Lower-damage Walls

QuakeCoRE FP4 2017 project

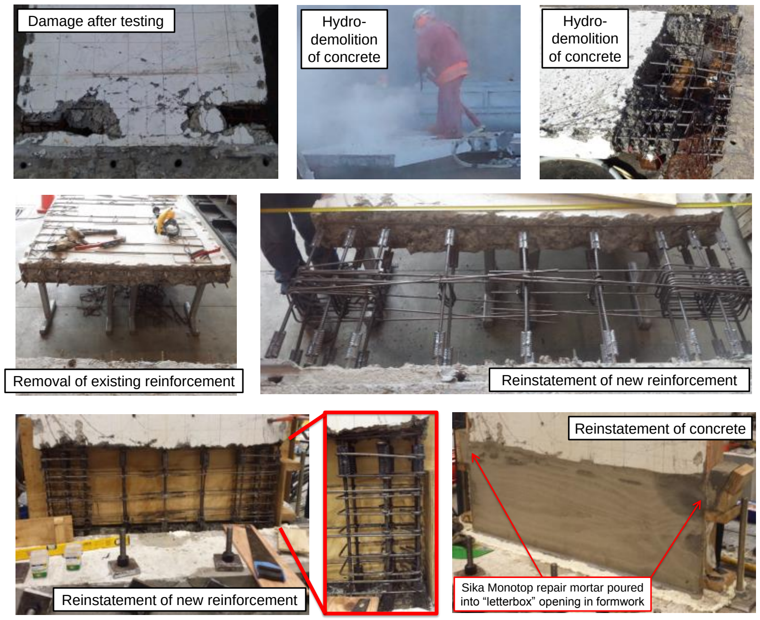
Team

- Rick Henry (Auckland)
- Keri Ryan (University of Nevada, Reno)
- Ken Elwood (Auckland)
- Alessandro Palermo (Canterbury)
- Yiqiu Lu (Auckland – Post-doc)
- Stephen Blount (University of Nevada, Reno - MSc)
- Zhibin Li (Auckland – CSC exchange)

- Peter Smith (FP4 advisor, NZSEE president)
- Nic Brooke (Compusoft)
- Craig Stevenson (Aurecon)

Background

- Repair of conventional concrete walls possible but difficult [2016 QC project]
- Low-damage concrete walls mostly based on PT rocking systems
- Need a range of alternative solutions



