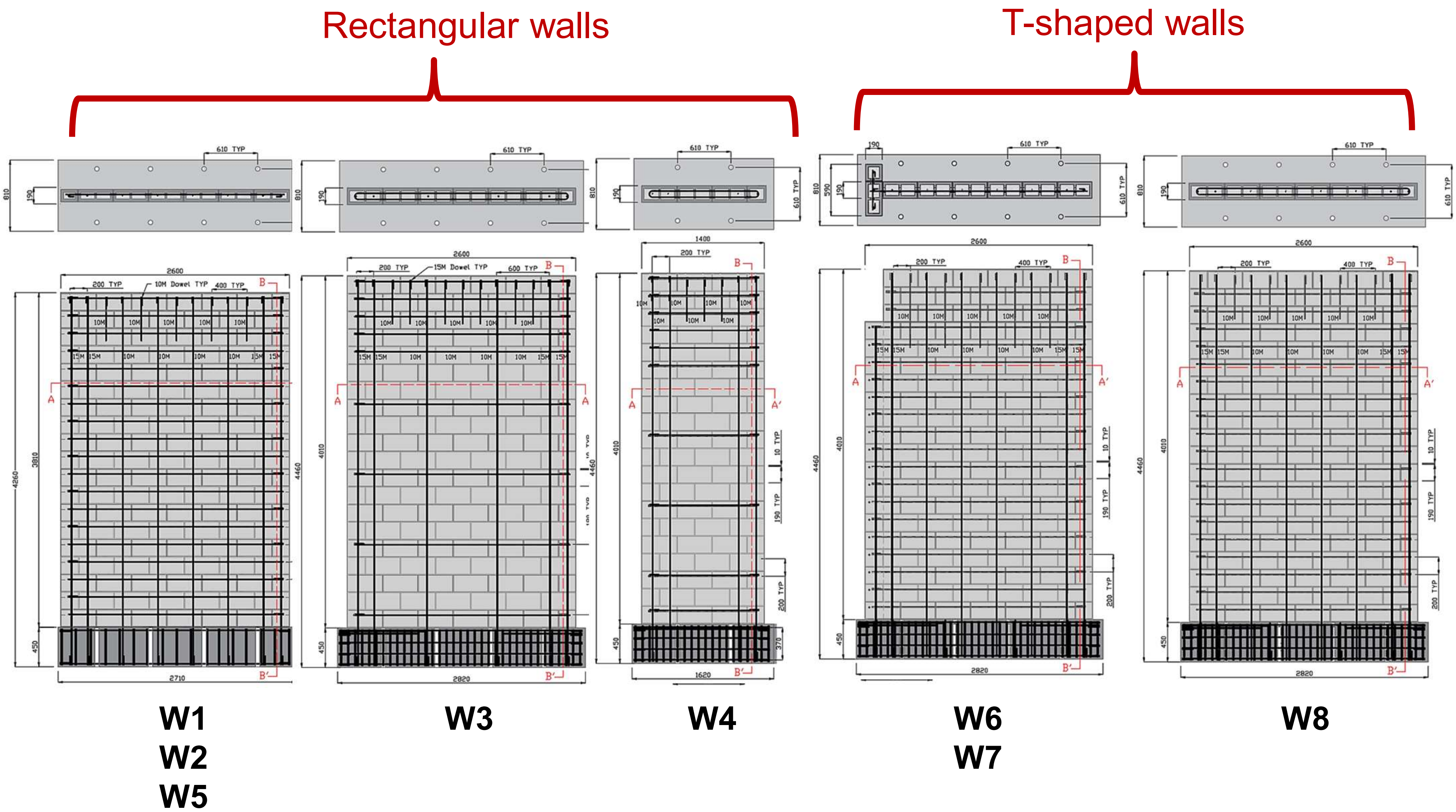
UBC Research Program: Specimens

Phase 1



Phase 2

Phase 2 Specimens: Geometry and Reinforcement Details



Observed Seismic Failure Mechanisms for RM Shear Walls

Primary failure mechanisms:

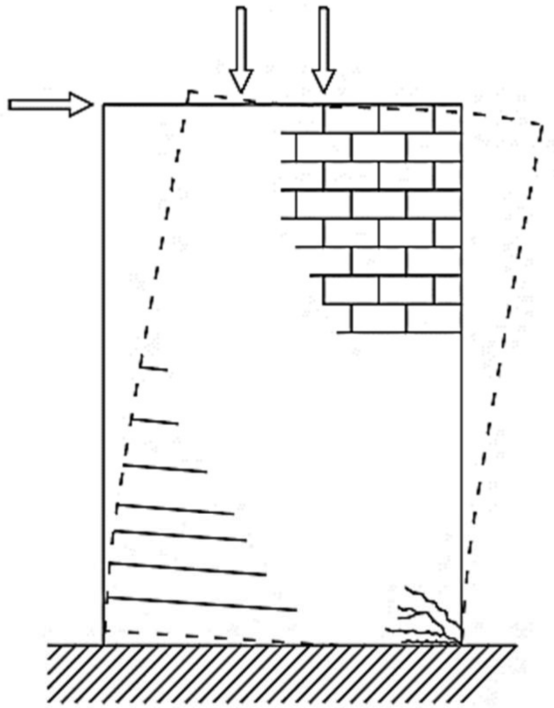
- Ductile-Flexure
- Shear-Flexure

Secondary failure mechanisms:

- Sliding
- Toe-Crushing
- Bar-Buckling
- Bar Fracture
- Rocking/Bond-Slip
- Lateral Instability

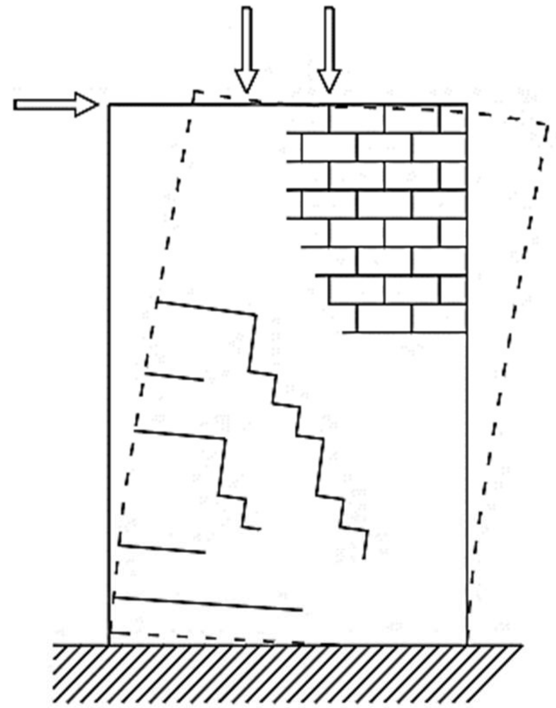
Robazza et al. (2020)

