Development and Seismic Evaluation of Pier Systems with Pocket Connections and UHPC Columns

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Accelerated Bridge Construction (ABC)

ABC is a bridge construction technique that uses innovative design and new construction methods in a safe and cost-effective manner to expedite construction.

Time-Consuming Construction Tasks:

- Installing formworks
- Placing reinforcing steel
- Casting concrete
- Curing concrete
- Removing formworks

Solution? → Prefabricated Reinforced Concrete Members

Major Advantage:

- Reduce onsite construction time → Better serving the traveling public

Major Disadvantage:

- Lack of research results and guidelines for seismic design of prefabricated members and connections.

Past Research on Connections

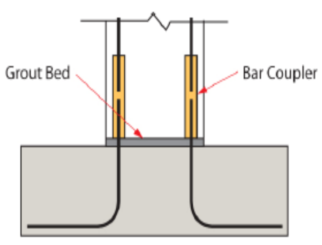
Connections of the prefabricated members are particularly critical in moderate and high seismic zones.

Type of connections:

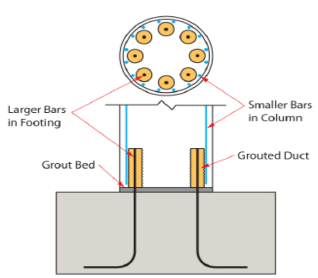
- ➢ Bar coupler
- ➢ Grouted duct
- ➢ Pocket (socket) connection

Advanced Materials in Plastic Hinge Zones

- Shape memory alloys
- Elastomeric bearings
- Ultra-high performance concrete (UHPC)
- Engineered cementitious composite (ECC)

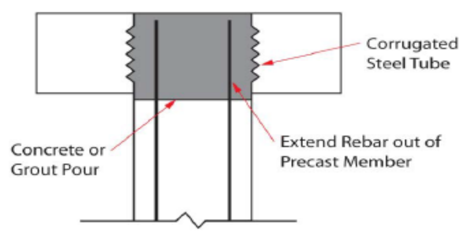


Bar coupler

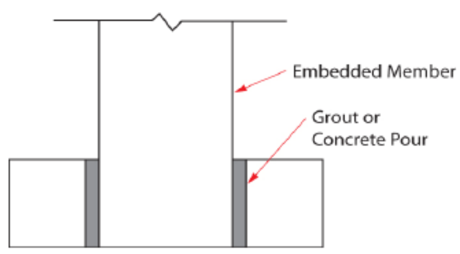


Typical grouted duct.

Marsh et al. (2011)



Pocket connection concept.



Member socket connection concepts.

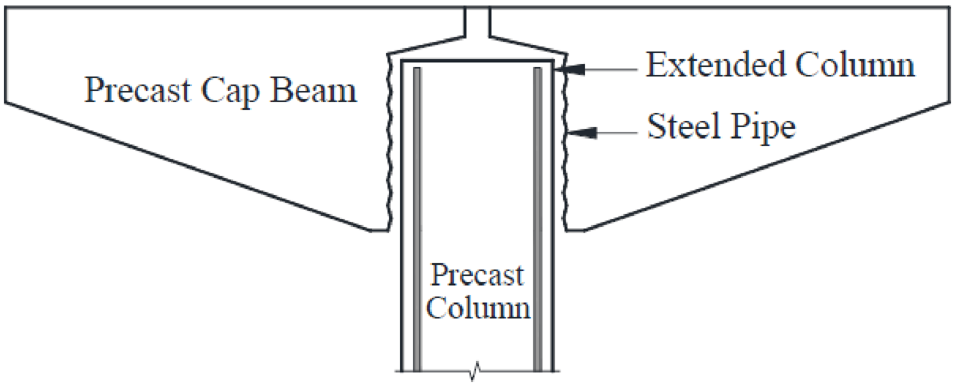
Marsh et al. (2011)

Motaref et al. (2010)

Tazarv and Saiidi (2014)

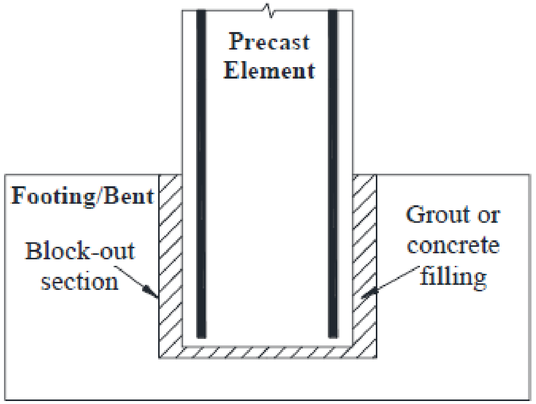
Pocket Connections

Cap Beam Pocket Connection



Tazarv and Saiidi (2015)

Footing Pocket Connection



Tazarv and Saiidi (2015)

Column Embedment Length in Cap Beam

Mehraein and Saiidi (2016) :1.0xD_c
Mehrsoroush and Saiidi (2016) :1.2xD_c
Larosche et al. (2014) :1.3xD_c
Restrepo et al. (2011) :1.2xD_c

Column Embedment Length in Footing

Kavianipour and Saiidi (2013) :1.5xD_c
Haraldsson et al. (2013) :1.1xD_c
Tran et al. (2012) :1.4xD_c
Motaref & Saiidi (2011) :1.5xD_c

Research Objectives

- Evaluate the seismic performance of precast square columns with pocket connections in the footing and cap beam

- Determine the effectiveness of advanced materials incorporated in design of columns
  - Carbon fiber reinforce polymer (CFRP) tendons
  - Ultra-high performance concrete (UHPC)
  - Engineered cementation composite (ECC)

- Develop seismic design methods for square/rectangular columns and pocket connections utilizing the results from this and previous studies.

