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## Seismic Repair/Retrofit of Cast-In-Place or Precast Columns of Reinforced Concrete Bridge Piers

Presented by: Chris P. Pantelides, PhD, PE, SE, University of Utah, Salt Lake City Utah

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# Seismic Repair/Retrofit of Cast-In-Place or Precast Columns of Reinforced Concrete Bridge Piers

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## Introduction

- After strong earthquakes (1994 Northridge) many bridges collapse or are severely damaged
- Concentrated damage is designed to occur at the ends of columns based on current design methodology (Plastic Hinge)
- Seismic repair of damaged columns is preferable to replacement
- Rapid construction, minimal interruption, and economy are desirable in any repair method
- There is little research regarding repair of severely damaged RC bridge columns of existing bridges

# Introduction

- Most existing bridges in high seismic regions are cast-in-place
- During large earthquakes the longitudinal reinforcement buckles or fractures and concrete crushes and spalls: repair of such damage involves removal of core concrete and replacement of the buckled and fractured steel reinforcement which requires significant time and effort
- Phase I: Repair of FOUR columns constructed with Accelerated Bridge Construction (ABC)
- Phase II: Repair of TWO Cast-In-Place (CIP) columns and TWO ABC columns [one column was separated from the cap beam]



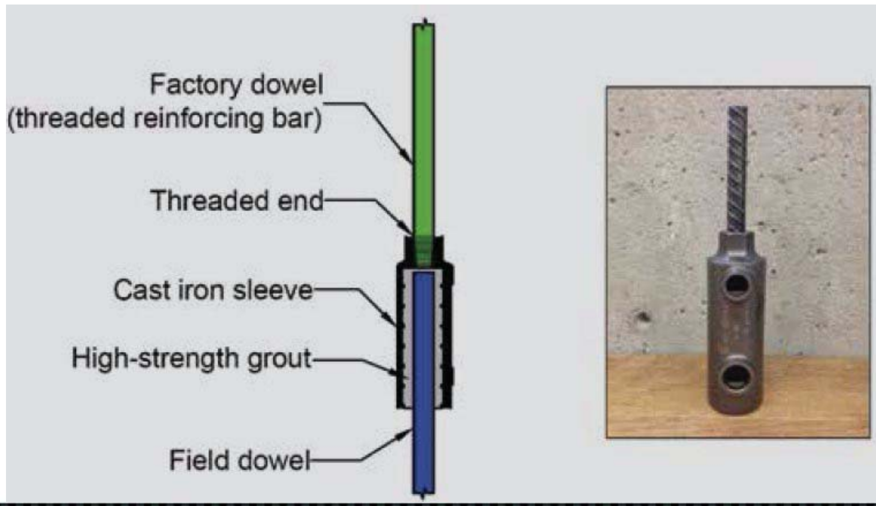


# PHASE I: Repair of Accelerated Bridge Construction (ABC) Columns

- The use of precast bridge elements is popular for accelerated bridge construction
- The ability to repair damaged bridge components is a good alternative to replacement
- Elements with grouted splice sleeve connections are good candidates for repair due to localized damage

# Original Test Specimens (ABC)

- Description of Splice Sleeve System
  - Lenton Interlock
    - Threaded bar
    - Non-Shrink Grout
    - Splice Sleeve



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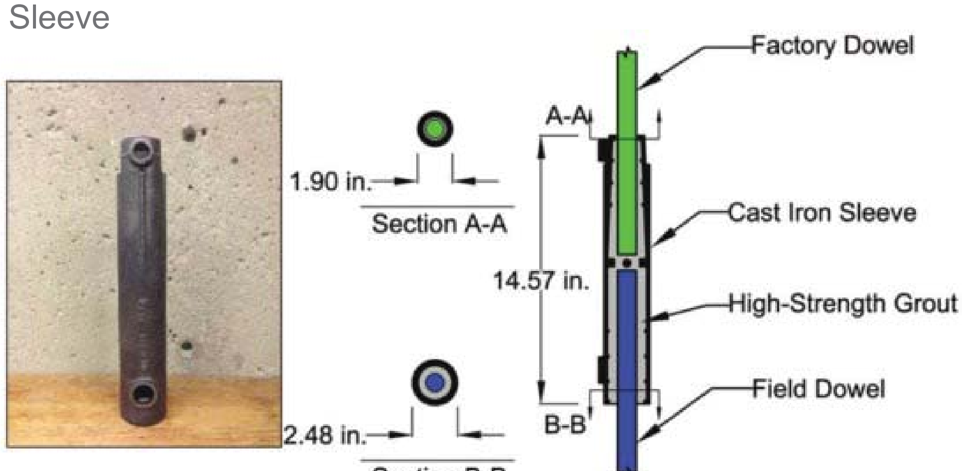
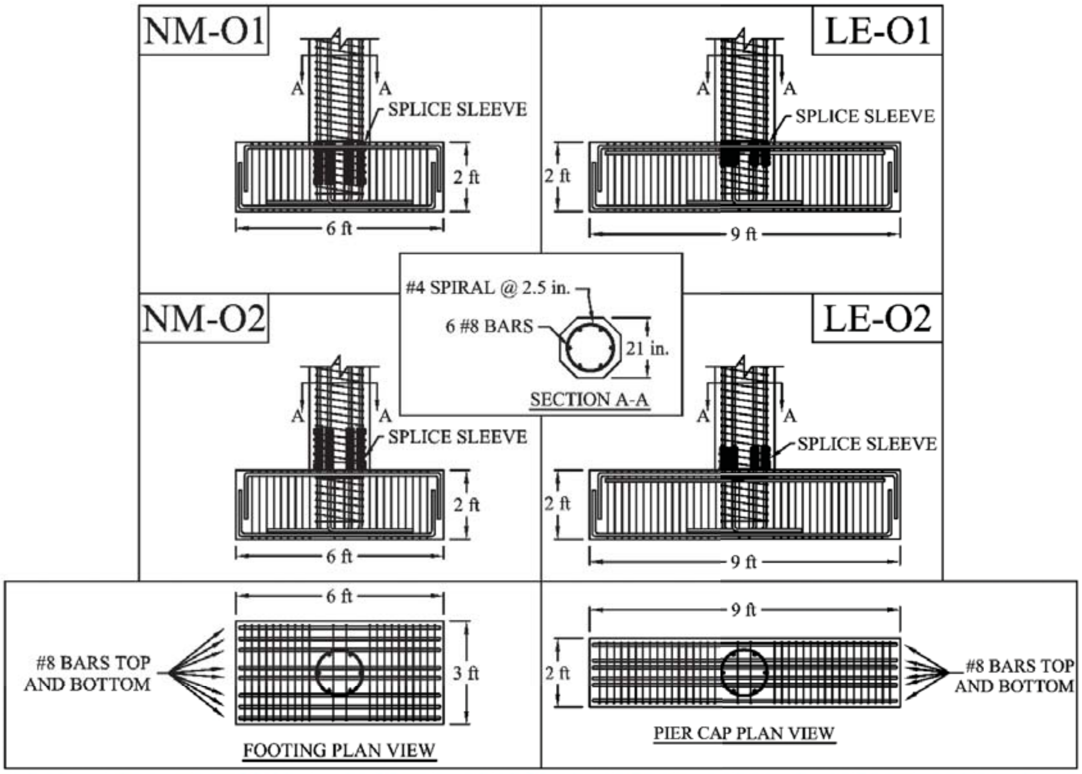
# Original Test Specimens (ABC)

- Description of Splice Sleeve System
  - NMB Splice Sleeve
    - Grouted bars
    - Non-Shrink Grout
    - Splice Sleeve



# ABC Test Specimens



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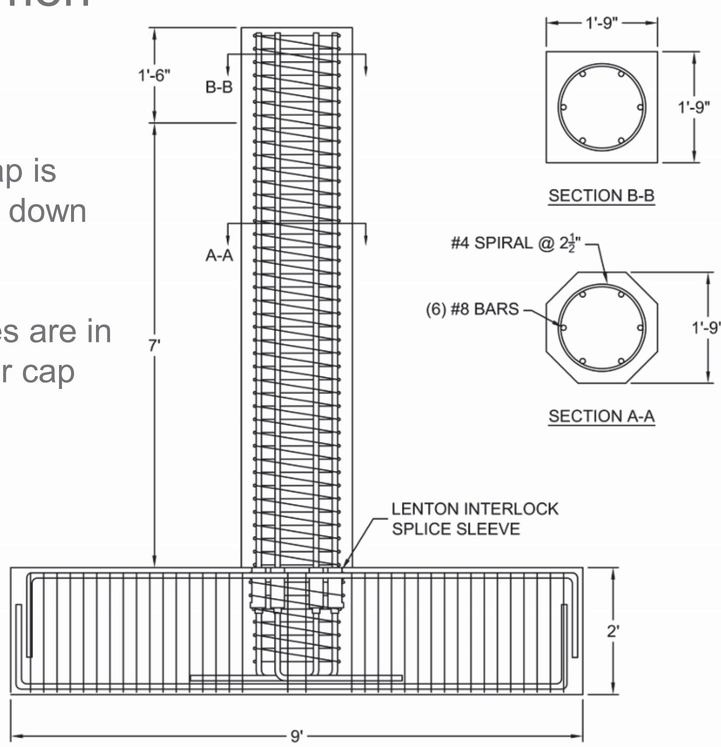
# Original ABC Test Specimen LE-O1

- Pier cap is upside down
- Splice Sleeves are in the pier cap




Experimental Program: Phase I

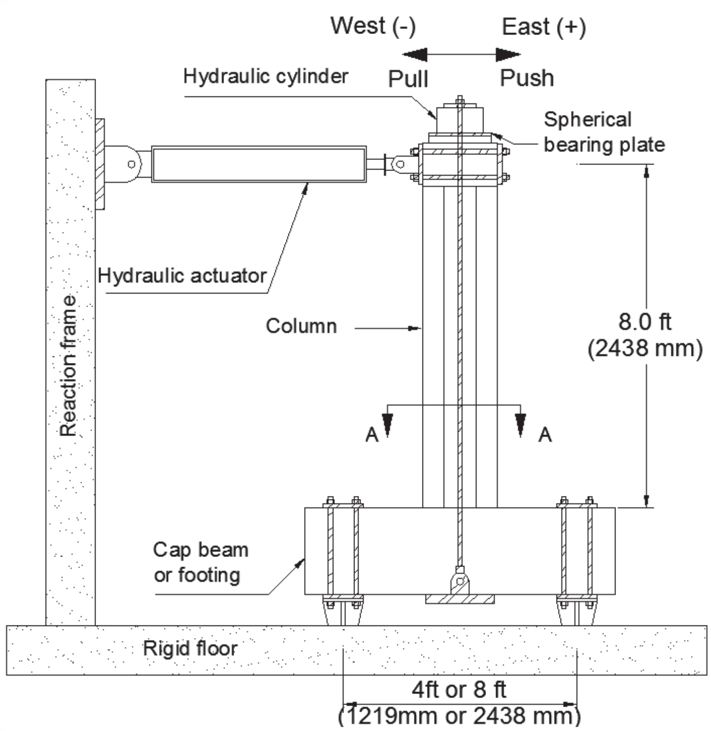
# Material Properties

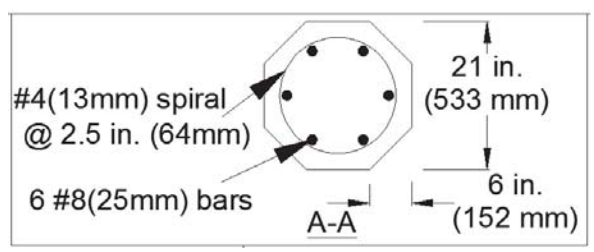
| Material properties | | NM-O1 | NM-R1 | NM-O2 | NM-R2 |
|---|---|---|---|---|---|
| Longitudinal bars | $f_y$, ksi (MPa) | 68 (469) | 68 (469) | 68 (469) | 68 (469) |
| | $f_u$, ksi (MPa) | 93 (641) | 93 (641) | 93 (641) | 93 (641) |
| Concrete compressive strength | Test day, ksi (MPa) | 5.5 (38) | 6.4 (44) | 8.4 (58) | 9.3 (41) |

| Material properties | | LE-O1 | LE-R1 | LE-O2 | LE-R2 |
|---|---|---|---|---|---|
| Longitudinal bars | $f_y$, ksi (MPa) | 68 (469) | 68 (469) | 75 (517) | 75 (517) |
| | $f_u$, ksi (MPa) | 93 (641) | 93 (641) | 103 (710) | 103 (710) |
| Concrete compressive strength | Test day, ksi (MPa) | 6.0 (41) | 6.1 (42) | 8.2 (57) | 9.4 (65) |



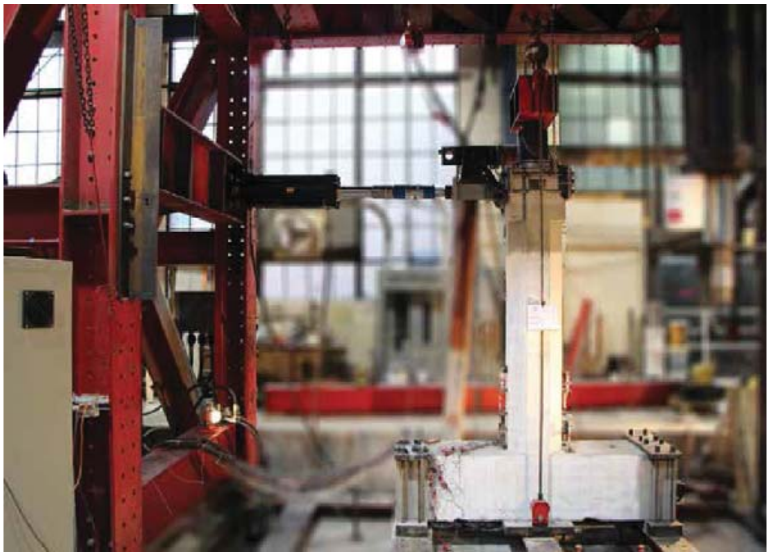


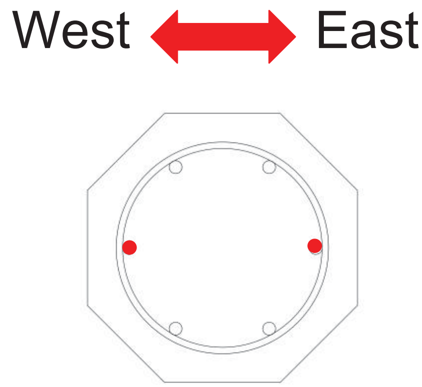



- ✓ Longitudinal rebar ratio: 1.3% (1%-4%)
- ✓ Volumetric spiral ratio: 2.0% (>0.5%)