Primary Failure Mechanisms



(a)

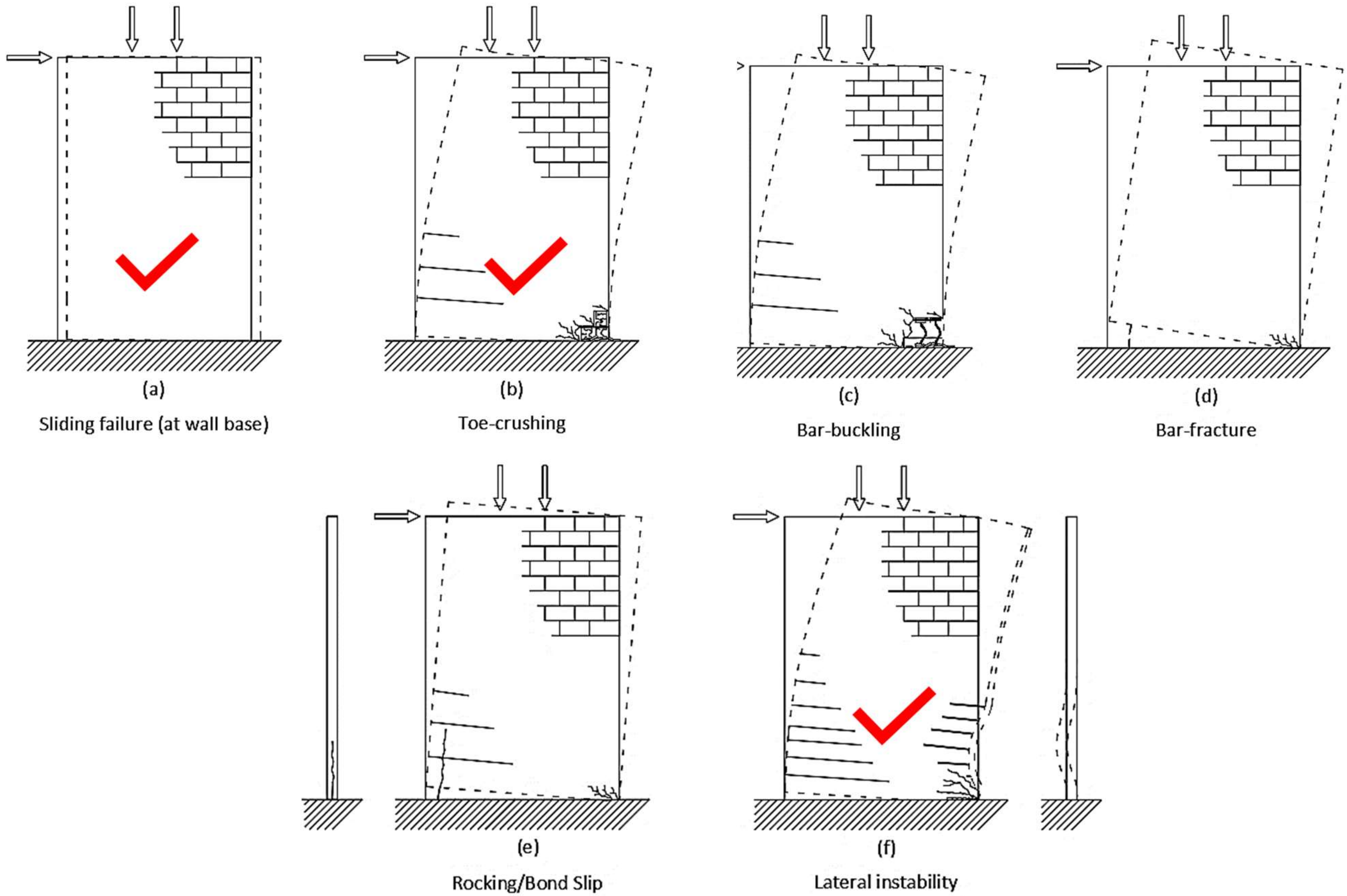
Ductile flexure



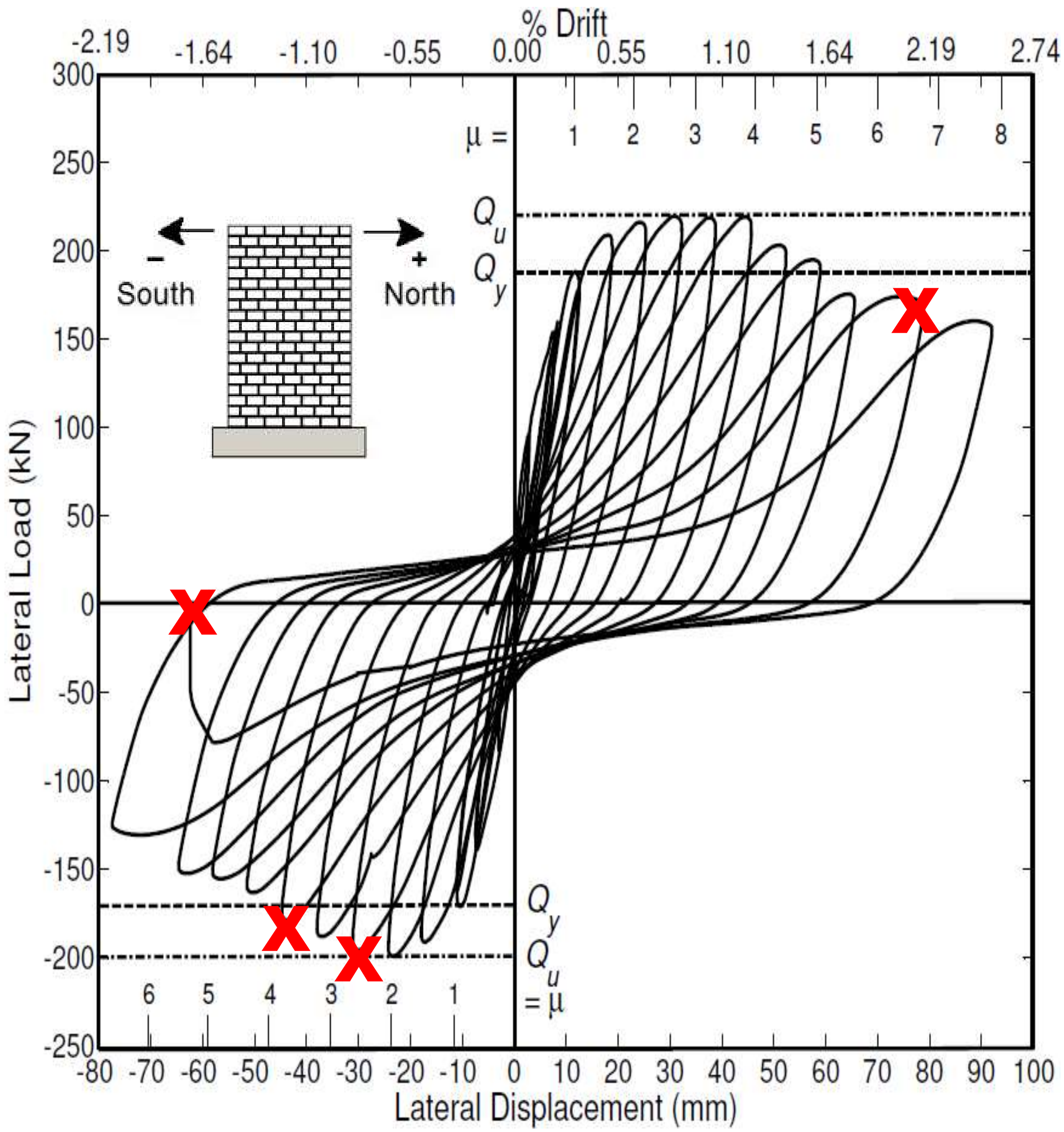
(b)

