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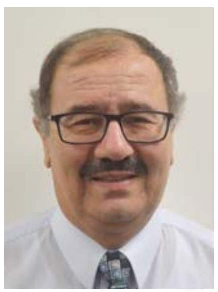

MPC-526 Seismic Repair of Concrete Wall Piers Using CFRP Active Confinement

Presented by:
Chris P. Pantelides, **Ph.D., P.E., S.E., Ph. D.**

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Seismic Repair of Concrete Wall Piers Using CFRP Active Confinement

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Department of Civil and Environmental Engineering

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Outline

- Concrete Wall Pier Overview
- As-Built Concrete Wall Pier (Test 1)
- Modern Code Compliant Concrete Wall Pier (Test 2)
- Retrofit of As-Built Concrete Wall Pier 1 – CFRP Vertical Anchors (Test 3)
- Retrofit of As-Built Concrete Wall Pier 2 – CFRP NSM Bars (Test 4)
- Repair of As-Built Concrete Wall Pier – Mild Steel Vertical NSM Bars (Test 5 = Repair of Test 1 Specimen)
- Repair of Modern Code Compliant Concrete Wall Pier – Headed Steel Bars & CFRP Shell with Concrete Grout (Test 6 = Repair of Test 2 Specimen)
- Conclusions

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Concrete Wall Piers

Bridge built with Concrete Wall Piers in Utah

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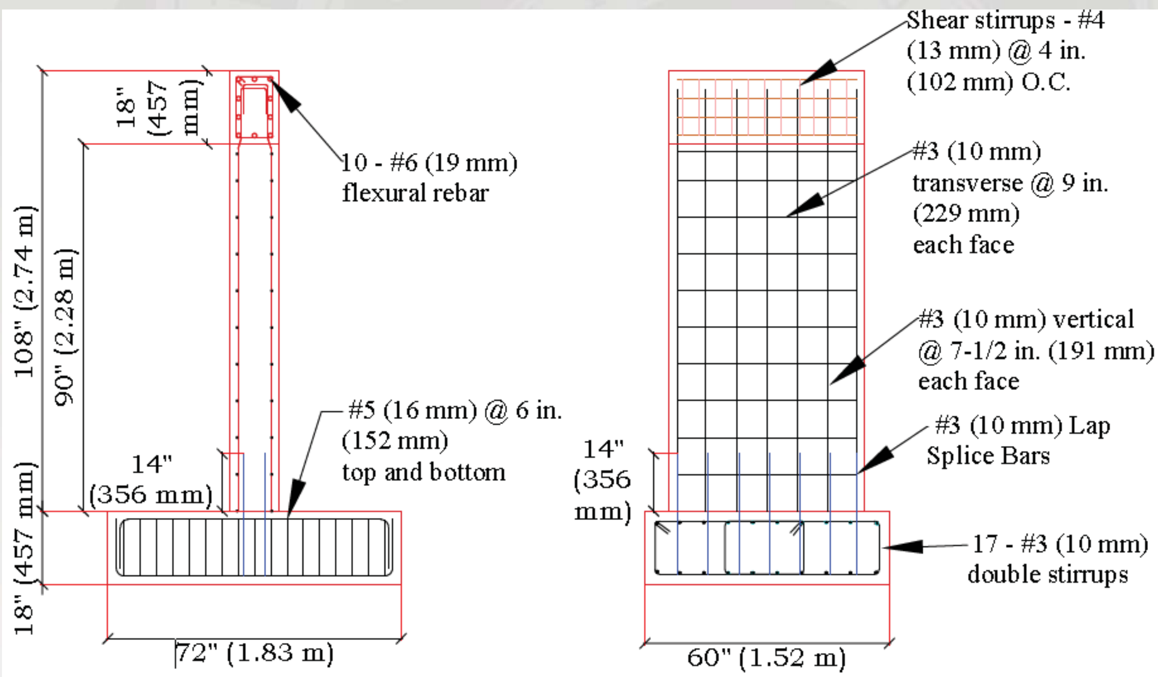
Concrete Wall Pier Deficiencies

- Constructed prior to AASHTO Bridge Design Code in 1970's
- Designed to support gravity loads
- Not design for seismic loads

Test 1: As-Built Concrete Wall Pier

As-Built Concrete Wall Pier

Deficiencies



- Steel Reinforcing Ratio
- Lap-Splices of Longitudinal Reinforcement
- Seismic Hooks
- Plastic Hinge Confinement
- Bar Spacing

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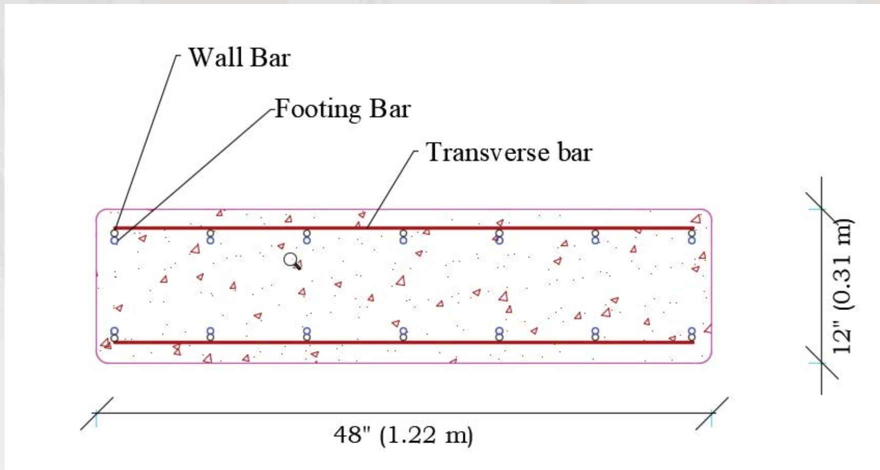
As-Built Wall Pier



As-built (AB) specimen dimensions and steel reinforcement: cross sectional details at lap splice region

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As-Built Wall Pier

- Half-scale specimen of actual wall pier

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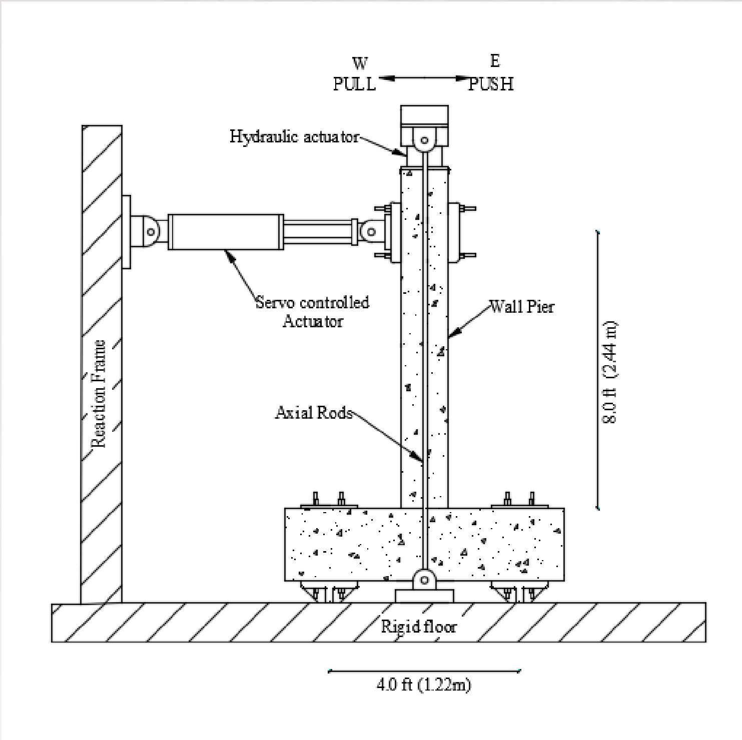
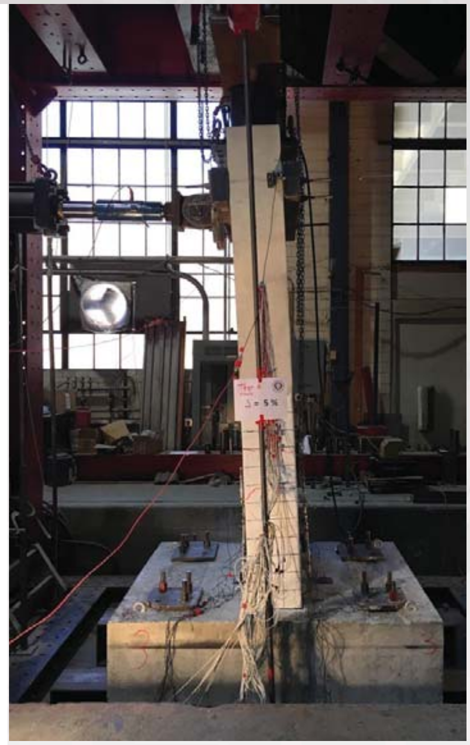
Test Set-Up





- Quasi-Static Cyclic Testing

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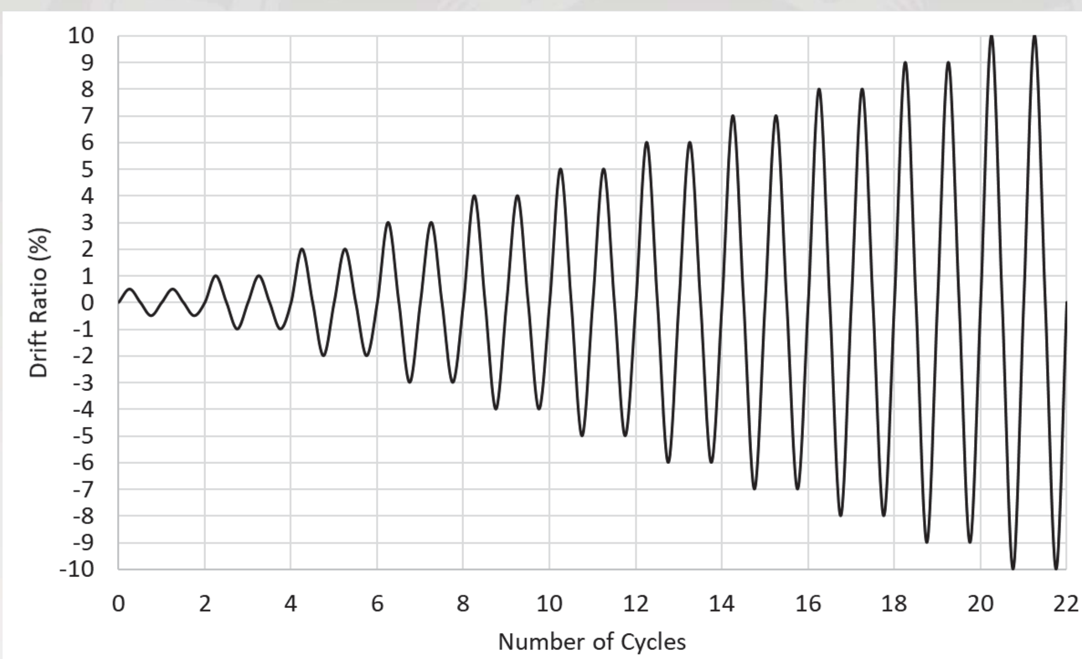
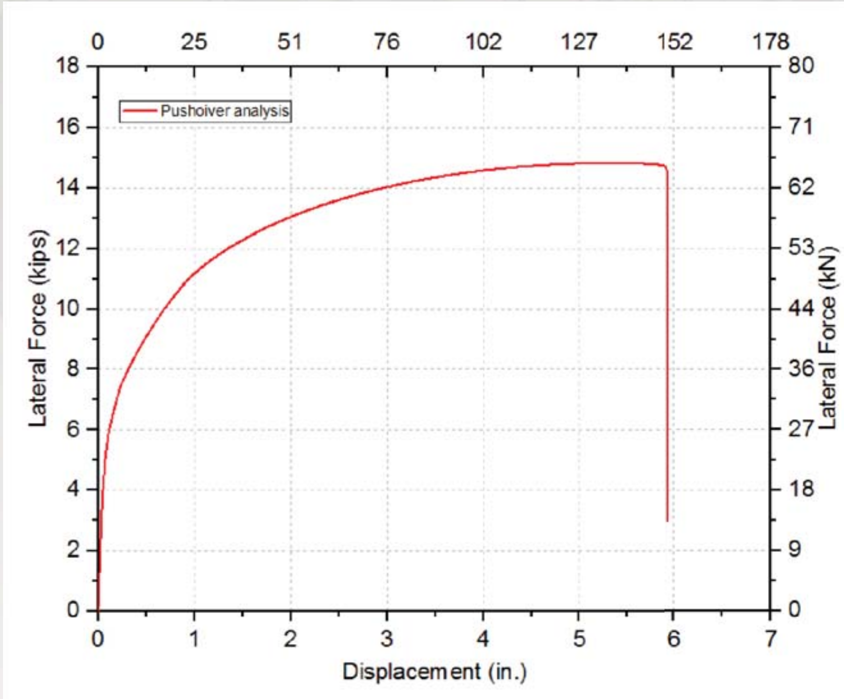
Cyclic Loading