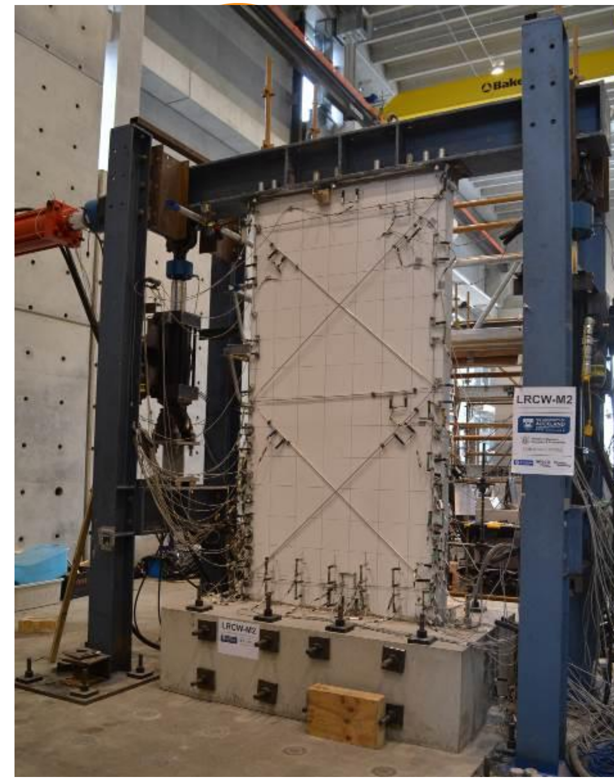
Objectives

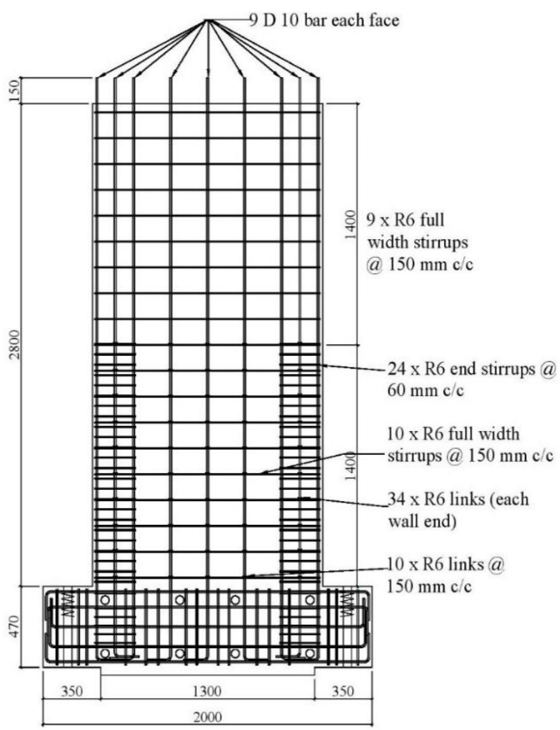
QuakeCoRE
NZ Centre for Earthquake Resilience

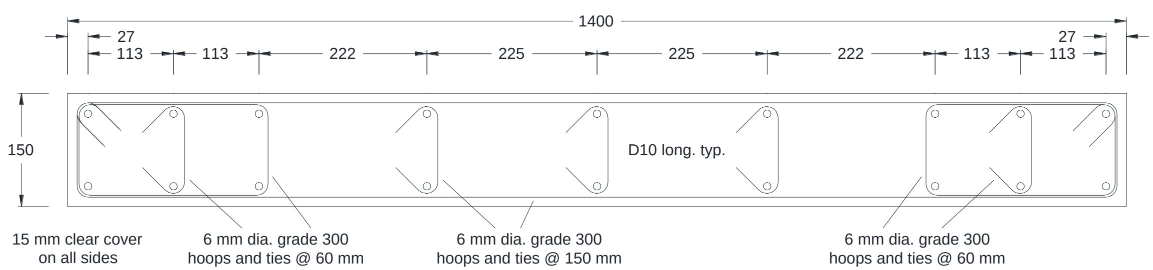
- Experimentally evaluate lower-damage modifications relative to a benchmark conventional RC wall
  - Debonded reinforcement (DBR)
  - Fiber-reinforced concrete (FRC)
  - ECC cutouts in wall boundary elements (ECC)
  - ECC cutouts + higher axial load (ECC-H)
- Assess the reparability and residual capacity of the tested alternative wall solutions

Benchmark (BM) Wall

- M5 (Lu 2016)
- Designed per NZS 3101:2006 Amendment 3
  - Shear span ratio = 2
  - Axial load ratio = 3.5%







Wall #1: Debonded Reinforcement (DBR)

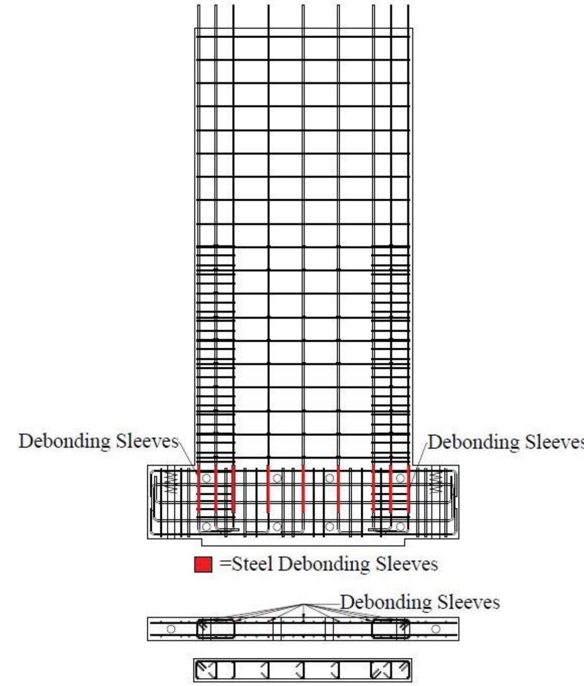
QuakeCoRE
NZ Centre for Earthquake Resilience