## Original Test Setup (Ameli et al. 2015; 2016)





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# Test Procedure

Two cycles per drift level

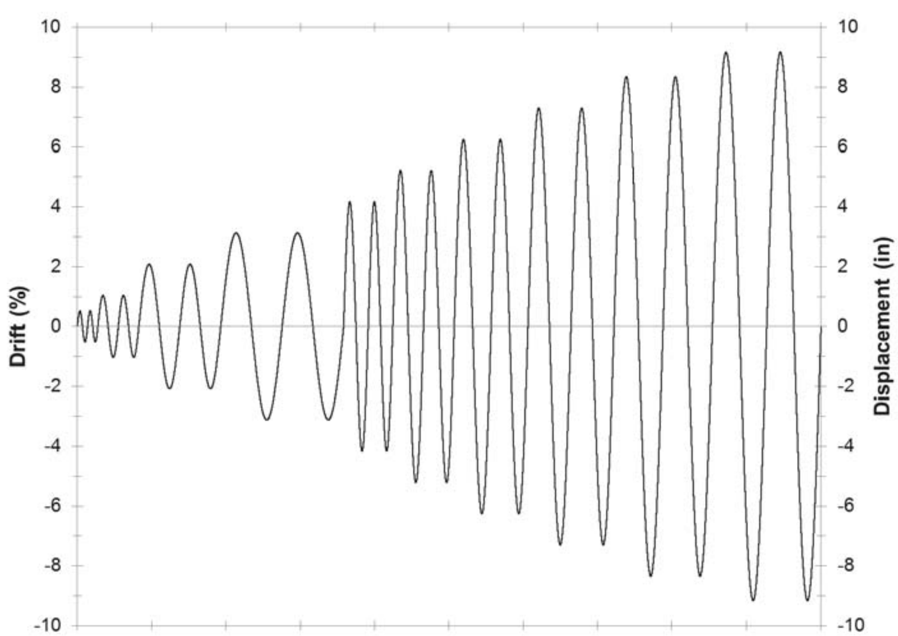
Loading rate up to 3% Drift Ratio:

1.2 in./min

Loading Rate after 3% Drift Ratio:

4 in./min

The axial load was set to 6% of the column axial compression capacity



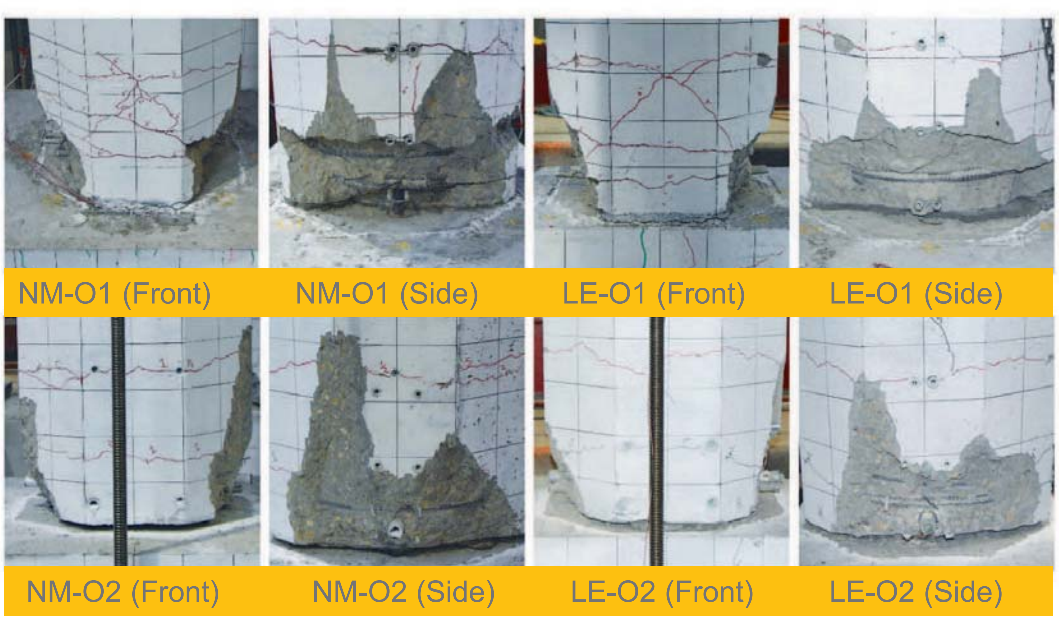
# Original ABC Test Specimen Results

| Test criteria | NM-O1 | NM-O2 | LE-O1 | LE-O2 |
|---|---|---|---|---|
| Maximum load, kip (kN) | 38.8 (173) | 42.0 (187) | 36.3 (161) | 44.8 (199) |
| Ultimate drift ratio, % | 6.69 | 7.91 | 6.50 | 6.00 |
| Displacement ductility | 6.1 | 6.8 | 5.8 | 3.1* |
| Reserve capacity, kip (kN) | 21.4 (95) | 23.6 (105) | 20.6 (92) | 15.9 (71) |
| Failure mode | East bar fracture | East bar fracture | West bar fracture | GSS bar pullout |

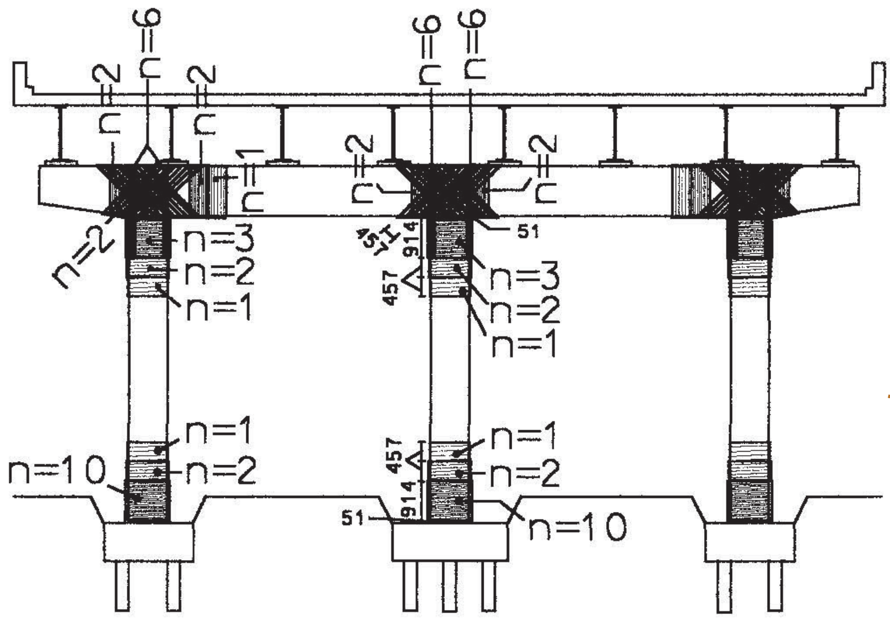




# Damaged Original Specimens



Repair Design Concept → Carbon Fiber Reinforced Polymer (CFRP)




CFRP jackets

Pantelides et al. 1999



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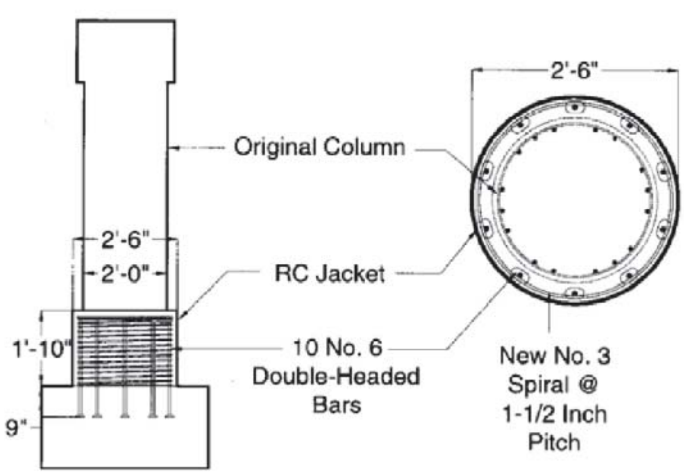
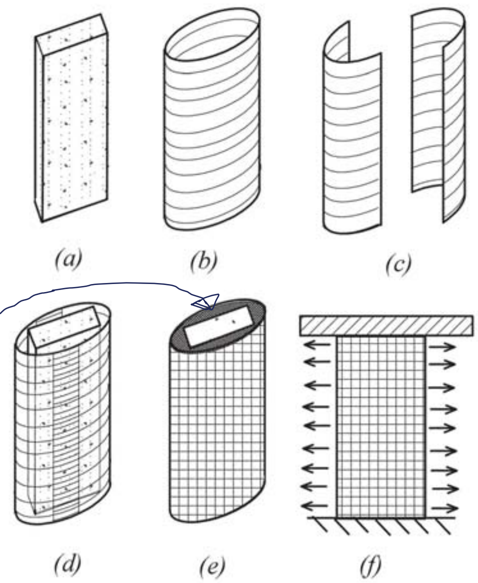
Repair Design → Lehman et al. 2001 repaired a damaged column by casting a concrete jacket reinforced with double-headed longitudinal steel around the damaged region




Experimental Program: Phase I

## Repair Design Concept → Carbon Fiber Reinforced Polymer (CFRP)

**Expansive Grout**




CFRP jacket shape modification

**Post-tensioned CFRP jacket**

Yan et al. 2006



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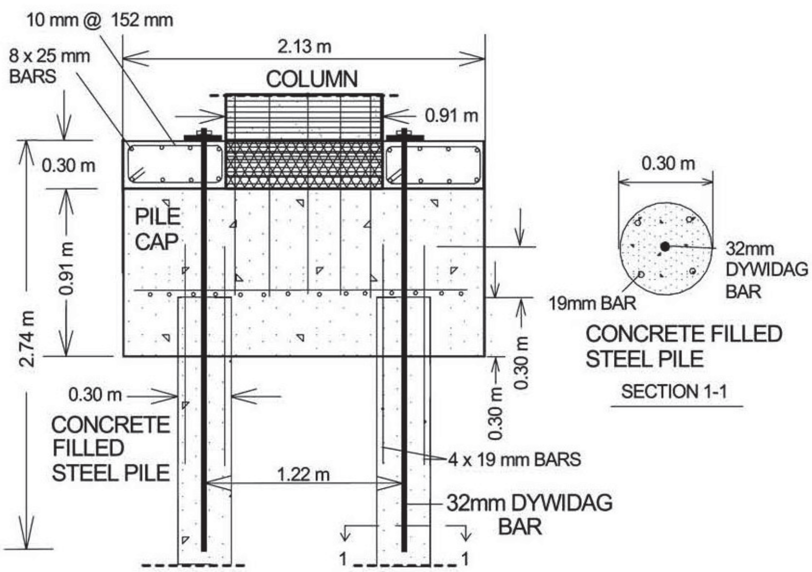
## Repair Design Concept → Carbon Fiber Reinforced Polymer (CFRP)

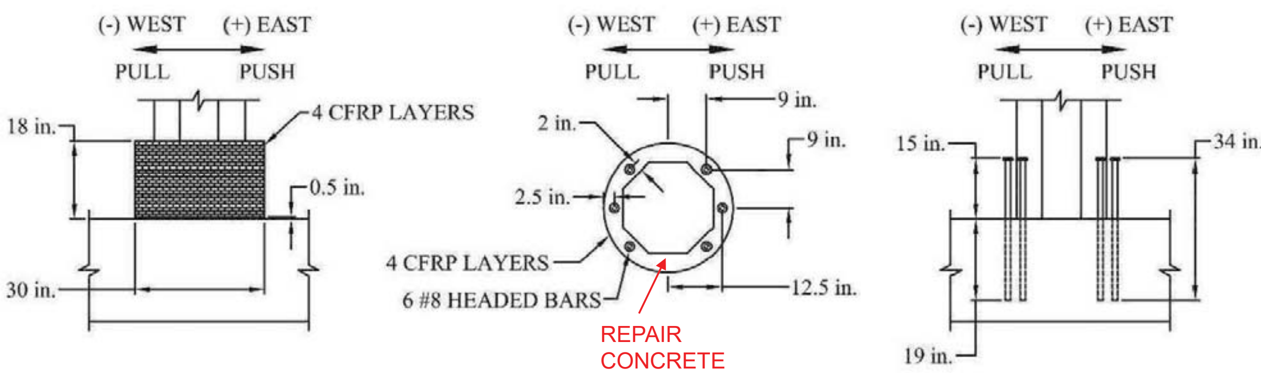



Grade beam-to-pile connection

Pantelides et al. 2007

Experimental Program: Phase I

# Repair Design → Carbon Fiber Reinforced Polymer (CFRP) Donut **(Plastic Hinge Relocation)**




Parks et al. 2016



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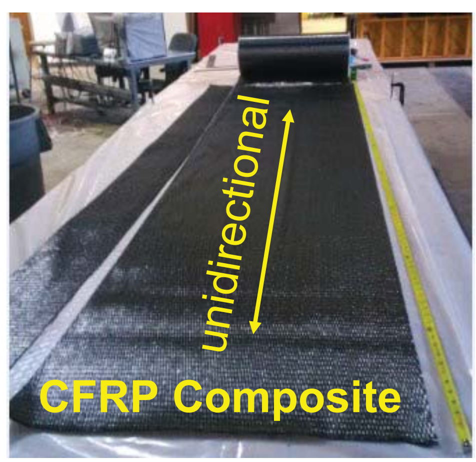
# Why CFRP?