- Displacement Based Loading Protocol

Static Pushover Analysis



- Static Pushover analysis – To estimate the displacement and load carrying capacity of the seismically deficient structure
- Non linear Fiber model developed in OpenSees

As-Built Wall Results

Failure Mode: Lap-Splices

Spalling at 4% drift of as-built wall pier

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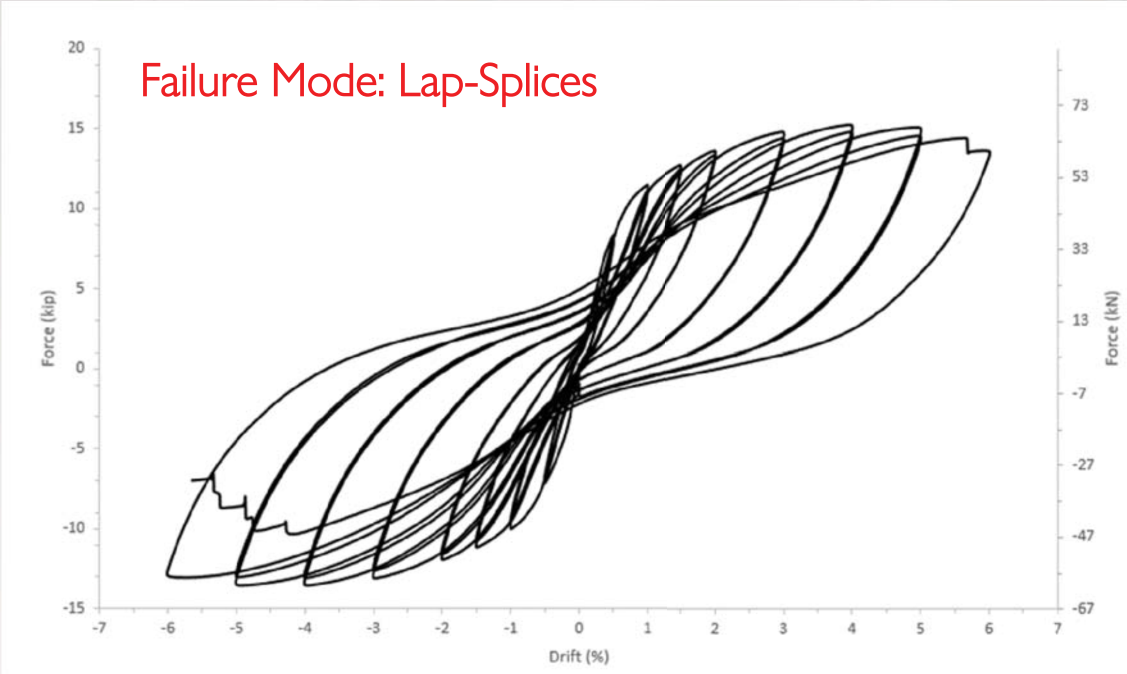
As-Built Wall Results



- Energy: 500 kip-in. (56.5 kN-m)
- Drift: 6.0% (5.76 in. (146.3 mm))

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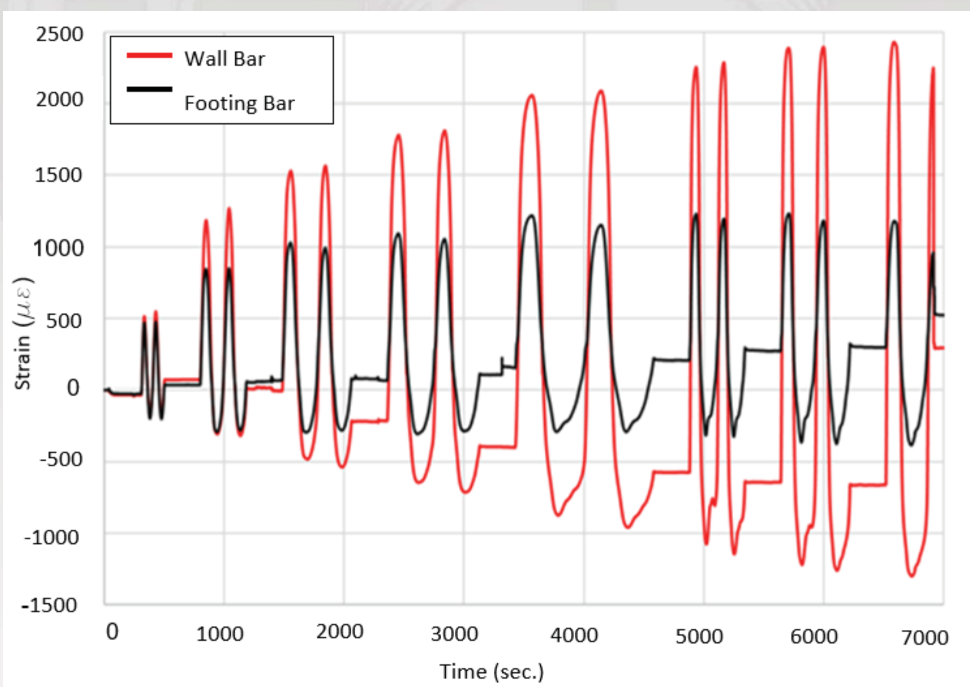
As-Built Wall Results

Failure Mode: Lap-Splices



As-built wall pier strain in lap-spliced bars

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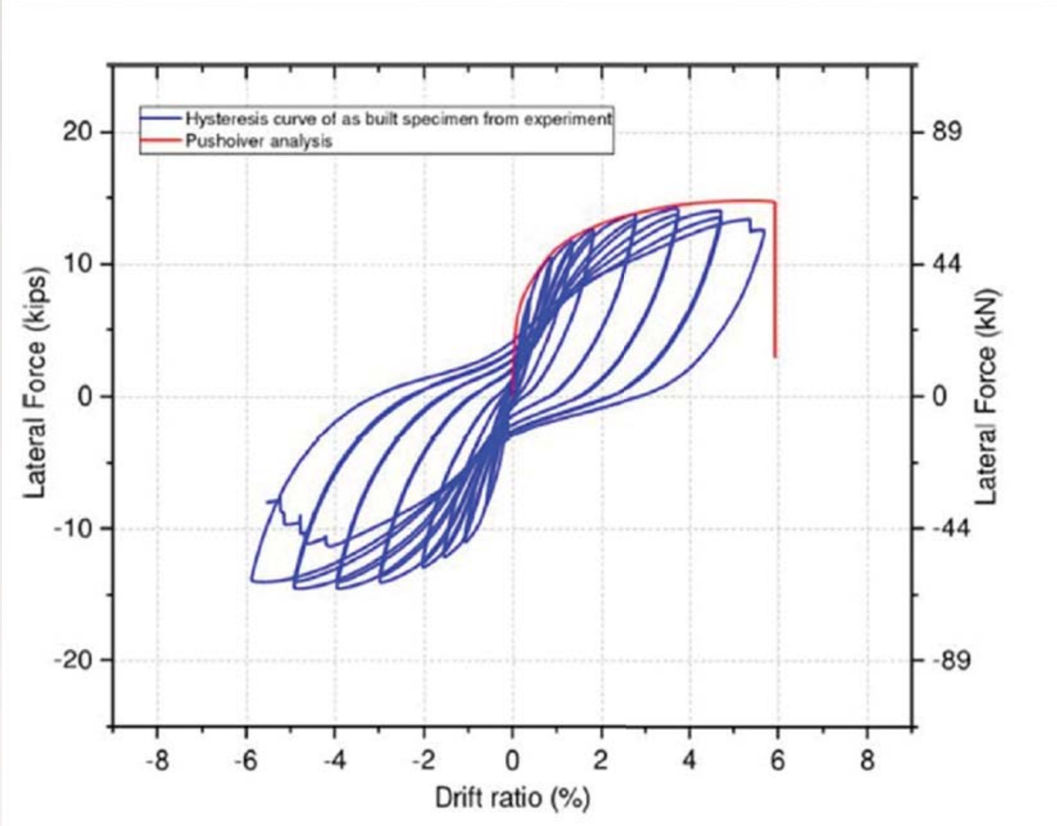
Comparison of Model versus As-Built Wall Pier



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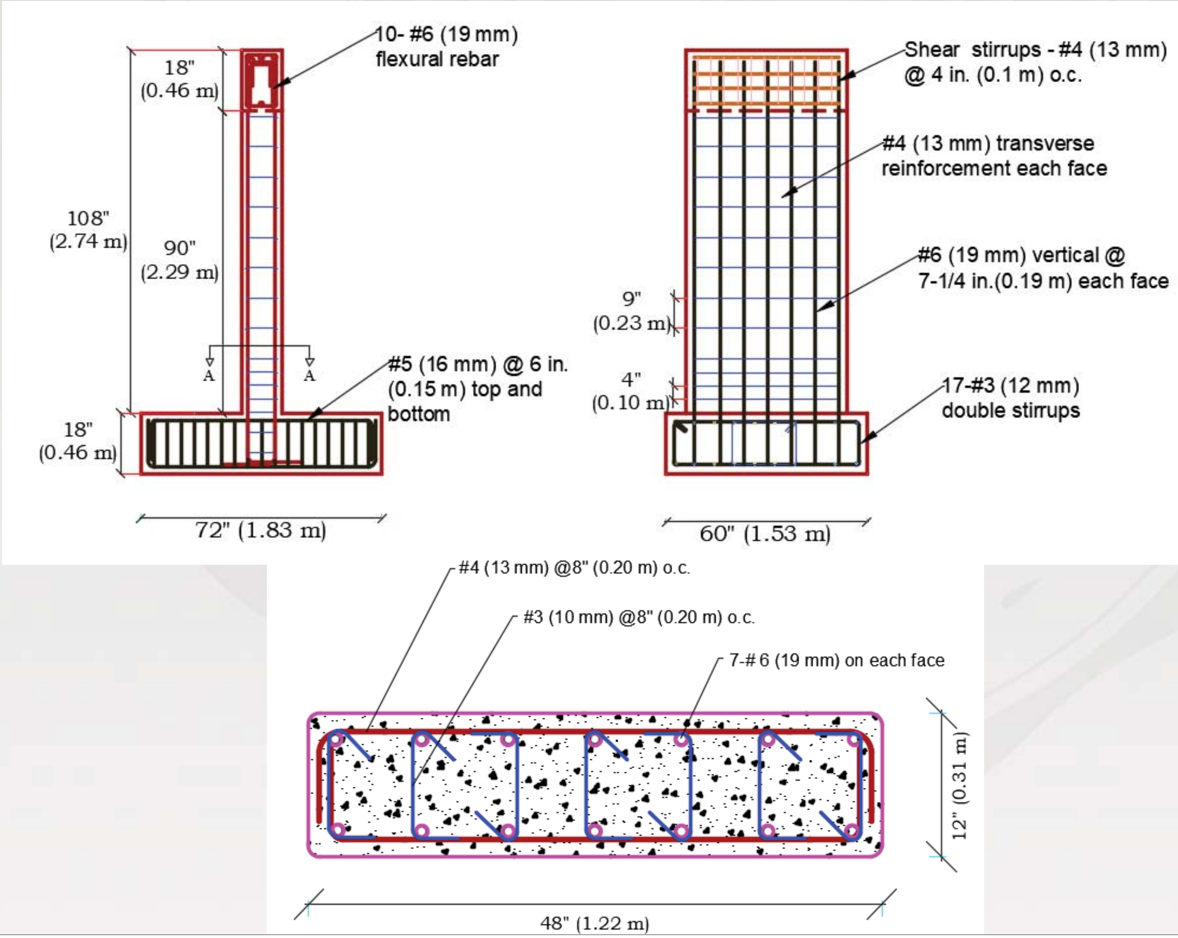
Test 2: Modern Code Compliant Concrete Wall Pier

