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NEW ZEALAND

Seismic Performance of Repaired Lightly Reinforced Concrete Walls

Christopher Motter, Aaron Clauson, James Petch, Matias Hube, Richard Henry, Kenneth Elwood

October 17, 2018

Research Motivation

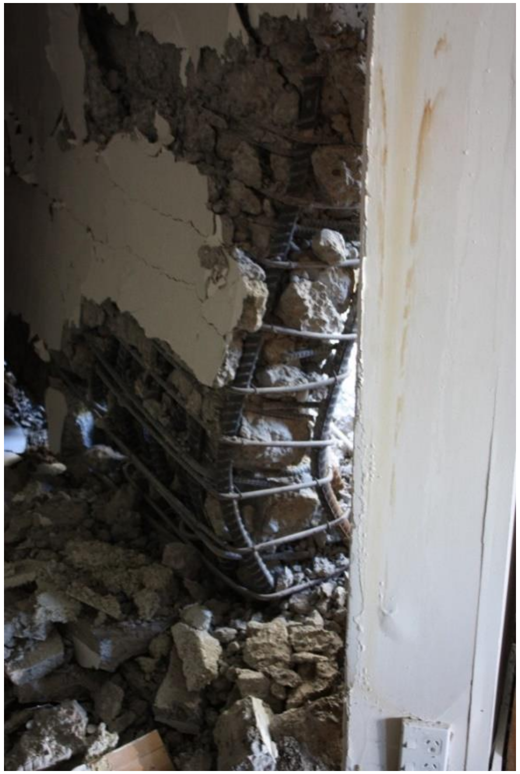
- 2010-2011 Canterbury, New Zealand Earthquake damage (Marquis et al, 2017)
  - More than $NZ 40 billion in losses
  - Closure of Christchurch Central Business District for more than two years
  - Demolition of ~60% of multi-story concrete buildings in Christchurch Central Business District
    - Included demolition of structures with low damage ratios (cost of repair to cost of replacement)
      - More guidance needed on assessment of residual capacity and expected performance of repaired components

Christchurch Wall Damage

Dunning Thornton, 2011

Elwood, 2013

Christchurch Wall Damage



Courtesy of R. Henry

Elwood, 2013

Research Objective

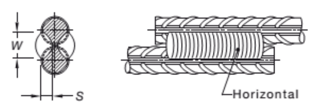
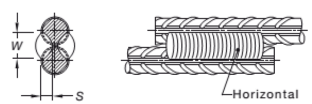
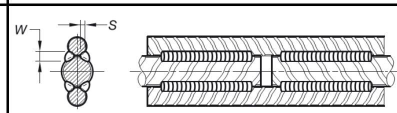
Is it feasible to repair and restore performance in heavily-damaged RC elements (e.g., walls)?

Repair of RC wall in 11-story building in Vina del Mar after Maule, Chile (2010) Earthquake (photo courtesy of Jorge Carvallo)

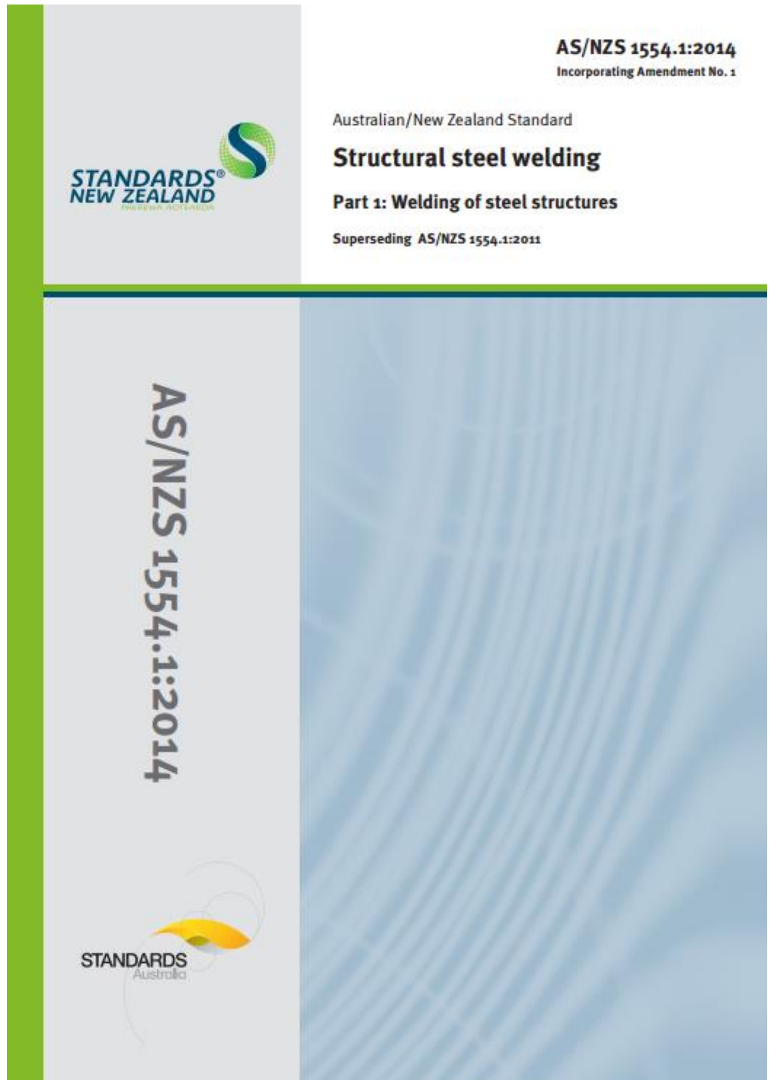
Repair of RC wall in 18-story building in Santiago after Maule, Chile (2010) Earthquake (Sherstobitoff et al, 2012)

Tensile Testing of Reinforcement Connections

Tensile Testing of Reinforcement Connections

No. of specimens	Connection	Reinforcement	Drawing	Electrode	Weld position	Current	Pre/Post Heat
2	Straight Bar	HD10		None	None	None	None
2	Straight Bar	HD16		None	None	None	None
3	Double lap splice	HD10		AS/NZS 4857 B-E7618-GA H5 (P118)	Longitudinal	100A	Pre Heat ~100°C
3	Double lap splice	HD16		AS/NZS 4857 B-E7618-GA H5 (P118)	Longitudinal	100A	Pre Heat ~100°C
1	Indirect butt splice	HD16		AS/NZS 4857 B-E7618-GA H5 (P118)	Longitudinal	100A	Pre Heat ~100°C
3	Mechanical coupler	HD16		None	None	None	None

Tensile Testing of Reinforcement Connections



AS/NZS 1554.1:2014
Incorporating Amendment No. 1

STANDARDS NEW ZEALAND

Australian/New Zealand Standard

Structural steel welding

Part 1: Welding of steel structures

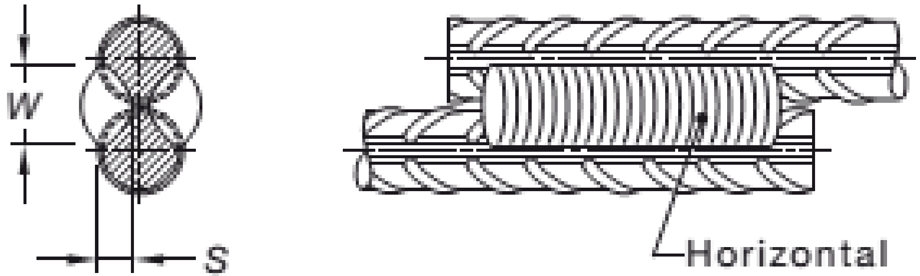
Superseding AS/NZS 1554.1:2011

AS/NZS 1554.1:2014

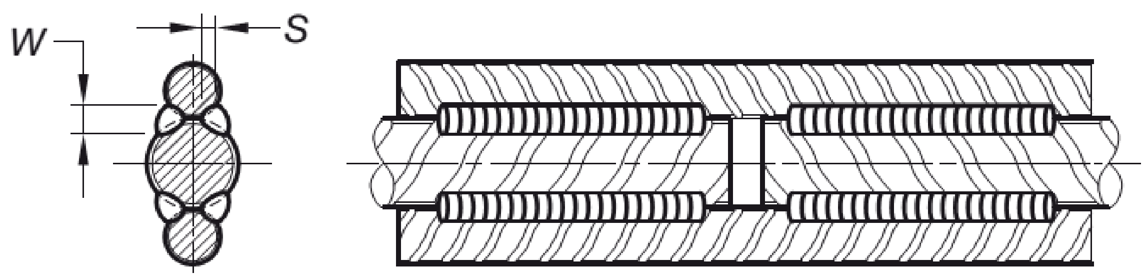
STANDARDS Australia

Tensile Testing of Reinforcement Connections

Double Lap Splice Weld:

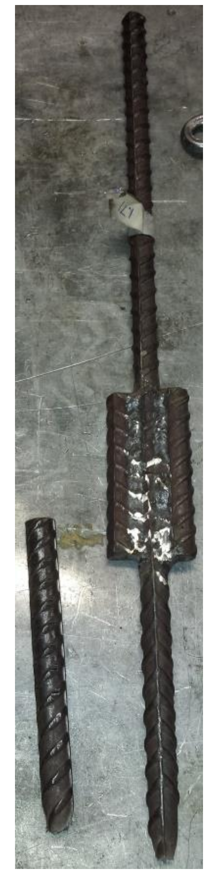


Indirect Butt Splice Weld:

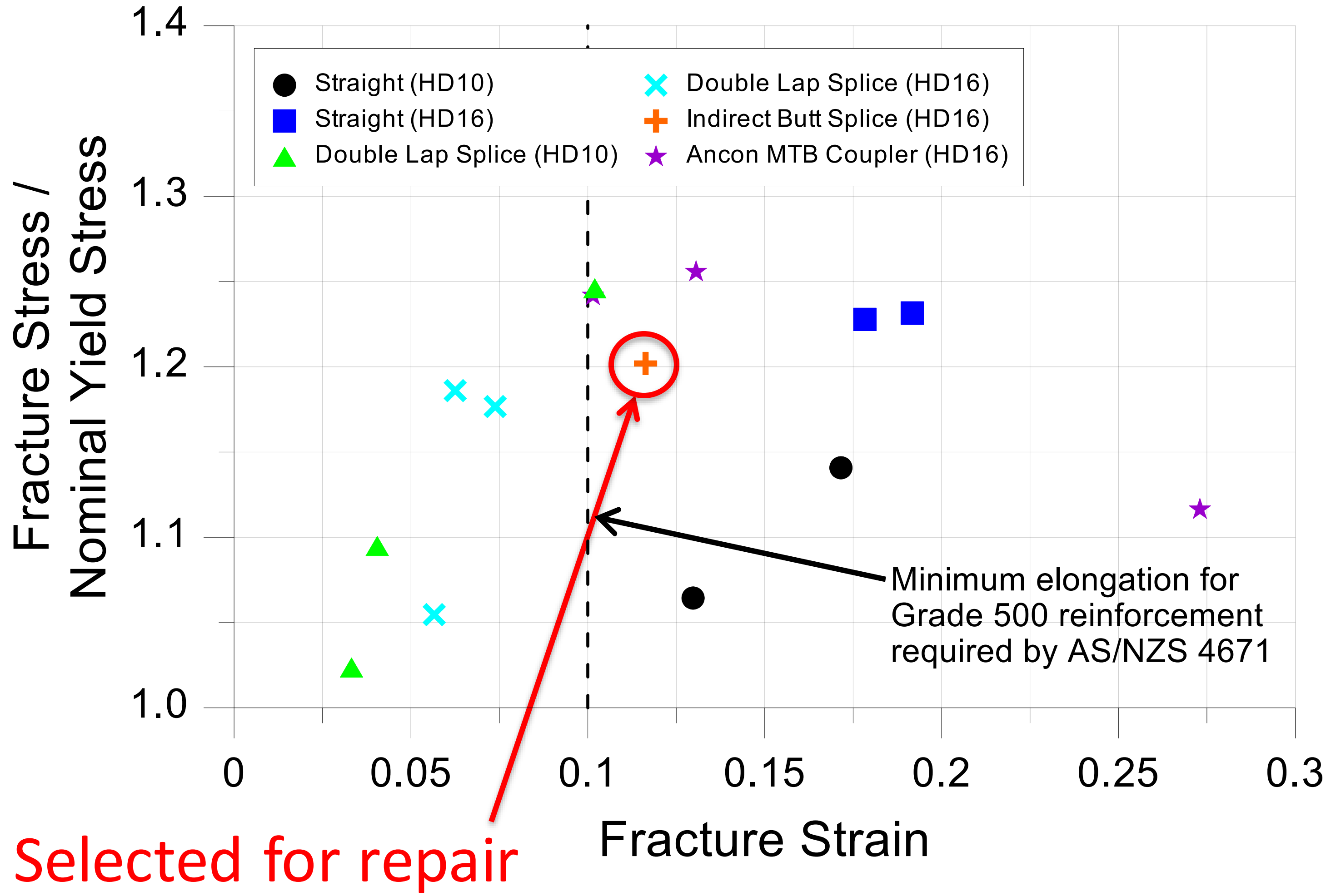


Mechanical Coupler:

Tensile Testing of Reinforcement Connections

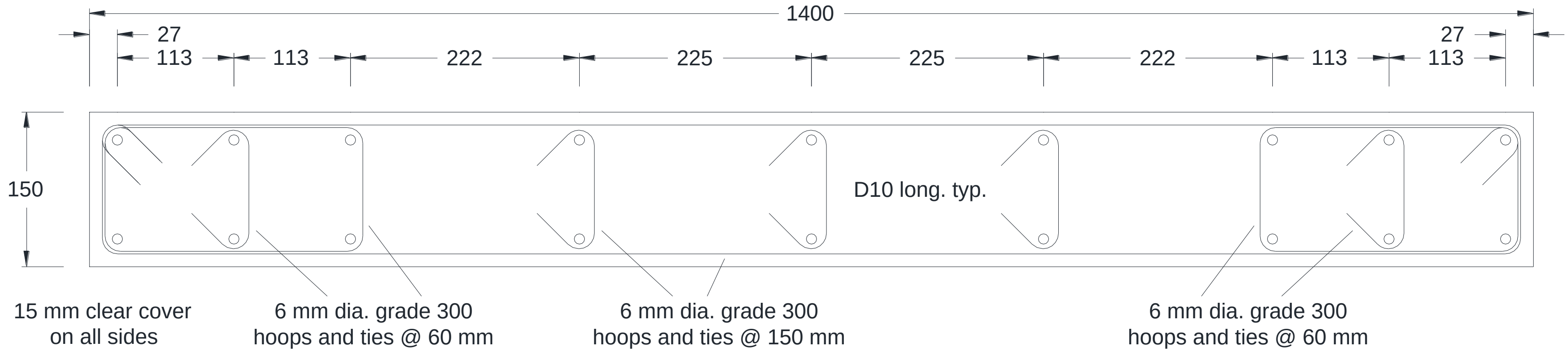


Tensile Testing of Reinforcement Connections



Testing of Original Wall Specimens

Original Tests

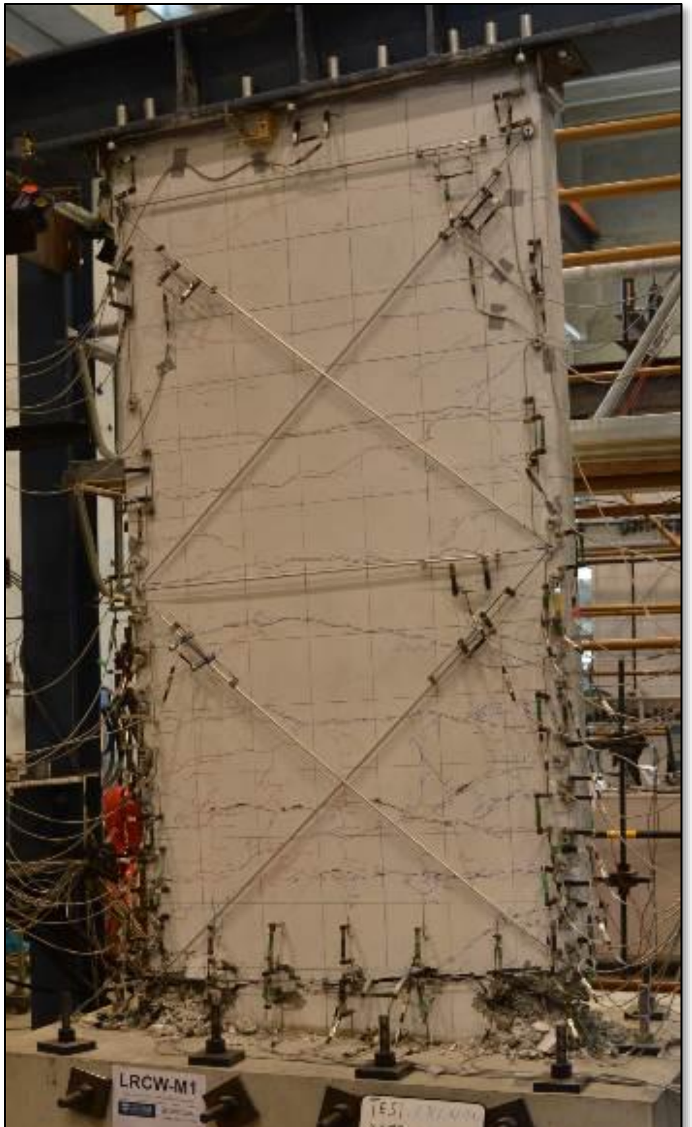


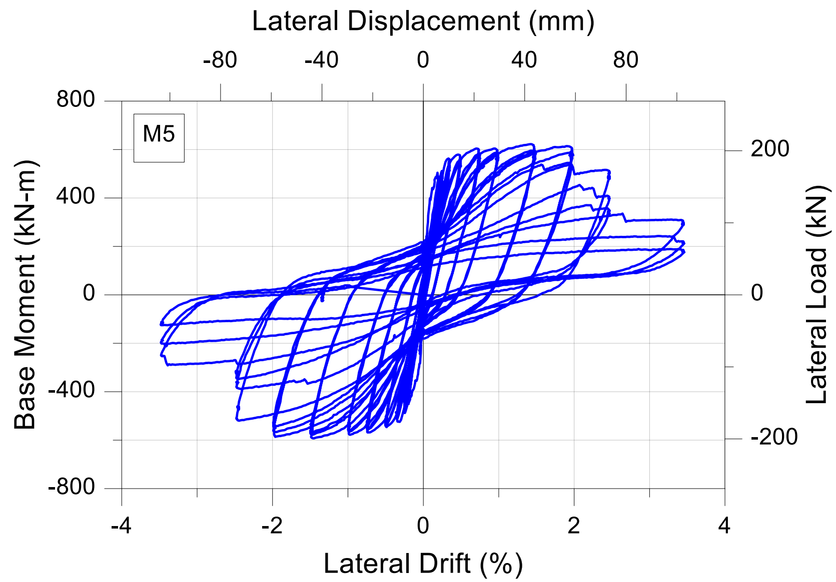
NZS 3101 A3 minimum reinforcement:

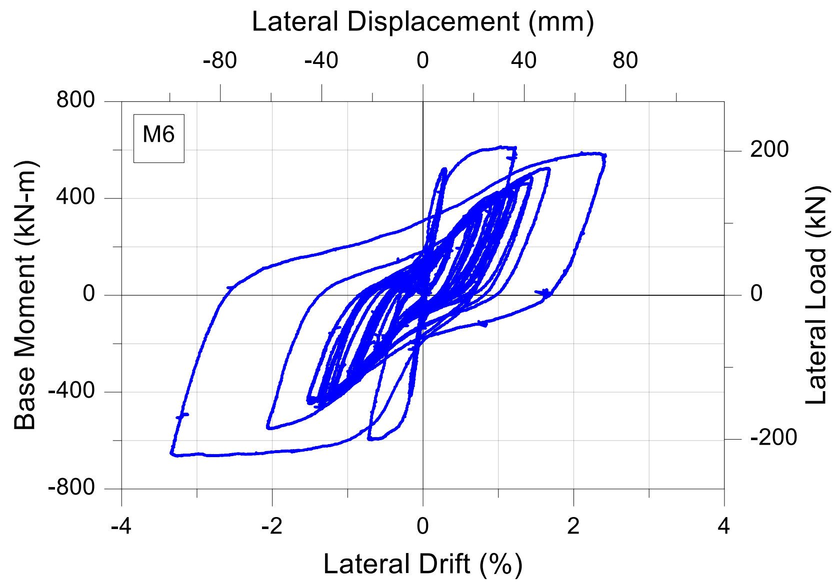
$$\rho_{le} \geq \frac{\sqrt{f_c'}}{2f_y} \quad \text{in end region}$$

$$\rho_{l} \geq \frac{\sqrt{f_c'}}{4f_y} \quad \text{in web}$$

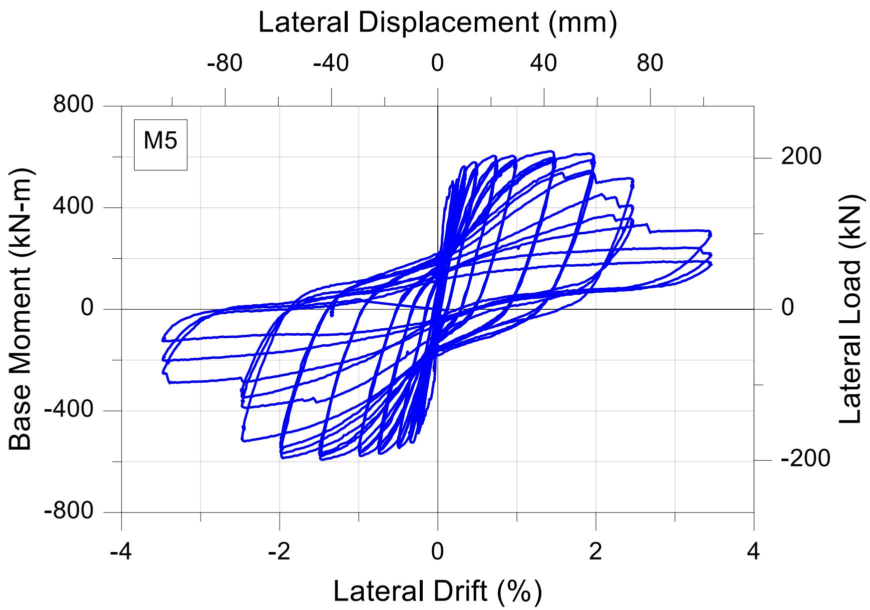
Original Tests

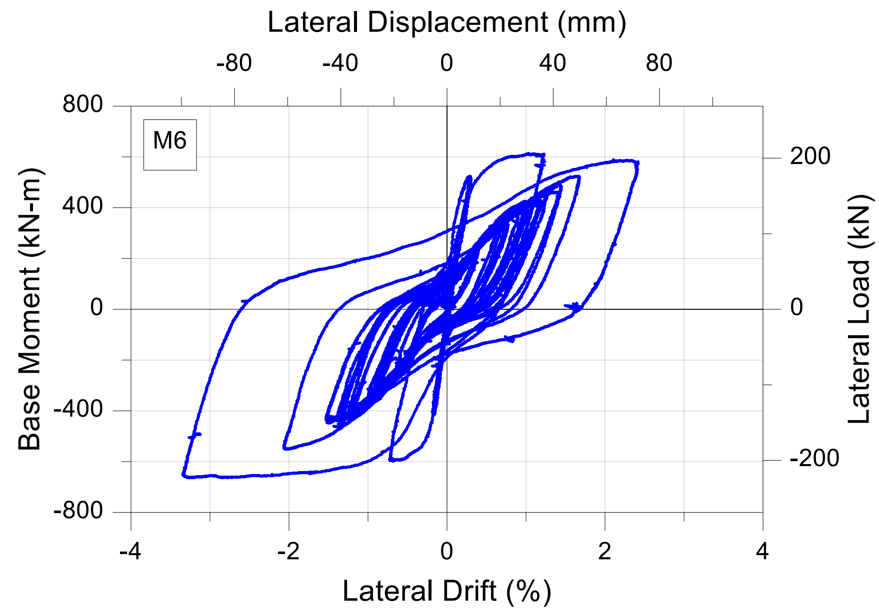






Original Tests





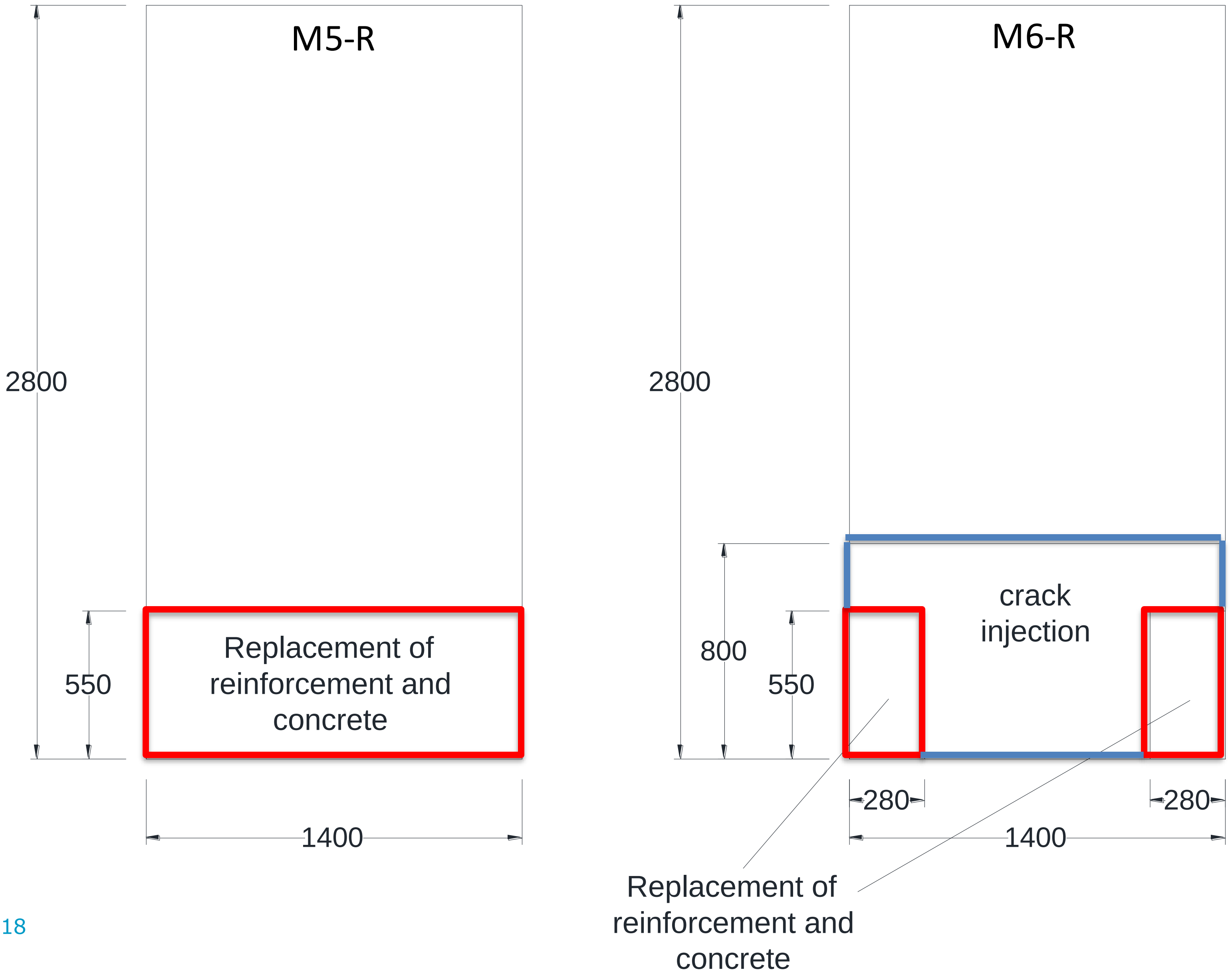
Repair of Wall Specimens

Repair Procedures: Overview

- M5-R
  - Replace all concrete and steel over ~ plastic hinge region (hydro-demolition)
  - No crack Injection above repair, as cracks deemed too small