Shear-flexure

Secondary Failure Mechanisms



Progressive Damage of a Ductile RM Shear Wall



Specimen W2, Robazza (UBC)

Primary and Secondary Failure Mechanisms: Examples

Legend:

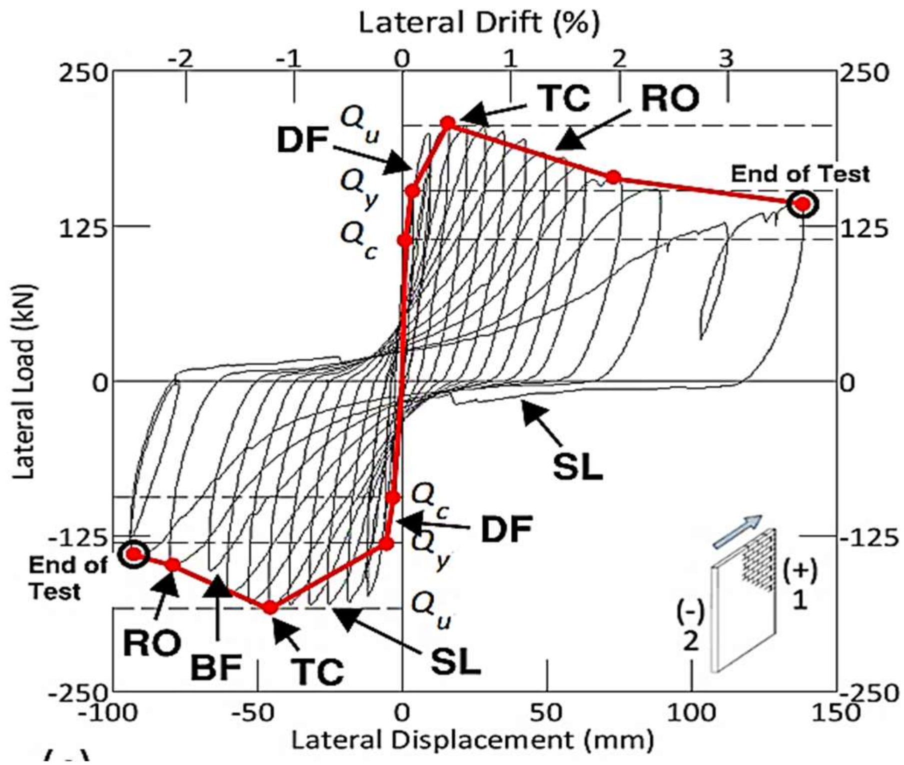
DF = Ductile Flexure

TC = Toe-Crushing

SL = Sliding

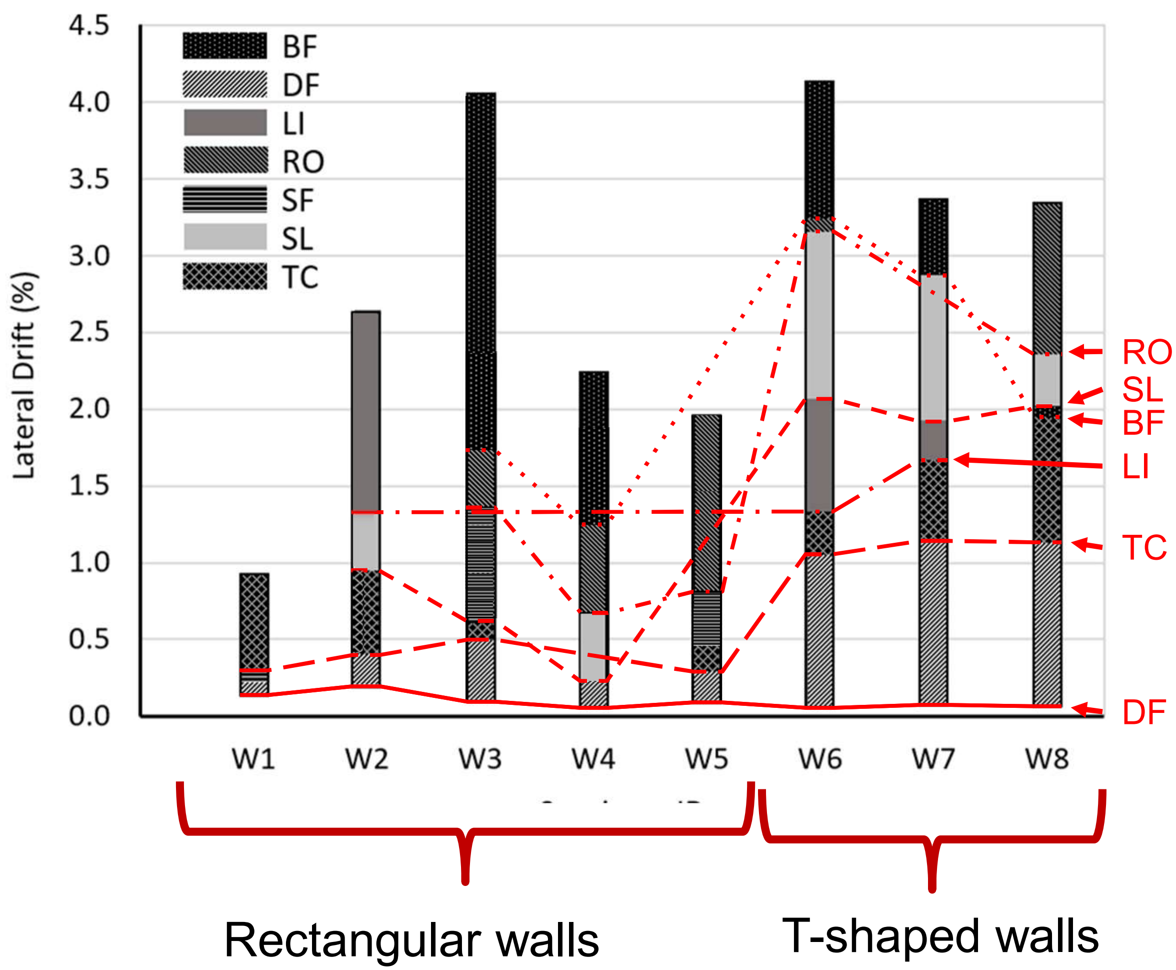
RO = Rocking/Bond-Slip

BF = Bar-Fracture



Specimen W3, Robazza (UBC)