Modern Code Compliant Wall Pier



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Modern Code Compliant Wall Pier

Modern code compliant wall pier reinforcement

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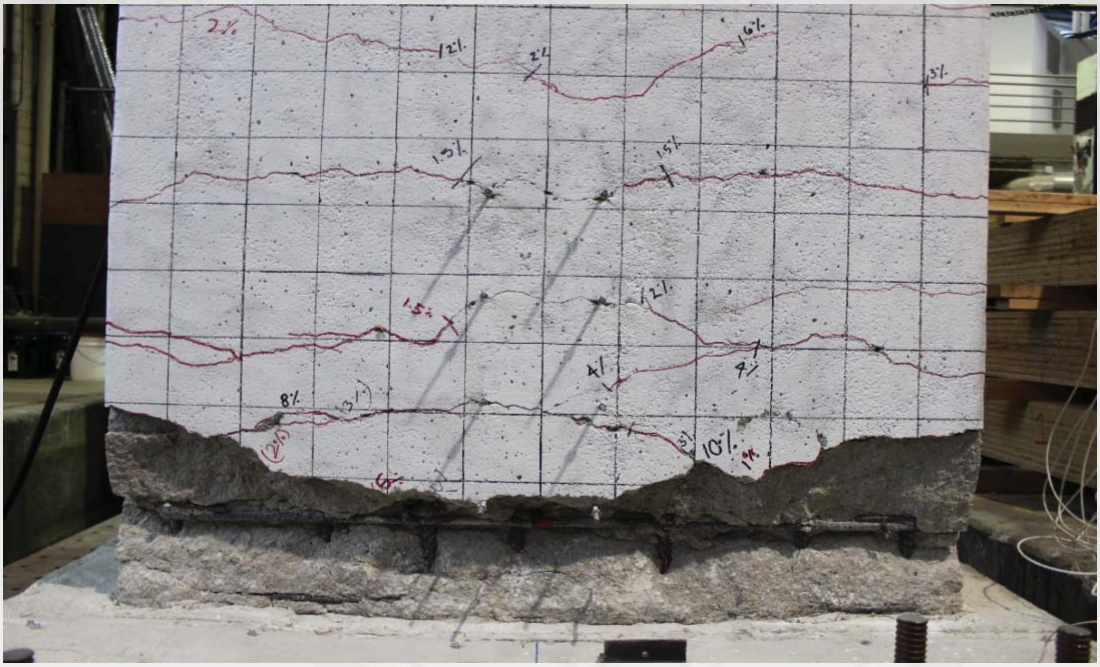
Modern Code Compliant Wall Pier



MCC specimen damage

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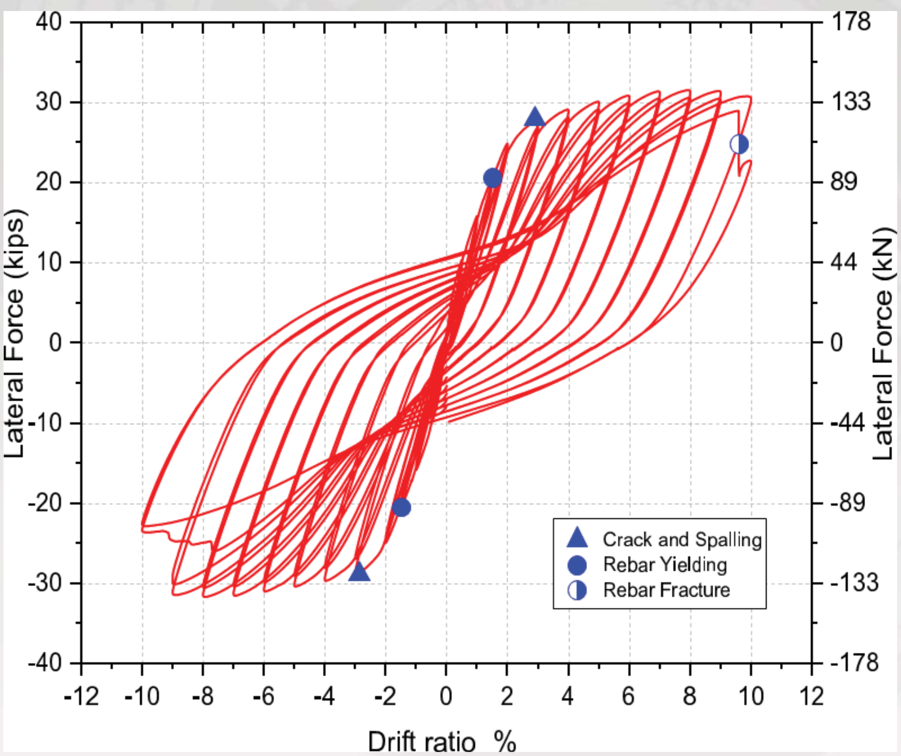
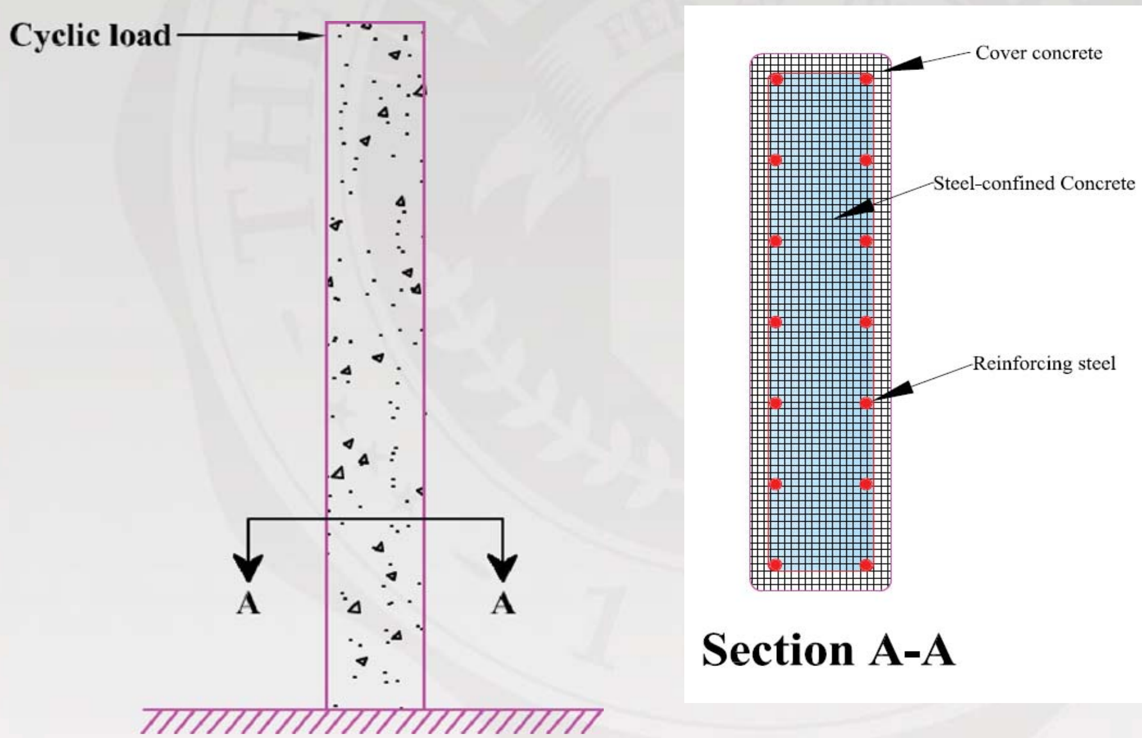
Modern Code Compliant Wall Pier



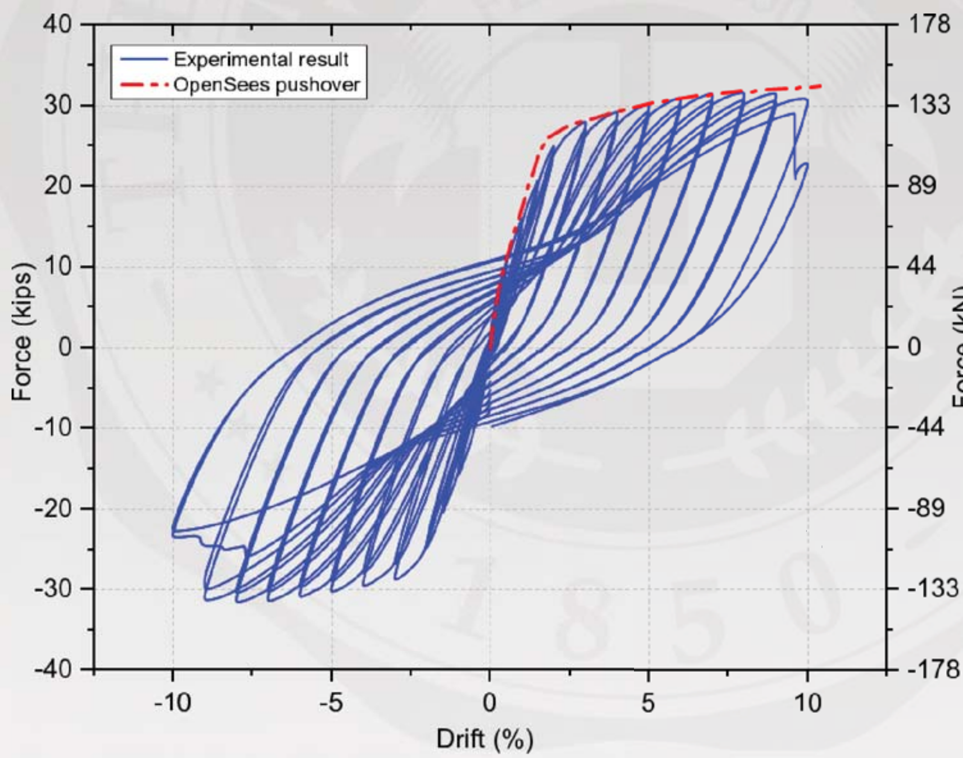
Hysteresis of modern code compliant specimen