- High strength
- Light weight
- Non-corrosive

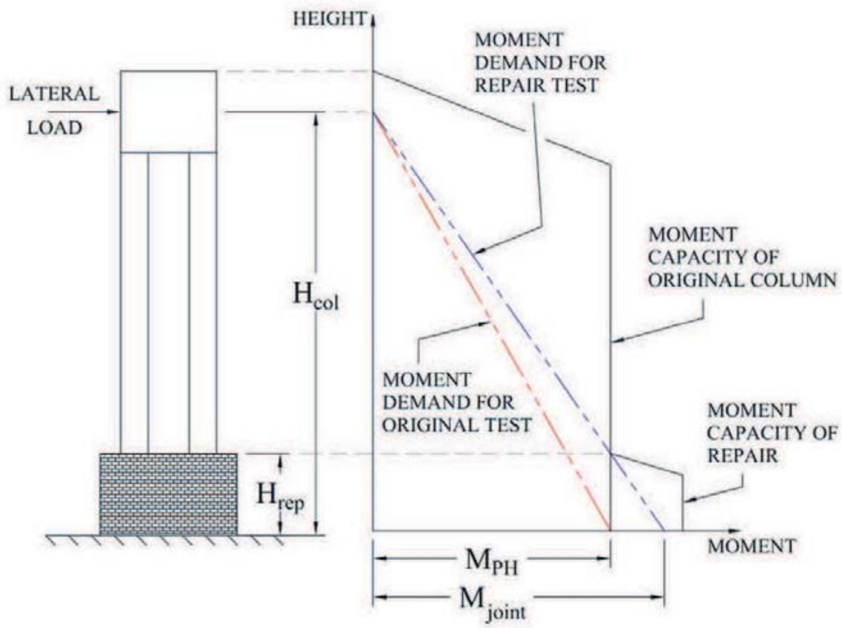
❑ Improves ductile performance
❑ Enhances shear strength
❑ Provides stay-in-place form




➢ Ultimate Tensile Strength: 113 ksi
➢ Modulus of Elasticity: 9400 ksi
➢ Ultimate Tensile Strain: 1.2%     ASTM D3039

Experimental Program: Phase I

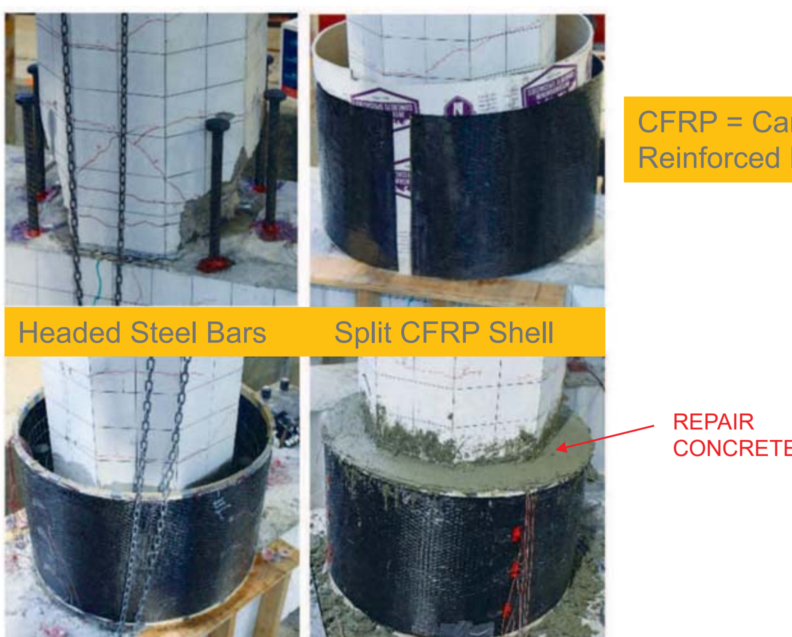
# Repair – Bending Moment Demand (Plastic Hinge Relocation)








# Repair Procedure (Plastic Hinge Relocation)

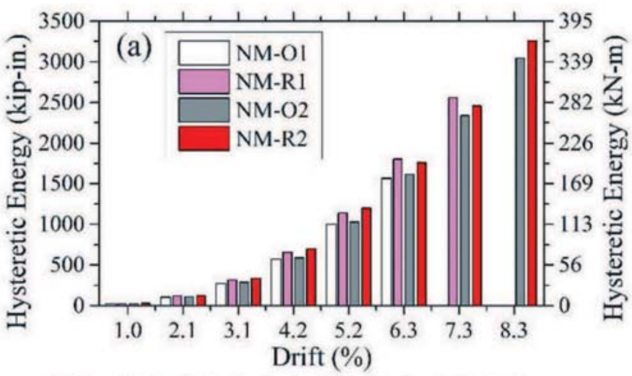


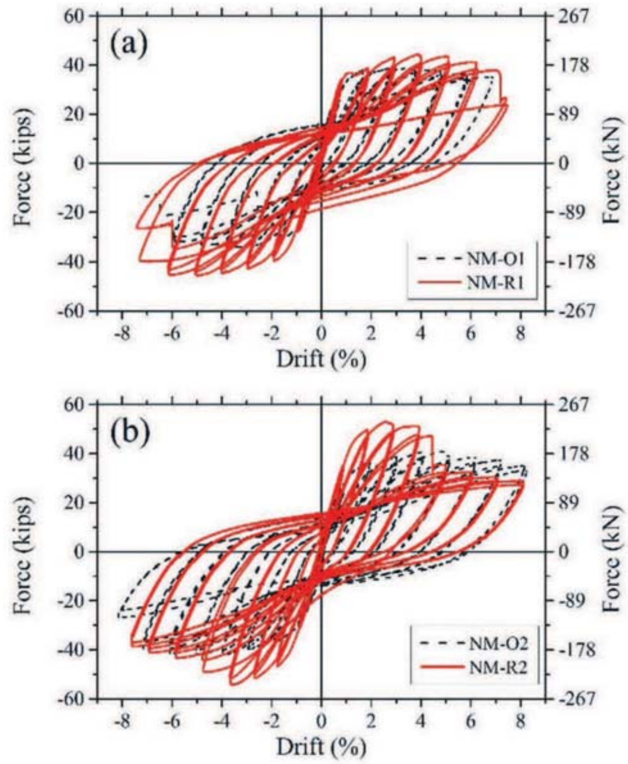

Headed Steel Bars | Split CFRP Shell

Spliced CFRP Shell | CFRP Shell with Concrete Fill

CFRP = Carbon Fiber Reinforced Polymer

# Phase I: ABC Test Results Repair NM



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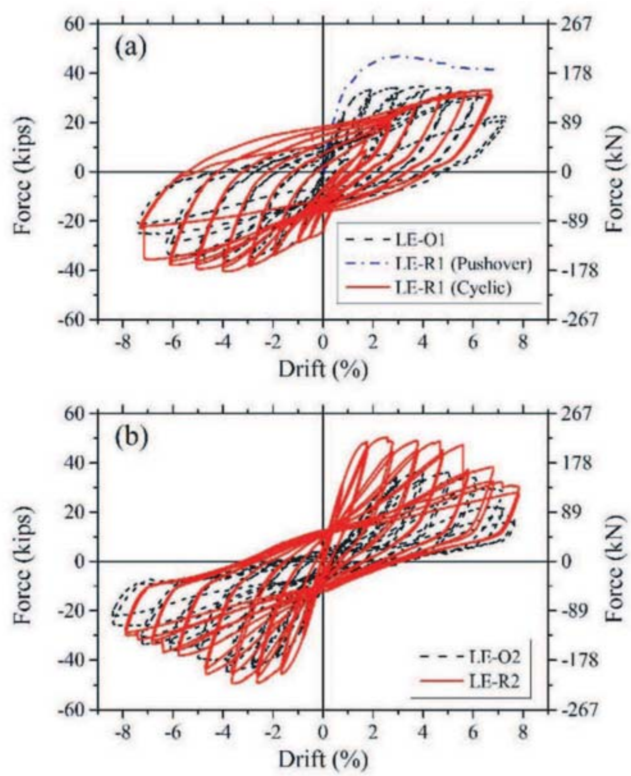
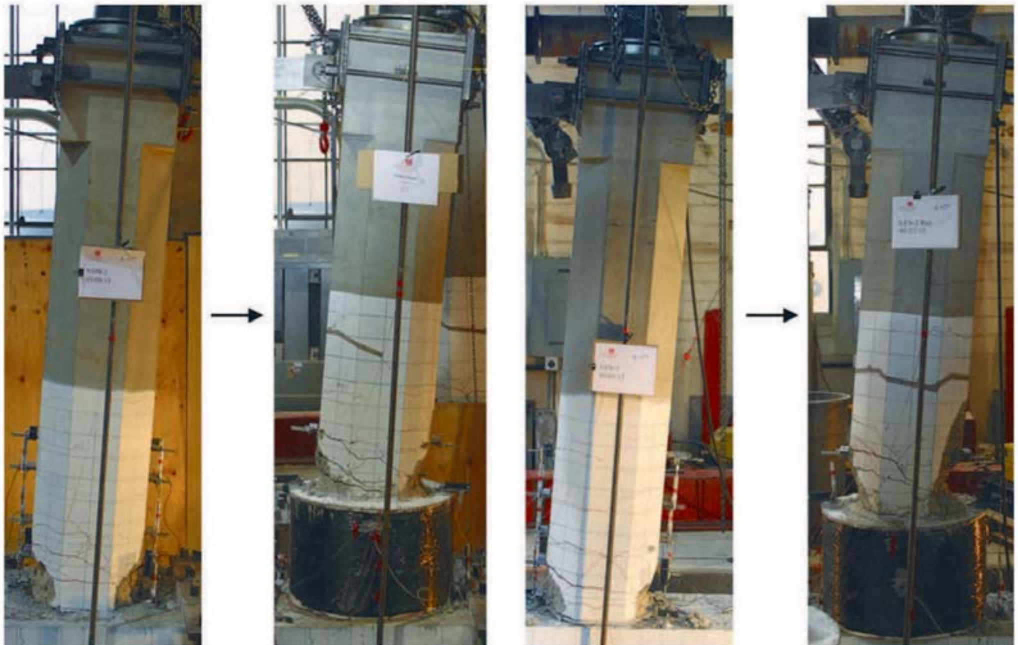
# Phase I: ABC Test Results Repair LE




Experimental Program: Phase I

# Phase I: ABC Test Results



NM-O1 NM-R1 LE-O1 LE-R1



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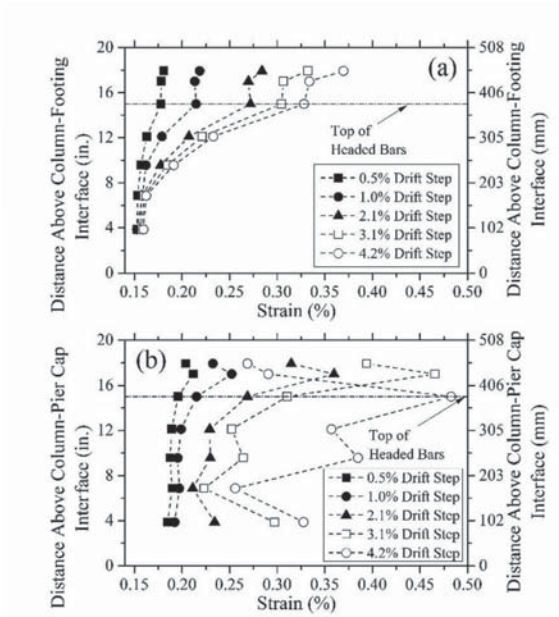
# ABC Test Results Repaired Specimens

| Test criteria | NM-R1 | NM-R2 (West) | NM-R2 (East) |
|---|---|---|---|
| Maximum load, kip (kN) | 45.6 (203) | 54.2 (241) | 53.0 (236) |
| Ultimate drift ratio, % | 6.96 | 5.89 | 4.60 |
| Displacement ductility | 6.0 | 3.9 | 3.9 |
| Failure mode | West and east bar fracture | West bar fracture | |

| Test criteria | LE-R1 (Monotonic) | LE-R1 (Cyclic) | LE-R2 |
|---|---|---|---|
| Maximum load, kip (kN) | 46.8 (208) | 40.5 (180) | 50.5 (225) |
| Ultimate drift ratio, % | 6.88 | 7.20 | 6.17 |
| Displacement ductility | 6.6 | — | 4.6 |
| Failure mode | — | East bar fracture | CFRP wrap fracture |

Experimental Program: Phase I

# CFRP Shell Performance




NM-R2

LE-R2

Strain Profile CFRP Shell

Radial cracks in repair concrete (NM-R1)



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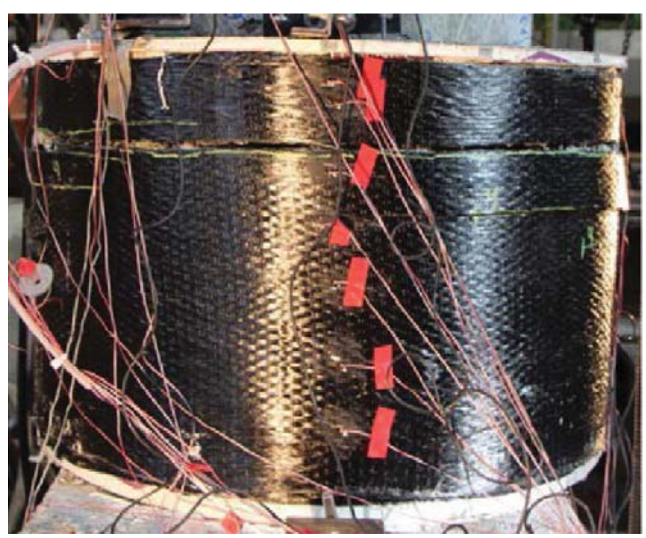
- Due to the lack of vertical CFRP fiber and too much expansion from repair concrete, circumferential CFPR wrap cracked



LE-R2 will be repaired again

Experimental Program: Phase I

# PHASE II: Repair of Cast-In-Place and ABC Columns

The Phase II method incorporates fibers in the hoop and vertical direction of the CFRP shell implemented for four severely damaged specimens:

- ❖ Two columns cast-in-place (CIP) with severe damage including concrete crushing and longitudinal bars fractured and buckled
- ❖ Two columns are precast ABC specimens:
- one repaired for the second time with crack epoxy injection (PC2-O)
- one in which the column was completely separated from the cap beam