- M6-R
  - Replace all concrete and steel over ~ plastic hinge region only at wall end regions (jackhammer)
  - Crack injection at remaining locations

Repair Procedures: Overview



Repair Procedures: M5-R

Removal of Concrete
(Hydro-demolition)

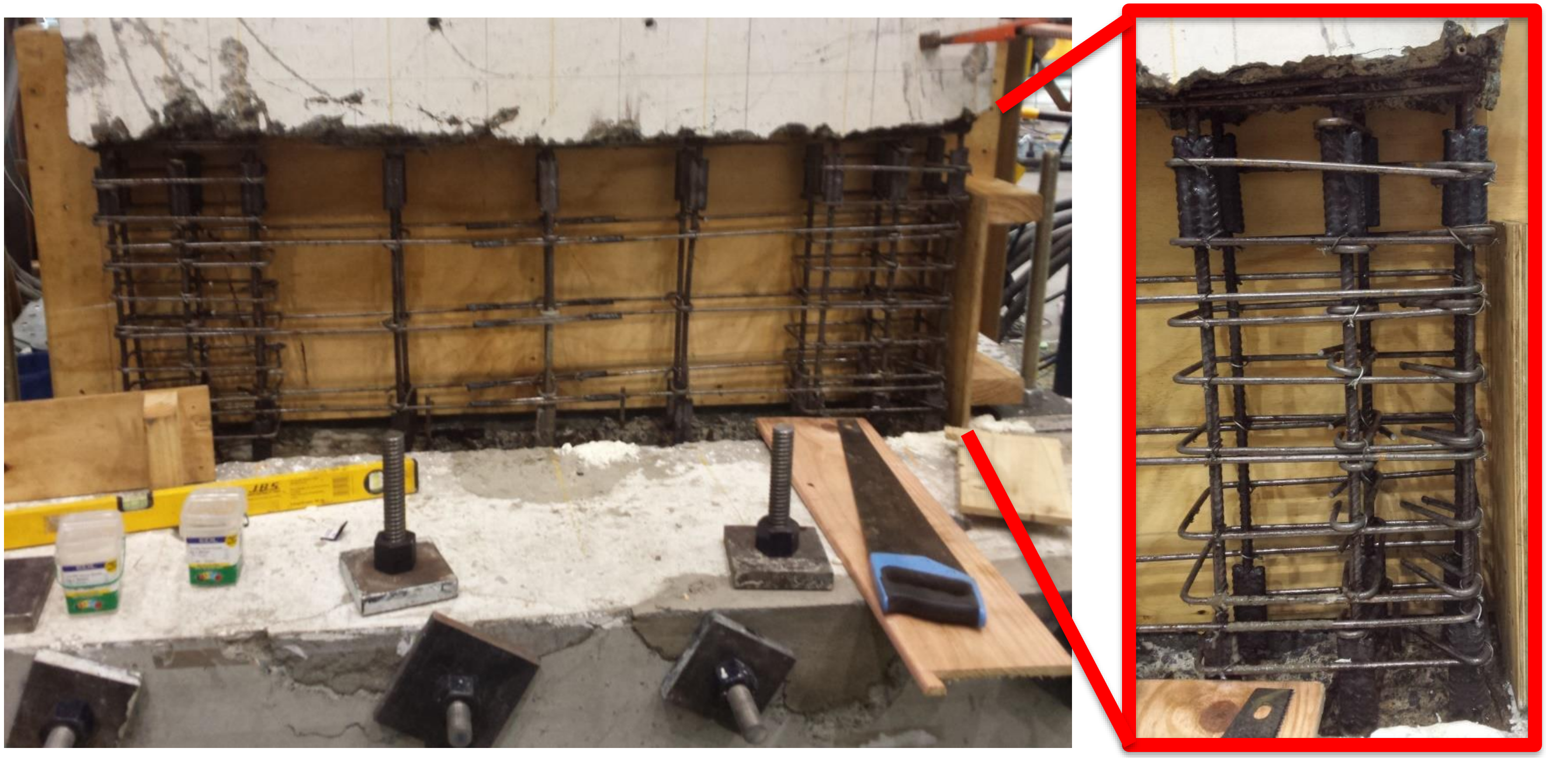
Repair Procedures: M5-R

Removal of Existing Reinforcement

Repair Procedures: M5-R

Reinstatement of New Reinforcement

Repair Procedures: M5-R



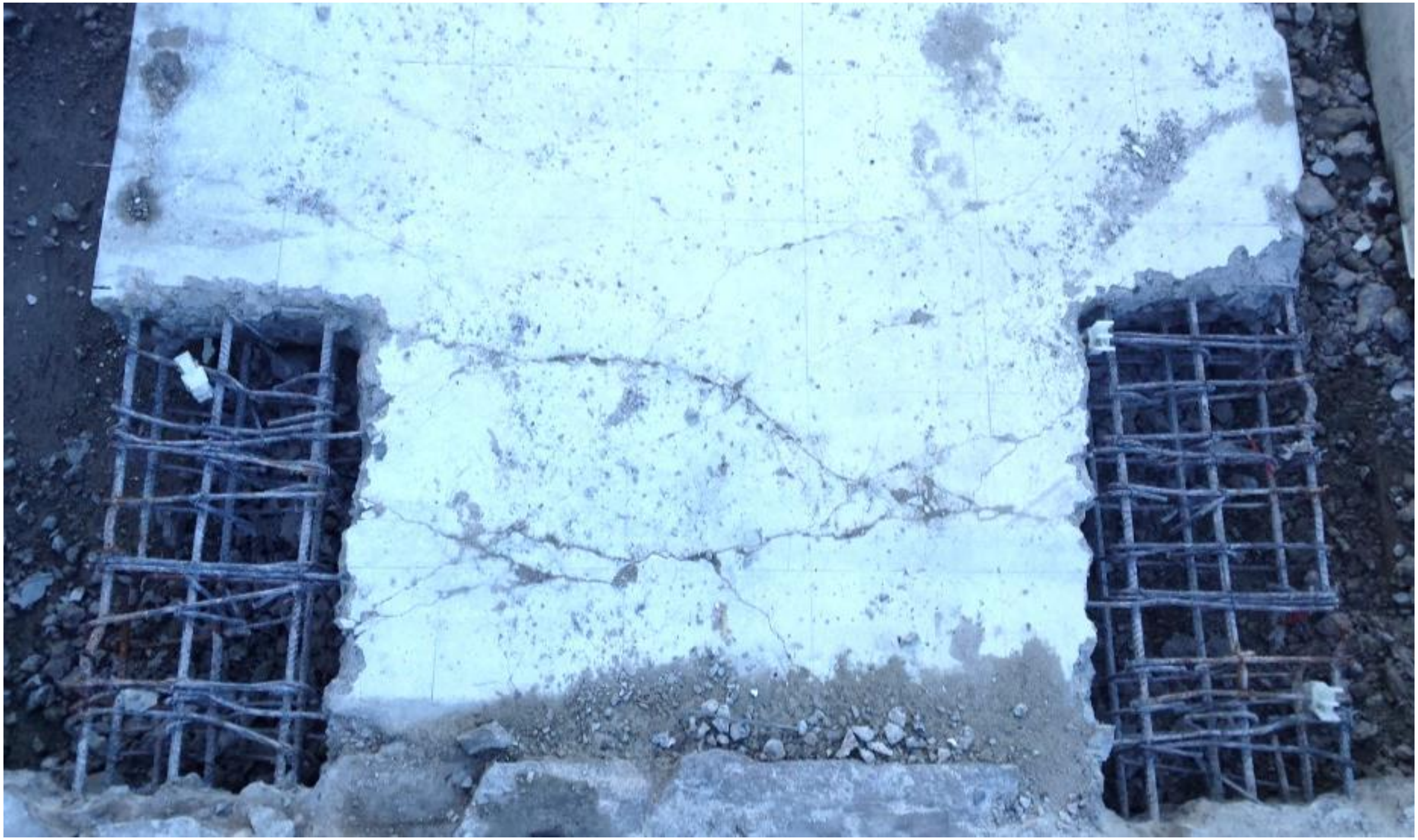
Reinstatement of New Reinforcement

Repair Procedures: M5-R

Reinstatement of New Mortar

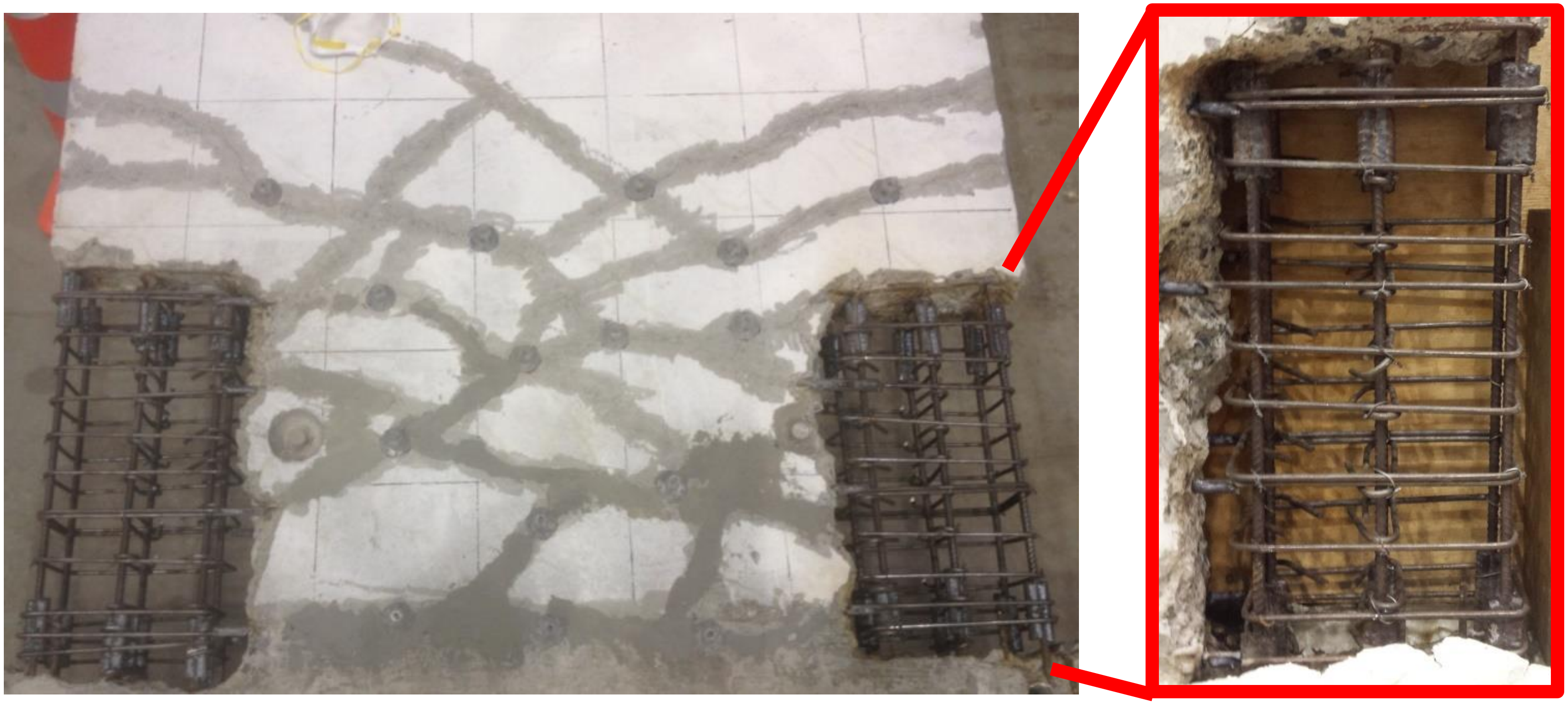
(repair mortar – tested at 35-MPa on test day)

Repair Procedures: M6-R



Removal of Concrete
(Jackhammer)