This study consisted of:

- Experimental study
- Analytical investigation
- Design method development

Test Models:

- Single column bent
- Two-column bent

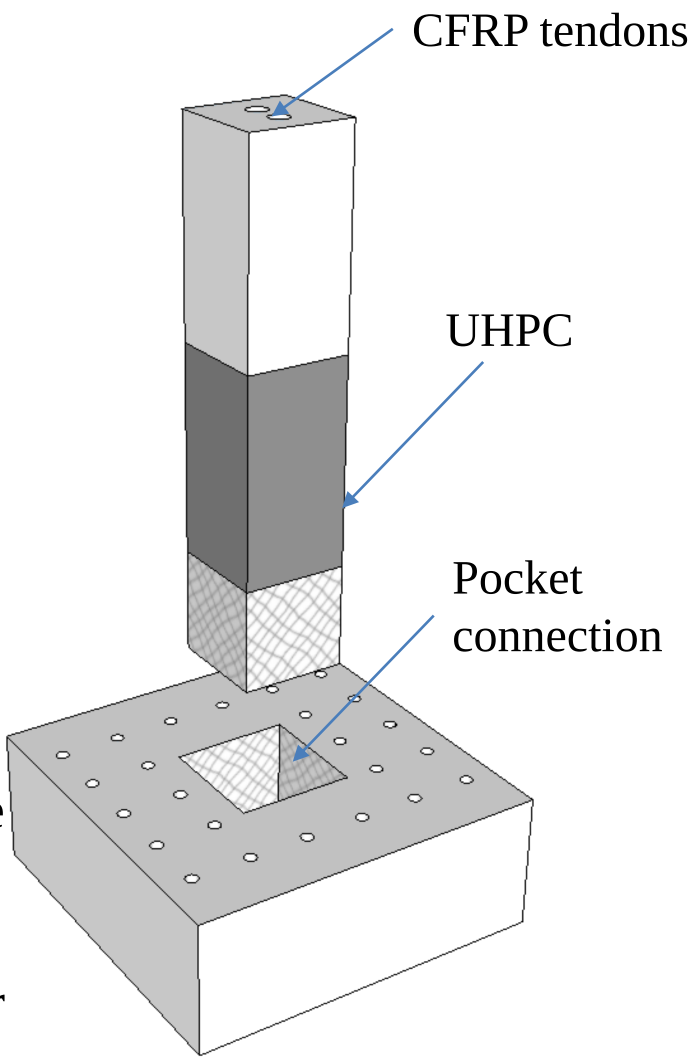
Column Model

Novel Aspects

- Precast column and footing with pocket connection
- Ultra-High Performance Concrete (UHPC) in plastic hinge
- Post-tensioning using unbonded Carbon Fiber Reinforced Polymer (CFRP) tendons

Specific Objectives

- Evaluate the seismic response of a precast square column with pocket connection at the footing.
- Investigate effectiveness of unbonded carbon fiber reinforced polymer (CFRP) tendons
- Determine the effectiveness of ultra-high performance concrete (UHPC)



Column Model- (Cont'd)

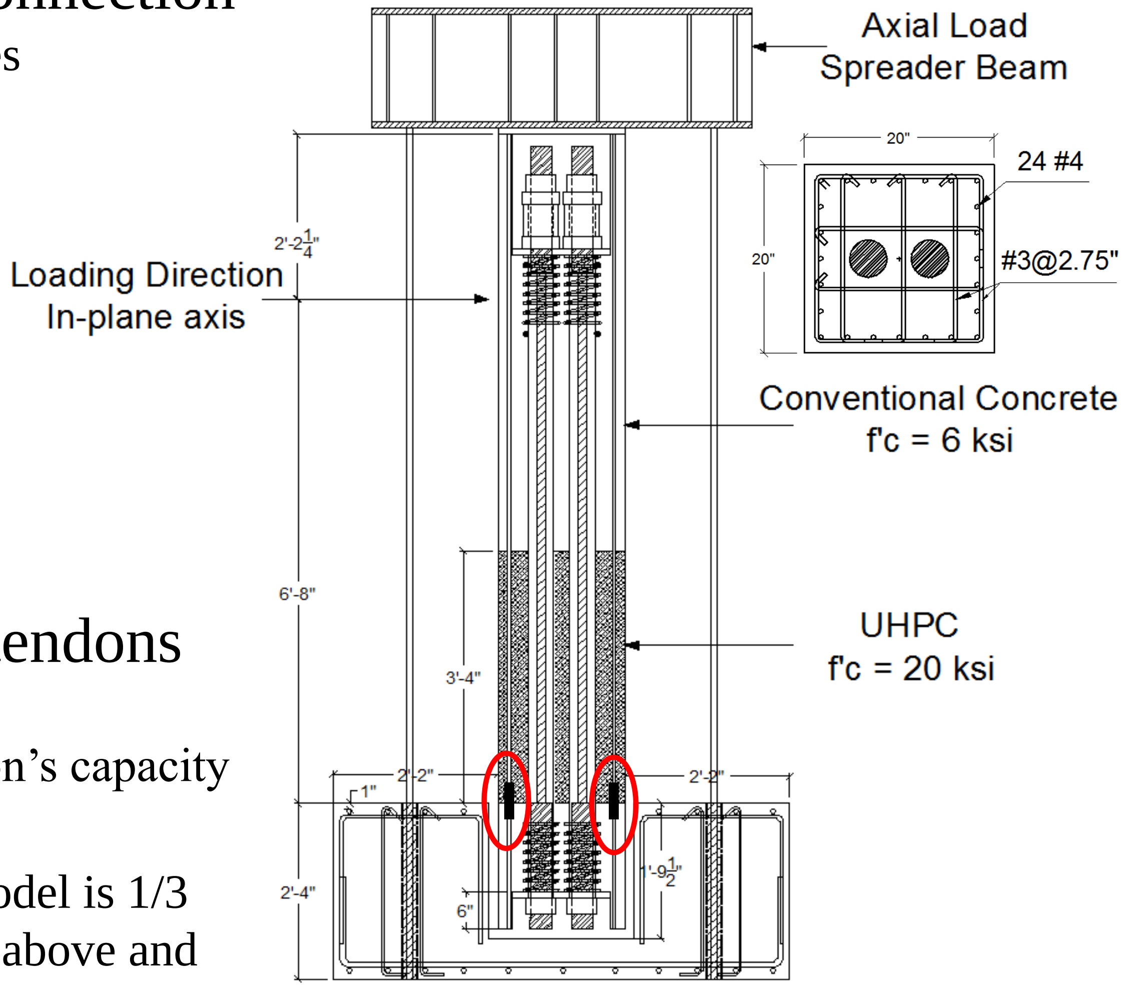
- Column-footing pocket connection
  - Embedment length = 1B = 20 inches
  - Pocket dimensions = 23" x 23"
  - Pocket depth = 21.5 inches

- UHPC
  - UHPC length = 2B = 40 inches
  - Compressive strength > 20 ksi
  - tensile strength > 0.7 ksi

- Post-tensioned w/ CFRP tendons
  - Initial tension force = 130 kips
  - Initial tension force = 25% of tendon's capacity