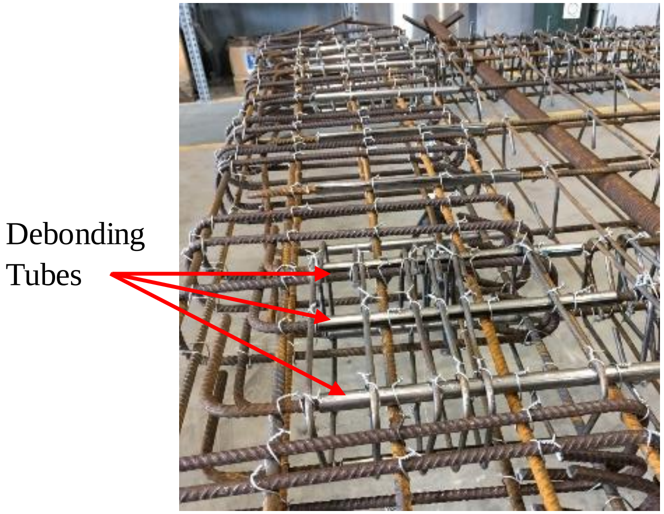
Philosophy:

- Promote single crack at wall base
- Prevent strain localization in reinforcement

Method:

- Debonded bar within sleeve to prevent buckling
- Debonding extends from base to 300 mm length into foundation

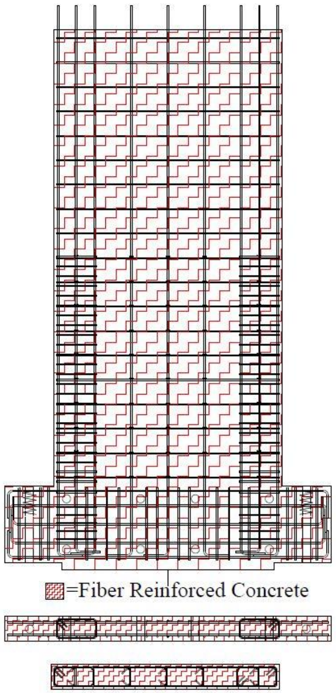




Wall #2: Fiber Reinforced Concrete (FRC)

Philosophy:

- Enhance performance with minimal impact to constructability.
- Fiber concrete offers increased tensile and compressive strength, and possible tensile strain hardening



Method:

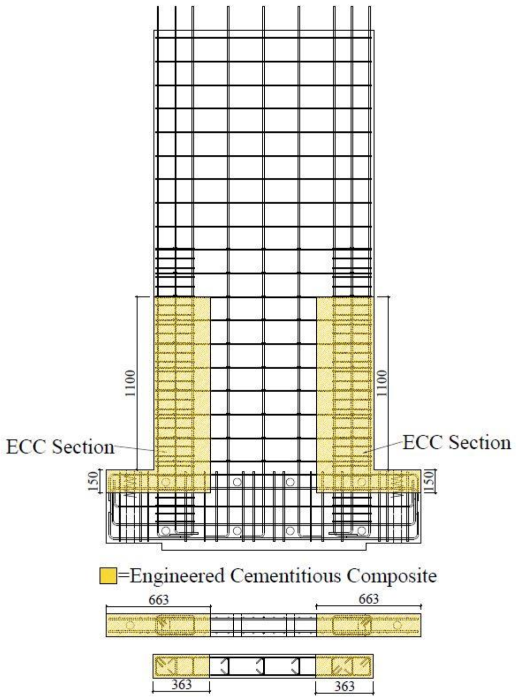
- Add steel fibers at 1% volume ratio to conventional concrete

Walls #3 & 4: ECC cutouts (ECC and ECC-H)

QuakeCoRE
NZ Centre for Earthquake Resilience

Philosophy:

- Use ECC in most damage prone boundary element regions of wall.
- Benefits of ECC
    - Tensile ductility and strain hardening behavior
    - Synthetic PVA fibers produce microcracking and prevent crack localization
    - Self-confining, no spalling