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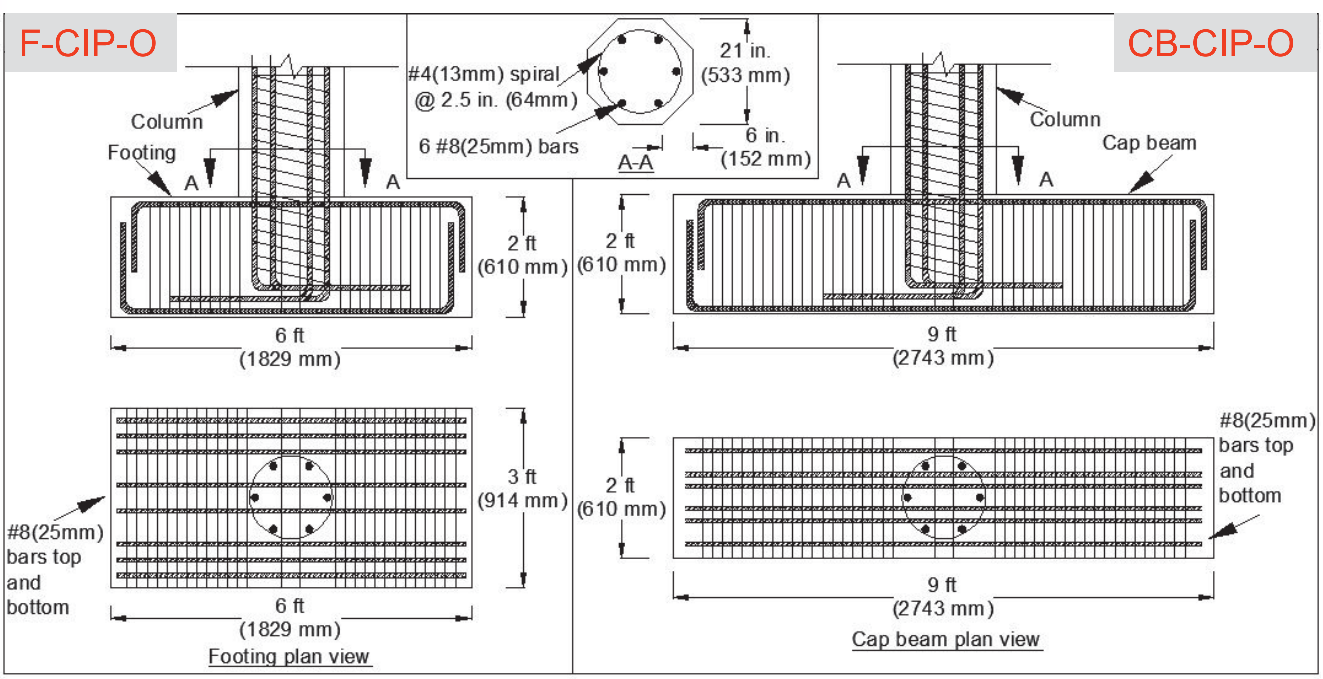
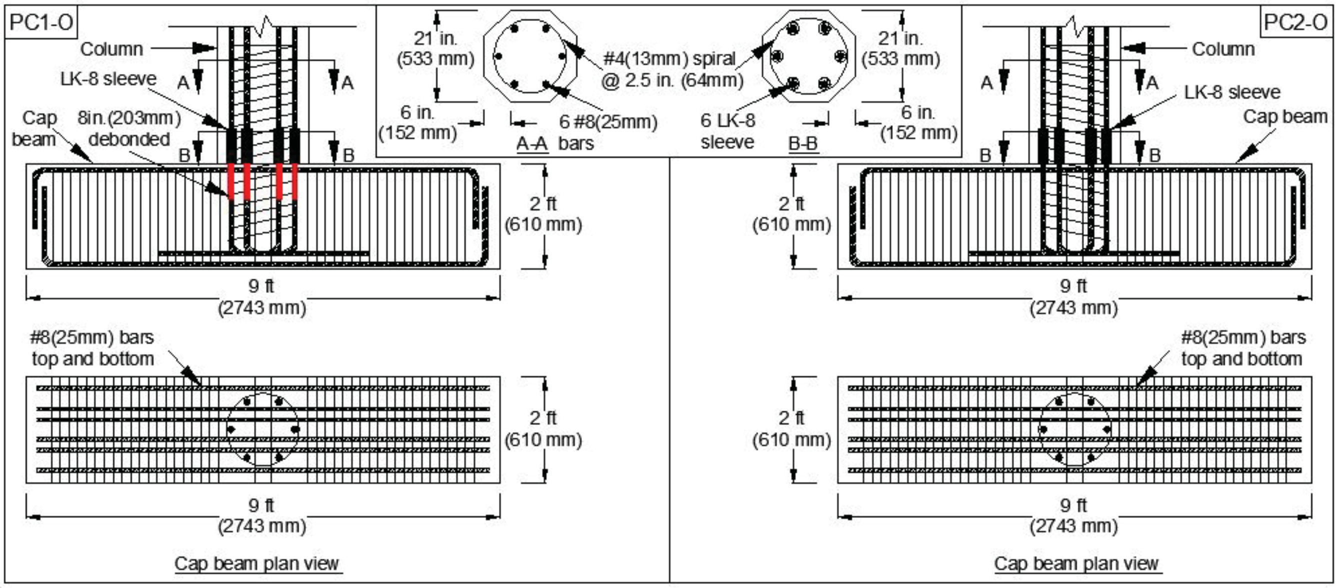
## Phase II: Original Cast-In-Place (CIP) Specimens



# Phase II: Original ABC Precast (PC) Specimens




PC1-O PC2-O



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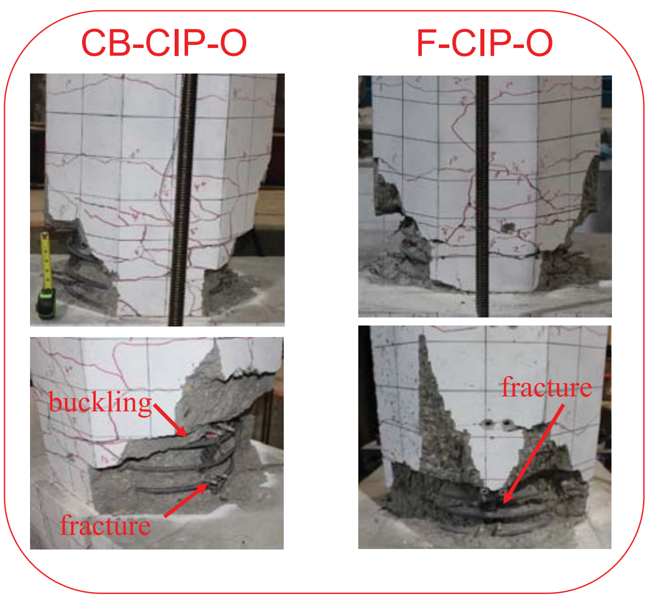
# Phase II: Original Specimen Results: CIP Specimens




CIP Specimens

- Severe concrete crushing (12 in. to 16 in. above interface)
- Fracture of extreme bars
- Buckling of extreme bars

Experimental Program: Phase II

## Phase II Original Specimen Results: PC Specimens

PC1-O

PC1-R1

PC1-O and PC2-O specimens
- ❖ Concrete spalling (8 in. to 12 in. above interface)
- ❖ All bars pulled out
- ❖ No bar fracture/buckling

PC1-R1 specimen
- ❖ Rupture of CFRP shell
- ❖ Severe extensive cracks

LE-R2

PC2-O





## Phase II Original Specimen Results: CIP Specimens

| TEST CRITERIA | CB-CIP-O | F-CIP-O |
|---|---|---|
| MAX. LOAD (kips) | 35.8 | 36.5 |
| ULTIMATE DRIFT RATIO (%) | 9.3 | 8.8 |
| DISPLACEMENT DUCTILITY | 9.9 | 8.9 |

## Phase II Original Specimen Results: PC Specimens

| TEST CRITERIA | PC1-O | PC1-R1 | PC2-O |
|---|---|---|---|
| MAX. LOAD (kips) | 41.0 | 49.9 | 39.7 |
| ULTIMATE DRIFT RATIO (%) | 6.7 | 5.6 | 5.5 |
| DISPLACEMENT DUCTILITY | * | 5.1 | 4.9 |

* Pre-damaged condition before testing



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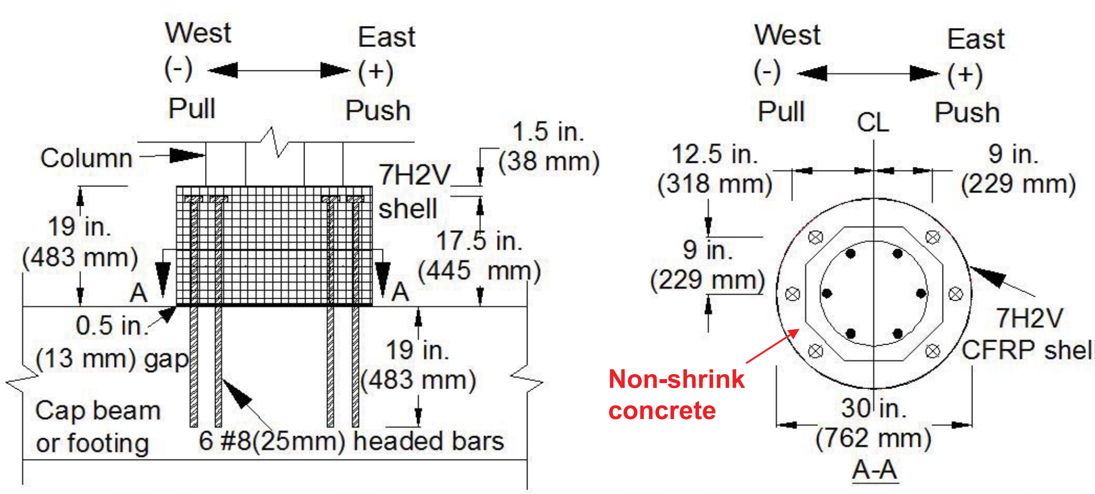
## Phase II: Repair Design (Plastic Hinge Relocation)

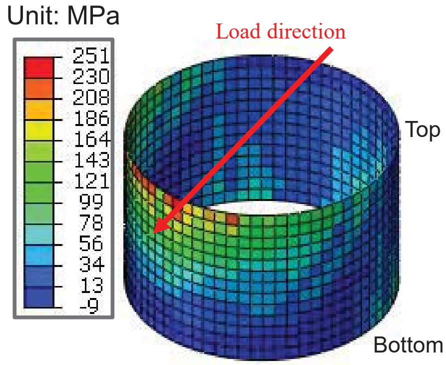
- CFRP shell: 19 in. high CFRP donut with 30 in. diameter based on P.H.
- Repair Concrete: 11.0 ksi non-shrink concrete

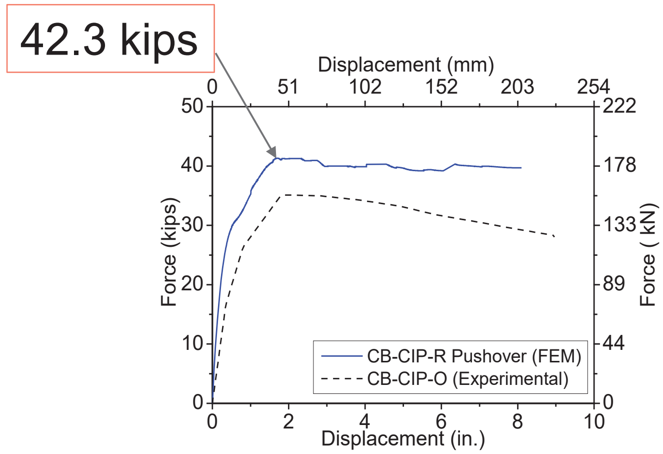
Six headed bars:

- 17.5 in. in the repair concrete
- 19 in. in the footing/cap beam



# FEM for CFRP Shell Design




- 7H2V (Seven hoop layers and two vertical layers)

ACI 440 efficiency factor of 58% for 3D FRP stresses

- Maximum hoop stress for 7H2V was 36.4 ksi or 55% of the allowable CFRP ultimate stress

- The maximum hoop stress for the model with four hoop layers was 63.5 ksi or 97% of the allowable CFRP ultimate stress



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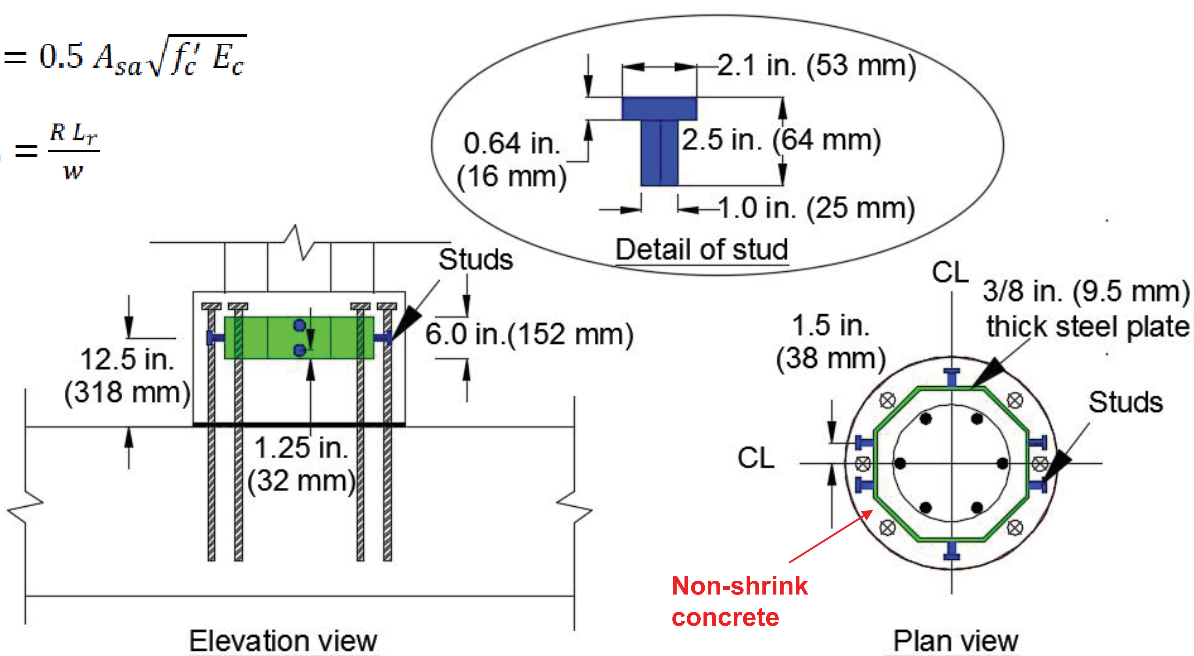
# Steel Collar Design (PC2-R)

## Wu and Pantelides 2018

$$Q_n = 0.5\, A_{sa}\sqrt{f_c'\, E_c}$$

$$Q_D = \frac{R\, L_r}{w}$$



# Rapid Construction of Repair

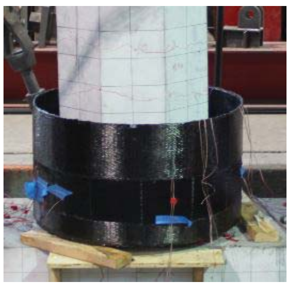
Total: 8 hours

6 hours

(a) Post-installed headed bars

(b) Temporary form for CFRP wrapping

1 hour



(c) CFRP shell – **7 Hoop & 2 Vertical Layers**

1 hour

(d) CFRP shell filled with non-shrink concrete



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# Rapid Construction of Repair

0.5 hour

removal of previous CFRP donut (PC1-R2)

epoxy crack injection (PC1-R2)

1.0 hour

cap beam w/o column (PC2-R)

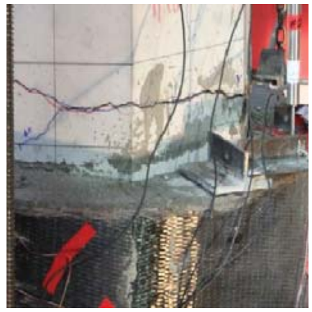
steel collar (PC2-R)

Experimental Program: Phase II

## Phase II: Repair Results

CB-CIP-R

Gap between column and CFRP donut at 2% drift ratio



Slip of the column at 5% drift ratio

Final damage (about 2.5 in. inside donut)

PC2-R

Final damage (PC2-R):
Concrete crushing 18 in. above CFRP donut; two extreme bars fractured



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## Phase II: Plastic Hinge Relocation