❖ Scale factor of the single column model is 1/3

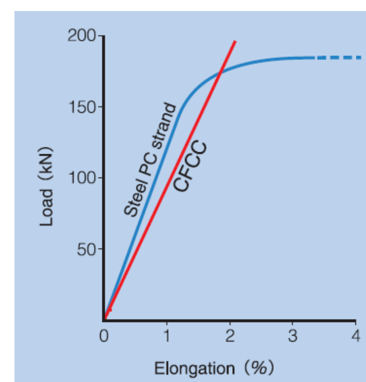
❖ Debonding long. bars over 4d_b each above and Below footing



CFRP Tendons

CFRP features:

- High tensile strength (~300 ksi)
- High tensile modulus (~21,030 ksi)
- Relaxation ~ 1.3%
- Noncorrosive
- Nonmagnetic
- Light weight (about 1/5 weight of steel strands)
- Low linear expansion (the coefficient of linear expansion is about 1/20 of the steel)



(Tokyo Rope)

UHPC Characteristics

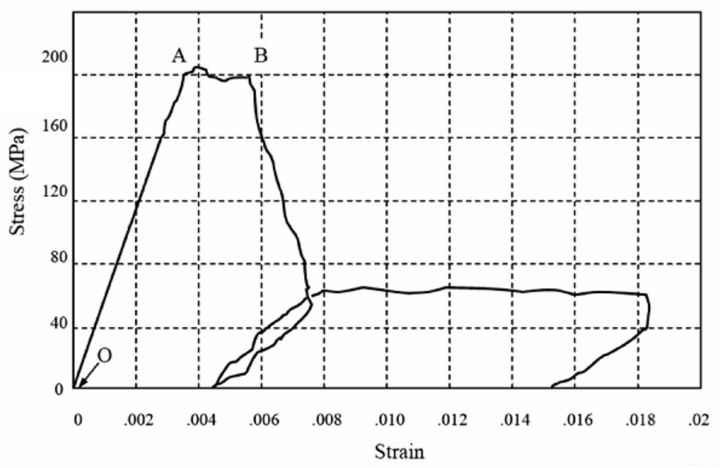
- High compressive strength > 20 ksi
- High tensile strain capacity
- Post-cracking tensile strength > 0.72 ksi
- High bond strength

Steel fibers:

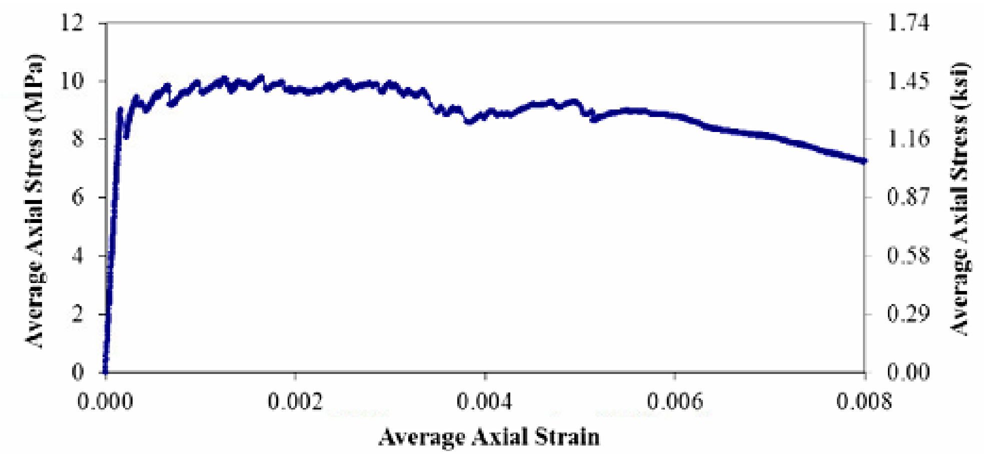
- 2% of the volume of the overall UHPC composite
- 0.008" diameter by 0.5" long straight fiber
- Minimum tensile strength of 290 ksi

Premix composite:

- Portland cement
- Silica fume
- Very fine aggregates such as quartz

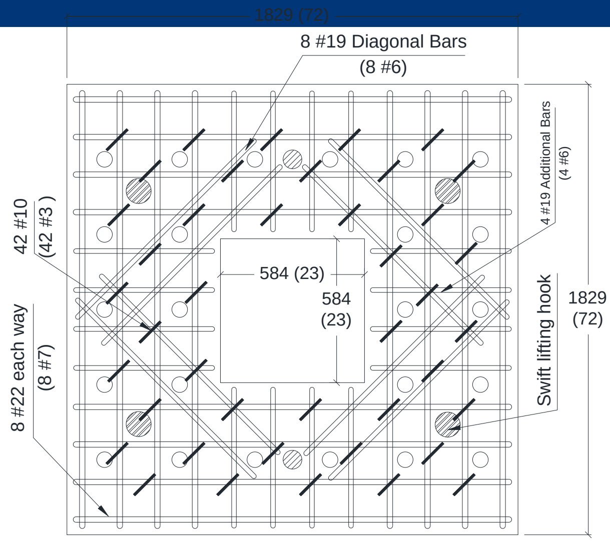


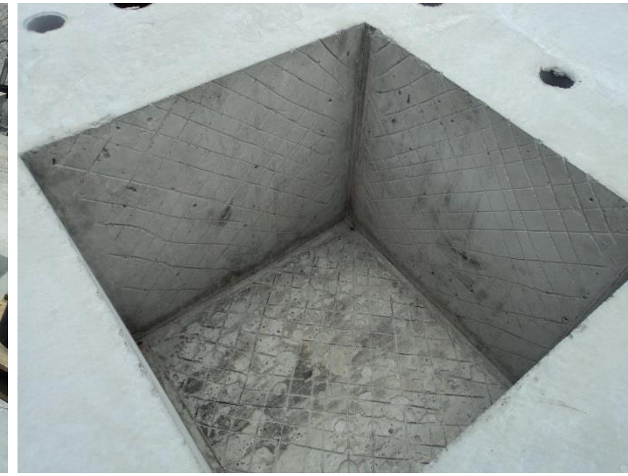
Gowripalan and Gilbert, 2000



Graybeal, 2006

Column Model





Column Model


(1)


(2)


(3)


(4)