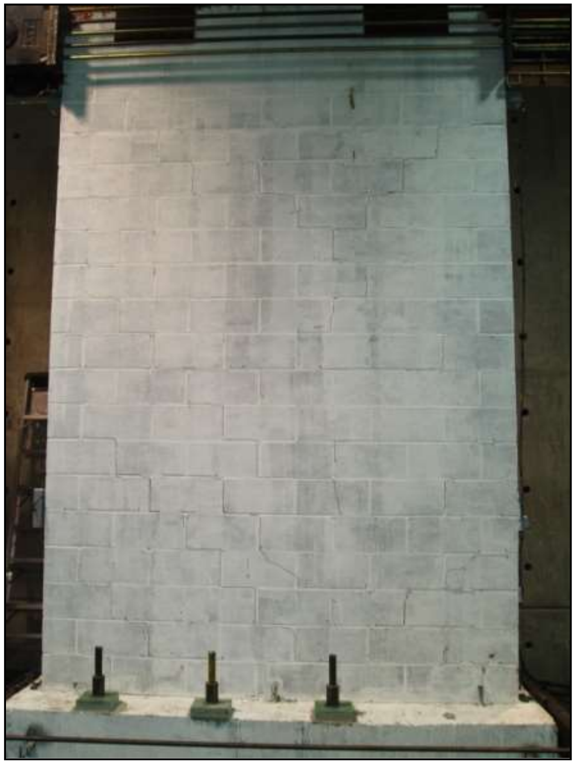
Failure Mechanisms and Lateral Drifts



BF = Bar-Fracture
DF = Ductile Flexure
LI = Lateral Instability
RO = Rocking/Bond-Slip
SF = Shear-Flexure
SL = Sliding
TC = Toe-Crushing

Robazza et al. (2020)

Performance of Ductile RM Shear Walls at Different Drift Levels



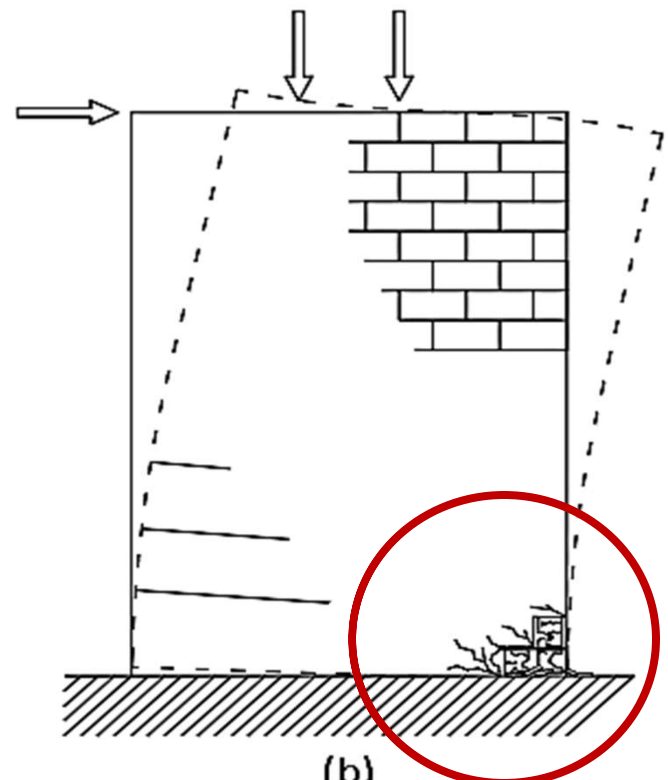
Onset of yielding:
0.18% Drift
Minor damage
(hairline cracks)

Damage at 1.11% Drift
NBC permits 1% drift for post-disaster buildings

Damage at the end of test: 3.9% Drift
NBC permits 2.5% drift for regular buildings

Toe Crushing Failure Mechanism (TC)

- Caused by the flexural behaviour
- Characterized by damage within the wall's toe region
- Initially, the damage is in the form of cracking, but ultimately spalling of face shells takes place, which causes a significant damage and decrease of the compression zone



(b)

Toe-crushing

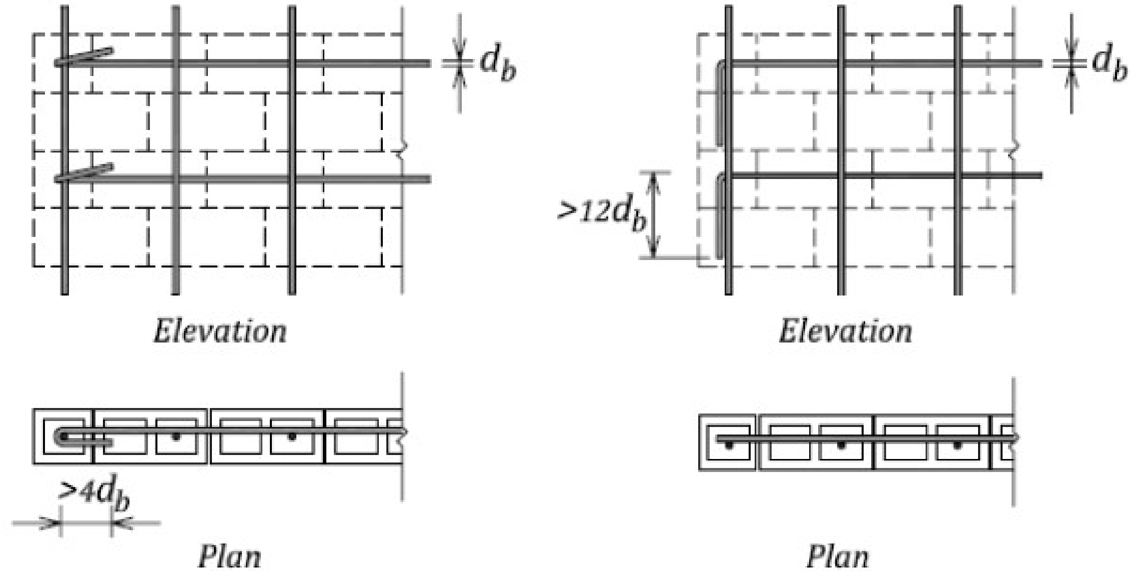
Toe Crushing -> Face Shell Spalling

Wall end zone (specimen W2)