CB-CIP-R F-CIP-R

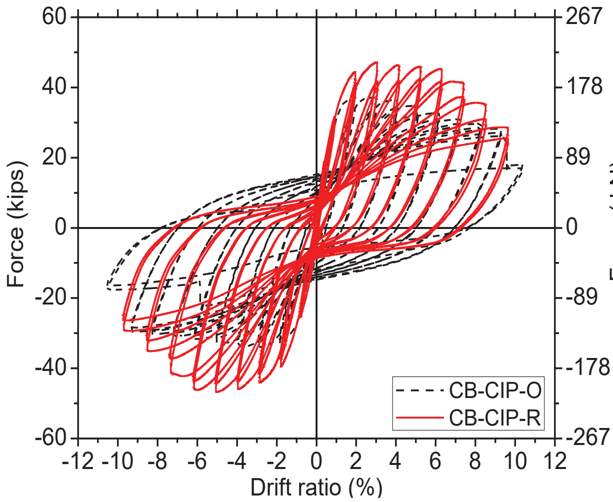
- 14 in. to 20 in. above donut
- 2.5 in. inside donut
- No bar fractured

PC1-R2 PC2-R

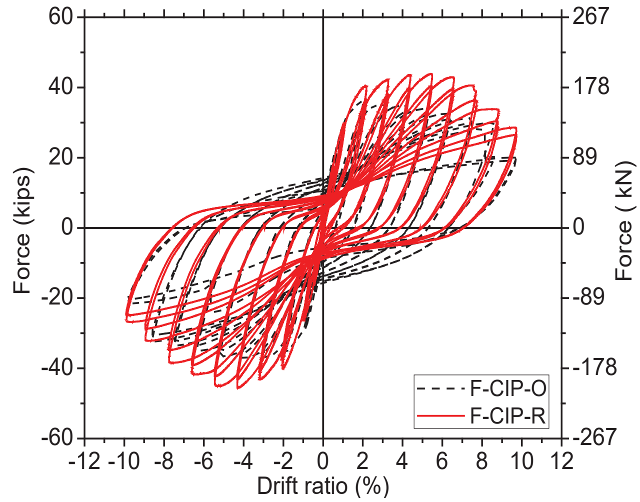
- 10 in. to 20 in. above donut
- No damage inside donut
- Two extreme bars fractured

Experimental Program: Phase II

## Phase II: Hysteretic Response CIP Specimens




CB-CIP




F-CIP



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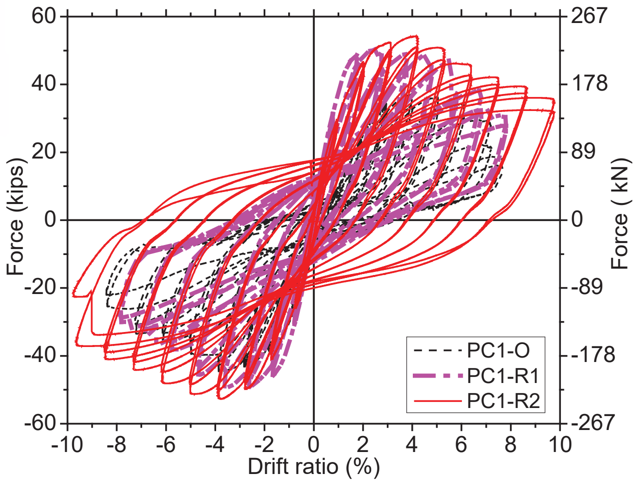
## Phase II Original Specimen Results: CIP Specimens

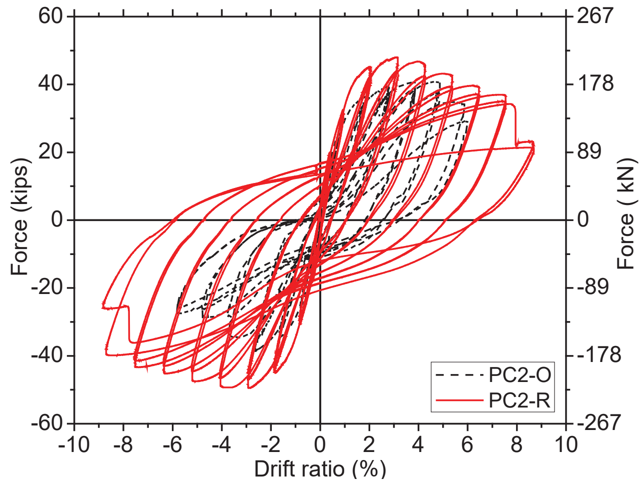
| TEST CRITERIA | CB-CIP-O | F-CIP-O | CB-CIP-R | F-CIP-R |
|---|---|---|---|---|
| MAX. LOAD (kips) | 35.8 | 36.5 | 47.0 | 44.7 |
| ULTIMATE DRIFT RATIO (%) | 9.3 | 8.8 | 8.1 | 8.4 |
| DISPLACEMENT DUCTILITY | 9.9 | 8.9 | 6.8 | 6.0 |

Experimental Program: Phase II

# Phase II: Hysteretic Response PC Specimens




PC1




PC2





# Phase II Original Specimen Results: PC Specimens

Second repair with crack epoxy injection (→ PC1-R2)

Repair with steel collar (→ PC2-R)

| TEST CRITERIA | PC1-O | PC1-R1 | PC1-R2 | PC2-O | PC2-R |
|---|---|---|---|---|---|
| MAX. LOAD (kips) | 41.0 | 49.9 | 53.4 | 39.7 | 48.8 |
| ULTIMATE DRIFT RATIO (%) | 6.7 | 5.6 | 7.8 | 5.5 | 7.6 |
| DISPLACEMENT DUCTILITY | * | 5.1 | 5.6 | 4.9 | 7.1 |

* Pre-damaged condition before testing

# Phase II: Repair Results

Second repair with epoxy injection

Repair with steel collar

| TEST CRITERIA | CB-CIP-R | F-CIP-R | PC1-R2 | PC2-R |
|---|---|---|---|---|
| MAX. LOAD (kips) | 45.6 | 43.8 | 53.4 | 43.3 |
| ULTIMATE DRIFT RATIO (%) | 8.1 | 8.4 | 7.8 | 7.6 |
| FAILURE MODE | Concrete crushing | Concrete crushing | Extreme bar fracture; Concrete crushing | Extreme bars fracture; Concrete crushing |
| DISPLACEMENT DUCTILITY | 6.8 | 6.0 | 5.6 | 7.1 |



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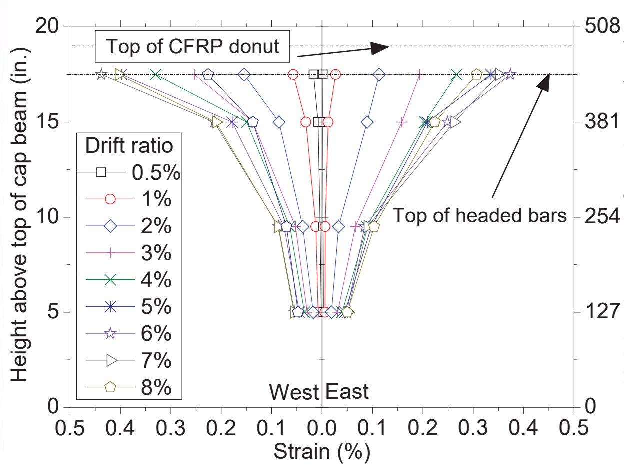
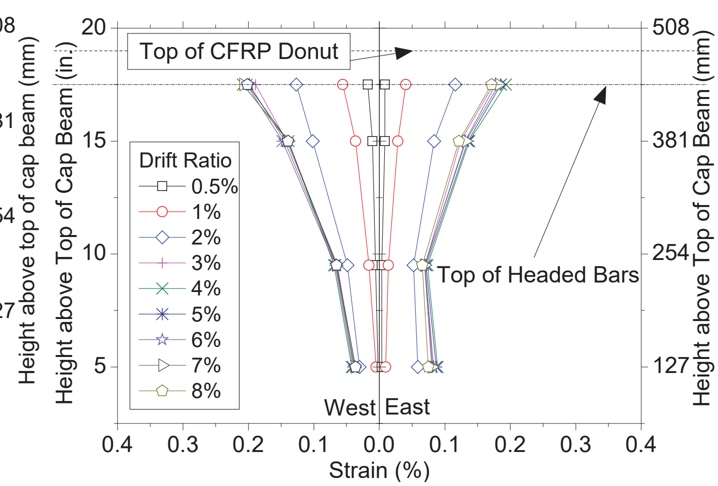
# Phase II: CFRP Hoop Strain Profile

CB-CIP-R




PC2-R




- <u>**Top 6 in.**</u> of the CFRP shell: CB-CIP-R: STRAIN 0.2 - 0.5%; PC2-R: STRAIN 0.2%
- The CFRP shell formed an effective tension ring

- Analytical Study
  - Description of Bond-slip
  - Analytical Models
  - Comparison of Results





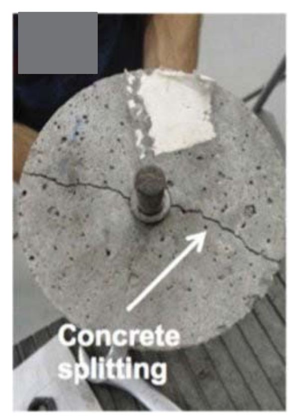
## Description of Bond-slip

- Bond-slip phenomenon between longitudinal bars and surrounding concrete cannot be ignored (Eligehausen et al. 1982; Harajli 2009)
- Bond-slip deformation occurs either in pullout mode or a splitting mode

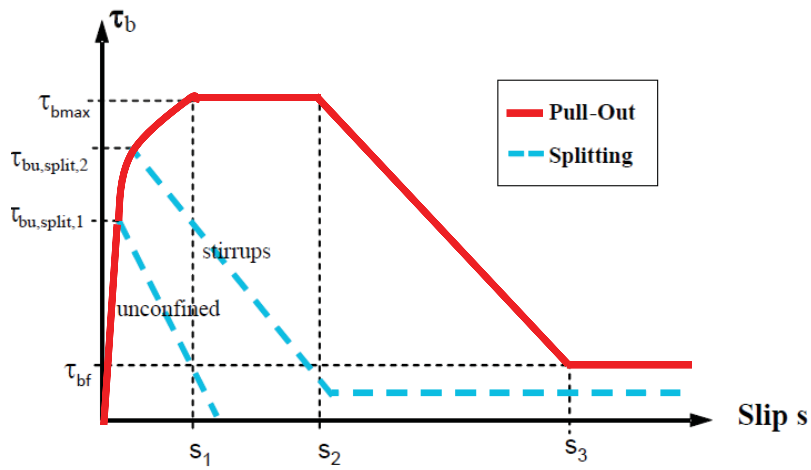
  For concrete not well confined bond failure occurs in a splitting mode
- Bond slip affects global response by reducing stiffness and strength

Pullout mode


Splitting mode



# CEB-FIB Model Code 2012



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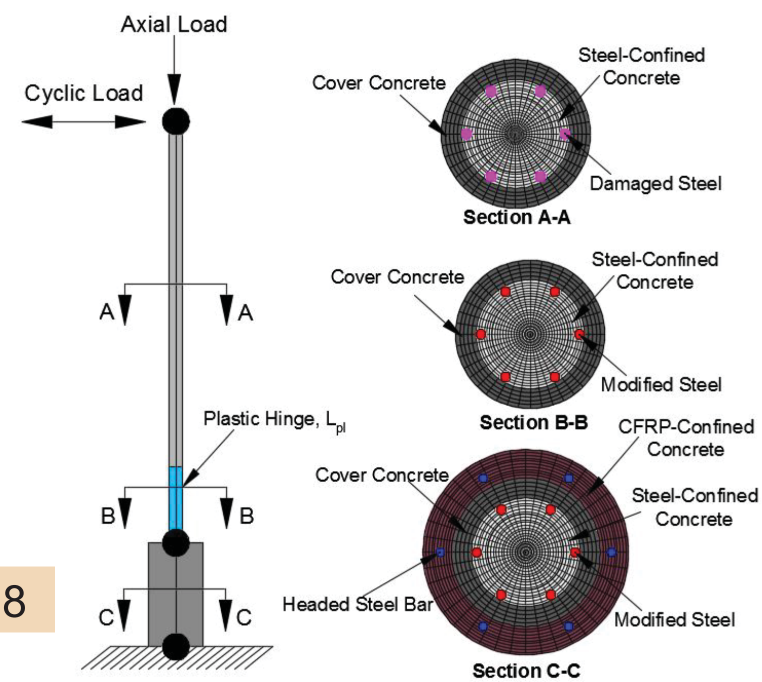
# Analytical Models

Model Fiber

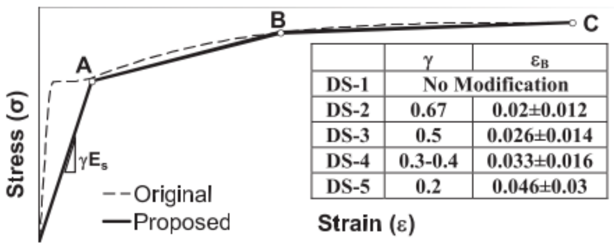
- Distributed plasticity considering bond slip concentrated in plastic hinge length
- Using the *BeamWithHinges* element for column



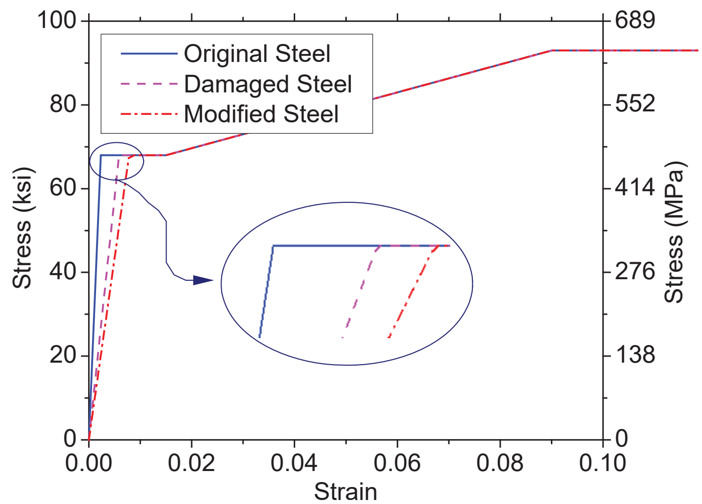

Wu and Pantelides 2018

# Considering Initial Damage

Reduced elastic modulus of steel, adapted from (Vosooghi and Saiidi 2013)




| | γ | $\varepsilon_B$ |
|---|---|---|
| DS-1 | No Modification | |
| DS-2 | 0.67 | 0.02±0.012 |
| DS-3 | 0.5 | 0.026±0.014 |
| DS-4 | 0.3-0.4 | 0.033±0.016 |
| DS-5 | 0.2 | 0.046±0.03 |