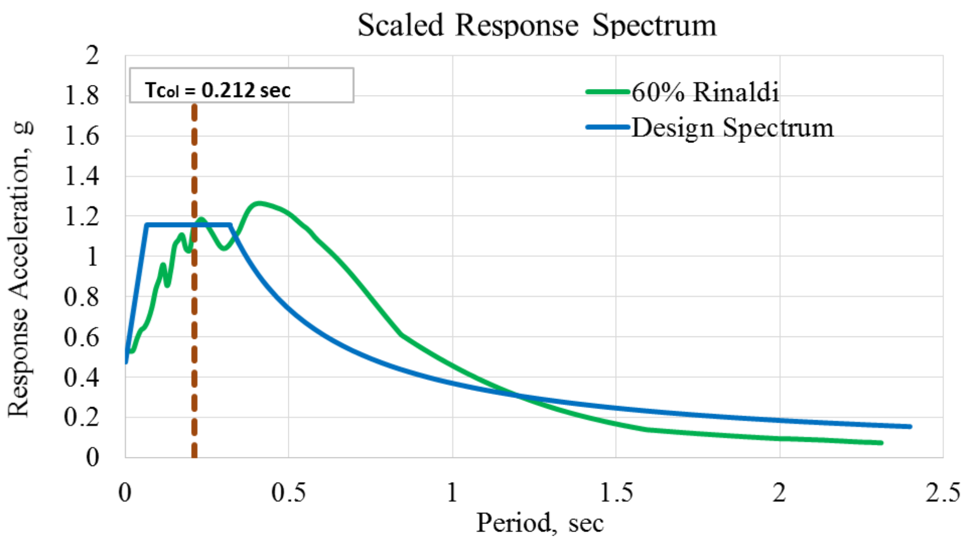
Column Model

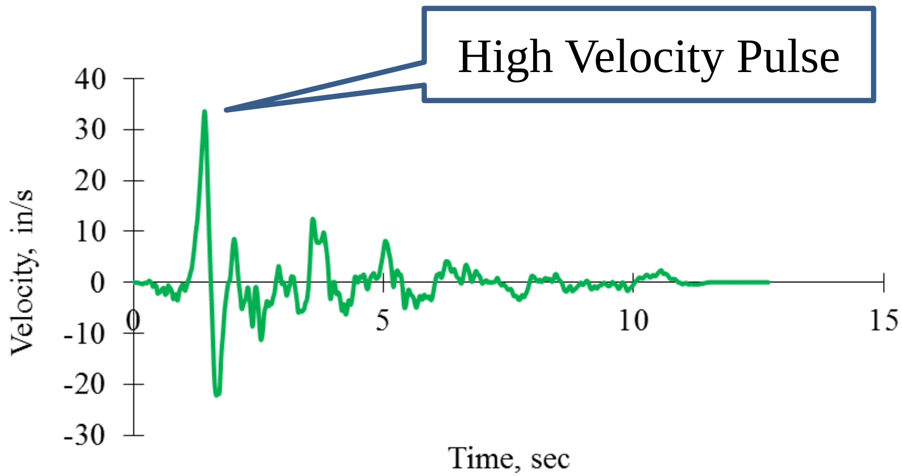
Northridge 1994 (M 6.7), Rinaldi Station

Design spectrum

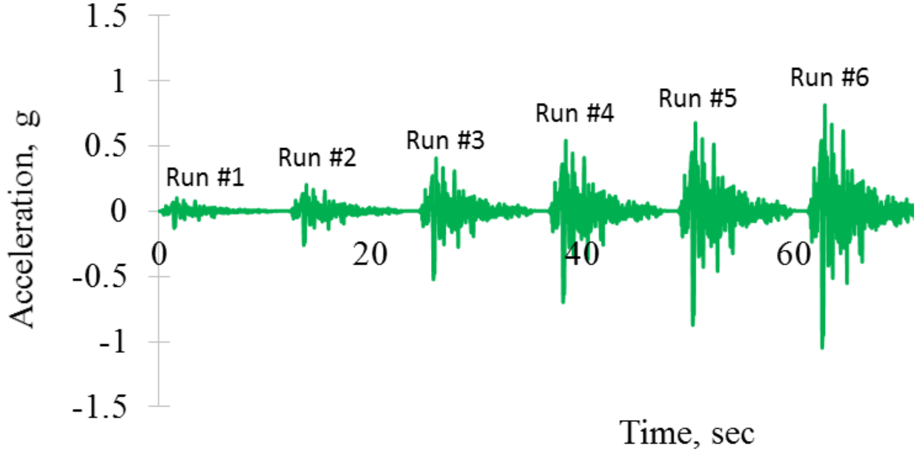
Location: Los Angeles area
Latitude: 3.84926 N
Longitude: 118.09252 W
Site class: D

According to AASHTO 2009
A_S=0.473g
S_{DS}=1.15g
S_{D1}=0.637g
T_S=0.552 sec
T_O=0.11 sec





Column Model



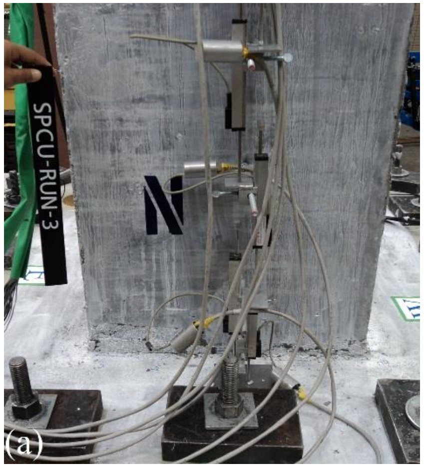
[Video, Run6 – Plastic Hinge](#)

[YouTube](#)

Run#	1	2	3	4	5	6
Design EQ	25%	50%	100%	133%	167%	200%

Column Model

Design Level
Max. Drift: 1.5%

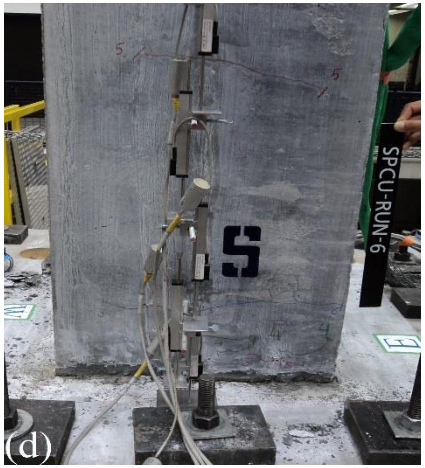


North

South

200% Design Level
Max. Drift: 6.82%

North



South

Damage State- (Cont'd)