Modern Code Compliant Wall Pier



OpenSees fiber model of modern code compliant concrete wall pier

Modern Code Compliant Wall Pier



Comparison of the analytical pushover with experimental results

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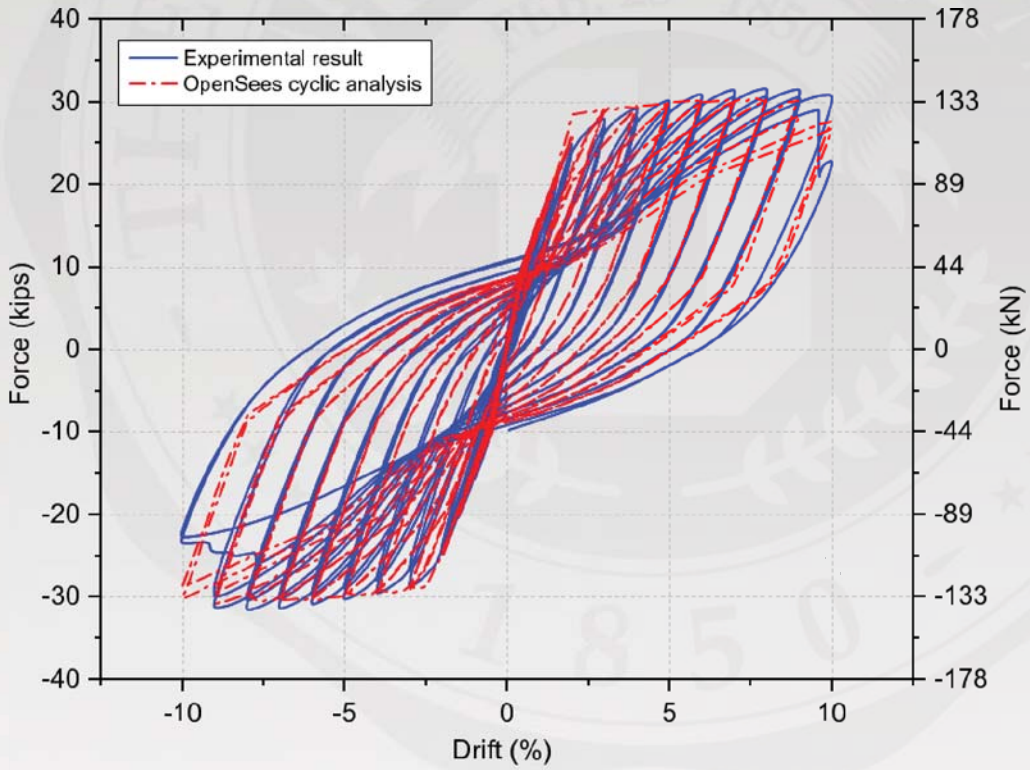
Modern Code Compliant Wall Pier



Hysteresis comparison: OpenSees cyclic load analysis with experimental results

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Retrofit Methods

How do we fix the deficiencies of the As-built Wall Pier before an earthquake occurs?

Carbon Fiber Reinforced Polymers (CFRP)

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Properties of Carbon Fiber Reinforced Polymer (CFRP)

- Light Weight
- Corrosion Free
- Higher Tensile Strength than Steel
- Can be molded to any shape
- Lower modulus of elasticity than steel

CFRP Sheet (Laminate)

CFRP Anchor

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Carbon Fiber Reinforced Polymer Anchors

TABLE 1. CFRP Anchor Properties

Properties	Average Values
Tensile Strength	1,138 MPa (165 ksi)
Tensile Modulus	103 GPa (15 x 10^3 ksi)
Tensile Elongation	1.10%
Diameter	19 mm (0.75 in.)

Carbon Fiber Reinforced Polymer Near Surface Mounted (NSM) Bars

TABLE 2. CFRP NSM Bar Properties

Properties	Average Values
Tensile Strength	2,068 MPa (300 ksi)
Tensile Modulus	131 GPa (19 x 10^3 ksi)
Tensile Elongation	1.58%
Size	12.7 mm (0.50 in.)

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Carbon Fiber Reinforced Polymer Laminate

TABLE 3. CFRP laminate Properties

Properties	Average Values
Tensile Strength	1,240 MPa (180 ksi)
Tensile Modulus	74 GPa (10,700 ksi)
Tensile Elongation	1.7%
Thickness per layer	1.0 mm (0.04 in.)

Test 3: Retrofit of As-Built Concrete Wall Pier 1 – CFRP Vertical Anchors

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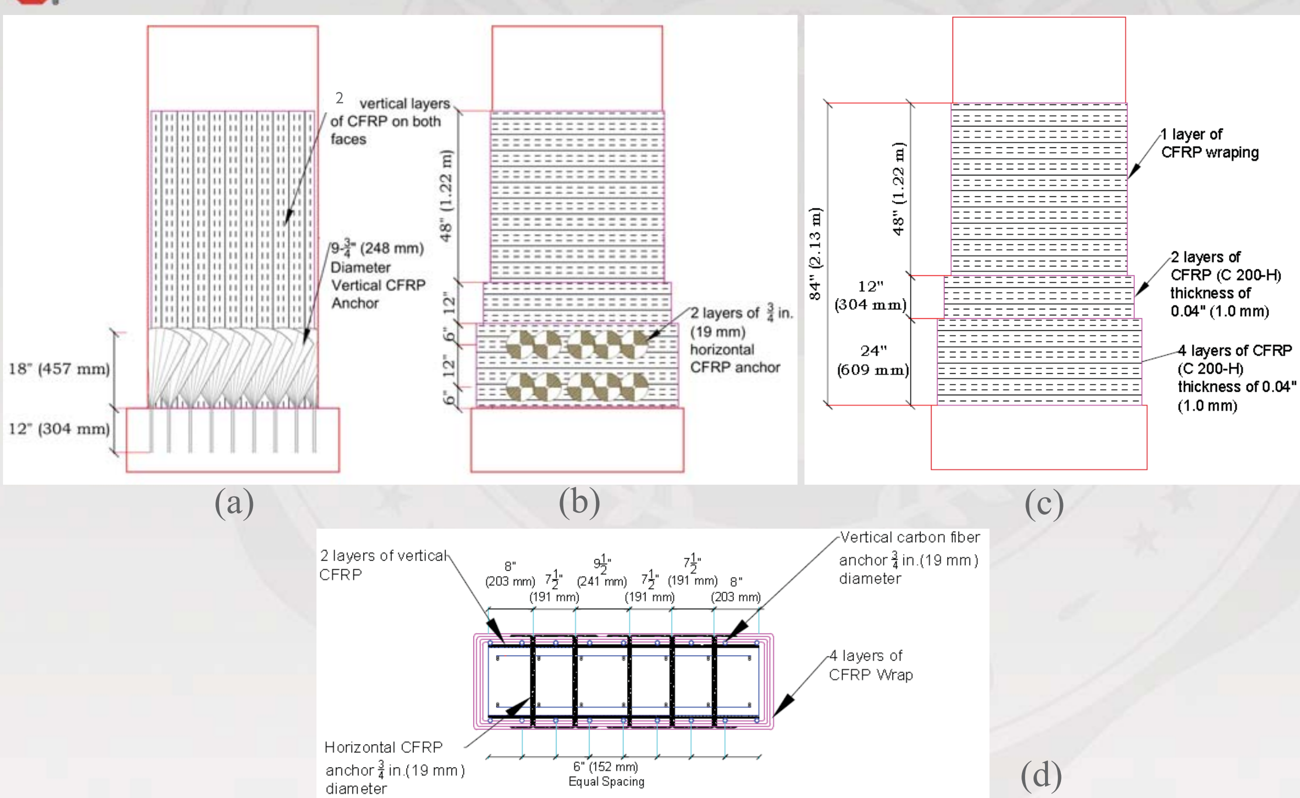

Retrofit design of wall pier *R1*: (a) 18 vertical CFRP sheets and vertical CFRP anchors; (b) 10 transverse (horizontal) CFRP anchors; (c) 4+2+1 hoop direction CFRP jackets; (d) wall cross-section at bottom 24 in.

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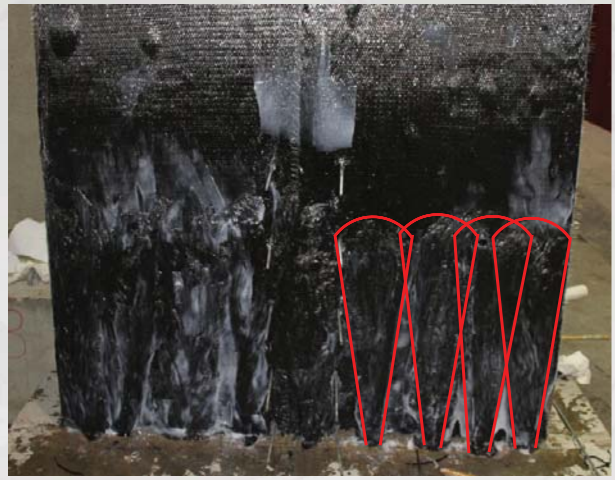
Vertical CFRP Anchors (9 on each face)

- Increase Flexural Resistance
- Create Positive Connection between Footing and Wall Pier



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Transverse (Horizontal) CFRP Anchors (5+5)

- Two rows of 5 CFRP anchors
- Increase Confinement in Plastic Hinge Region
- Increase Clamping Pressure on Lap Spliced Steel Rebar

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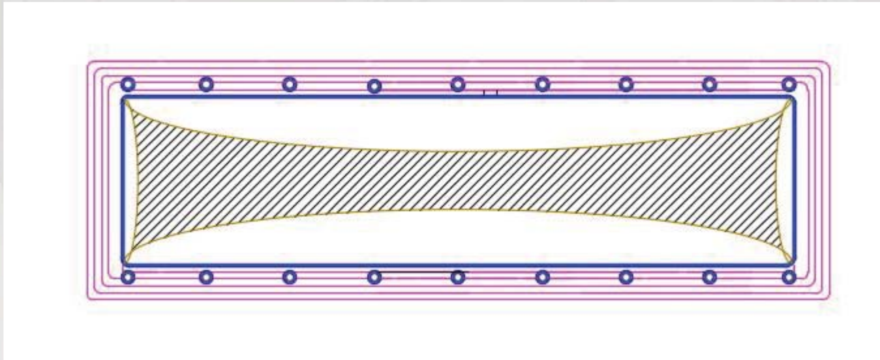
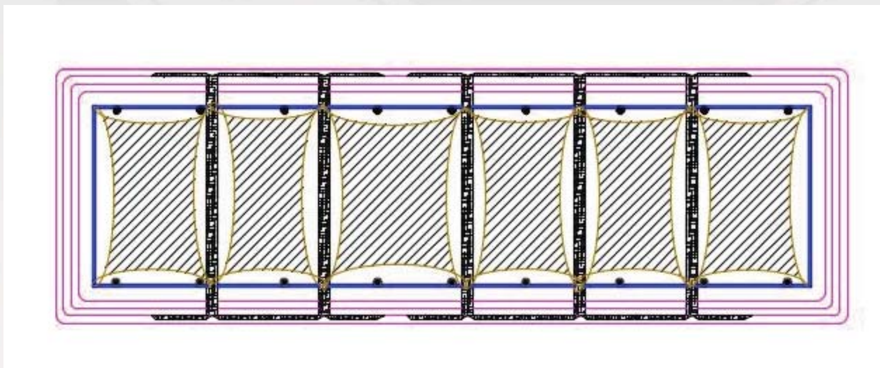
Transverse (Horizontal) CFRP Anchors: Confinement