Repair Procedures for M6-R



Reinstatement of reinforcement &
Preparation for crack injection

Repair Procedures for M6-R

Reinstatement of New Mortar

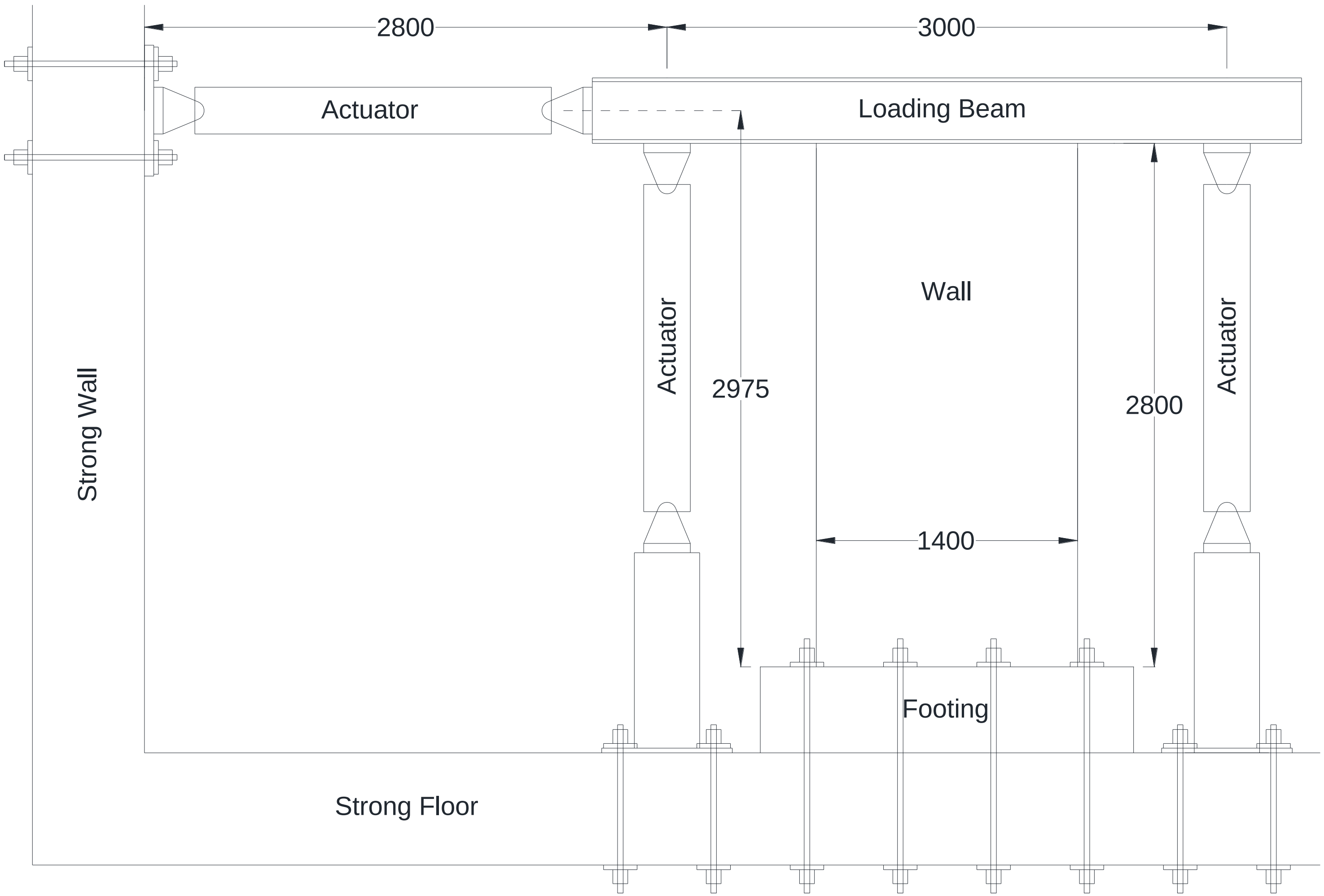
(Sika Monotop repair mortar – tested at 32-MPa on test day)

&

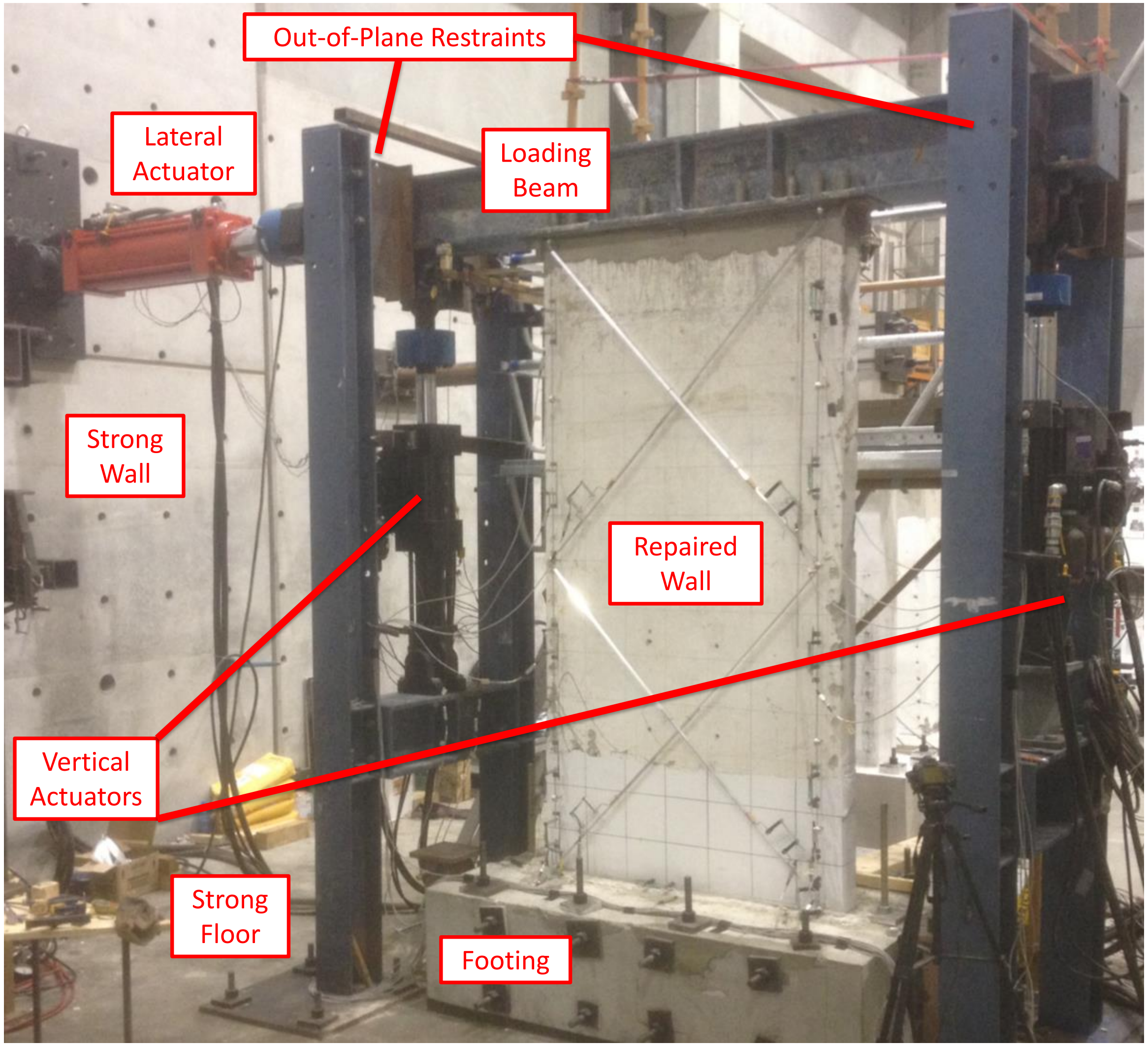
Preparation for crack injection

Testing of Repaired Specimens

Test Set-Up

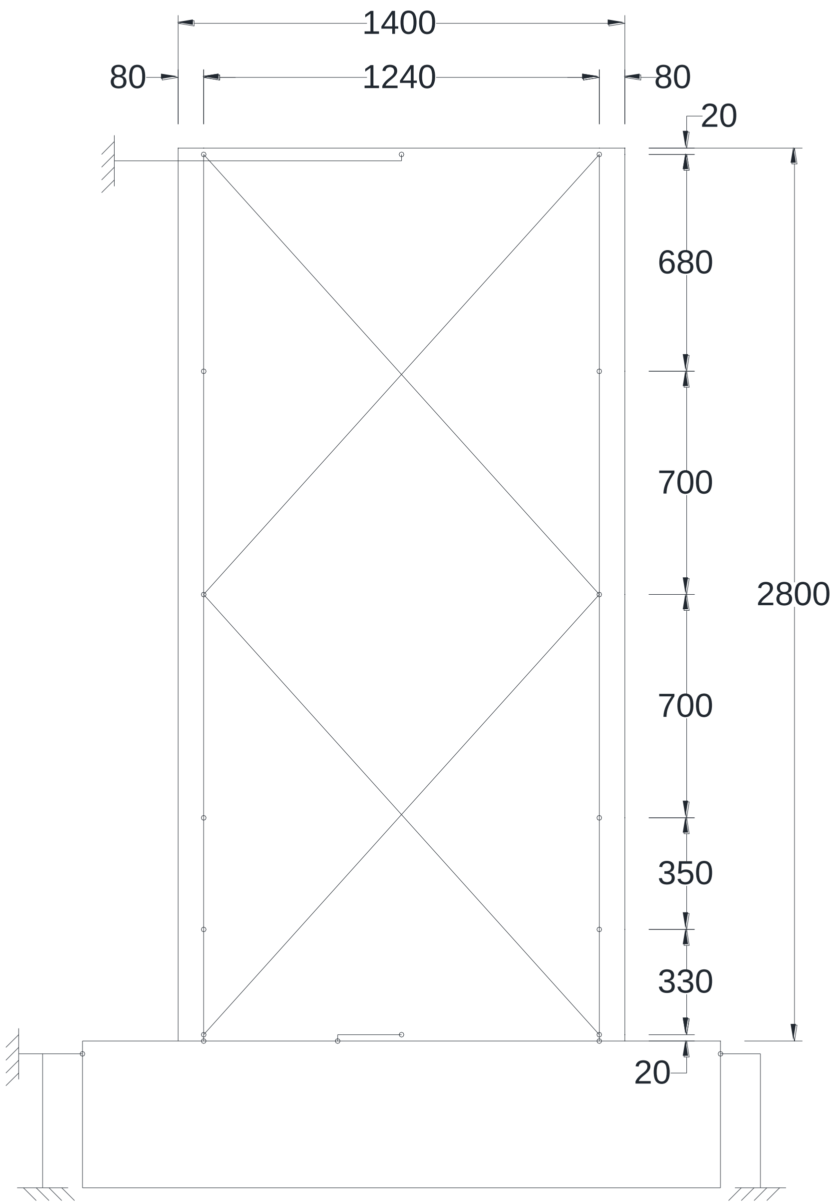

2800
3000
Actuator
Loading Beam
Wall
Actuator
2975
Actuator
2800
Strong Wall
1400
Footing
Strong Floor

Test Set-Up



Out-of-Plane Restraints
Lateral Actuator
Loading Beam
Strong Wall
Repaired Wall
Vertical Actuators
Strong Floor
Footing

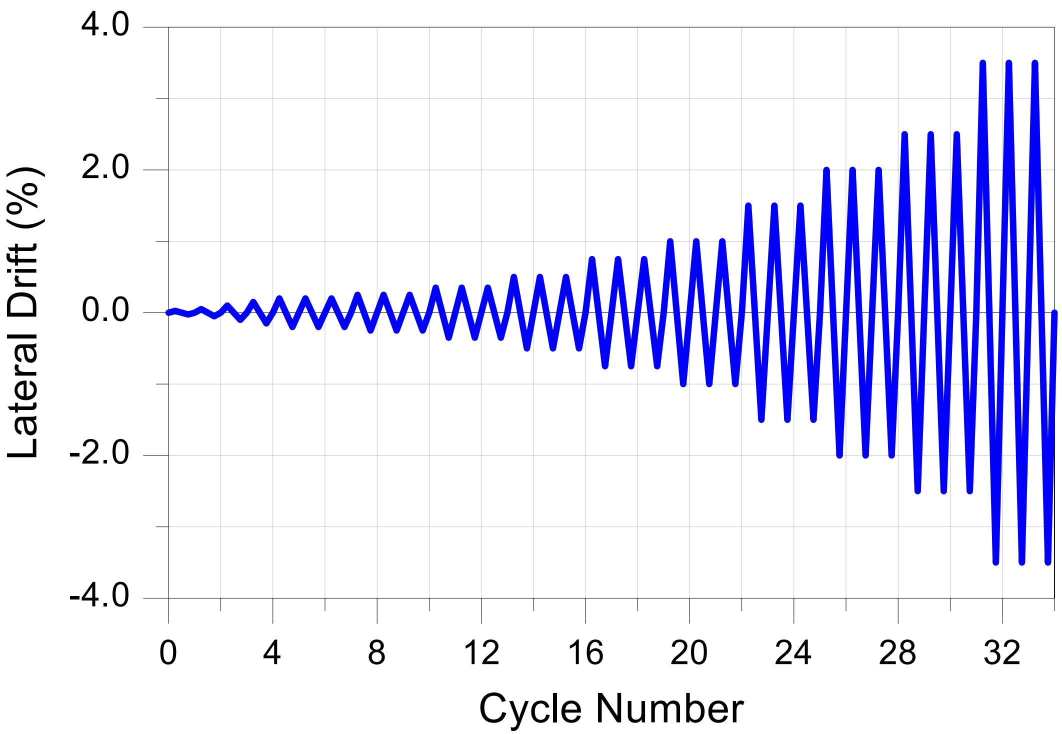
Instrumentation

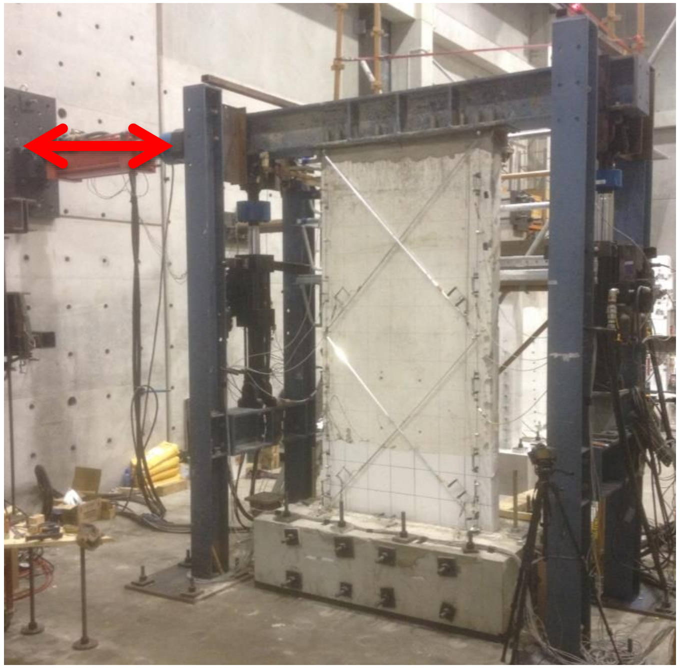


Testing Protocol

- Four force-controlled cycles at roughly 1/16, 1/8, 1/4, 1/2 of V@Mn
- Three displacement-controlled cycles each at:

  0.2%, 0.25%, 0.35%, 0.5%, 0.75%, 1.0%, 1.5%, 2.0%, 2.5%, 3.5%





Test Results

Damage: 1.5% drift, 1st cycle

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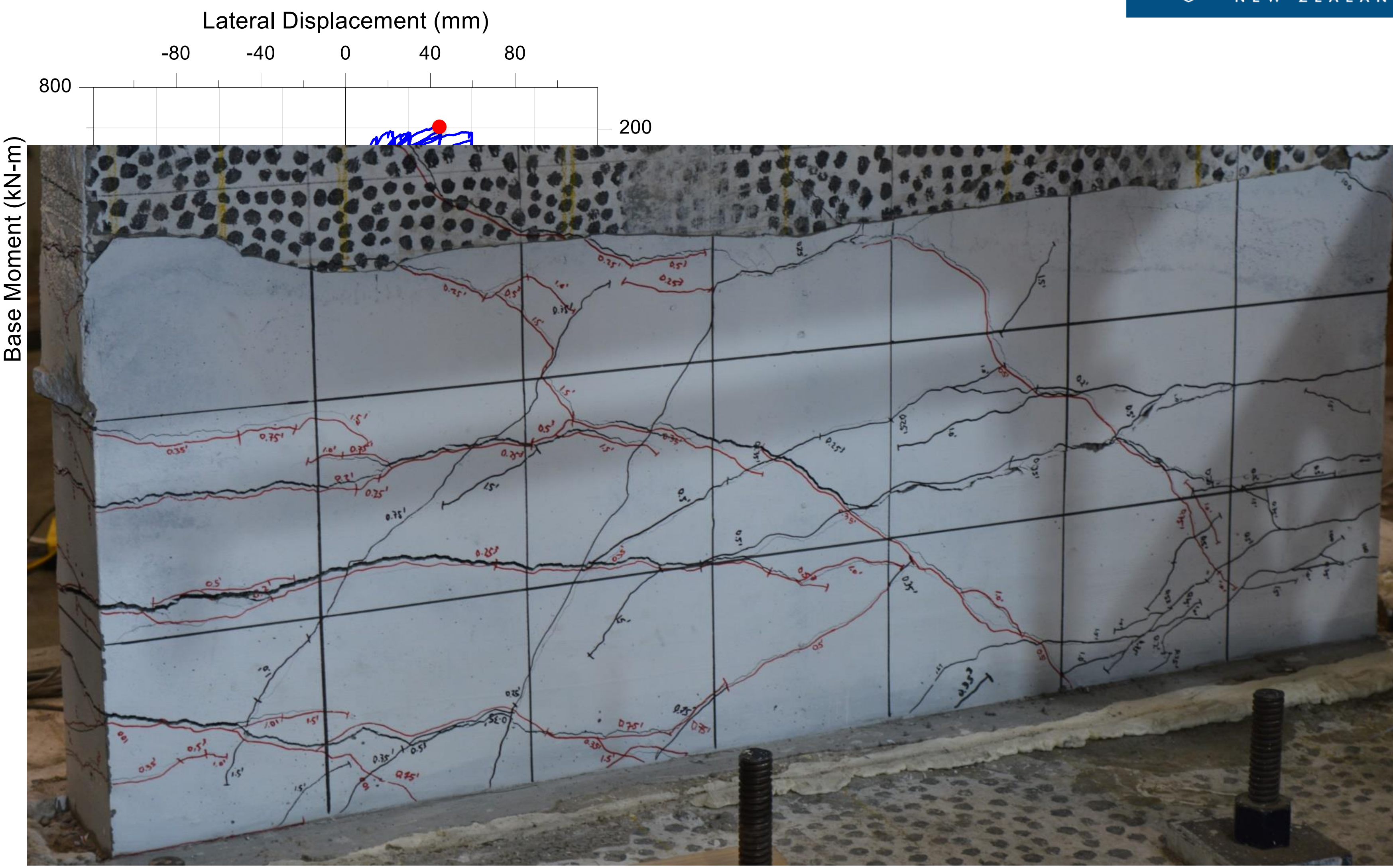

Damage: 2% drift, 1st cycle positive

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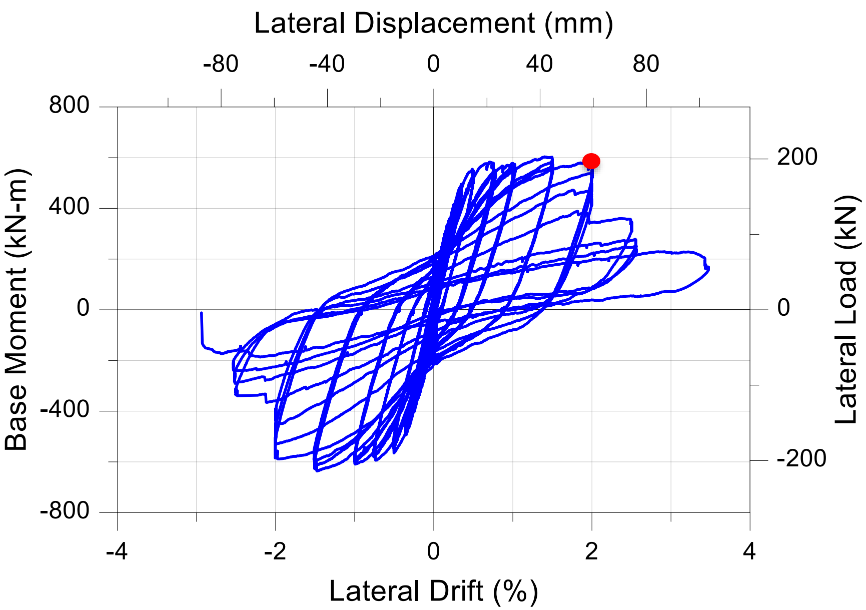