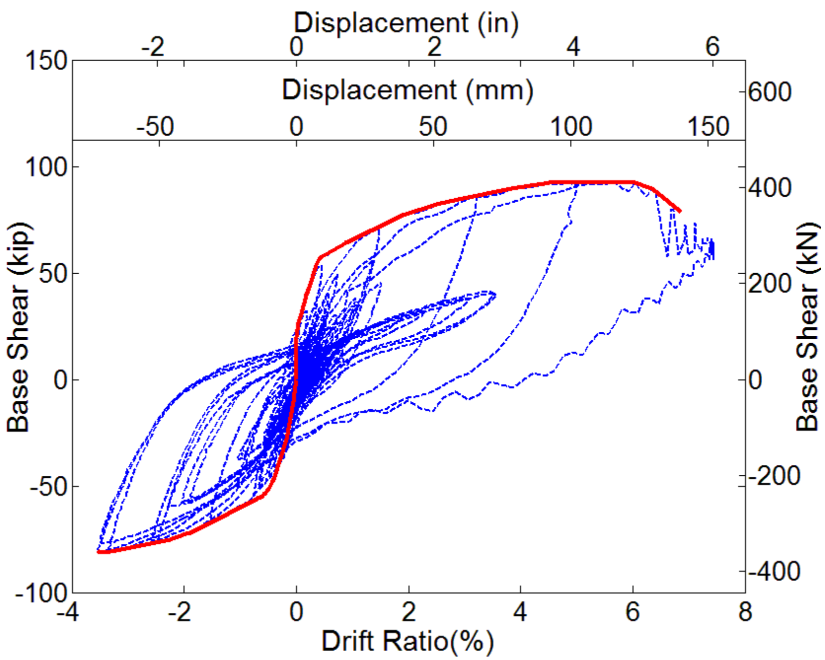
Run #6
Max. Drift: 6.82%

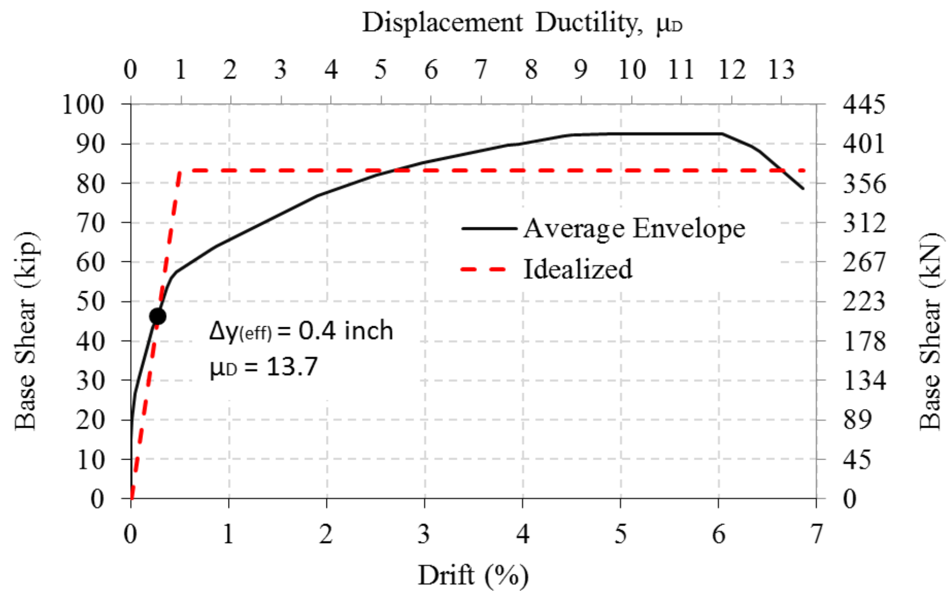
Nakashoji, 2014

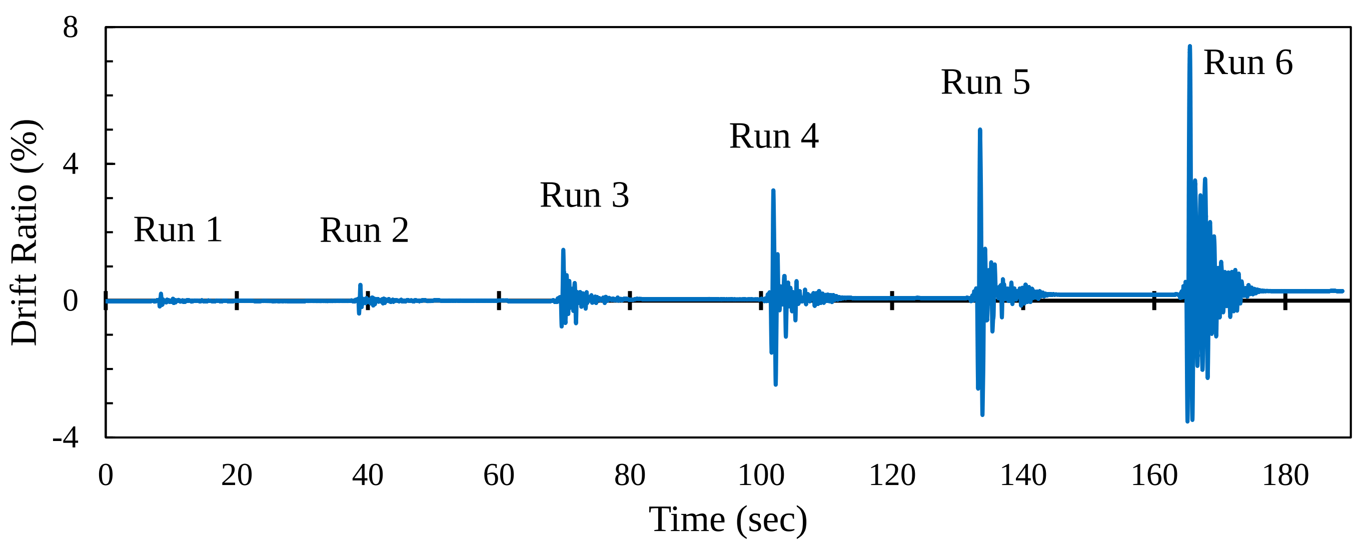
Nakashoji, 2014

Mehraein, 2016

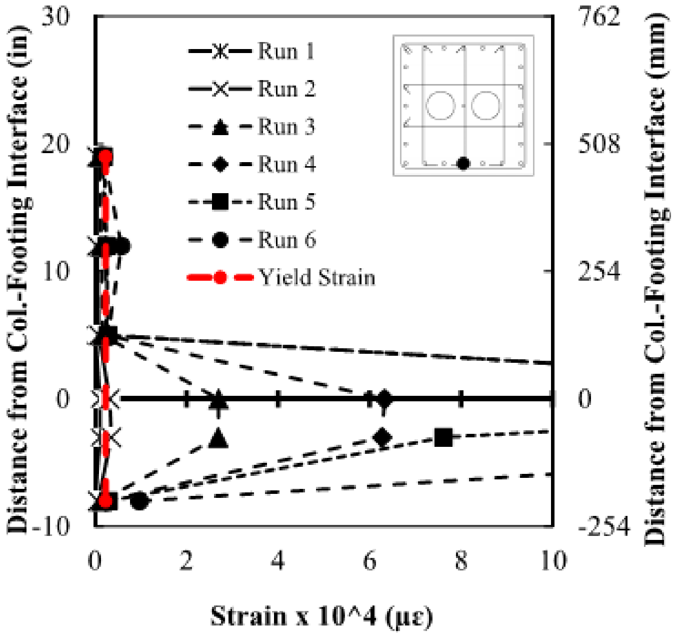
Column Model

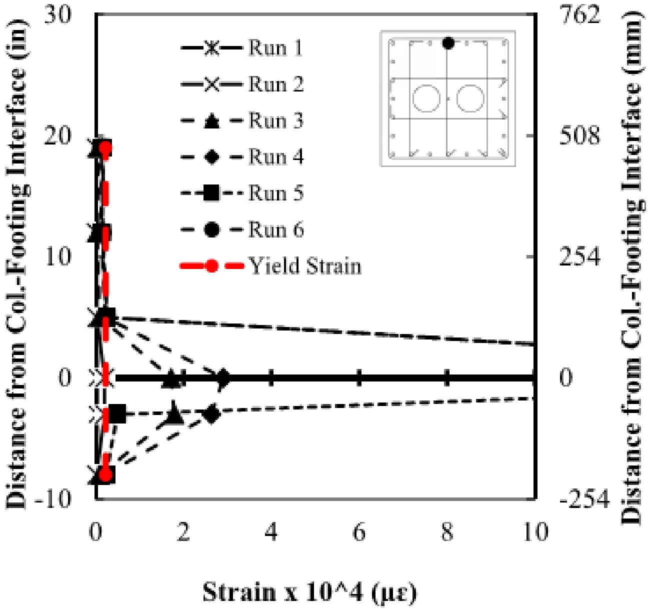


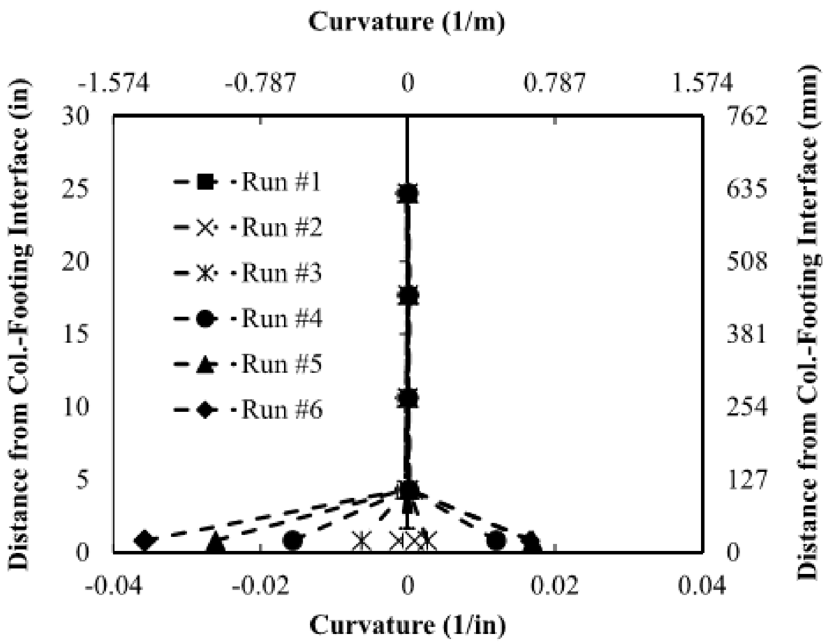




Test Results-(Cont'd)







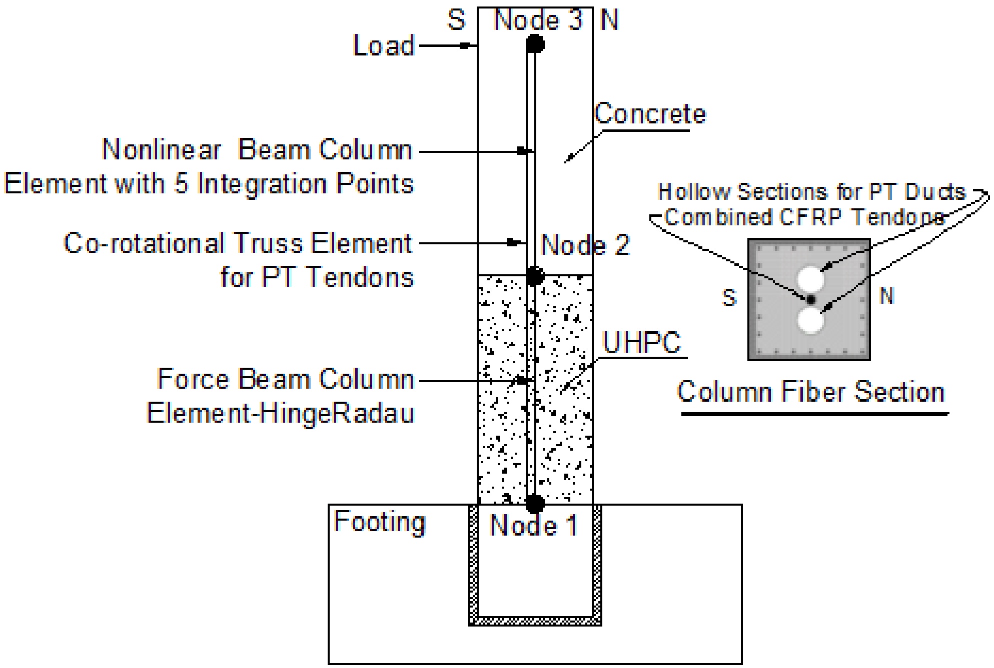
Observations-Column Model

- Pocket connection performed well without significant damage in footing.
- Embedment length of 1.0 times the column dimension in the pocket was adequate to provide the plastic moment at the base.
- CFRP tendons effectively eliminated the residual drift during different levels of earthquakes.
- UHPC mitigated the seismic damage, and apparent damage of the column model was limited to minor spalling of cover UHPC and a crack at the column-footing interface.
- Debonding of the longitudinal bars for 4db each above and below the footing interface was effective.
- Diagonal bars were effective around the pocket and reached 25% of the yield strain during the test.