Masonry prism testing

face shell spalling at failure

Detailing of Horizontal Reinforcement (Hooks)

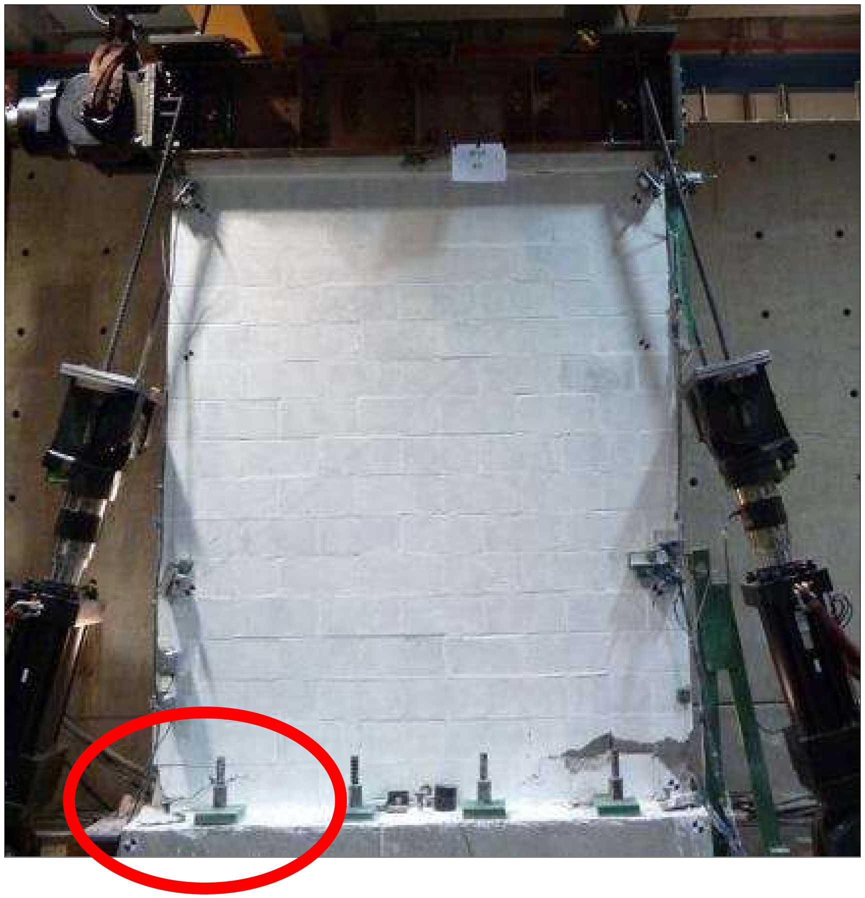


180 degree hooks *required only for Ductile walls (R_d=3.0)*

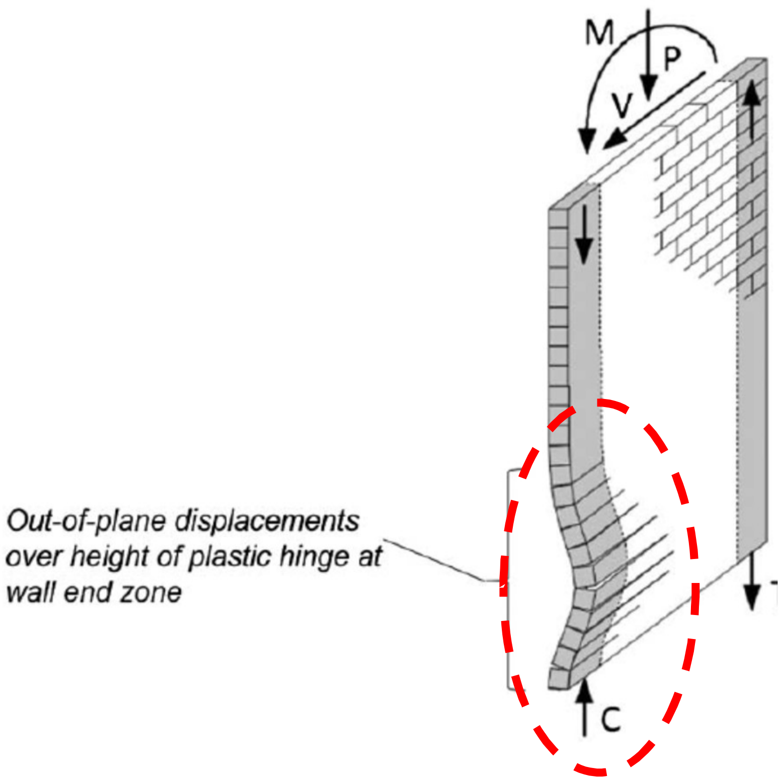
90 degree hooks *permitted for other wall classes*

Source: Anderson and Brzev (2018)

Horizontal Reinforcement with 180^o Hooks: Good Performance at High Seismic Demands