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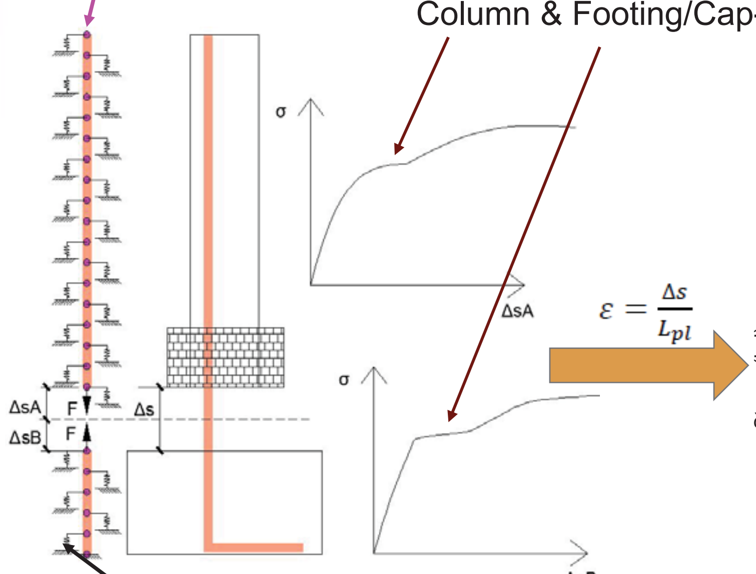
# Schematic of Bond-slip Model

damaged steel

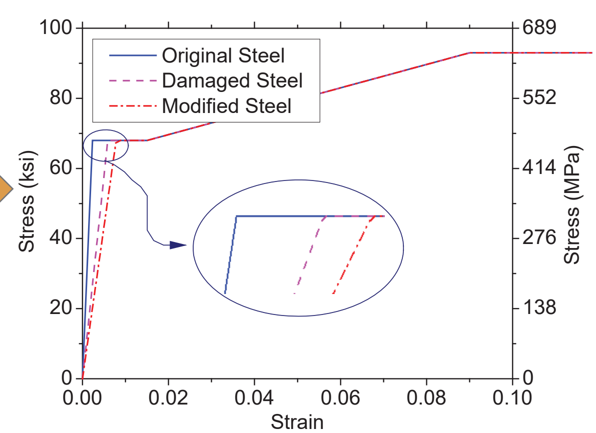
Bond-slip from two parts:
Column & Footing/Cap-beam




bond stress-slip

$$\varepsilon = \frac{\Delta s}{L_{pl}}$$

**Low-cycle *fatigue***
(Kunnath et al. 2004)



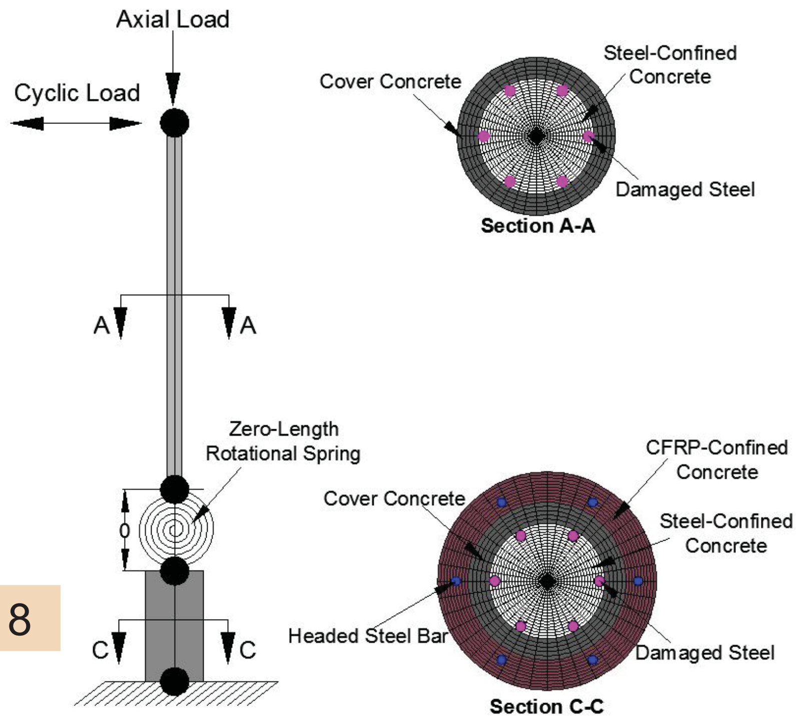

Analytical Study

# Analytical Models

Model RS

- Concentrated plasticity in non-linear moment rotational spring
- Using *Hysteretic* material to define spring

Wu and Pantelides 2018

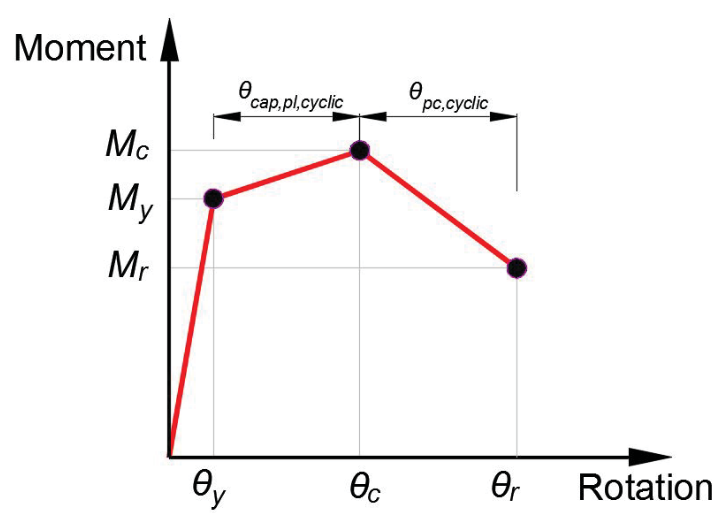






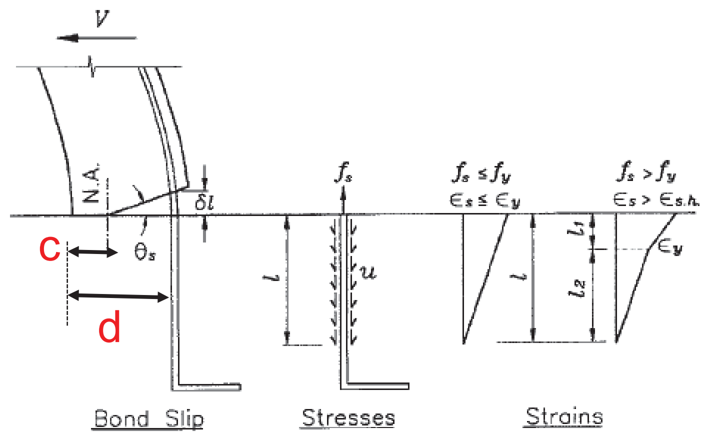

# Moment-rotation Relationship

Moment-rotation curve based on existing models (Haselton et al. 2016)



# Calculation of Moment-rotation Relationship

- Sectional analysis to get moment-curvature
- Considering steel strain and bond strength to get rotation




Adapted from Wehbe et al. 1999

$$\theta = \frac{\delta l}{d - c}$$



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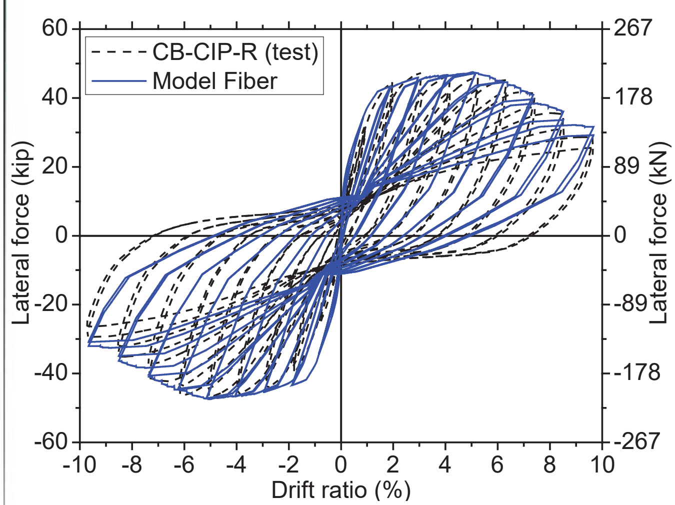
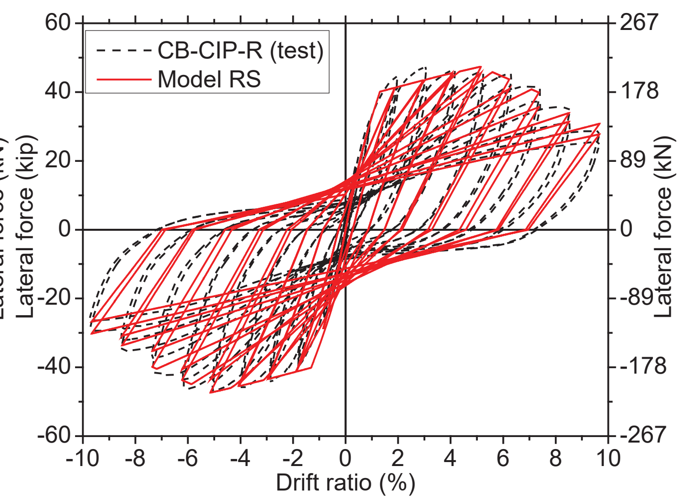
# Comparison of Results: Specimen CB-CIP-R




Test vs Model Fiber




Test vs Model RS

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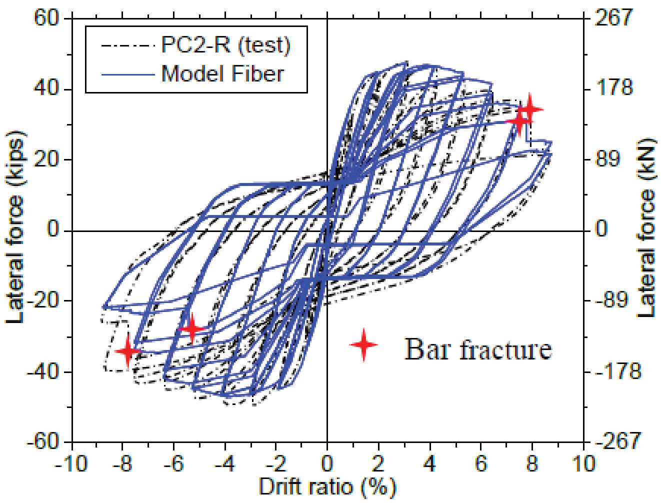
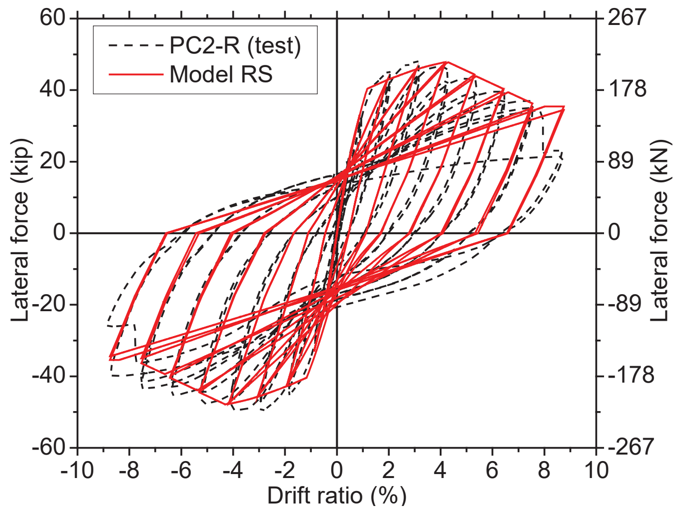
# Comparison of Results: Specimen PC2-R




Test vs Model Fiber




Test vs Model RS

Analytical Study

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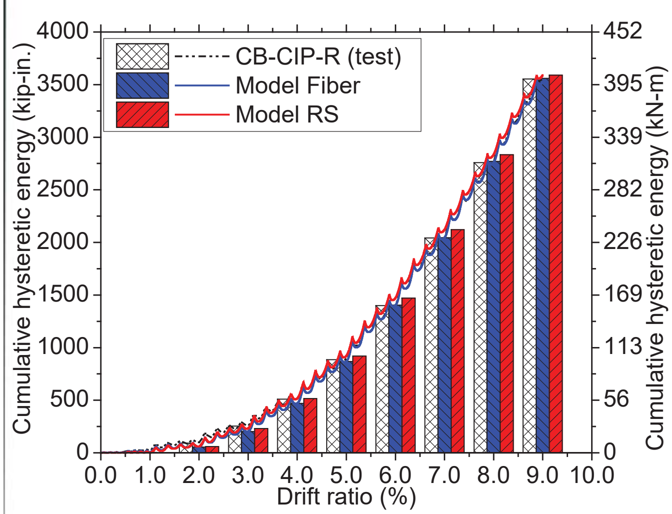
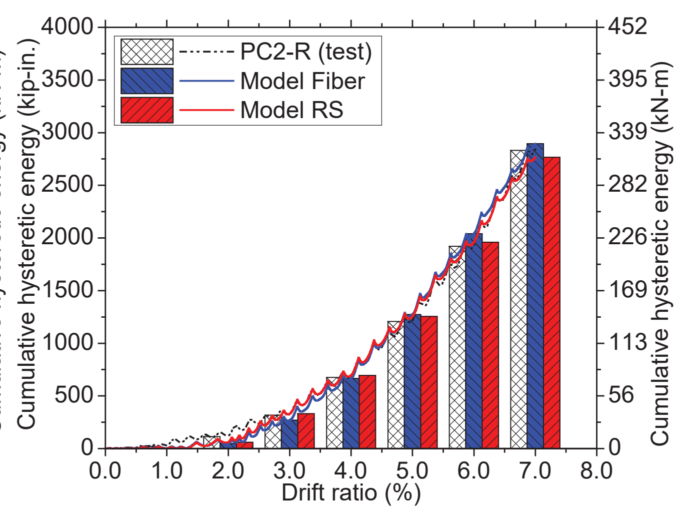
# Comparison of Results: Hysteretic Energy




CIP-R




PC2-R

Analytical Study

- Retrofit of Bridge
  - As-built multi-column bridge bent
  - Practical design of CFRP donut
  - Nonlinear pushover analysis
  - Nonlinear time-history analysis