Analytical Study-Column Model

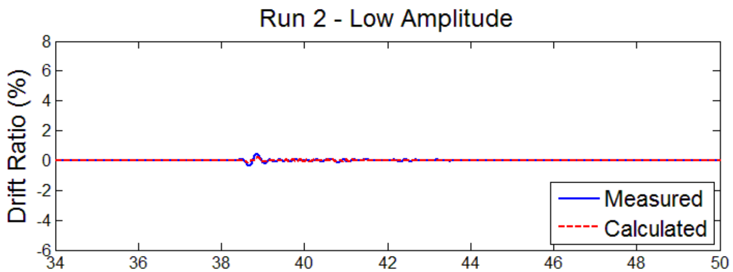
Specific Objectives:

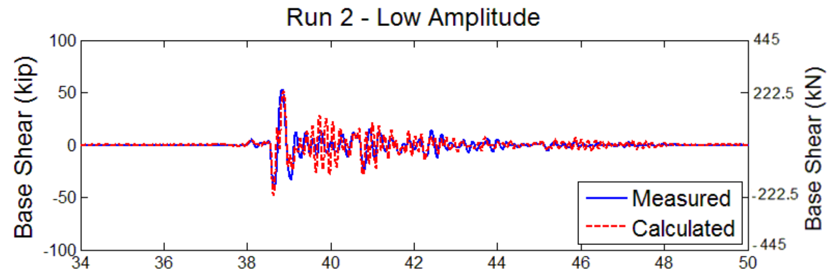
- Determine if available modeling methods can sufficiently duplicate the seismic response of the column model, and
- Evaluate the effect of CFRP/UHPC combination versus Steel/Concrete combination on the seismic response of columns.