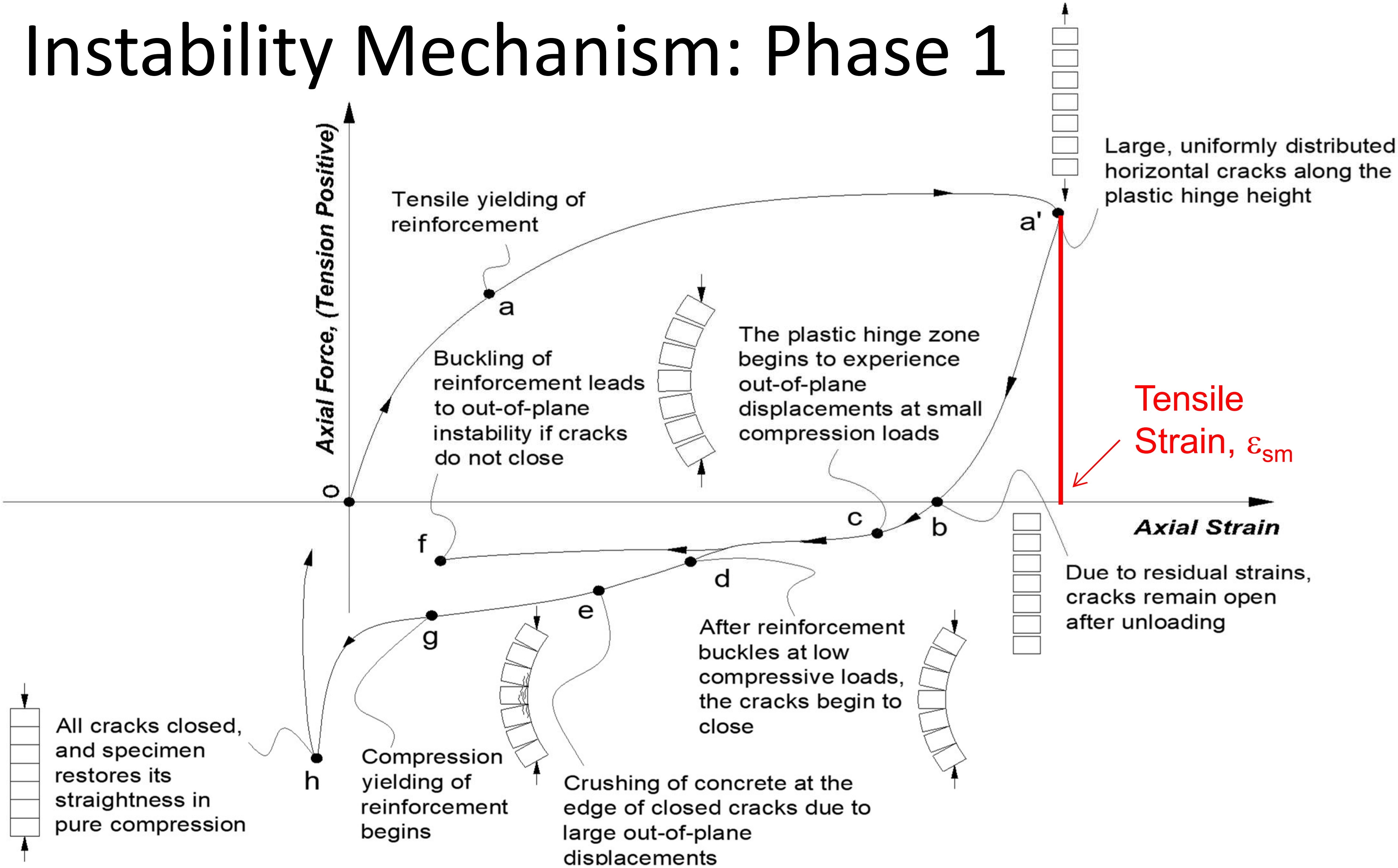
Lateral Instability Mechanism (LI)



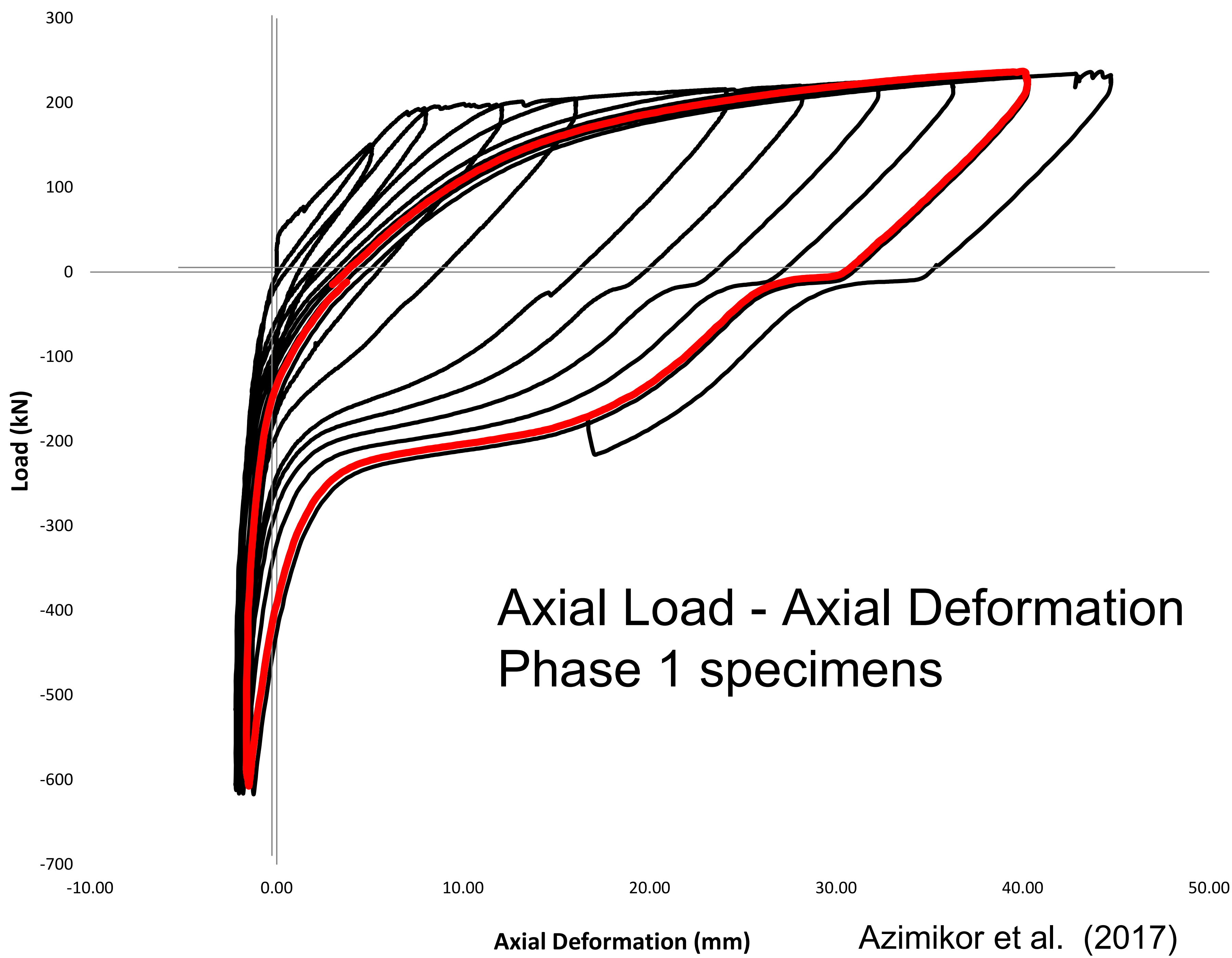
Phase 1 specimens:
h/t=27
Azimikor (2012)

Phase 2: specimen W2
h/t=27
Robazza et al. (2018, 2019)

Instability Mechanism: Phase 1



Azimikor et al. (2017)