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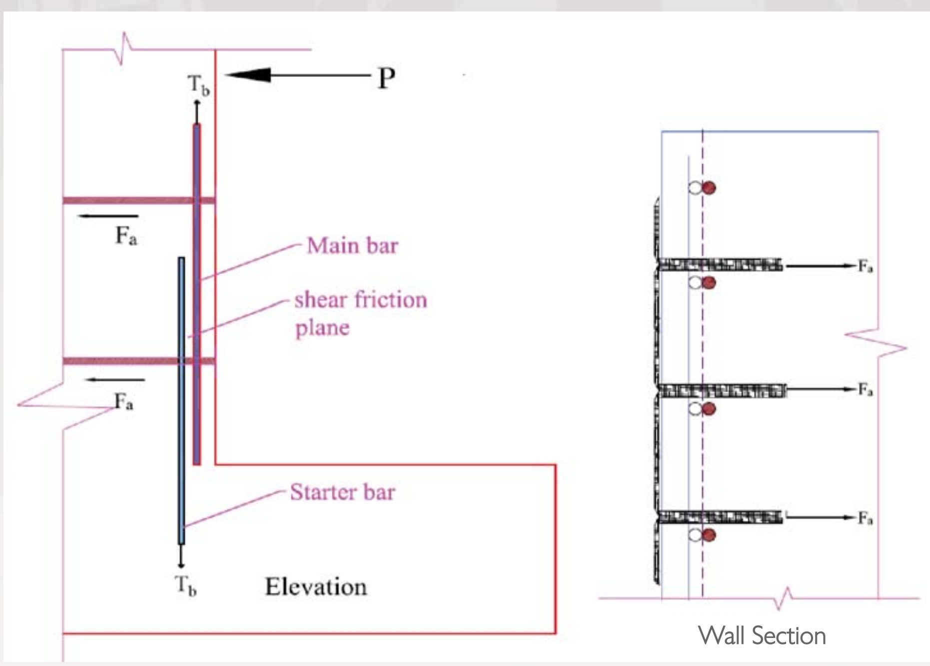
Transverse (Horizontal) CFRP Anchors: Shear Friction Improves Clamping Pressure on Lap Splice



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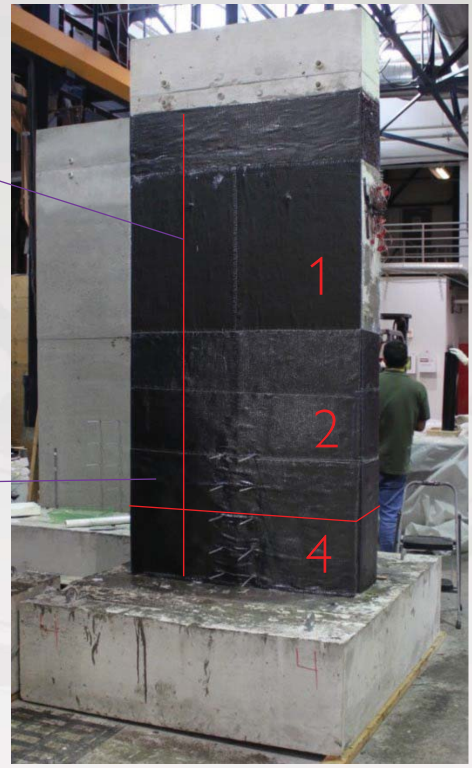
Carbon Fiber Reinforced Polymer Laminates

- Two vertical CFRP layers on each wall face to improve flexural bond
- 4+2+1 CFRP hoop sheets to improve confinement



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Retrofit 1: CFRP Vertical Anchors

CFRP on each wall face:

- Vertical CFRP Anchors : 9
- Unidirectional Vertical CFRP Sheets : 2
- Horizontal CFRP Anchors : 5+5
- Unidirectional Hoop Direction CFRP Sheets: 4+2+1

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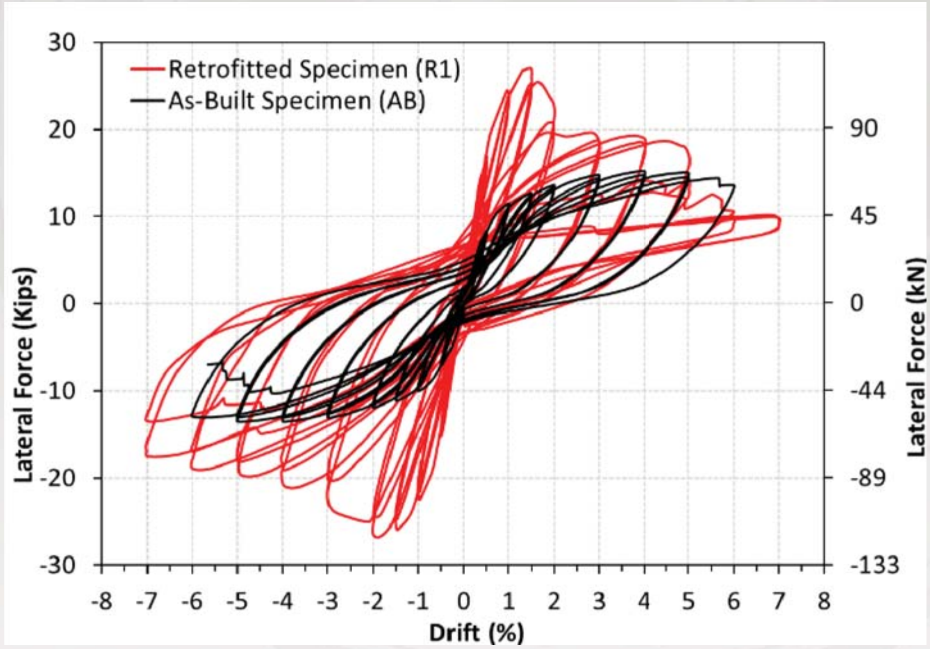
Retrofit 1: Results



Comparison of hysteresis curves of as-built specimen *AB* and retrofit specimen *R1*

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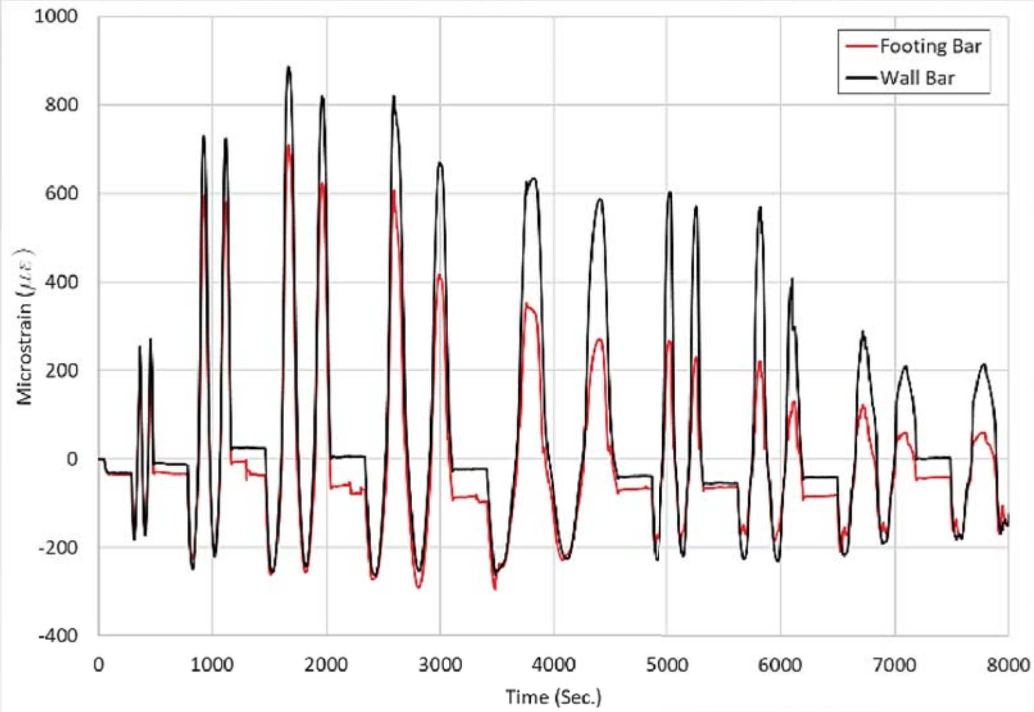
Retrofitted Wall Pier 1 damage

(a)

(b)

Behavior of retrofitted wall pier *R1*: (a) CFRP jacket debonding at 1.5% drift ratio; (b) vertical CFRP anchor failure at 2.0% drift ratio



Retrofitted specimen *R1* lap-splice strain in the footing and wall bars

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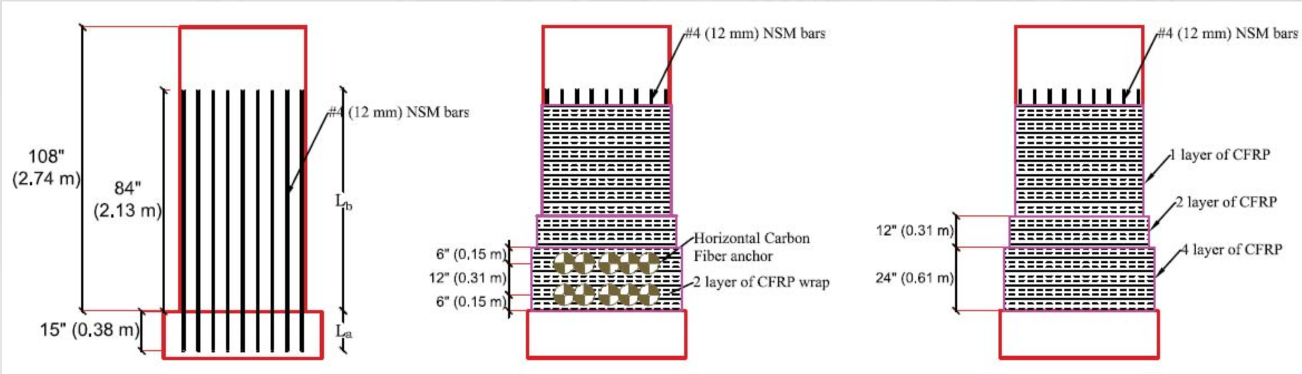
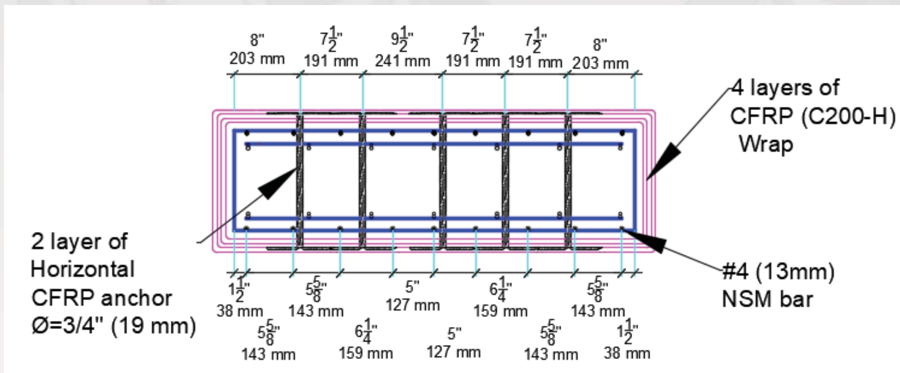
Test 4: Retrofit of As-Built Concrete Wall Pier 2 – CFRP NSM Bars



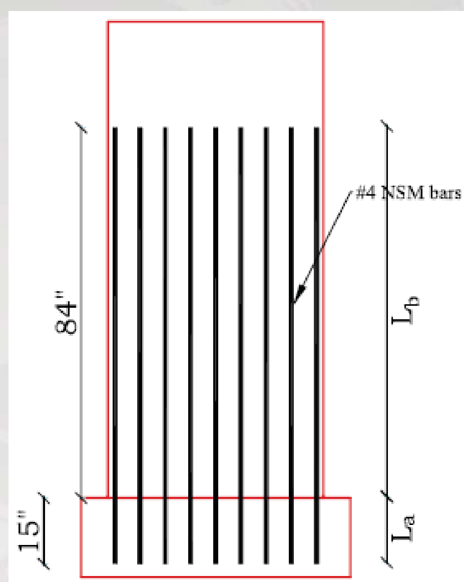
(a) (b) (c)



(d)

Retrofit design for wall pier *R2*: (a) 18 vertical CFRP NSM rods; (b) 10 transverse CFRP anchors; (c) 4+2+1 CFRP jackets; (d) wall cross-section at bottom 24 in.