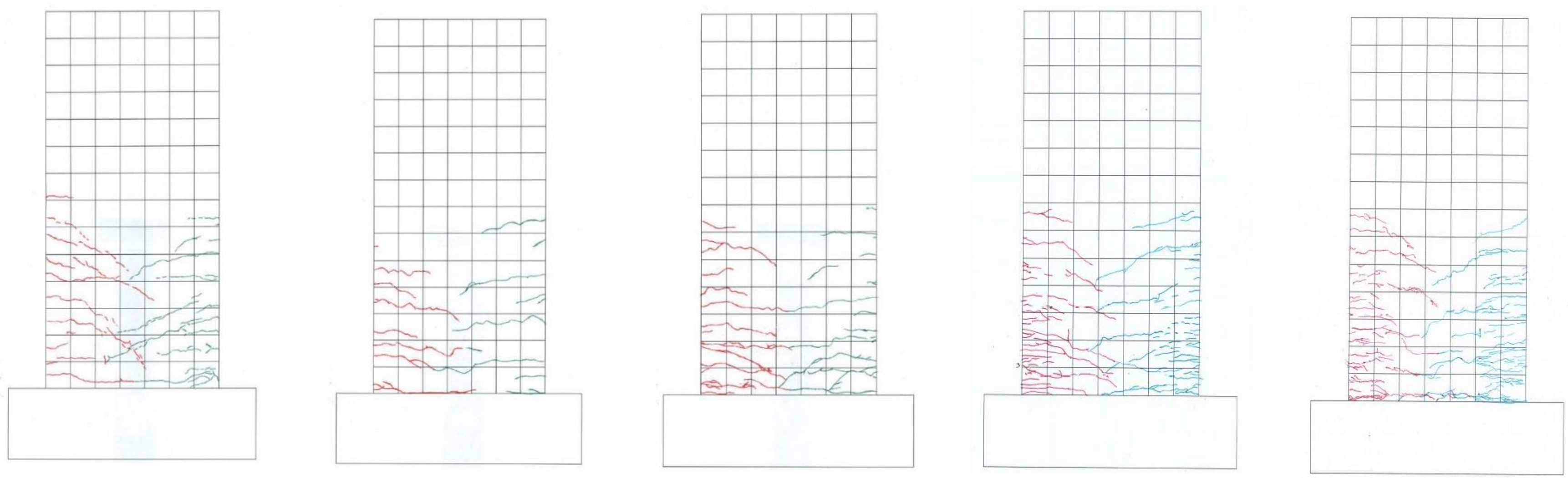


Method:

- Replace concrete with ECC in plastic hinge region
- Cast concrete first, followed by ECC after removal of boundary formwork.
- Mixed ECC in buckets with a drill in the laboratory.

QuakeCoRE
NZ Centre for Earthquake Resilience

Response at low drifts



(a) BM (b) DBR (c) FRC (d) ECC (e) ECC-H

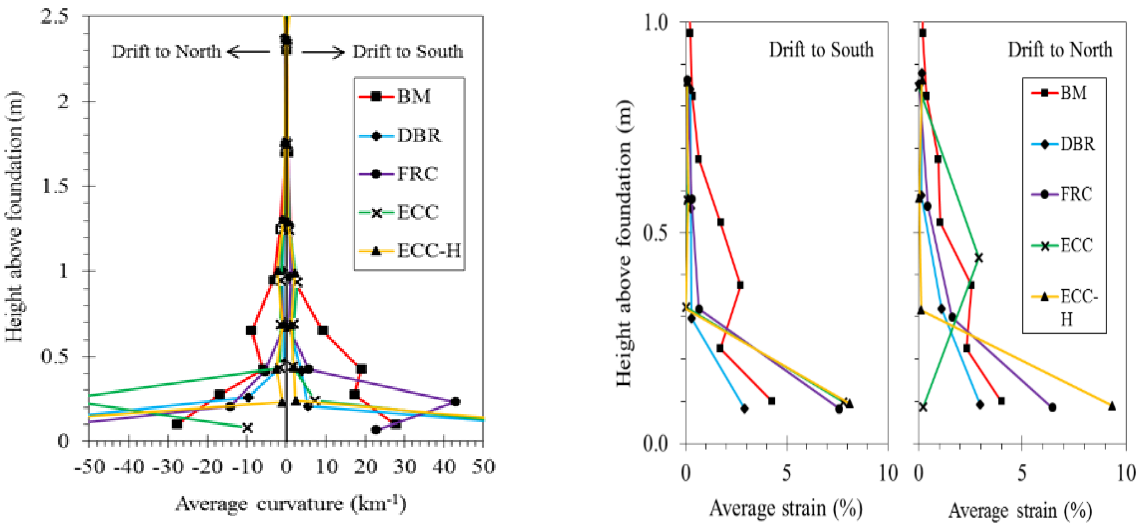
Crack pattern maps at 0.50% drift

Comparison of average crack spacing and max crack width

	Wall				
At 0.50% drift	BM	DBR	FRC	ECC	ECC-H
Average Number of Cracks	10	10	15.5	27.5	24
Average Crack Spacing	140	141	90	51	58
Maximum Crack Width		3.3	1.5	2.3	1.7

- ECC & FRC propagated cracks
- DBR mimicked rocking wall

Response at high drifts



(a) (b

Comparison of (a) average curvature and (b) average reinforcement strain at 1.50% drift for all walls.