300
200
100
0
-100
-200
-300
-400
-500
-600
-700
Load (kN)
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
Axial Deformation (mm)
Axial Load - Axial Deformation
Phase 1 specimens
Azimikor et al. (2017)

4. FUTURE RESEARCH NEEDS

Potential Topics

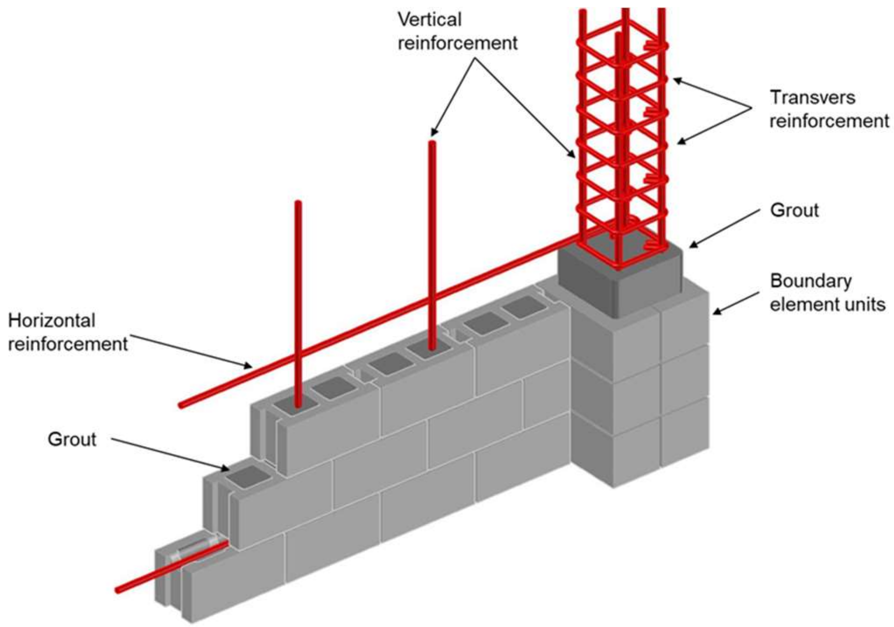
Some topics that may need to be explored in the context of current Canadian masonry practice and potential for future applications:

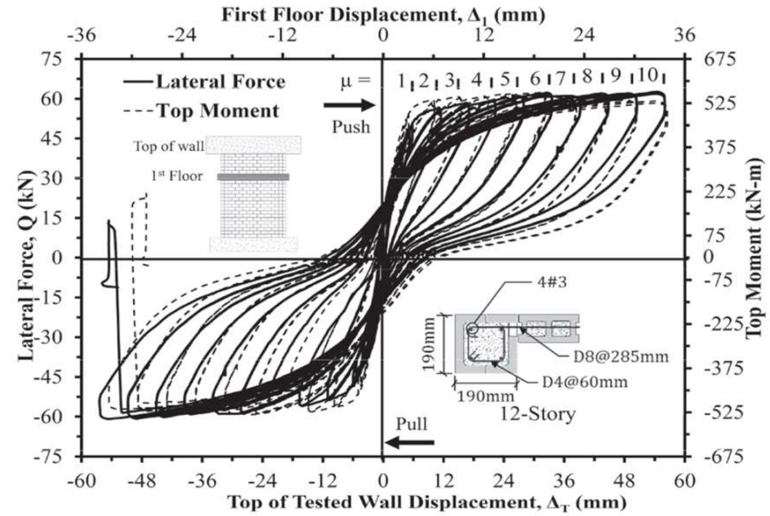
- Limiting seismic damage in ductile RM shear wall configurations via boundary elements
- Seismic behaviour of tall RM shear walls

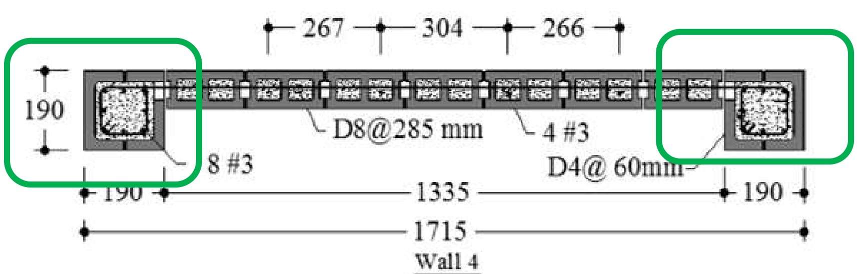
Ductile RM Shear Wall Configurations

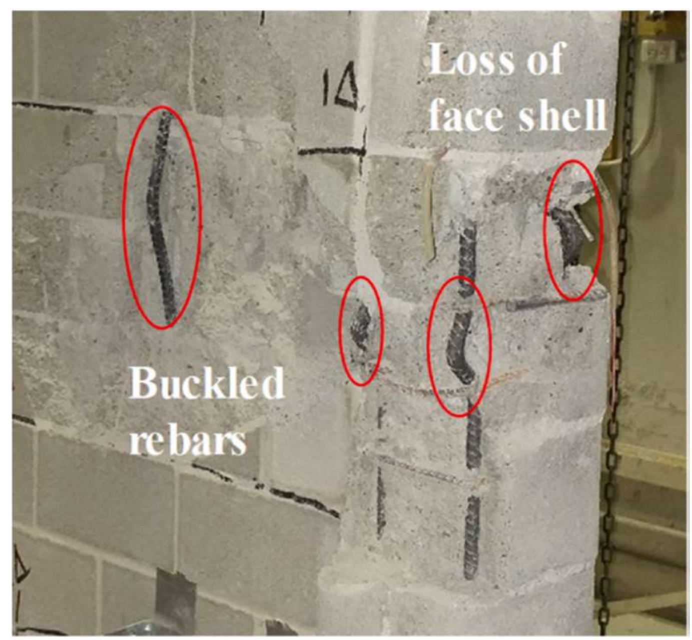
- Research on ductile RM shear walls with exterior boundary elements performed in the last 10 years at McMaster and Concordia University.
- The results indicate stable ductile behaviour, high ductility and limited damage, which are advantages of this design solution
- However, exterior boundary elements are visible and may not be attractive to architects