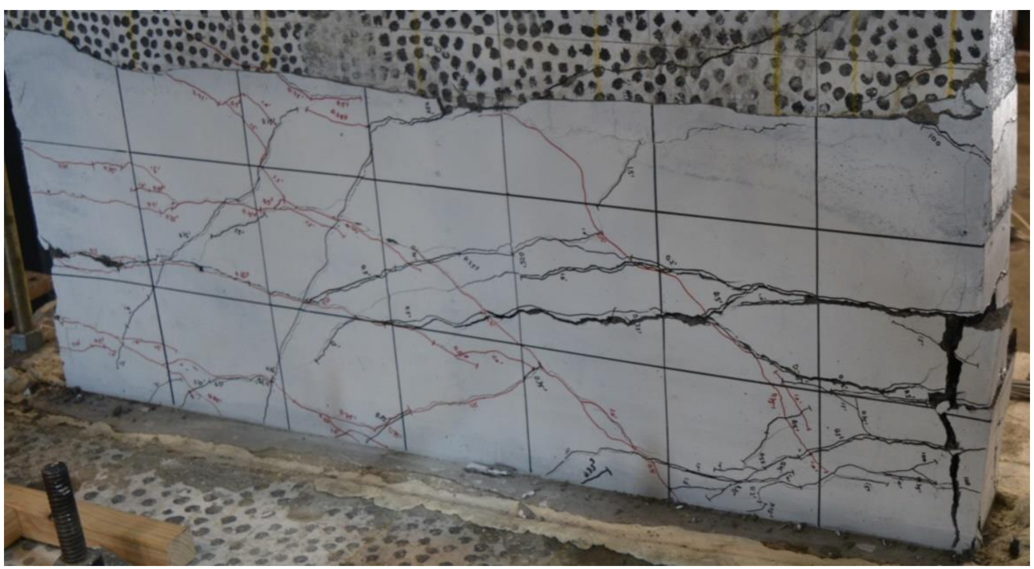

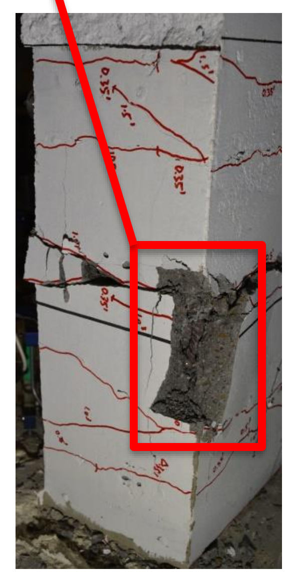

Damage: 2% drift, 1st cycle negative

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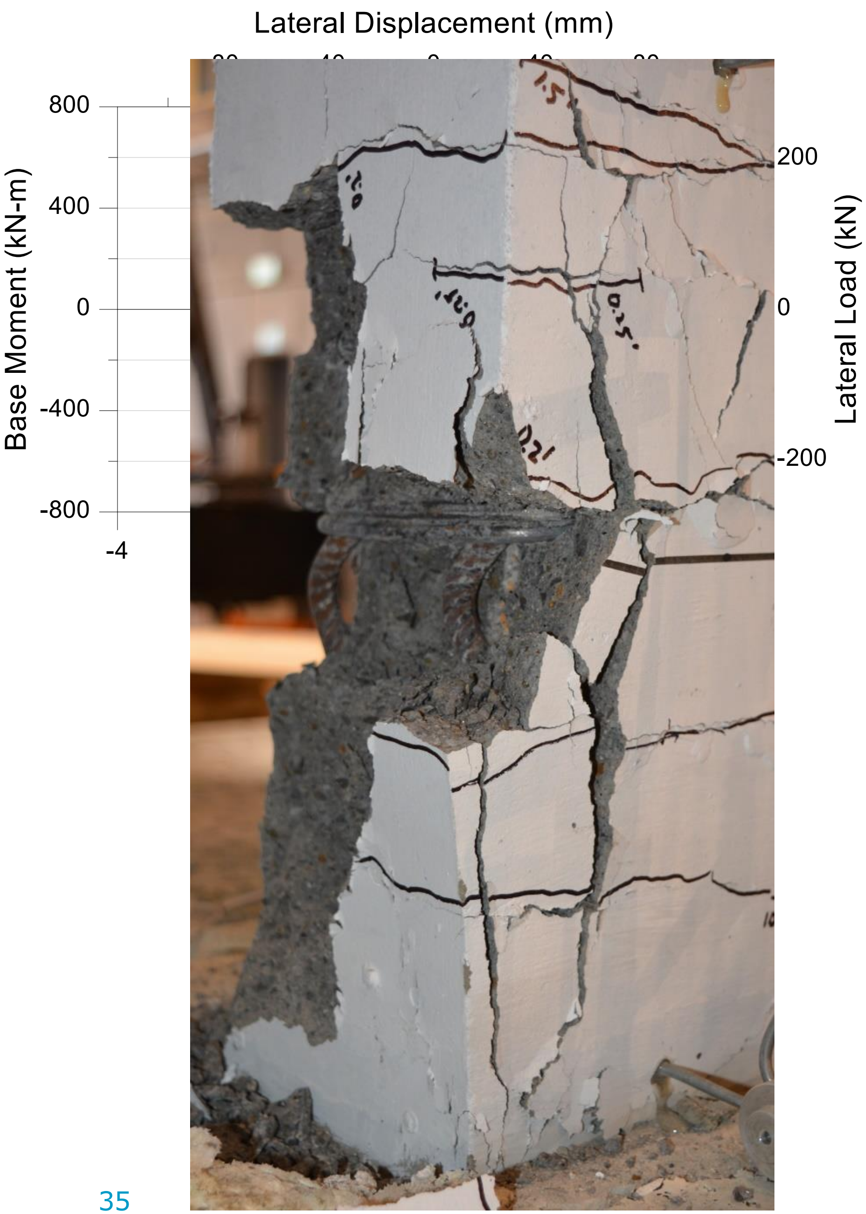
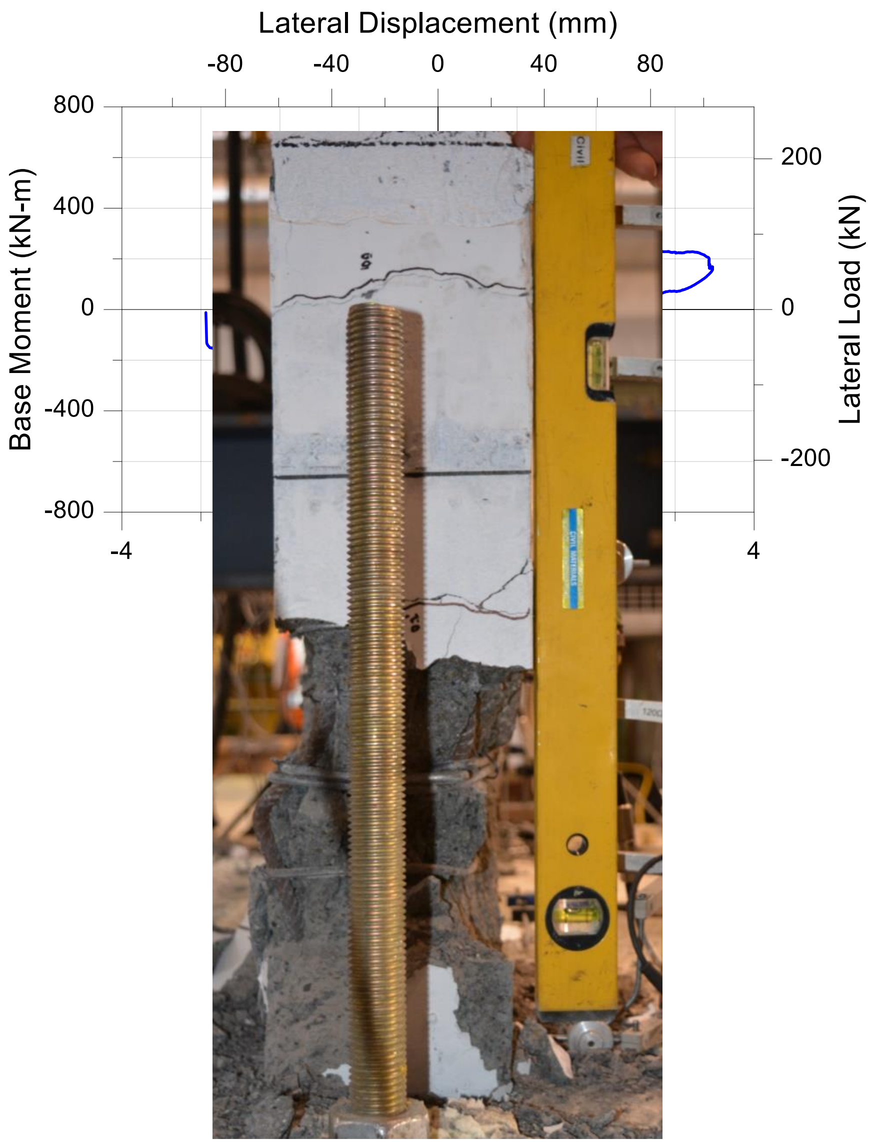
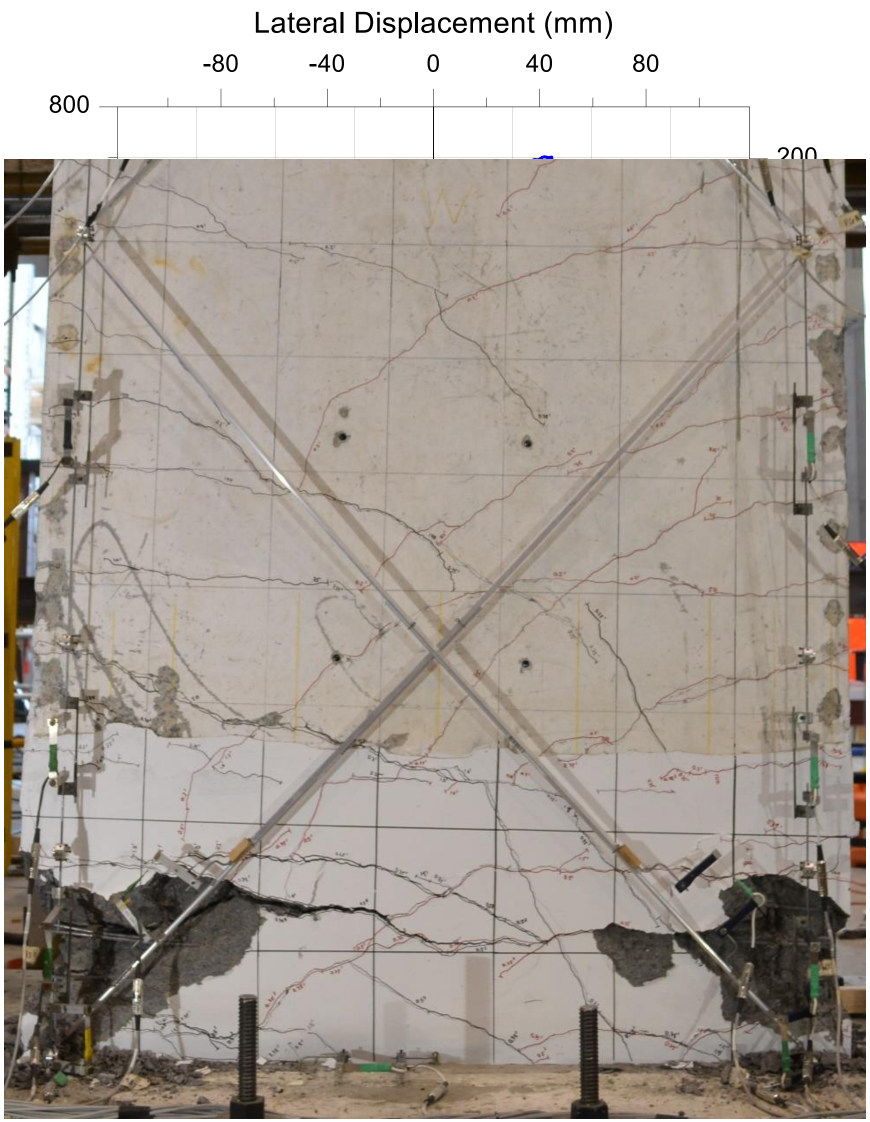


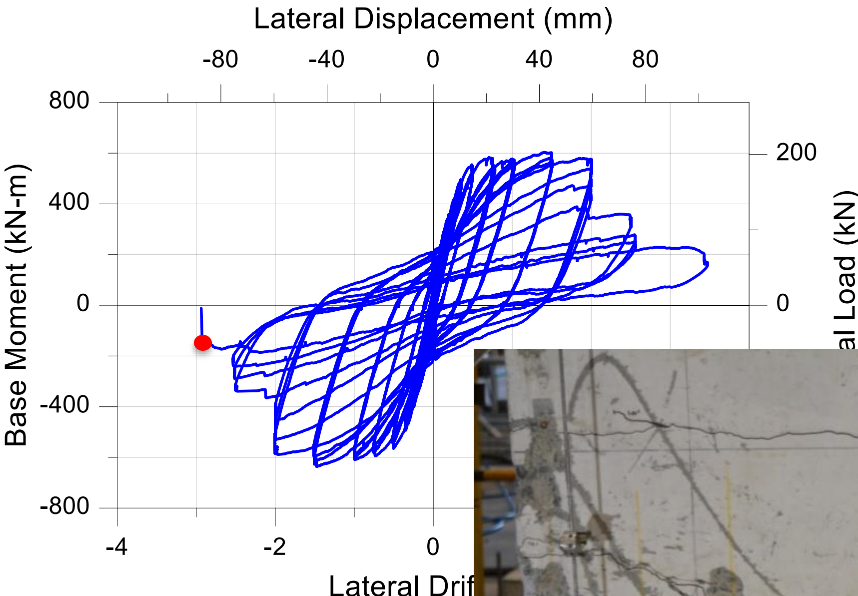
Damage: 2% drift, 3rd cycle negative



Damage: 2.5% drift, 1st cycle positive



Damage: going to 3.5% drift, 1st cycle neg.



Axial failure

Damage Comparison

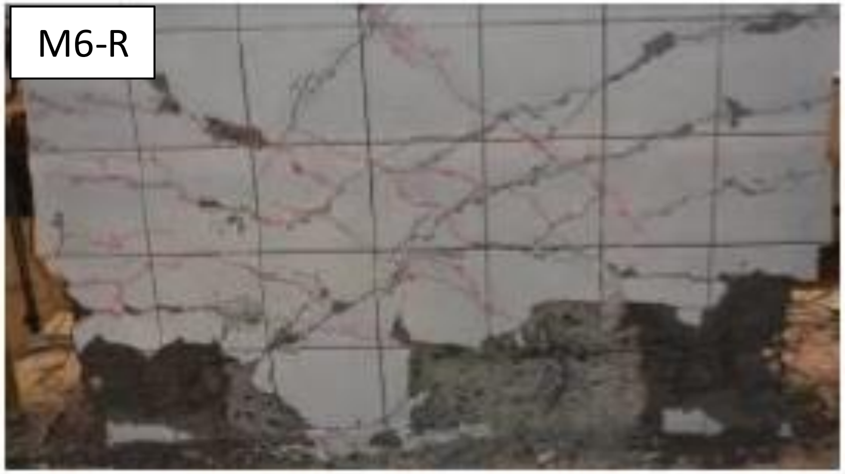
Cycle at which damage state is reached:

Spec.	Dir.	Cracking	Spalling	Reinf. Buckling	Reinf. Fracture
M5	+	0.2% (1st) [1]	2.0% (1st)	2.0% (3rd)	2.0% (3rd)
	-	0.2% (1st) [2]	1.5% (1st)	1.5% (3rd)	2.5% (2nd)
M5-R	+	100 kN (1st)	2.0% (1st)	2.0% (1st)	2.0% (3rd)
	-	100 kN (1st)	2.0% (1st)	2.0% (1st)	2.5% (1st)
M6-R	+	100 kN (1st)	2.0% (1st)	2.0% (1st)	2.5% (1st)
	-	75 kN (1st)	2.0% (1st)	2.0% (1st)	2.5% (1st)

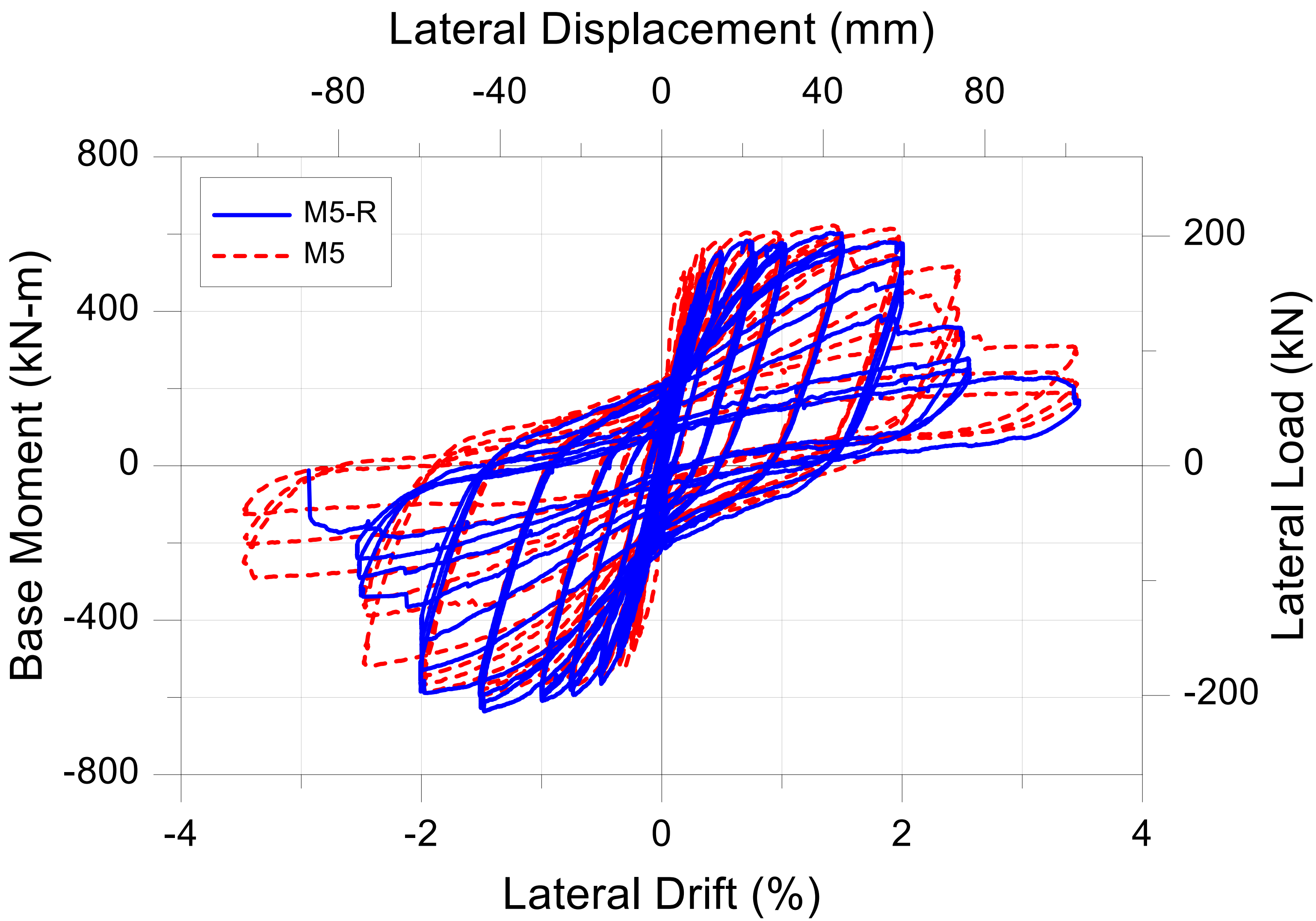
[1] Peak load of +163 kN (+82 kN for previous cycle).