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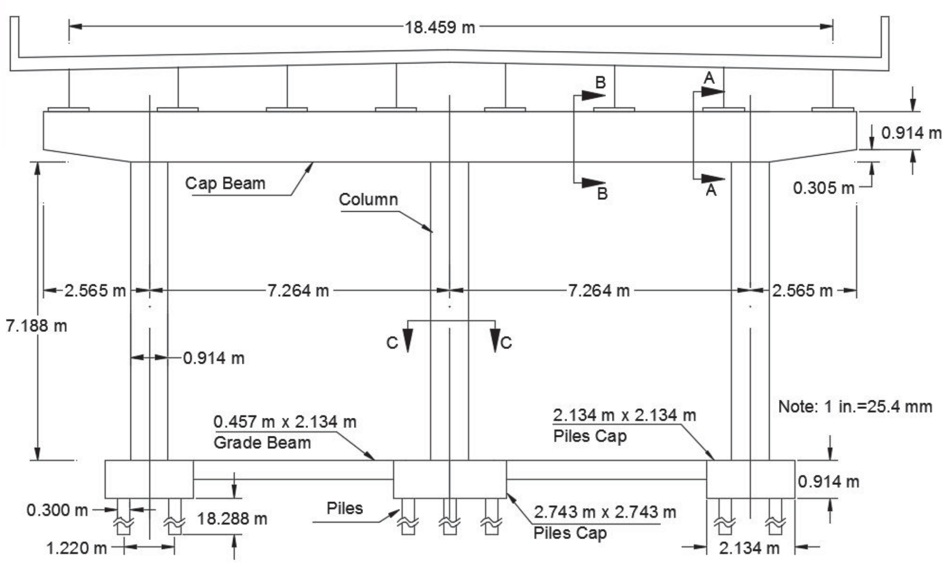
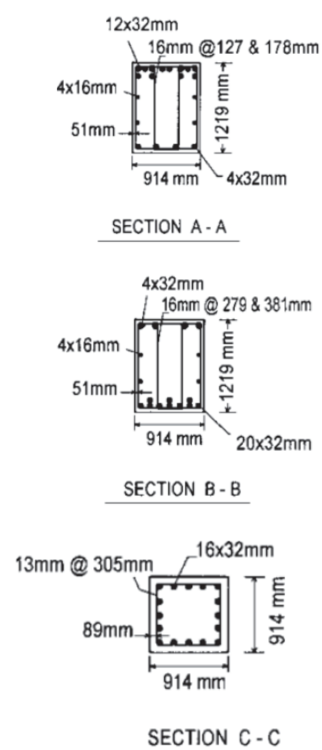
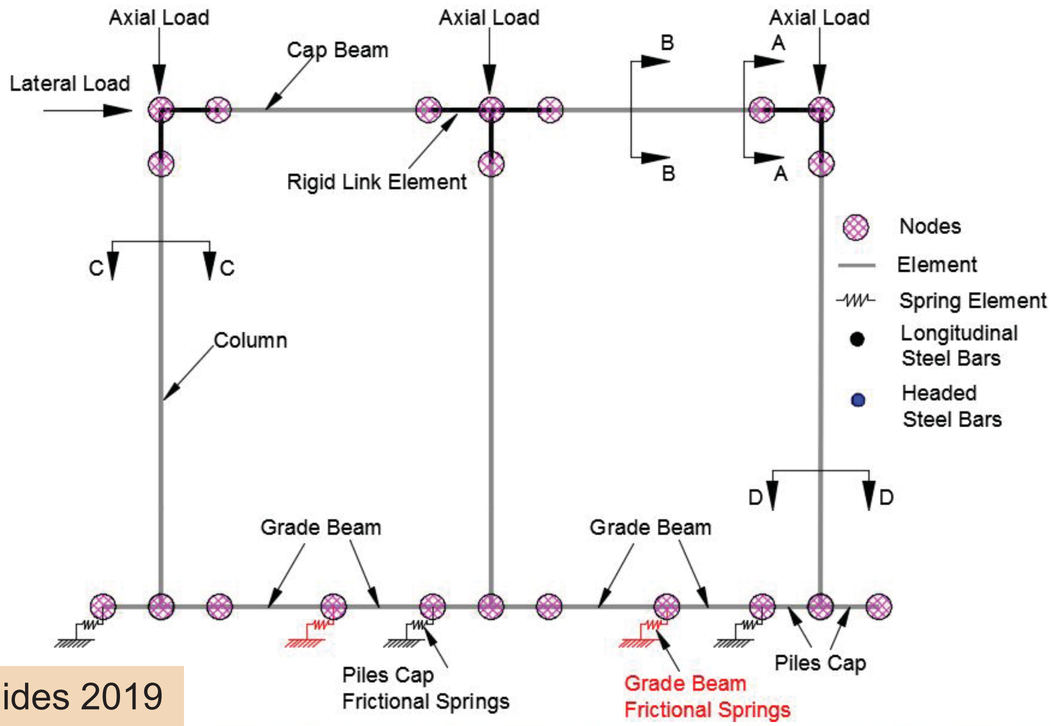
## As-built multi-column bridge bent




Pantelides et al. (1999)



# Schematic of bridge bent




Wu and Pantelides 2019



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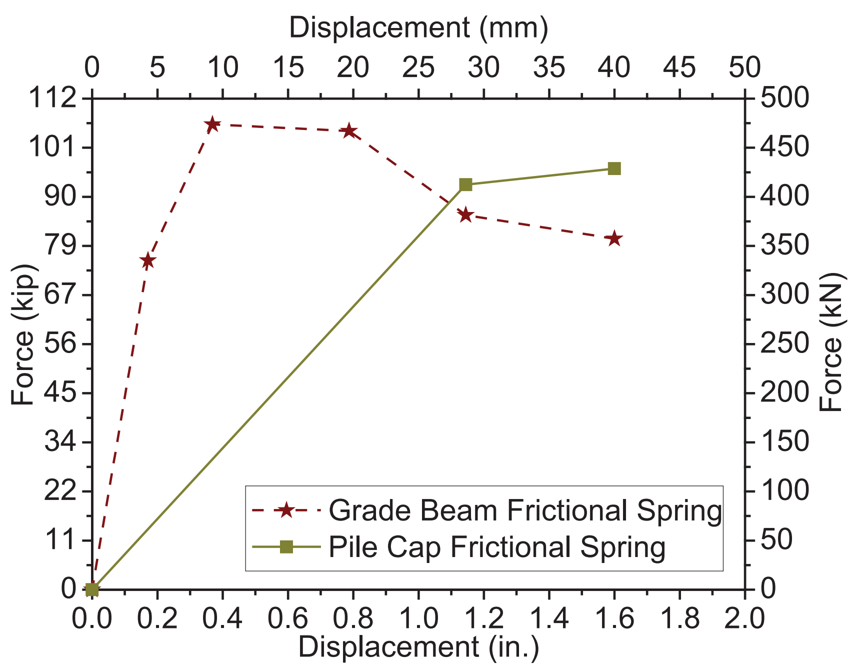
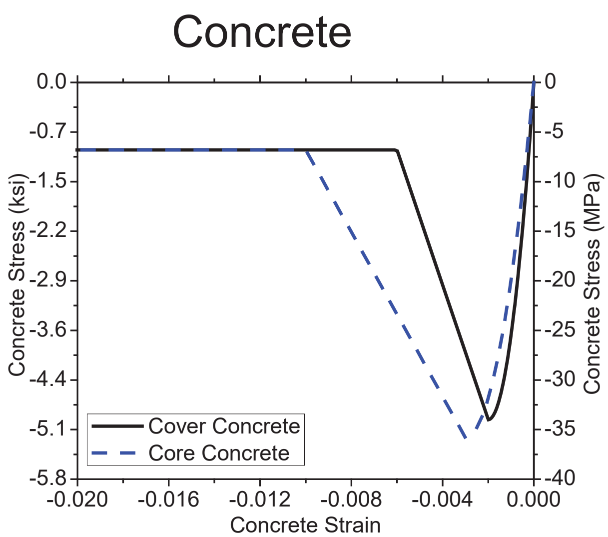
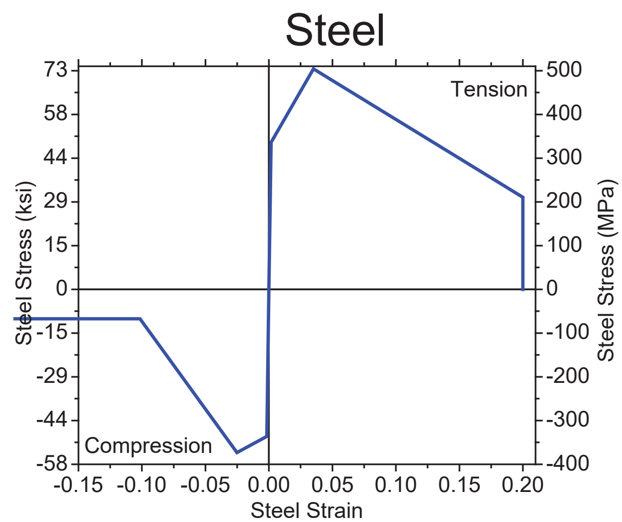
# Soil-structure interaction (SSI)




Simplified springs for pile cap and grade beam calibrated from Cook et al. (2002)

# Material constitutive models



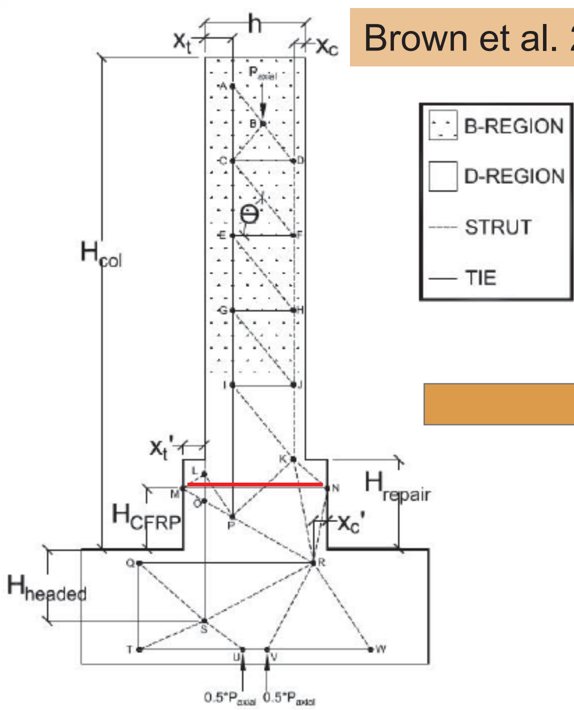

Rebar buckling was considered (Dhakal and Maekawa 2002)



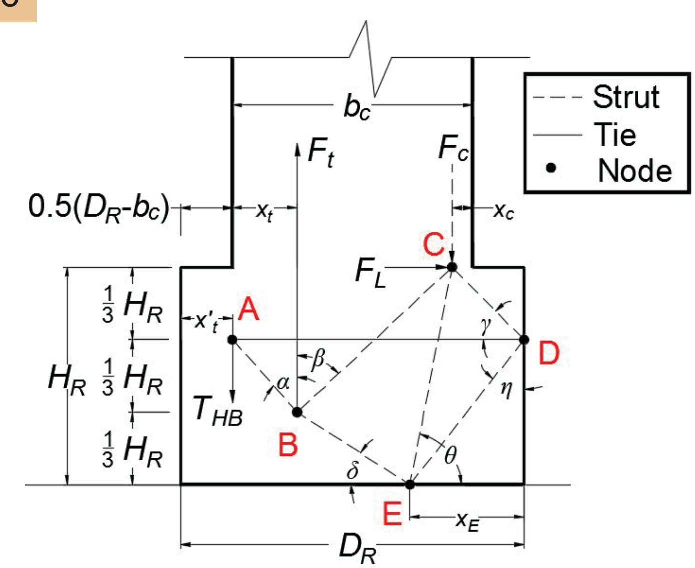


# Practical Design of CFRP Donut

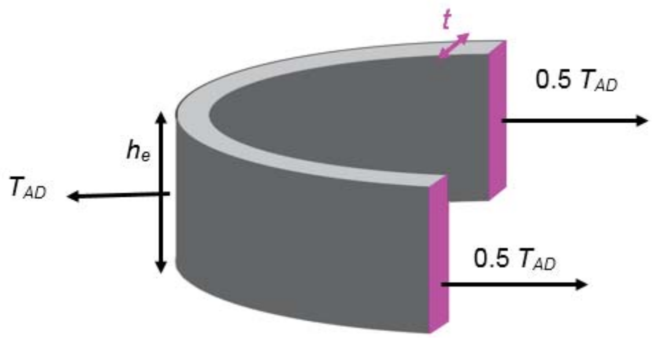
Brown et al. 2016




## Strut-and-tie model (STM)




Wu and Pantelides 2019




Benefits:

1. No need to analyze whole structure to get STM
2. Only lateral force and tension force from headed steel bars required
3. Convenient and practical for designers

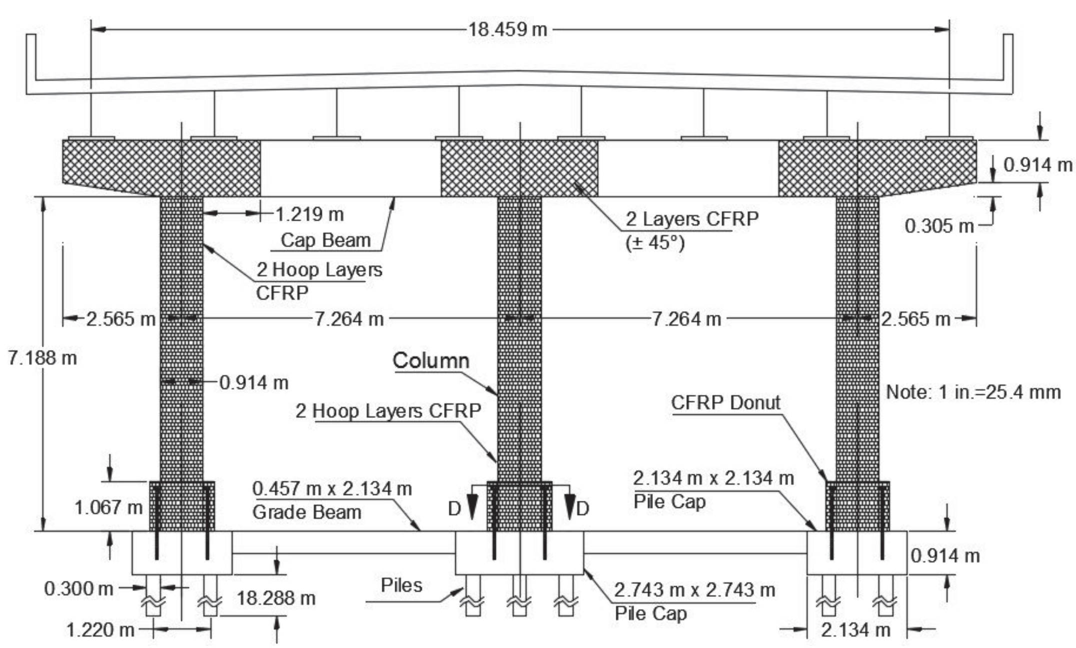
$$t = \frac{0.5\,T_{AD}}{E_f\,K_\varepsilon\,\varepsilon_{fu}\,h_e}$$