Near Surface Mounted (NSM) Bars



- Increases Flexural Resistance
- Creates Positive Connection between Footing and Wall Pier

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Horizontal CFRP Anchors (10)

- Increase Confinement in Plastic Hinge Region
- Increase Clamping Pressure on Lap Spliced Steel Rebar

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Retrofit 2: CFRP NSM Bars

CFRP on each wall face:

- CFRP NSM Bars: 9
- Horizontal CFRP Anchors : 5+5
- Unidirectional Hoop Direction CFRP Sheets : 4+2+1

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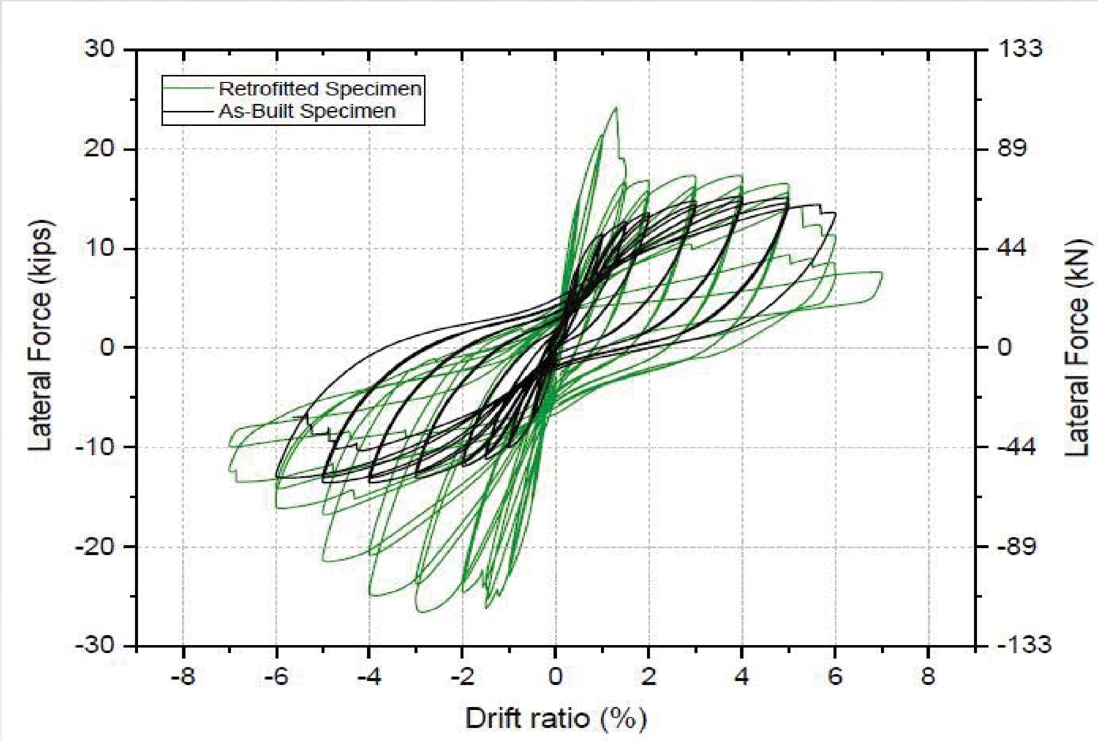
Retrofit 2: Results



Comparison of hysteresis curves of as-built specimen *AB* and retrofit specimen *R2*

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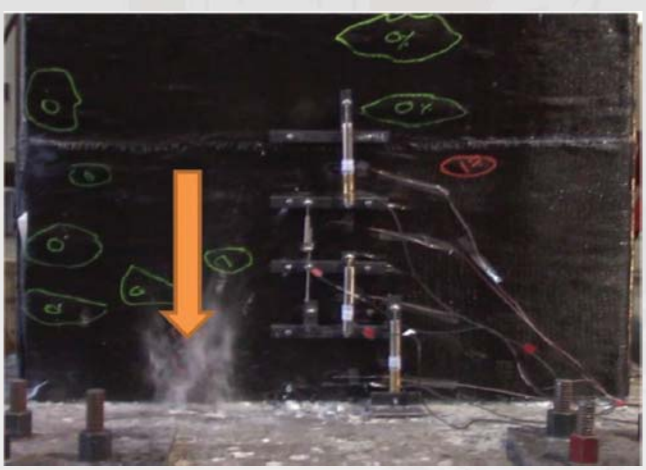
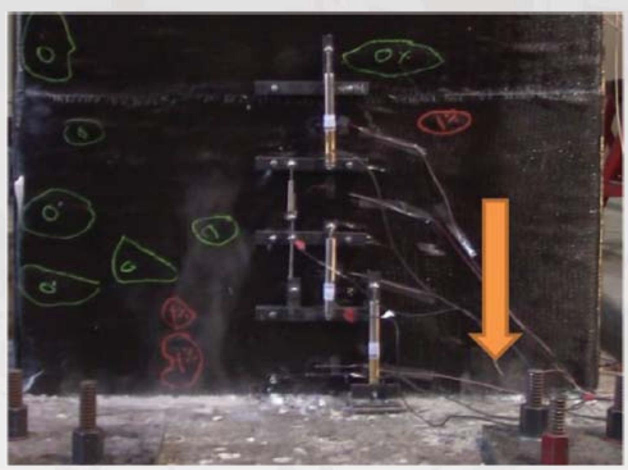
Retrofitted Wall Pier 2 damage

- NSM Bar Bond Failures





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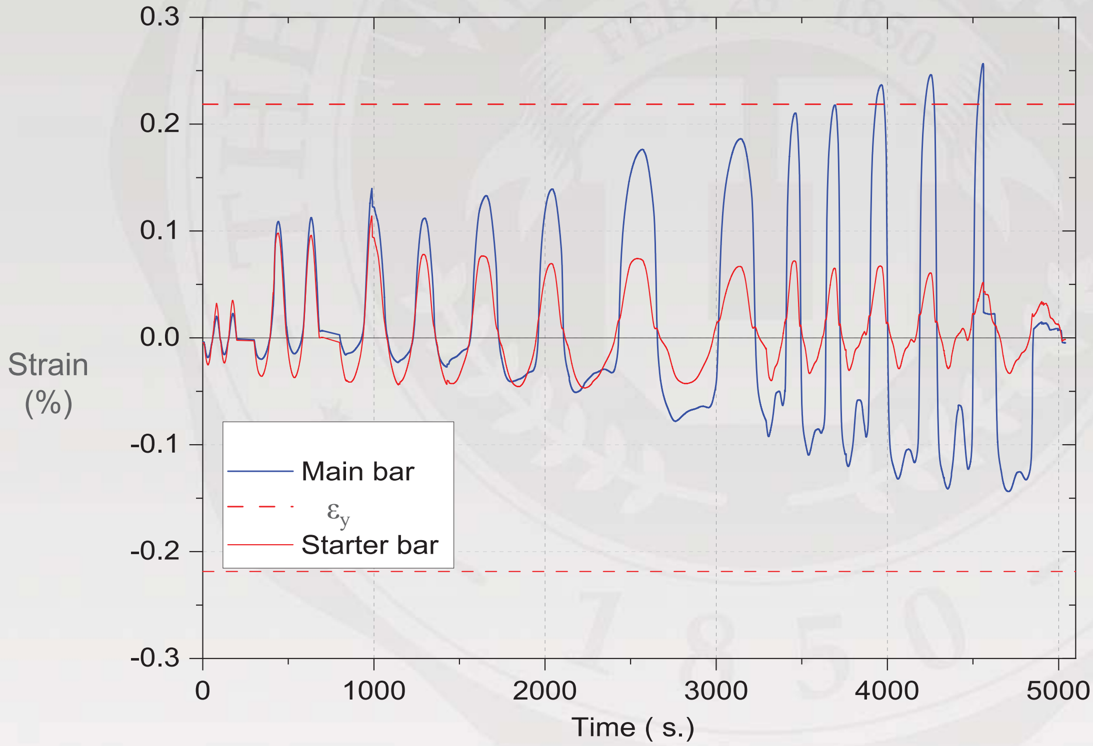

Retrofitted specimen *R2* lap-splice strain in the footing and wall bars

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Comparison of Test Results for Wall Piers

Test Criteria	As-built Wall Pier	Vertical Anchor Retrofit 1	CFRP NSM Retrofit 2
Average maximum lateral force Kips (kN)	15 (68)	26 (117)	25 (113)
Ultimate drift ratio	6.0 %	7.0 %	6.0 %
Hysteretic Energy dissipation Kip-in. (kN-m)	496 (56)	816 (92)	827 (93)
Failure mode	Lap splice failure	Vertical CFRP Anchor Tensile Failure	Bond Failure of CFRP NSM Bars

Repair Methods

How do we fix the damaged As-built Wall Pier after an earthquake occurs?

How do we fix the damaged Modern Code Compliant Wall Pier after an earthquake occurs?

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Test 5: Repair of As-Built Concrete Wall Pier – Mild Steel Vertical NSM Bars

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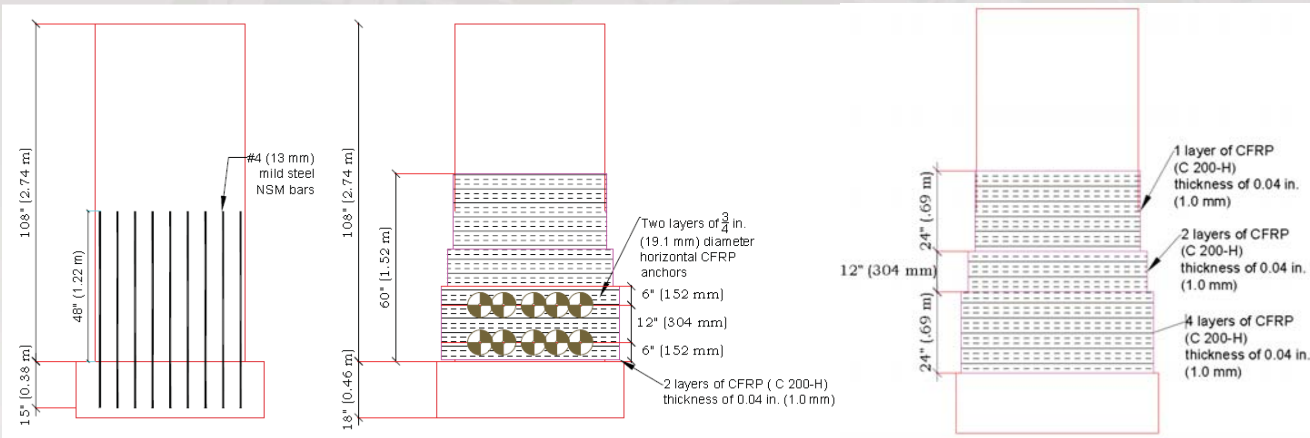
Repair of As-Built Concrete Wall Pier



(a) (b) (c)

Repair of specimen ABRP: (a) steel NSM bars; (b) horizontal CFRP anchors; (c) hoop direction CFRP jackets

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Repair of As-Built Concrete Wall Pier

Mild Steel NSM bar placement

Epoxy coverage of Mild Steel NSM bars

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Repair of As-Built Concrete Wall Pier

Application of CFRP hoop layers

Transverse (horizontal) CFRP anchors

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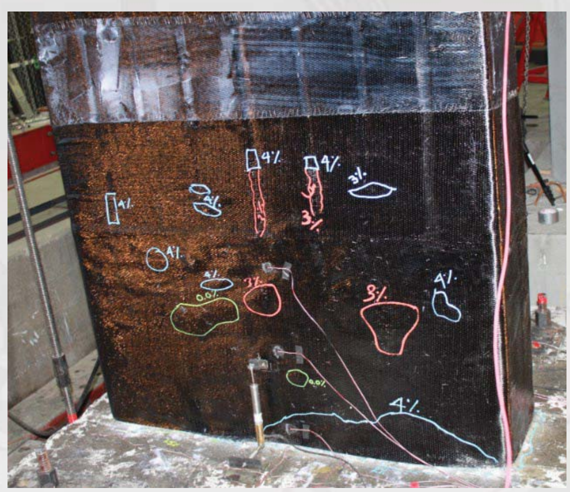
Repair of As-Built Concrete Wall Pier