- BM 2-3 dominant cracks
- Four LD walls localized to one crack
- BM better distribution of curvature & reinforcement strain
- DBR reduced reinforcement strain

Comparison of occurrence of buckling and associated reinforcement strain.

Test Wall	Drift at Buckling (%)		Average Reinforcement Tensile Strain (%)	
	Drift to North	Drift to South	Drift to North	Drift to South
BM	+2.00%[3]	-1.50%[3]	4.3%	4.4%
DBR	-2.50%[3]	+2.00%[2]	6.2%	3.8%
FRC	-1.00%[3]	+1.50%[2]	3.6%	6.6%
ECC	-	-1.00%[3]	-	4.6%
ECC-H	-1.00%[1]	-	5.5%	-
		Average	4.9%	4.9%

Reparability at 1.50% drift (FEMA-P58)

QuakeCoRE
NZ Centre for Earthquake Resilience

	Wall				
At 1.50% drift	BM	DBR	FRC	ECC	ECC-H
Average Number of Cracks	15.5	12.5	19	30	24
Average Crack Spacing	90	117	76	47	58
Maximum Crack Width		16.0	22.5	20.5	17.5

BM (DS2a)

- Epoxy inject dominant cracks
- Patch spalling of boundary elements

DBR (DS2)

- Paint surface crack

FRC (DS4)

- Replace steel and concrete due to bar buckling

ECC (DS4)

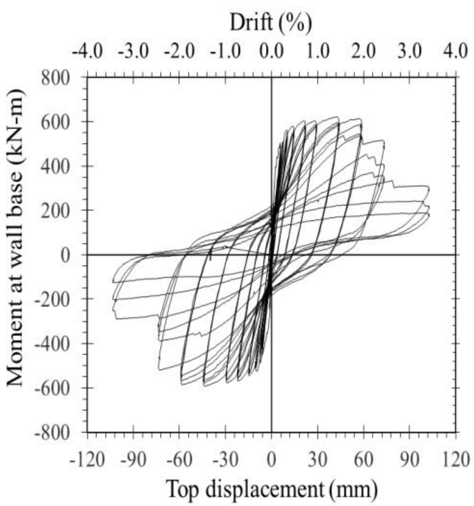
- Replace steel and concrete due to bar buckling

ECC-H (DS4)

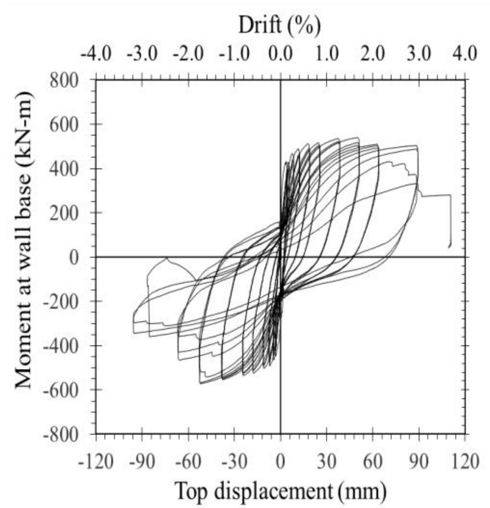
- Replace steel and concrete due to bar buckling