Wu and Pantelides 2019

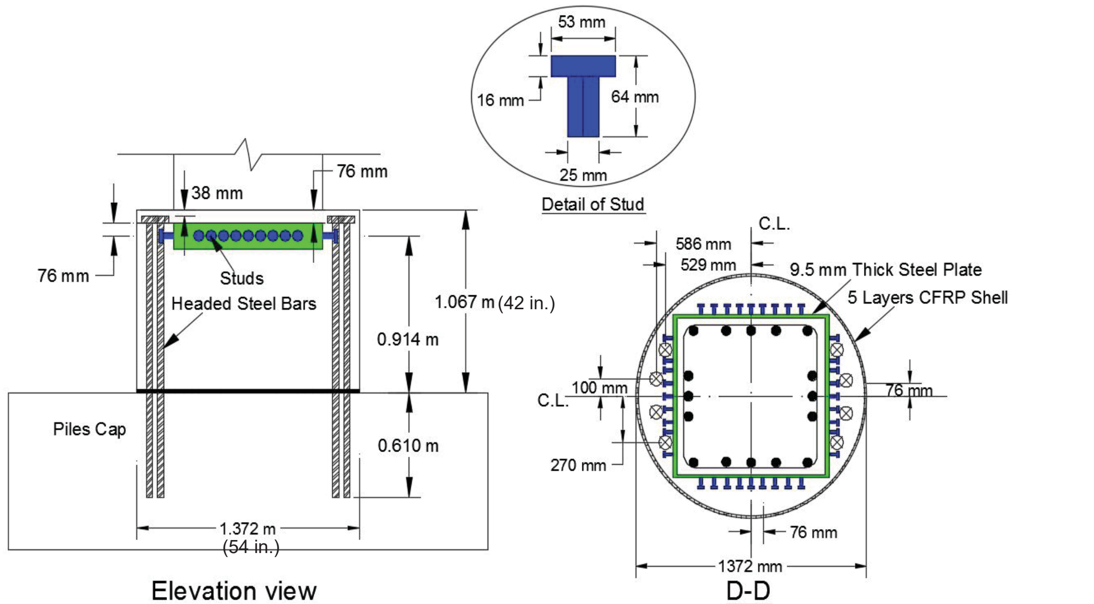




## Final Retrofit Design



# Design of CFRP Donut




Note: 1 in. = 25.4 mm



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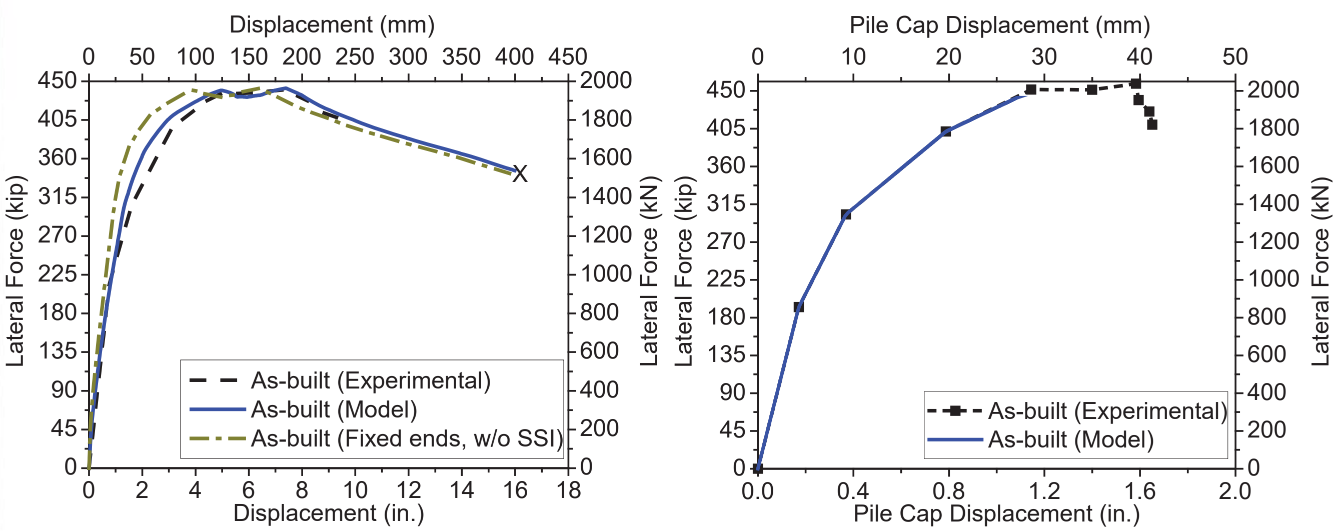
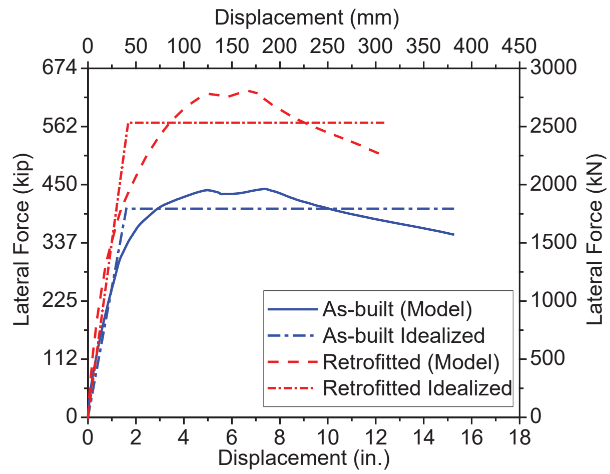
# Pushover Analysis



# Idealized Pushover Curves

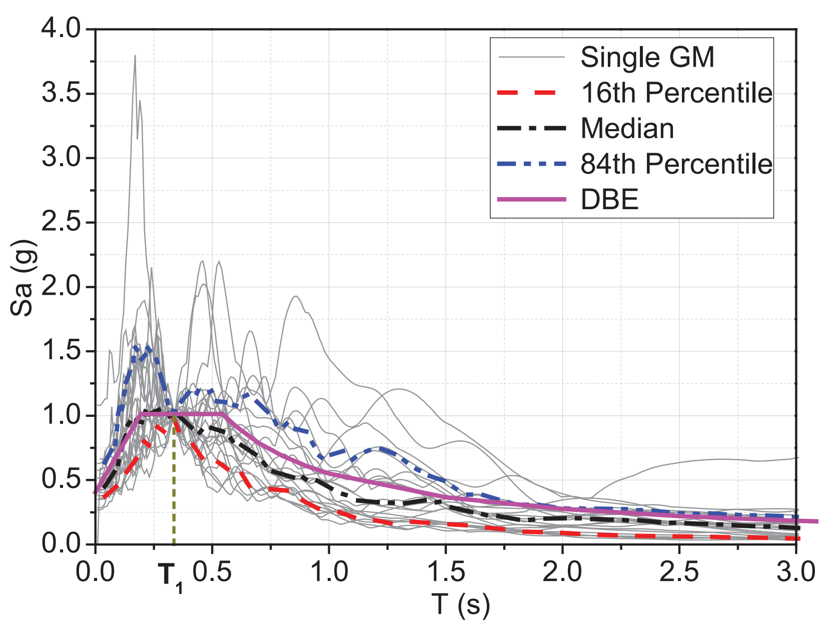
| | As-Built | Retrofitted |
|---|---|---|
| Maximum Lateral Force (kips) | 442 | 630 |
| Yield Force (kips) | 403 | 569 |
| Yield Displacement (in.) | 1.58 | 1.65 |
| Elastic Stiffness (kips/in.) | 256 | 346 |
| Displacement Ductility | 9.5 | 7.4 |







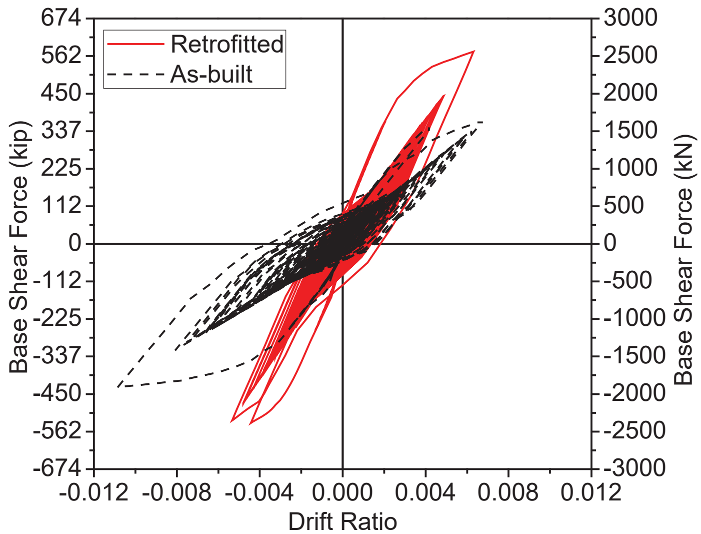

# Probabilistic Analysis (DBE and MCE levels)




22 far-field ground motions were selected from PEER

# Nonlinear time-history analysis

MCE level Imperial Valley 1979 earthquake




Hysteresis



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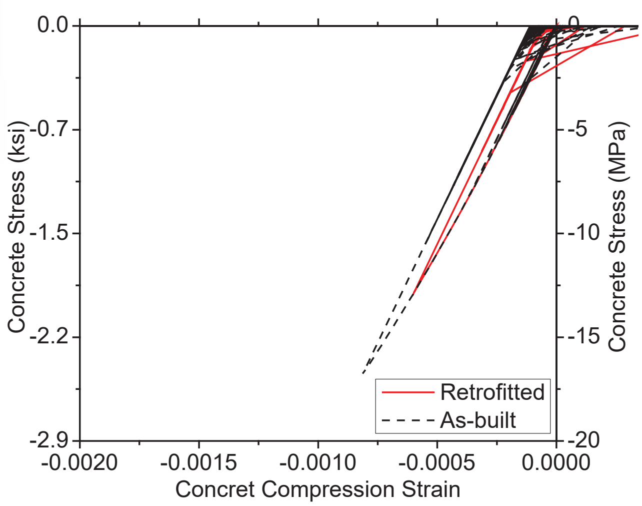
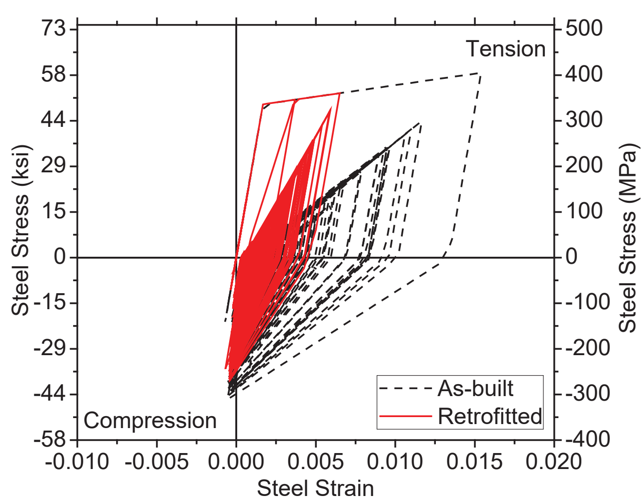
# Nonlinear time-history analysis




Concrete




Steel

## Definition of damage states (Mander et al. 2007)

| Damage state | Damage descriptions | | Drift ratio limits (%) |
|---|---|---|---|
| DS-1 | None | Pre-yielding | 0.0 |
| DS-2 | Minor/slight | Minor spalling | 0.5 |
| DS-3 | Moderate | Bar buckling | 1.9 |
| DS-4 | Major/extensive | Bar fracture | 5.1 |
| DS-5 | Complete/collapse | Collapse | 6.2 |



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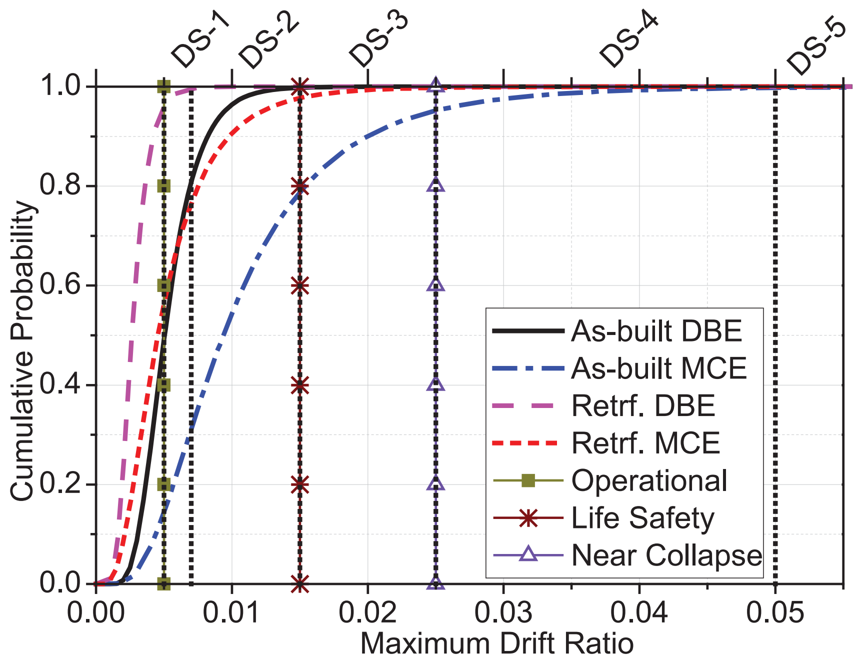
## Definition of limit states (Kowalsky 2000)

| Limit State | Strain Limits | | Drift Limits (%) |
|---|---|---|---|
| | Concrete Compression Strain (%) | Steel Tension Strain (%) | |
| Operational | 0.4 | 1.0 (Beam)<br>1.5 (Column) | 0.5 |
| Life Safety | 1.8 | 6.0 | 1.5 |
| Near Collapse | - | - | 2.5 |

## Cumulative Distribution Function (CDF)



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## Conclusions

1. Seismic rehabilitation method with CFRP composites in hoop and vertical directions with headed steel bars and nonshrink concrete for plastic hinge relocation - steel collar with shear studs implemented

2. Method restored strength and displacement capacity successfully for severely damaged concrete columns {concrete crushing and longitudinal steel bar fracture and buckling}

3. Two analytical models (Model Fiber and Model Rotational Spring) were developed with bond-slip effects, effects of previous loading history, cyclic degradation of column steel bars

4. Future modeling recommendation: both analytical models should be used to determine range of structural responses and obtain lower bound estimate of load and displacement capacity

## Conclusions

5. Analytical model with consideration of soil-structure interaction (SSI) was effective and reproduced experiments from in-situ tests - simplified springs were used to model soil-structure interaction
6. Proposed rehabilitation method using CFRP donuts and CFRP jackets was employed to retrofit as-built bridge bent - based on pushover analysis
7. Rehabilitation method increased lateral load capacity and elastic stiffness
8. Simplified design guidelines of proposed repair method were developed using strut-and-tie model (STM)

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- **Mountain Plains Consortium (MPC-405, MPC-491)**

- **Forterra Structural Precast**
- **Sika Corporation**
- **Headed Reinforcement Corporation**

- M Bryant, HEDCO Structures Lab Manager
- LD Reaveley, Professor Emeritus, University of Utah
- MJ Ameli, P Sankholkar, A Upadhyay, T Nye, R Barton, and D Tran

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