Footing crack at 1.5% drift ratio



East face CFRP jacket debonding at 4.0% drift ratio

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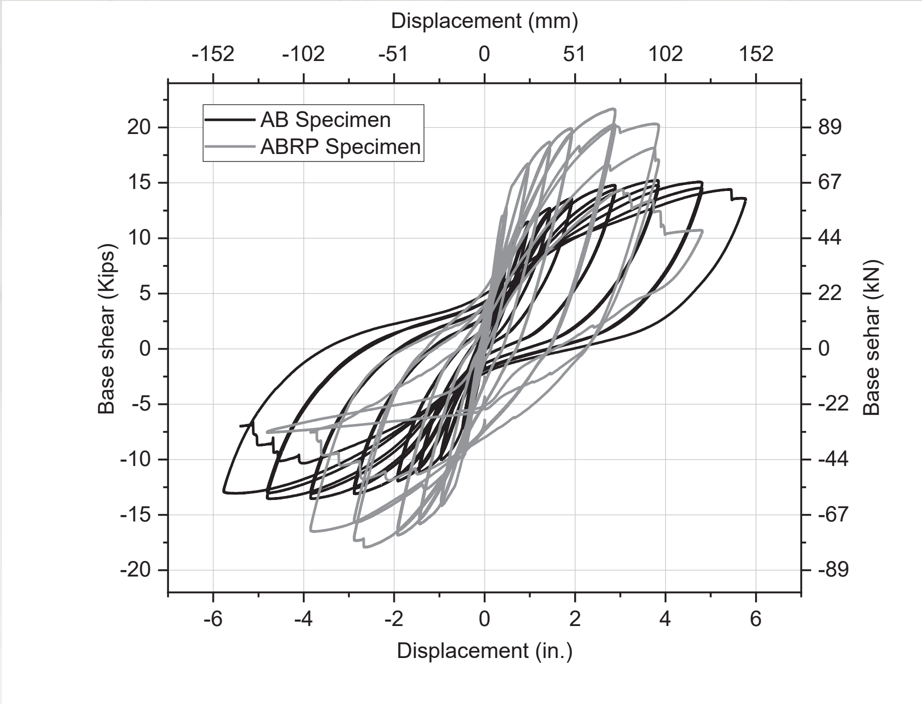
Repair of As-Built Concrete Wall Pier



Comparison of **As-built** and **As-built Repair** hysteresis

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Repair of As-Built Concrete Wall Pier

Summary of AB & ABR performance

Test criteria	As-built (AB)	Repaired (ABRP)
Average maximum lateral force	15.2 kip (68 kN)	21.6 kip (96 kN)
Drift ratio at peak force	4.0 %	3.0%
Ultimate drift ratio	6.0 %	5.0%
Failure mode	West Lap-Splice Failure	Debonding of mild steel NSM Bar
Yield force	13.0 kip (58 kN)	17.3 kip (77 kN)
Initial elastic stiffness	16.1 kip/in. (2.8 kN/mm)	23.6 kip/in. (4.1 kN/mm)
Yield displacement	0.81 in. (21 mm)	0.74 in. (19 mm)
Ultimate displacement	5.76 in. (146 mm)	4.80 in. (122 mm)
Displacement ductility	7.1	6.5

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Test 6: Repair of Modern Code Compliant Concrete Wall Pier – Headed Steel Bars & CFRP Shell Filled with Concrete Grout

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Repair of Modern Code Compliant Concrete Wall Pier

Headed steel bar installation process: (left) drilling holes; (right) headed bar placement for specimen MCRP

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Repair of Modern Code Compliant Concrete Wall Pier

Epoxy injection of cracks for specimen MCRP

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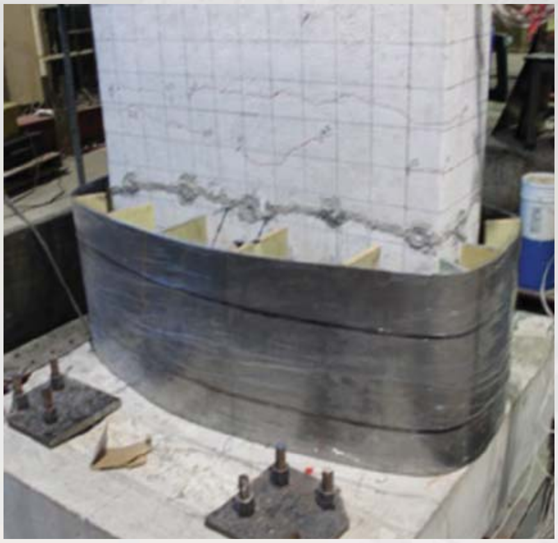
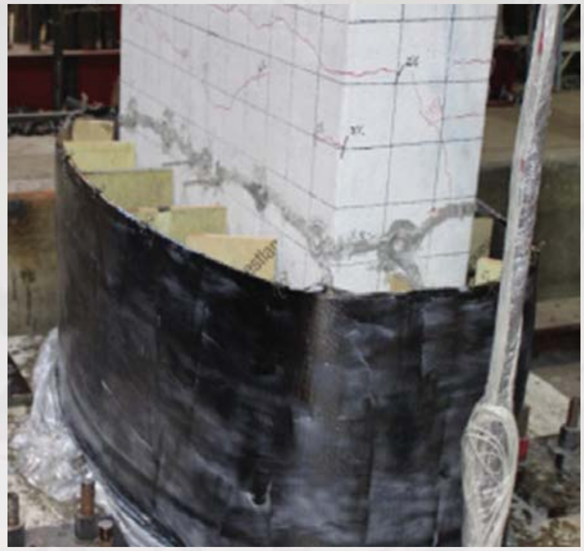
Repair of Modern Code Compliant Concrete Wall Pier

Steel collar with shear studs

Repair of Modern Code Compliant Concrete Wall Pier





CFRP donut formation: (left) shell formation with precut aluminum foil; (right) CFRP wrapped around the aluminum form

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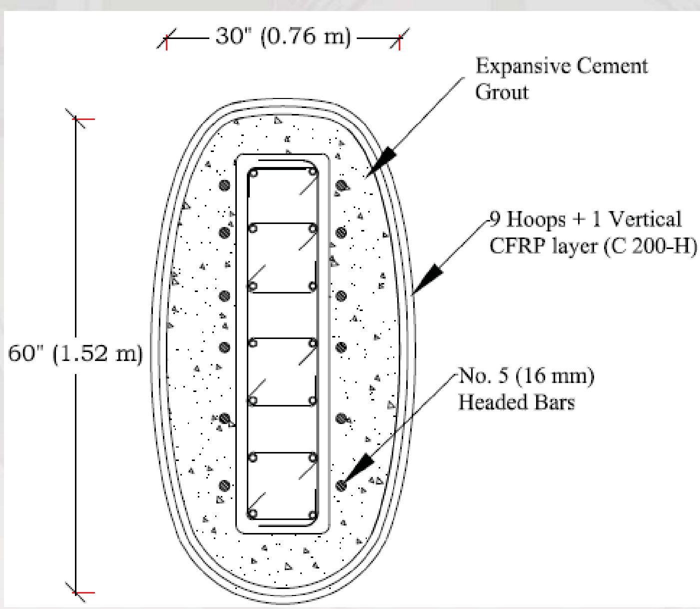
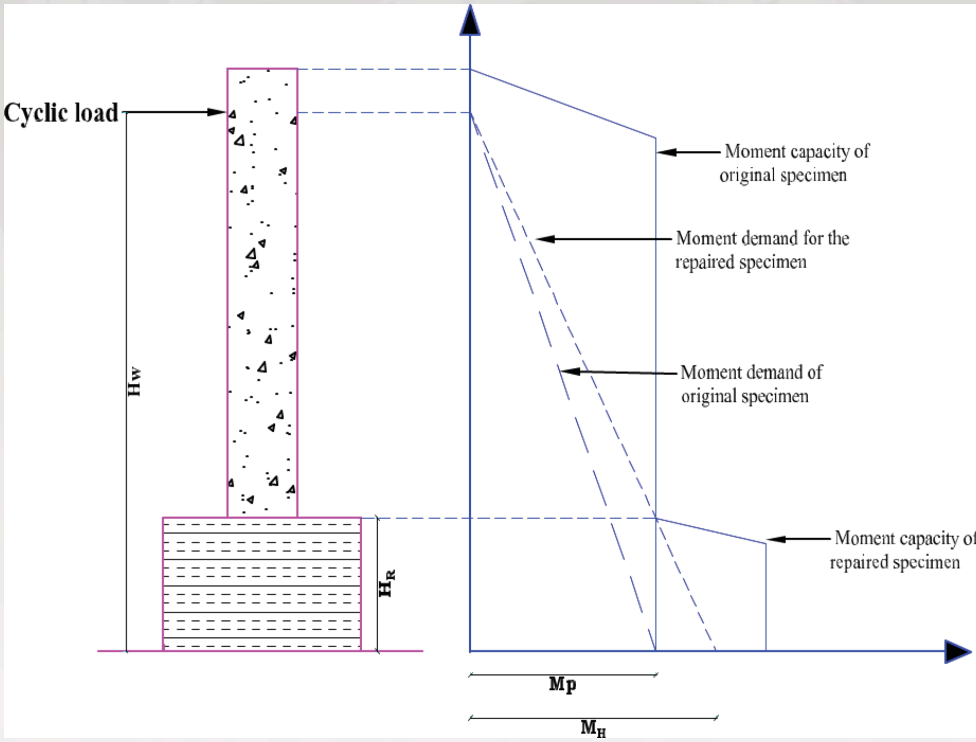
Repair of Modern Code Compliant Concrete Wall Pier



Repair cross-section

Repair of Modern Code Compliant Concrete Wall Pier



Moment demand and moment capacity of the repaired specimen

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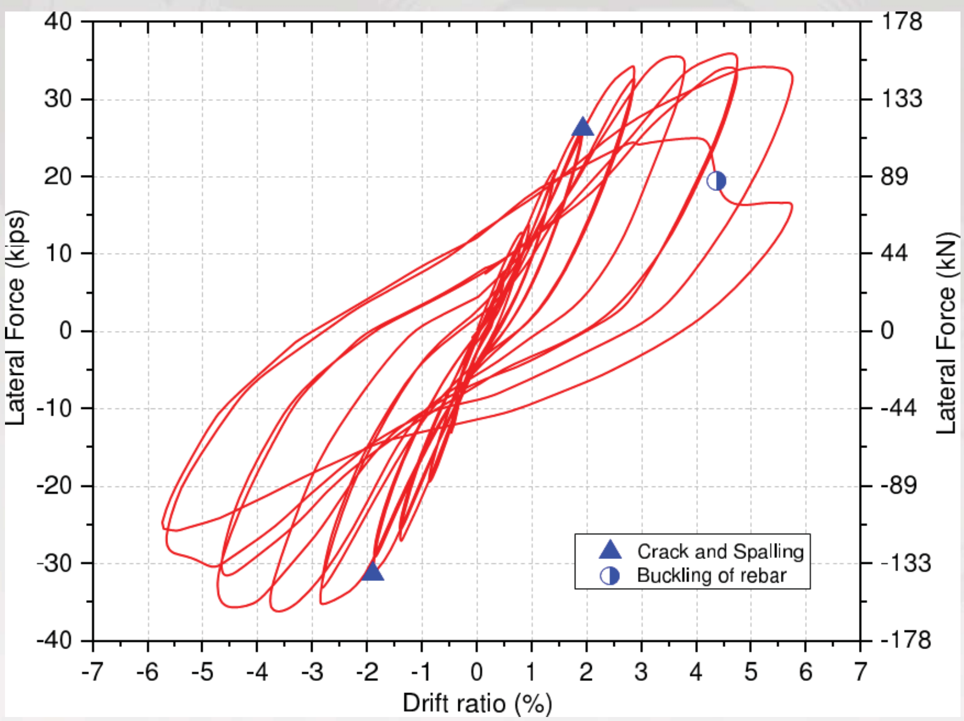
Repair of Modern Code Compliant Concrete Wall Pier