[2] Peak load of -151 kN (-82 kN for previous cycle).

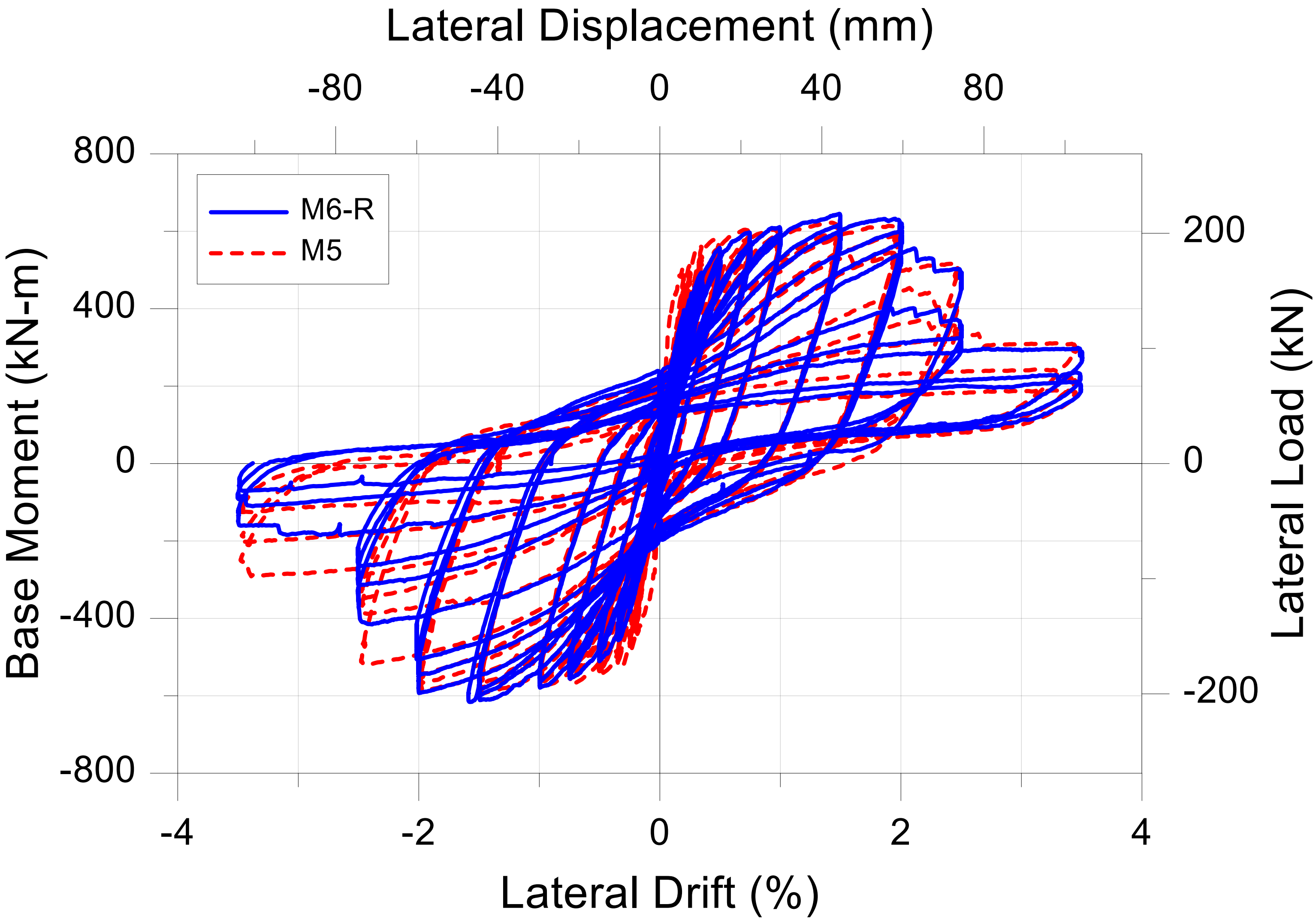
Damage at Completion of Test



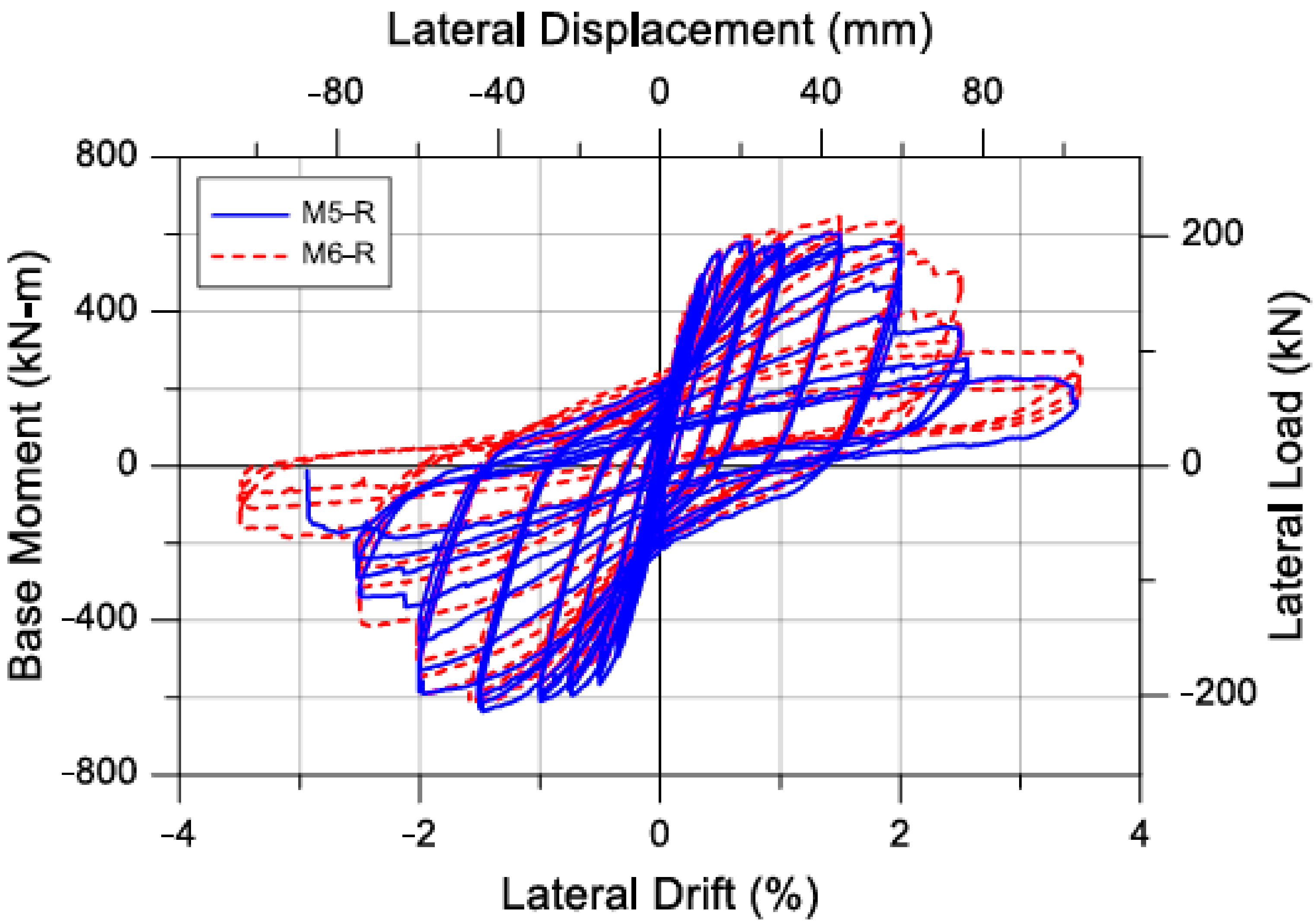
Load-Displacement



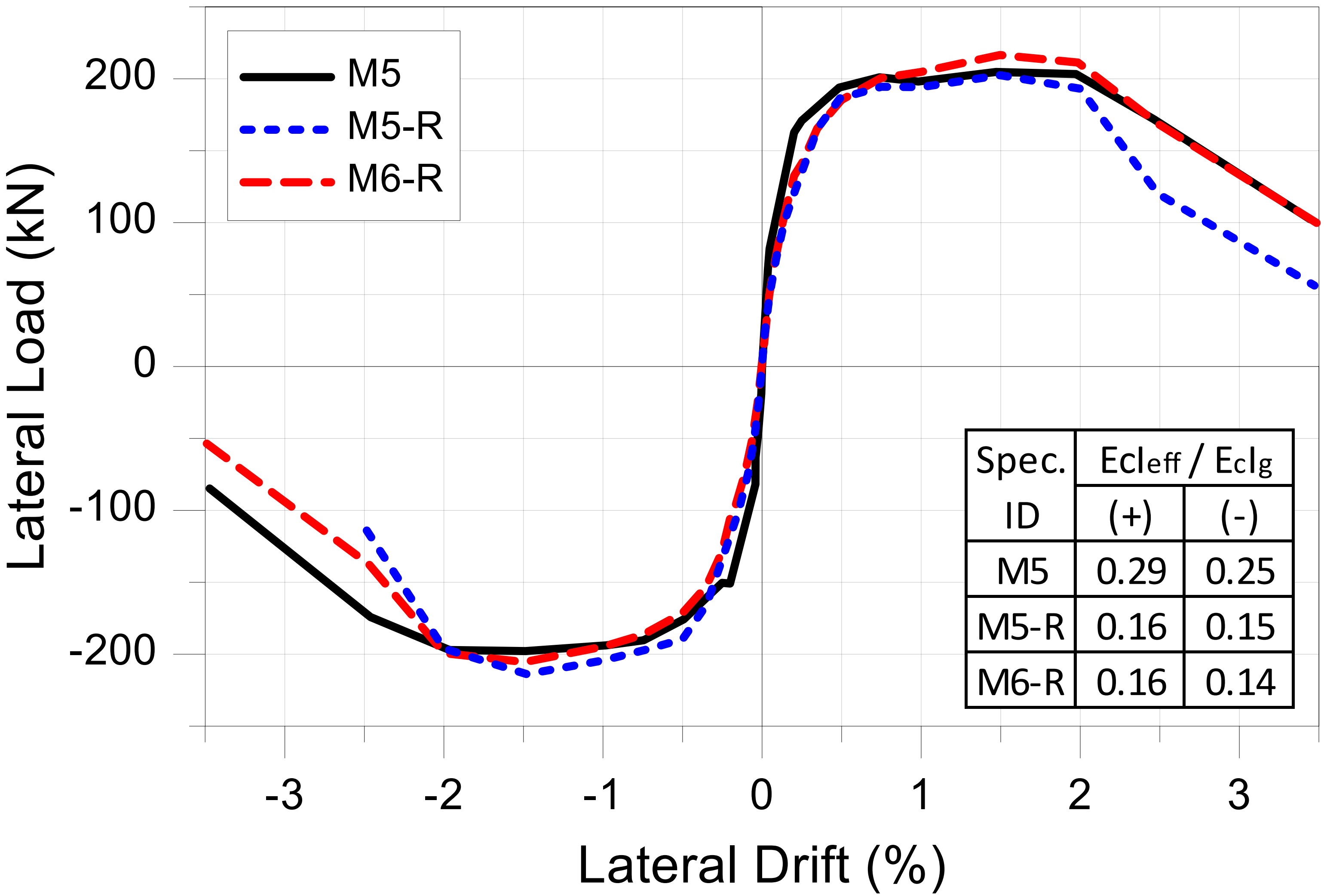
Load-Displacement



Load-Displacement

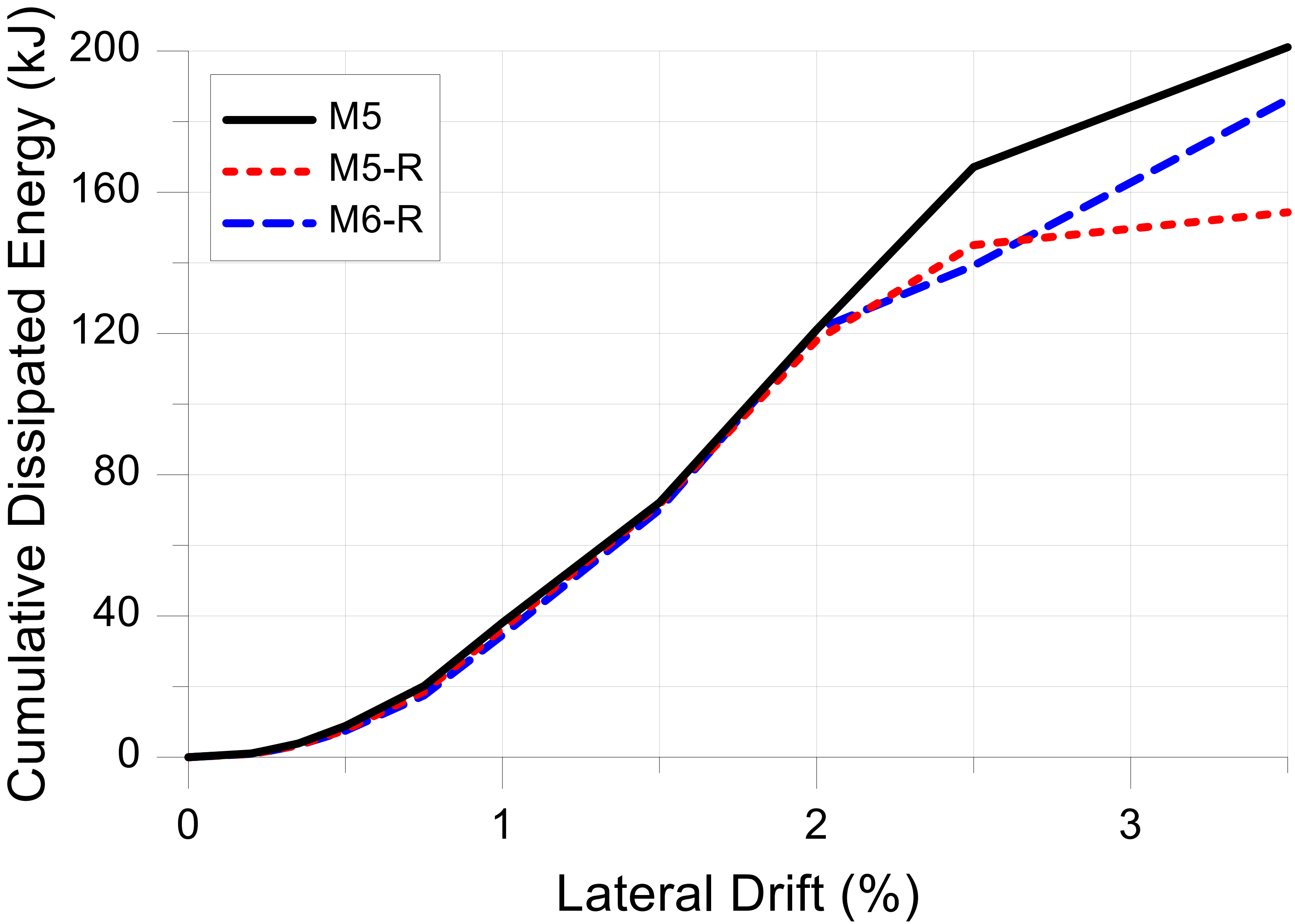


Backbones

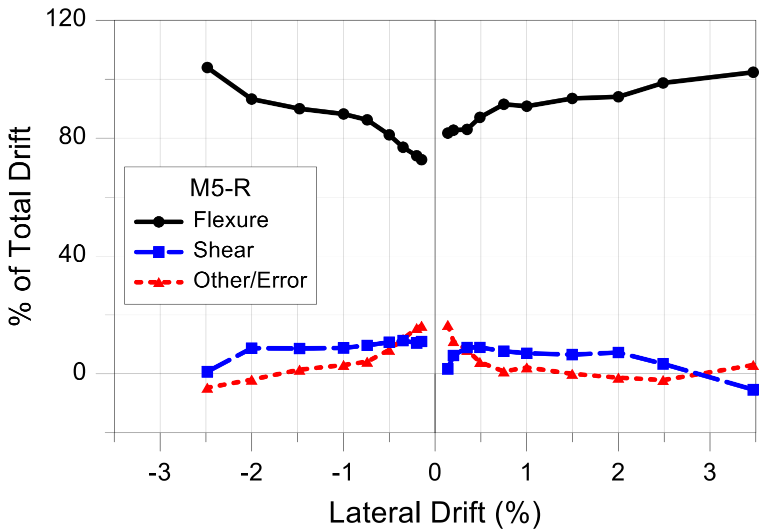


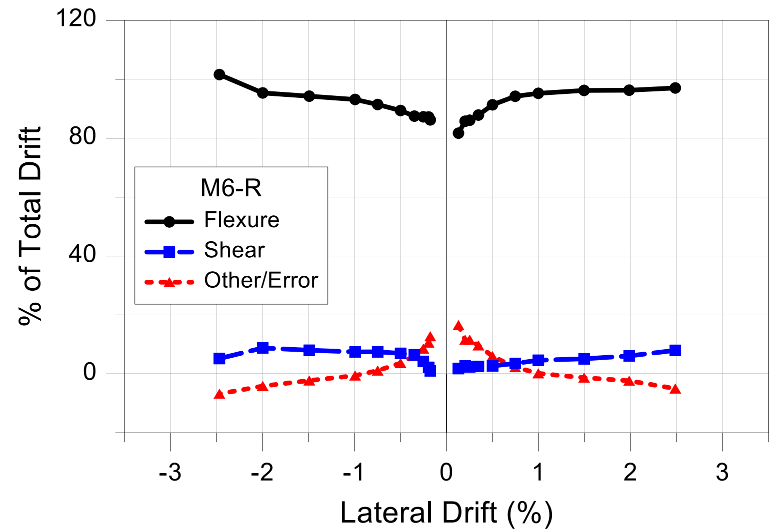
Spec. ID	EcIeff / EcIg (+)	EcIeff / EcIg (-)
M5	0.29	0.25
M5-R	0.16	0.15
M6-R	0.16	0.14

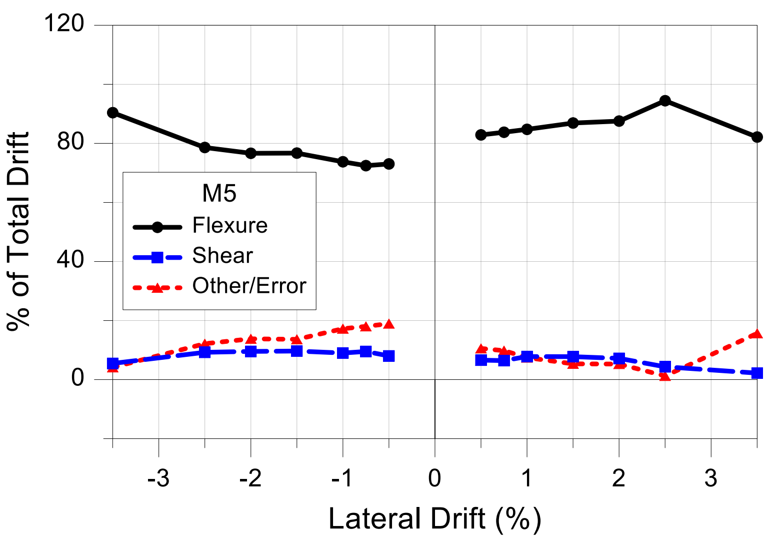
Dissipated Energy

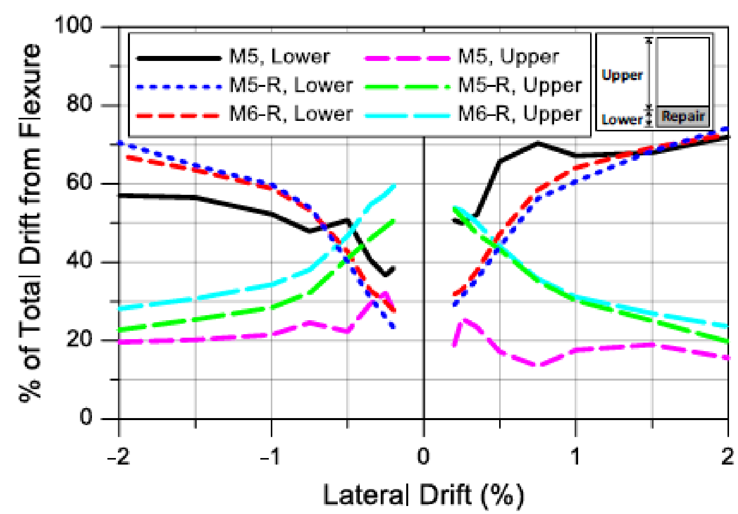


Sources of Deformation

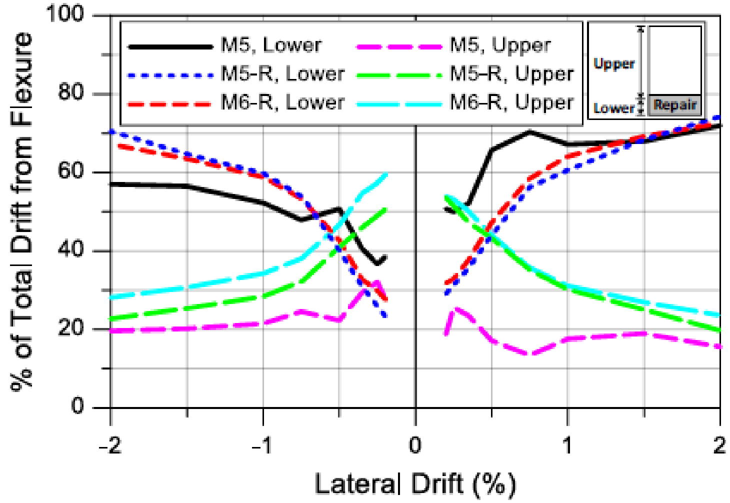


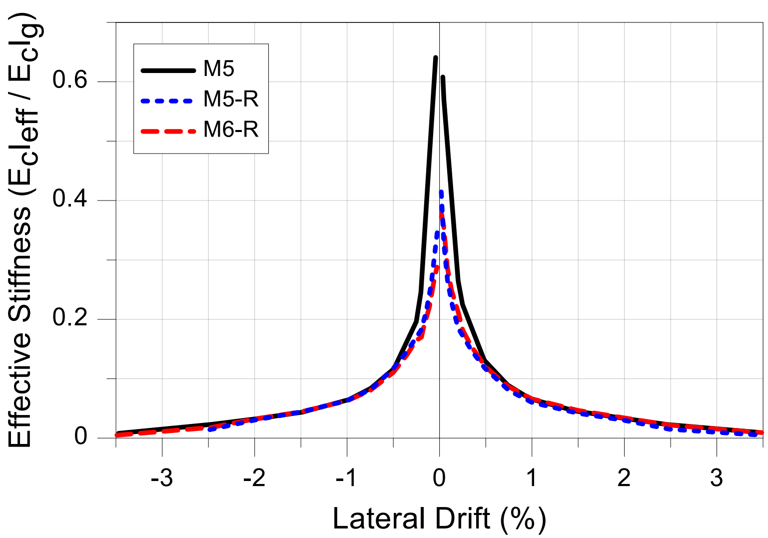


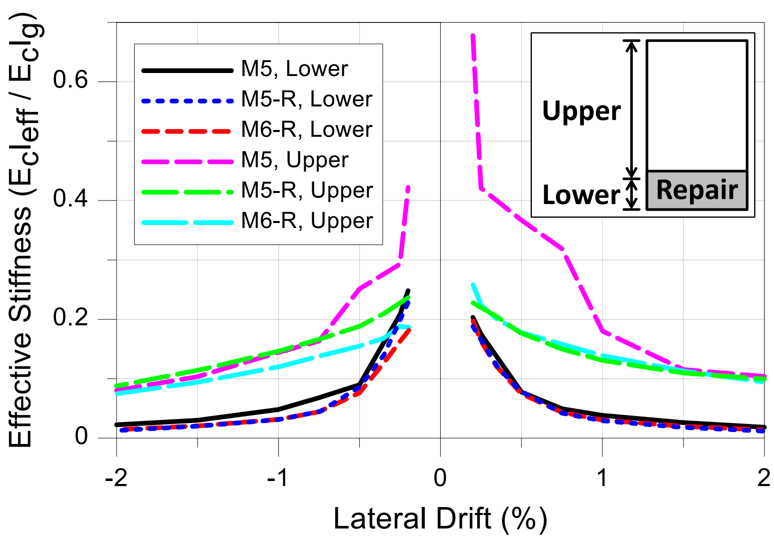




Effective Stiffness







Summary and Conclusions

- Similar performance (load-deformation, dissipated energy, damage) between repaired and original walls through 2.0% drift, with plastic hinge formation at the base of the wall
- Performance restored through indirect butt splice welds of rebar and replacement of damaged concrete with repair mortar
- Repairs based on the level of observed damaged were found appropriate
  - If concrete crushing or rebar buckling or fracture is observed at wall end regions, recommend replacing rebar and concrete along full wall length over height of yielding
  - If spalling of concrete is not observed in the web, repairs in the web may be limited to epoxy injection of cracks

Summary and Conclusions

- Flexural deformation accounted for >80% of elastic deformation
- Effective elastic stiffness roughly 0.15EcIg, which was 33-50% lower than that of the original wall
- Stiffness restored in regions where concrete and reinforcement were repaired but not in unrepaired regions
- Effective elastic stiffness in repaired regions ~50% of that used for the original wall was appropriate in unrepaired regions, with full stiffness value used in repaired regions (led to 41% overall stiffness reduction for tested walls)

Research Objective Revisited

Is it feasible to repair and restore performance in heavily-damaged RC elements (e.g., walls)?

Repair of RC wall in 11-story building in Vina del Mar after Maule, Chile (2010) Earthquake (photo courtesy of Jorge Carvallo)

Repair of RC wall in 18-story building in Santiago after Maule, Chile (2010) Earthquake (Sherstobitoff et al, 2012)

Acknowledgements

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Thank You

Questions?