QuakeCoRE
NZ Centre for Earthquake Resilience

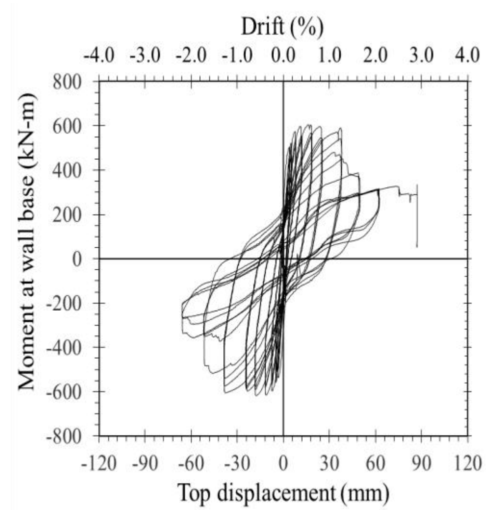
Moment- Displacement Response



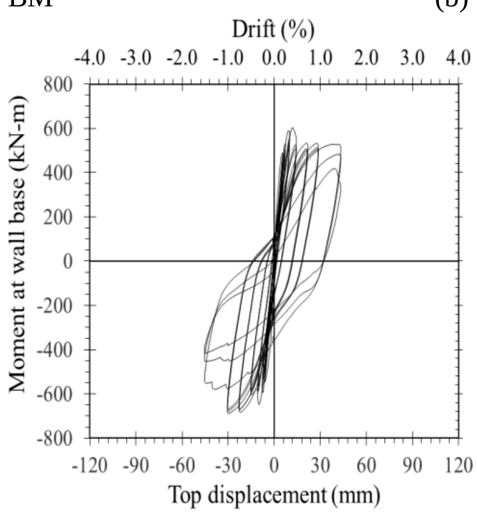
(a) BM



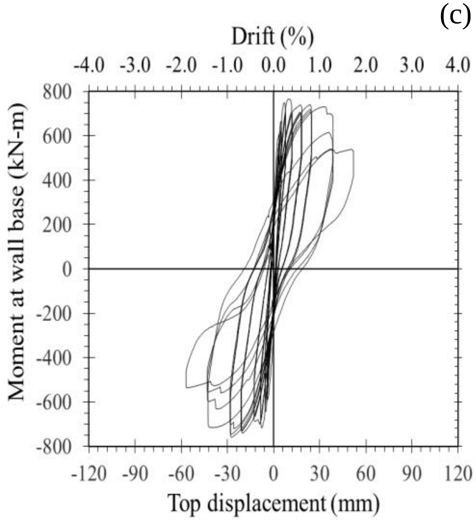
(b) DBR



(c) FRC



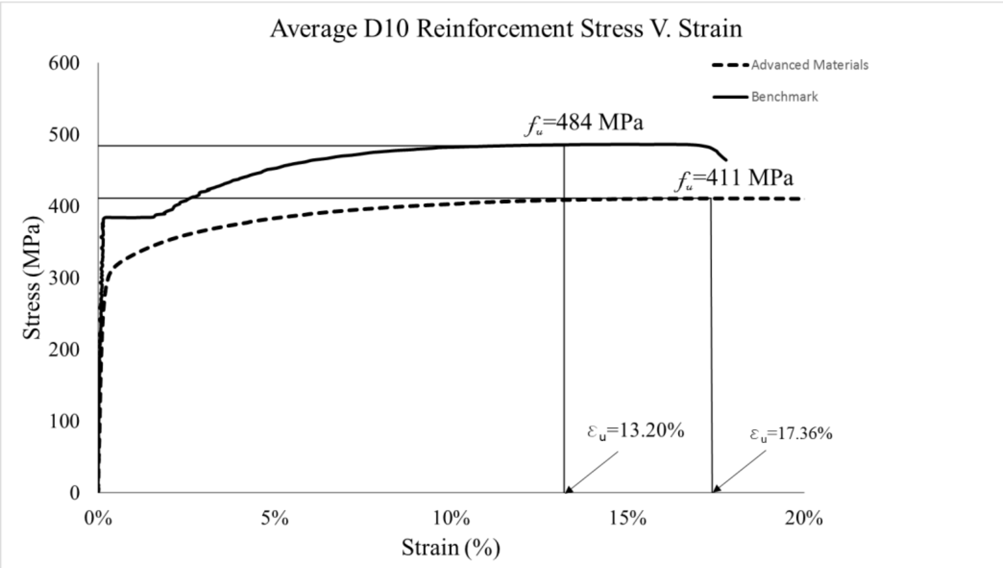
(d) ECC



(e) ECC-H

Test Wall	Direction	Mmax_Test (kN-m)	Drift Cycle
BM	+	635.5	+1.50%[1]
	-	-615.2	-1.50%[1]
DBR	+	540.4	+2.00%[1]
	-	-572.1	-2.00%[1]
FRC	+	605.2	+0.75%[1]
	-	-618.1	-0.75%[1]
ECC	+	603.6	+0.50%[1]
	-	-688.0	-0.75%[1]
ECC-H	+	766.4	+0.50%[1]
	-	-759.0	-1.00%[1]

Material Tests



Comparison of D10 vertical steel characteristics.