Hysteresis of repaired specimen MCRP

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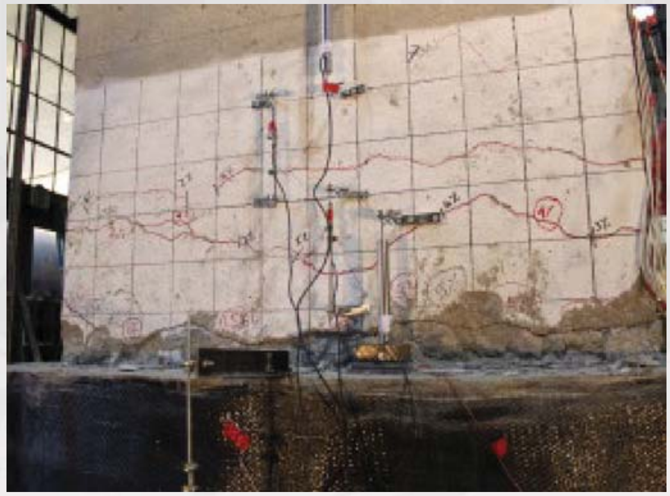
Repair of Modern Code Compliant Concrete Wall Pier



Experimental observation of specimen MCRP at a 5% drift ratio

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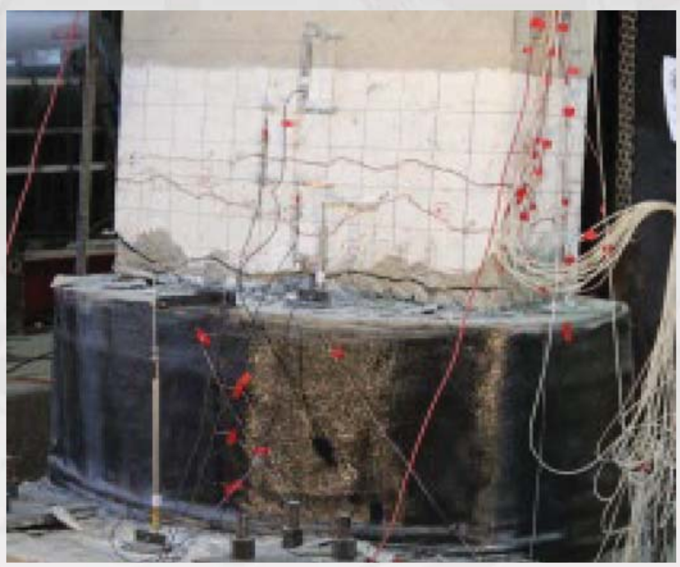
Repair of Modern Code Compliant Concrete Wall Pier



Failure of repaired modern code compliant wall pier: 6% drift ratio

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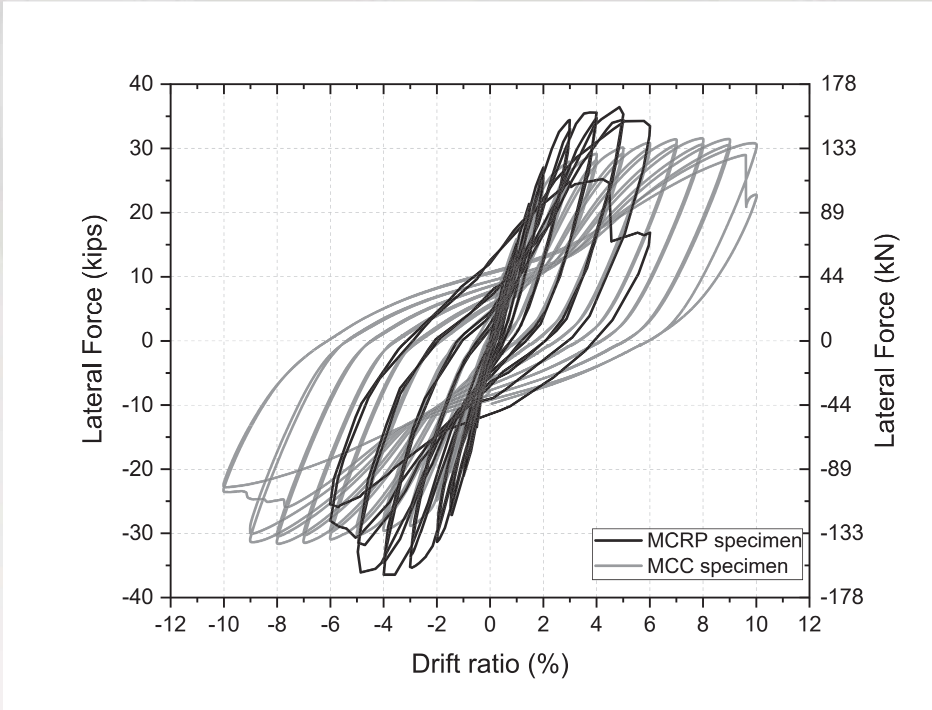
Repair of Modern Code Compliant Concrete Wall Pier



Comparison of Modern Code Compliant and **Modern Code Compliant Repair** hysteresis

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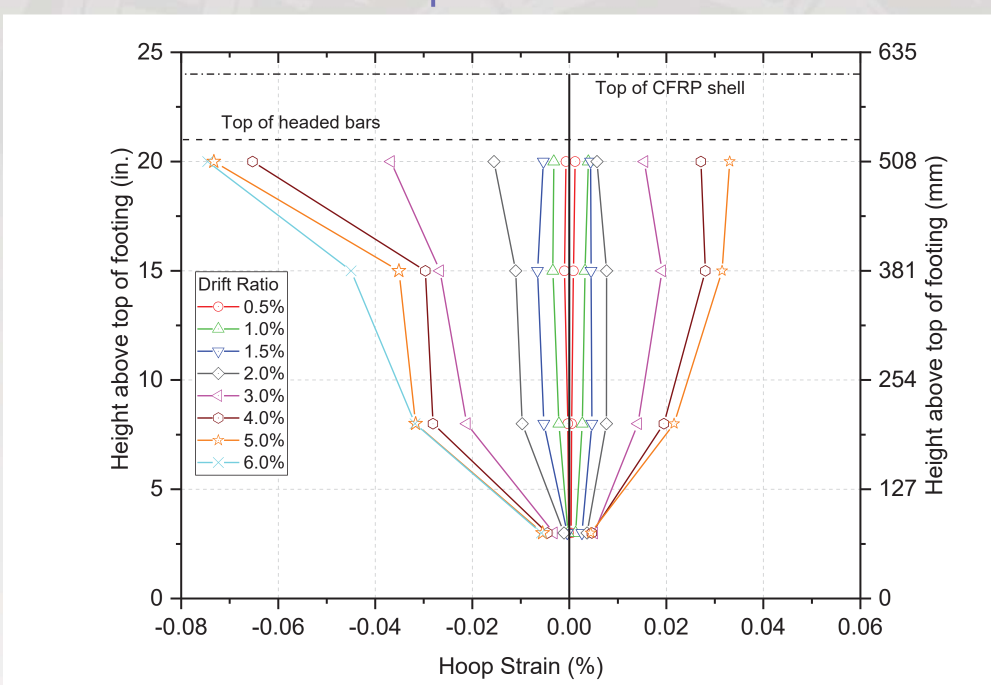
Repair of Modern Code Compliant Concrete Wall Pier



Hoop strain in CFRP shell of modern code compliant wall pier repair

Repair of Modern Code Compliant Concrete Wall Pier

Summary of MCC & MCRP performance

Test criteria	Modern code compliant (MCC)	Repaired (MCRP)
Average maximum lateral force	31.6 kip (141 kN)	36.4 kip (162 kN)
Drift ratio at peak force	8.0 %	5.0%
Ultimate drift ratio	10.0 %	6.0%
Failure mode	West bar fracture	Buckling of original wall steel bars
Yield force	29.8 kip (133 kN)	33.8 kip (150 kN)
Initial elastic stiffness	21.4 kip/in. (3.7 kN/mm)	20.8 kip/in. (3.6 kN/mm)
Yield displacement	1.82 in. (46 mm)	1.79 in. (45 mm)
Ultimate displacement	9.62 in. (244 mm)	5.65 in. (143 mm)
Displacement ductility	5.3	3.2

Conclusions -Retrofit

- The as-built wall specimen *AB* was not able to develop the theoretical flexural capacity due to lap splice clamping failure
- Retrofit specimen *R1* utilized **vertical CFRP anchors**, transverse CFRP anchors, vertical CFRP sheets and CFRP jackets
- The lateral load for retrofit pier *R1* dropped in the first cycle of the 2.0% drift ratio due to fracture of two CFRP vertical anchors on the west side of the wall
- Retrofitted specimen *R1* performed better than the as-built specimen *AB* and reached a drift ratio of 7%
- The retrofitted wall pier *R1* at 2.0% drift ratio had 2.1 times the initial stiffness, 1.6 times the hysteretic energy dissipation, and 2.0 times the flexural capacity of the as-built specimen *AB*

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Conclusions -Retrofit

- The second wall pier retrofit specimen *R2* used **vertical CFRP NSM bars**, transverse CFRP anchors and CFRP jackets
- The hysteresis curves showed that retrofit specimen *R2* continued to resist the increased lateral force until the 1.5% drift ratio
- Debonding failure of two CFRP NSM bars was observed at this time; however, retrofit specimen R2 performed well in resisting the increased lateral force
- The CFRP jackets and transverse CFRP anchors remained intact and did not experience any cracks or fracture until a drift ratio of 7%
- Retrofit specimen *R2* had 1.9 times the initial stiffness, 1.7 times the hysteretic energy dissipation, and 1.6 times the flexural capacity of the as-built specimen AB

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Conclusions -Retrofit

- Both retrofit methods were successful in increasing the flexural capacity of the wall piers
- The retrofit methods provide alternatives for increasing the flexural strength of substandard bridge wall piers in an economical and fast manner
- In order to seismically upgrade the wall piers more efficiently, a CFRP jacket with an *increased number of layers* is needed to provide more confinement and improve the displacement ductility

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Conclusions -Repair

- The modern code compliant specimen *MCC* was able to develop the theoretical flexural capacity and performed very well up to a drift ratio of 10%
- The seismically deficient (*AB*) and *MCC* specimen were repaired after significant damage from cyclic loading simulating earthquake damage to upgrade their performance
- The repair of the as-built reinforced concrete pier wall (ABRP) failed in the second cycle of the 4.0% drift ratio due to debonding of the **mild steel NSM bars**
- The repaired as-built (ABRP) specimen performed better than the as-built specimen (AB) with increased stiffness. lateral force and hysteretic energy

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Conclusions -Repair

- The repair for the modern code compliant wall pier specimen (*MCRP*) used a rapid seismic repair method, which utilizes plastic hinge relocation using a **CFRP shell and headed steel bars**
- This repair method was successfully applied to restore both the load carrying capacity as well as stiffness of a damaged reinforced concrete wall pier with a cross-section aspect ratio of four
- The repair method was able to strengthen the damaged region considering the additional bending moment and shear
- No failure was observed in the repair system; the CFRP shell was intact and did not experience any cracking, while continuously providing confinement and shear strength to the repaired region
- The repaired specimen *(MCRP)* matched the displacement capacity and energy dissipation of the modern code compliant specimen up to a drift ratio of 6.0%

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