Research on Ductile RM Shear Walls with Exterior Boundary Elements









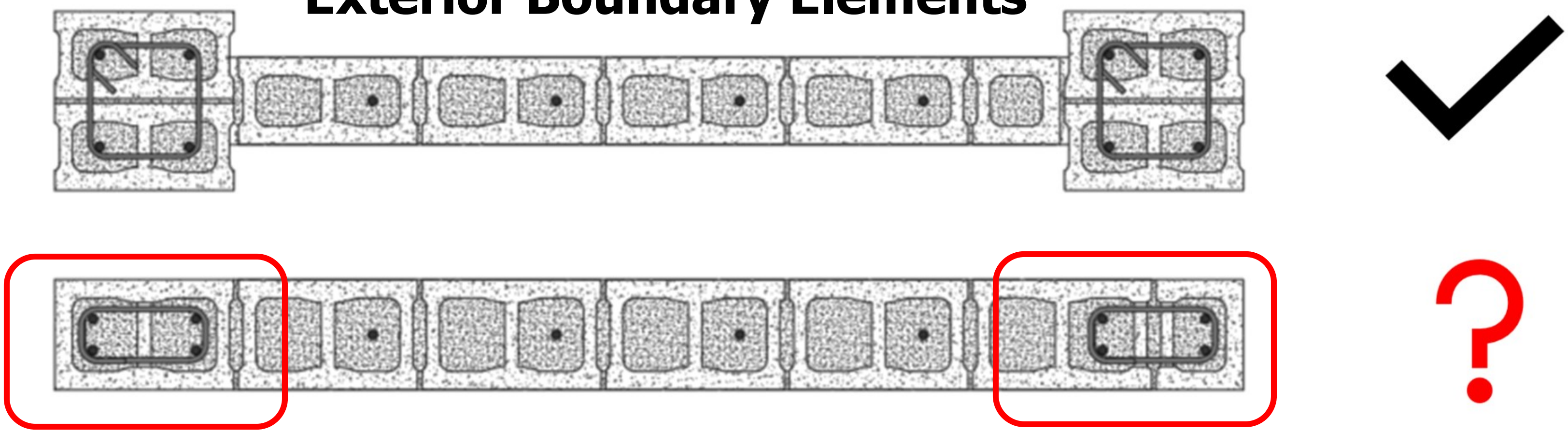
Damage at the wall end zone @2.2% drift

Aly and Galal (2020)

Concordia

Research Topic: Ductile RM Shear Walls with Integrated Boundary Elements

Exterior Boundary Elements



Integrated Boundary Elements

Research at the initial stage at UBC

- Possible in combination with thicker walls (25 cm or 30 cm thickness)
- Challenges associated with confinement/ties within the blocks, both in terms of anchorage (hooks) and tie spacing

Research Topic: Seismic Behaviour of Tall RM Shear Walls

- Limited experimental evidence on RM shear walls with higher height/length (H/L) aspect ratios
- Limited experimental evidence on the effect of high axial precompression and overturning moments (moment gradients) characteristic for tall buildings
- Influence of wall-to-floor interaction also needs to be studied

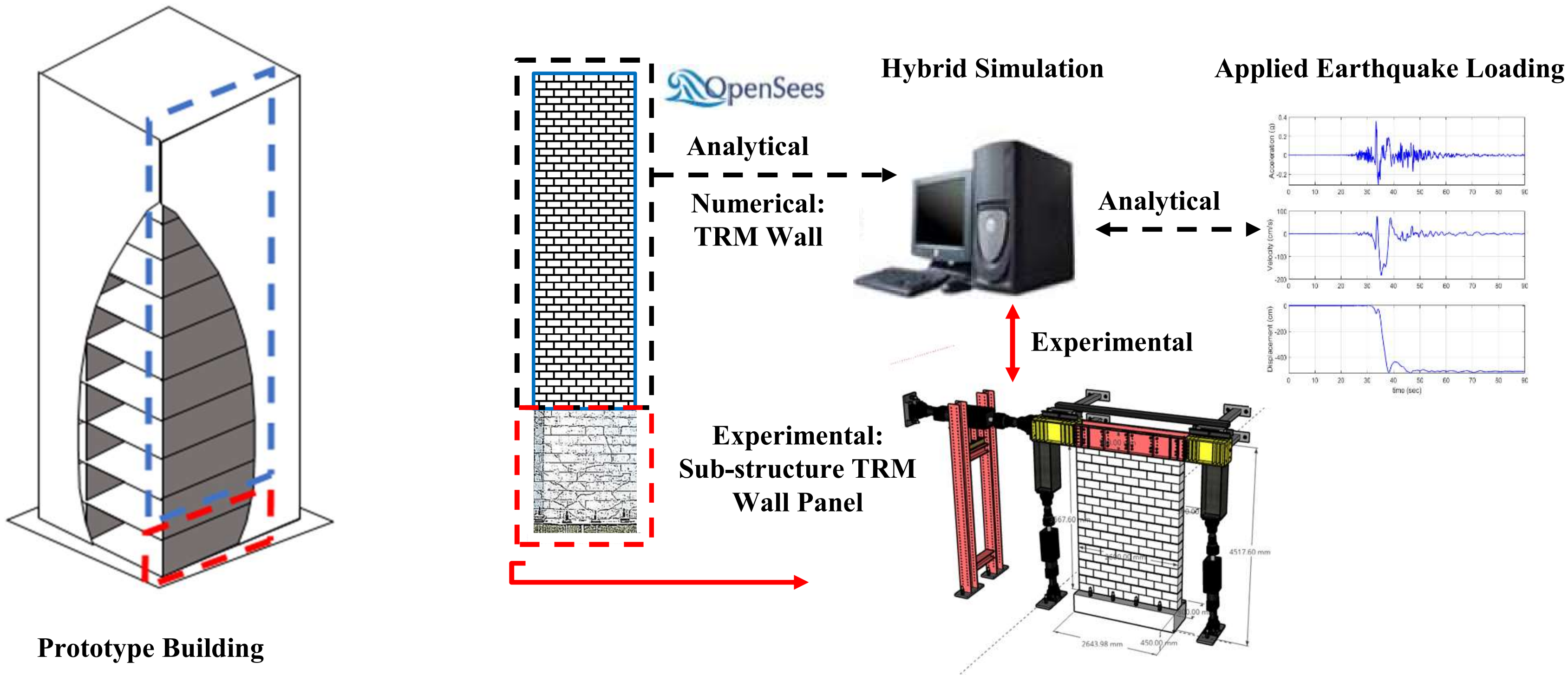
Shaking table testing of a 3-storey full-size RM building at UC San Diego, USA (Shing, Klingner, Stavridis, et al. 2011)

Shaking Table Testing of a 3-storey Full-size RM Building

TEST #14 - 1999 Chi-Chi EQ record at 150% (PGA = 1.5 g)
UC San Diego (Shing, Klingner, Stavridis, et al. 2011)

Future Research: Hybrid Simulation of a Masonry Building

System-level testing of tall RM (TRM) walls using hybrid simulation



A 5-year research project *Seismic Behaviour of Tall Reinforced Masonry Shear Walls* sponsored by an NSERC Alliance grant started in 2021 at UBC
PI: Prof. Tony Yang Co-PI: Svetlana Brzev

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Thank you!

Questions?