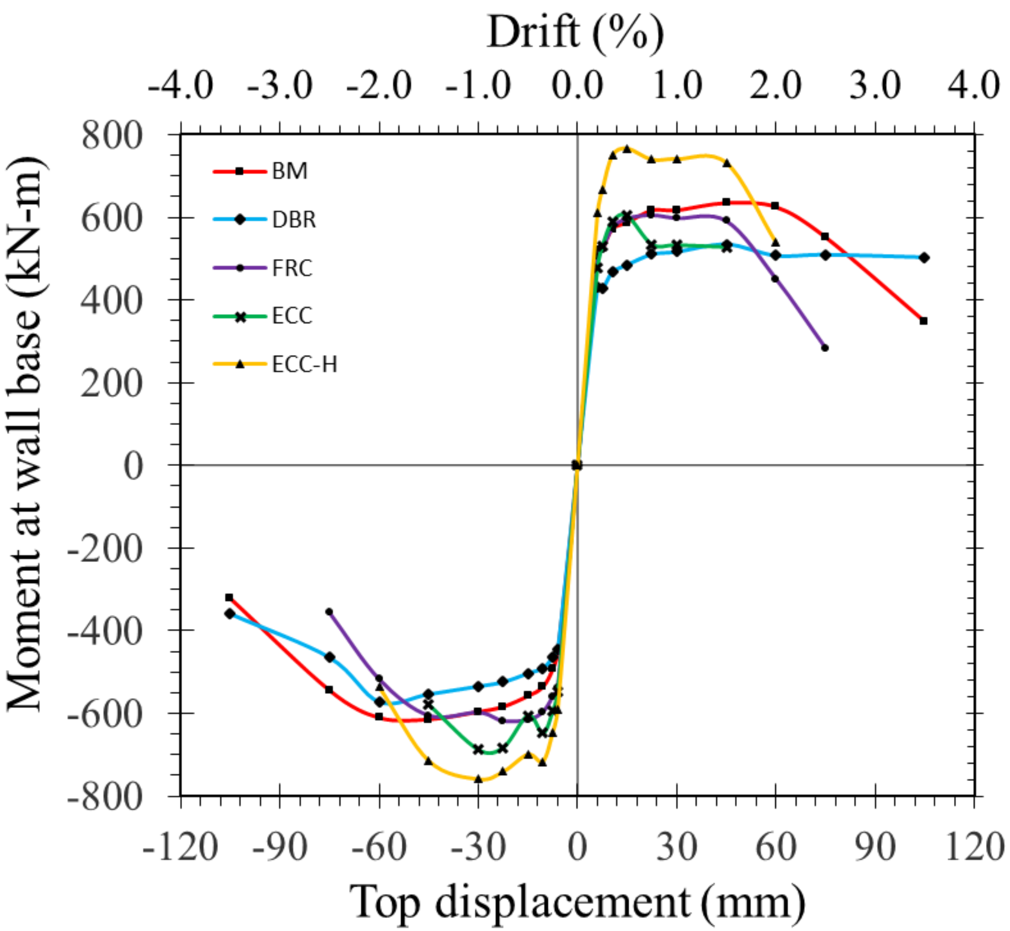
Steel	f_y	f_u	ε_y	ε_u
Benchmark (D10)	387	484	0.40%	13.20%
Advanced Materials (D10)	314	411	0.35%	17.36%
Benchmark (R6)	322	450	-	16.40%
Advanced Materials (R6)	340	462	0.34%	14.96%

Test Wall (days)	Concrete		
	f_{cm} (MPa)	f_t (MPa)	ρ_c (kg/m^3)
BM	31.2	2.15	2337
DBR (31)	35.8	3.19	2395
FRC (37)	38.6	3.95	2422
ECC (129)	52.0	3.26	2412
ECC-H (127)	43.6	3.48	2398

Test Wall (days)	ECC		
	f_{cm} (MPa)	f_t (MPa)	ρ_c (kg/m^3)
ECC (83)	47.3	5.1	2000
ECC-H (84)	50.5	5.0	2006

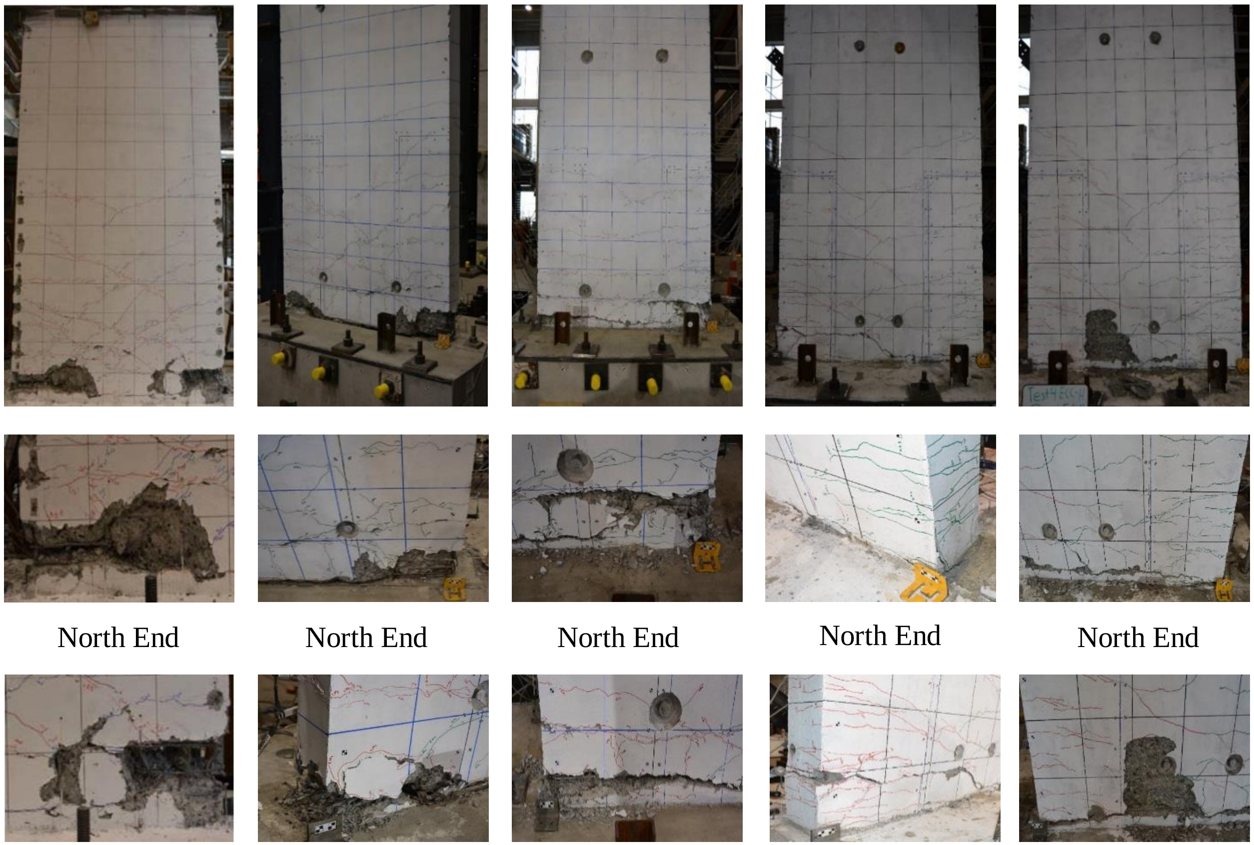
- Coiled steel in advanced material walls
- ECC walls tested 3 months later than other tests
- FRC and ECC had increased tensile properties

Backbone Curves



- Reduced ultimate steel strength lead to decreased moment capacity
- DBR strength would have been comparable to BM, FRC and ECC would have been higher
- ECC and FRC walls showed a deformation softening behavior which suggests tensile strain softening of materials

Final Condition of All Walls



Final condition of all test walls and exploded views of wall toes.

Test Wall	Concrete Spalling	Bar Fracture
BM	-1.50%[1]	+2.00%[3]
DBR	-1.50%[1]	+2.00%[3]
FRC	+0.75%[3]	+1.50%[3]
ECC	+1.50%[3]	-1.50%[1]
ECC-H	-1.00%[3]	-1.00%[3]

- ECC did not spall until buckling and fracture

Conclusions

QuakeCoRE
NZ Centre for Earthquake Resilience

- BM wall had best distribution of curvature and reinforcement strain over the wall height. Generally, lower damage modifications fell short of expectations.
- DBR concept delayed bar buckling, but fracture occurred almost immediately after buckling.
- ECC and FRC walls had increased crack propagation at low drifts, but eventually crack localization occurred and dominant cracks formed.
  - FRC likely to be more effective with higher fiber volume ratio (2%)
  - Hand mix method may have negatively impacted ECC material properties (tensile strain hardening)