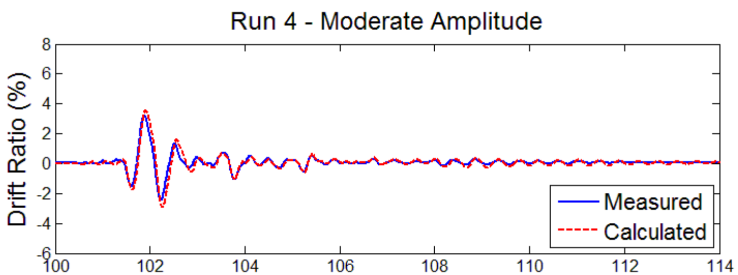


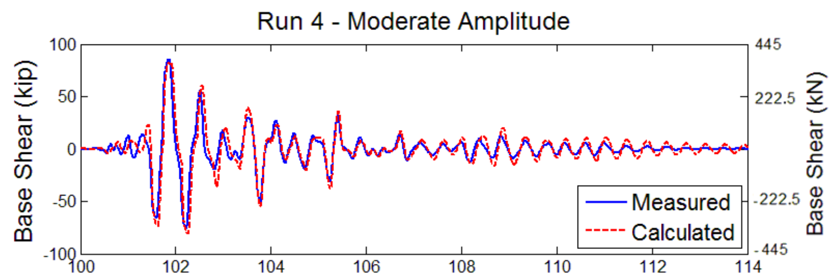
Software: OpenSees

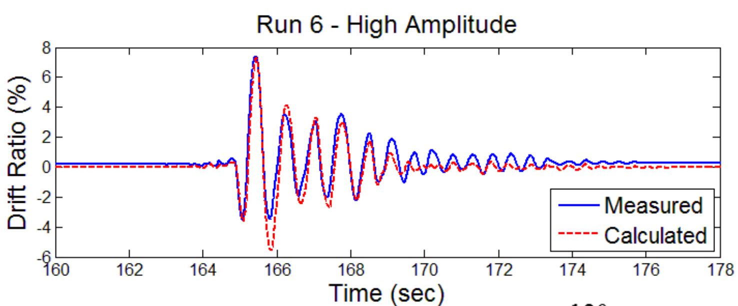
Analytical Results-Column Model

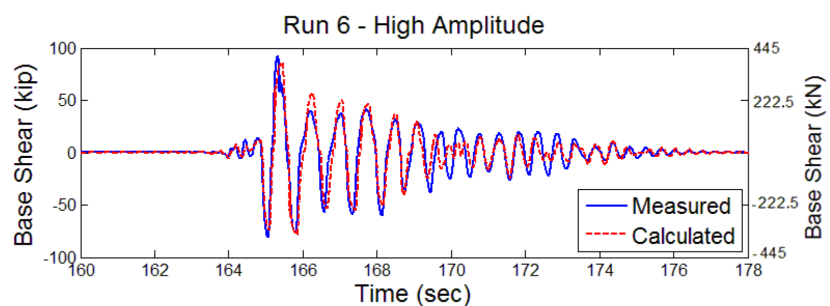


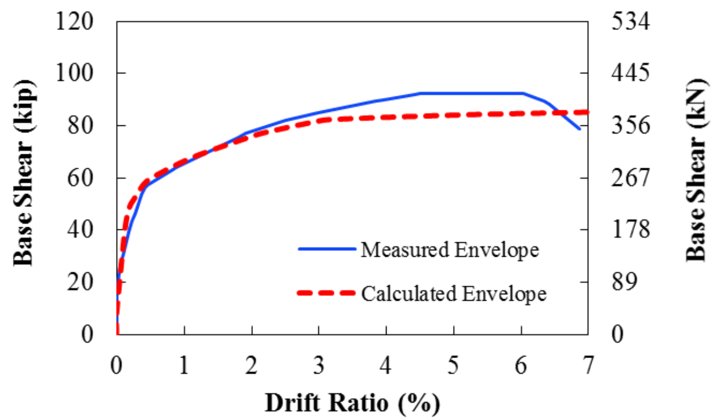










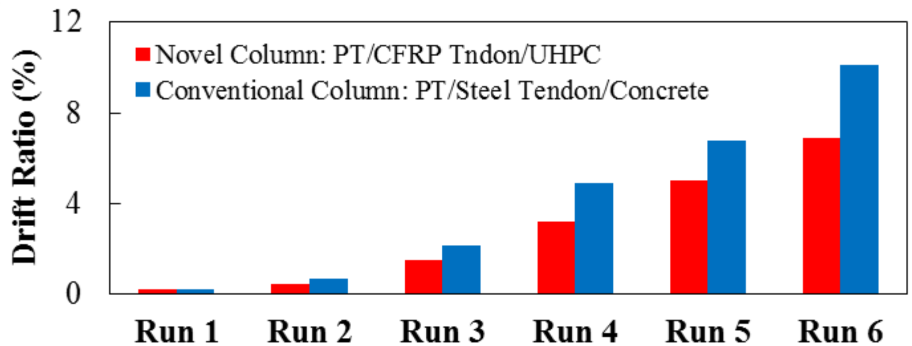


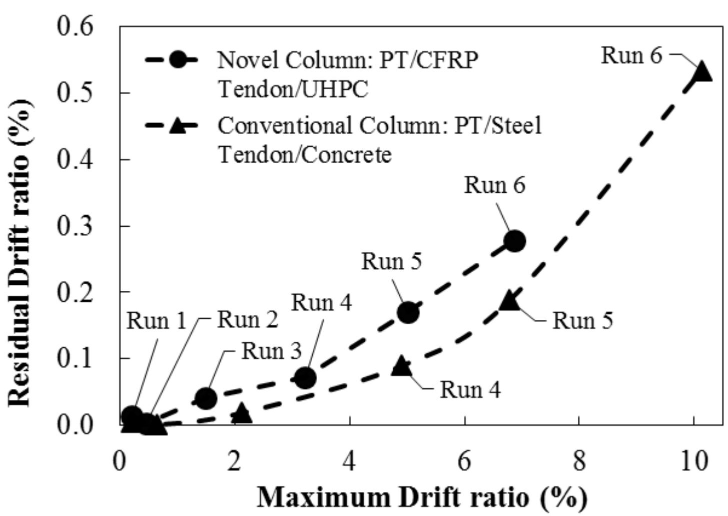
Analytical Results-Column Model (Cont'd)

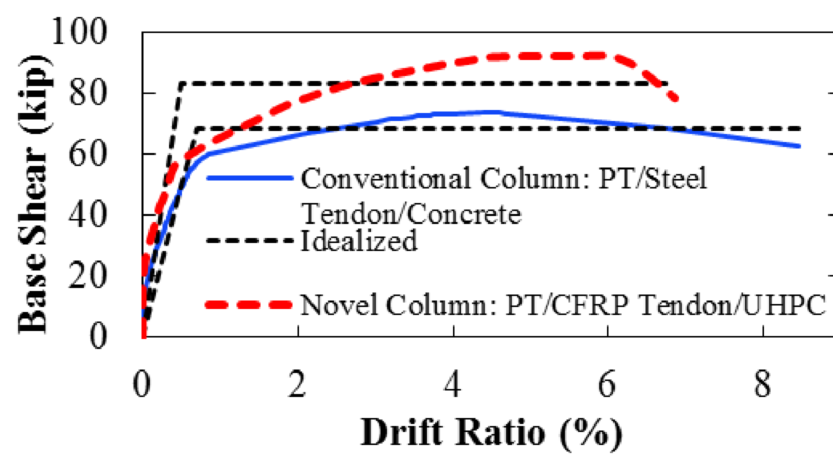
Novel Column: PT/CFRP Tendon/UHPC
vs
Conventional Column: PT/Steel Tendon/Concrete

Conventional Column was same as
Novel Column in terms of

- Geometry and cross section,
- Longitudinal and transvers steel reinforcements,
- Dead load
- Initial post-tensioning force
- Initial PT stress=25% Yield/Capacity







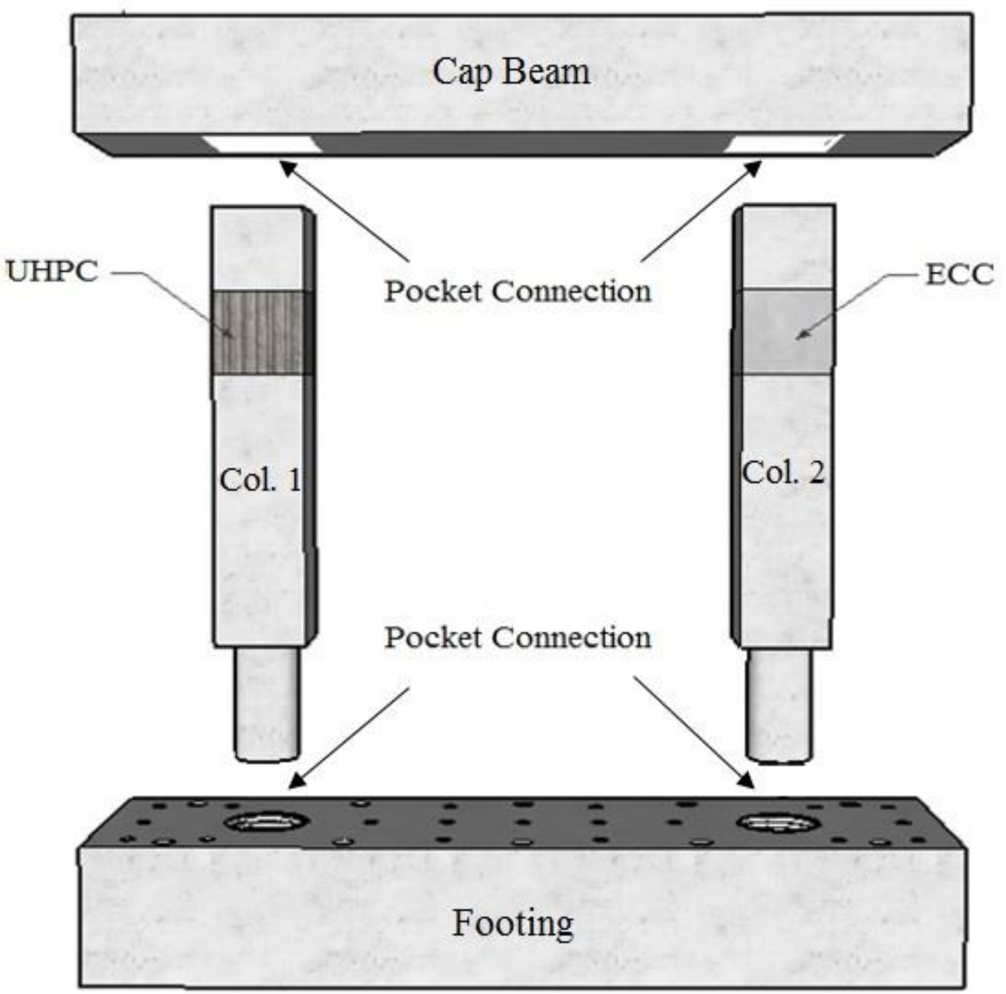
Lessons Learned from Analytical Study of Column Model

- Both steel and CFRP tendons were effective in eliminating residual displacements.
- The steel tendons in the conventional column yielded while the CFRP tendons reached only 65% of the guaranteed capacity in the novel column.
- Substantial damage in the convectional column was expected while the damage in the novel column was limited to minor cover spalling.

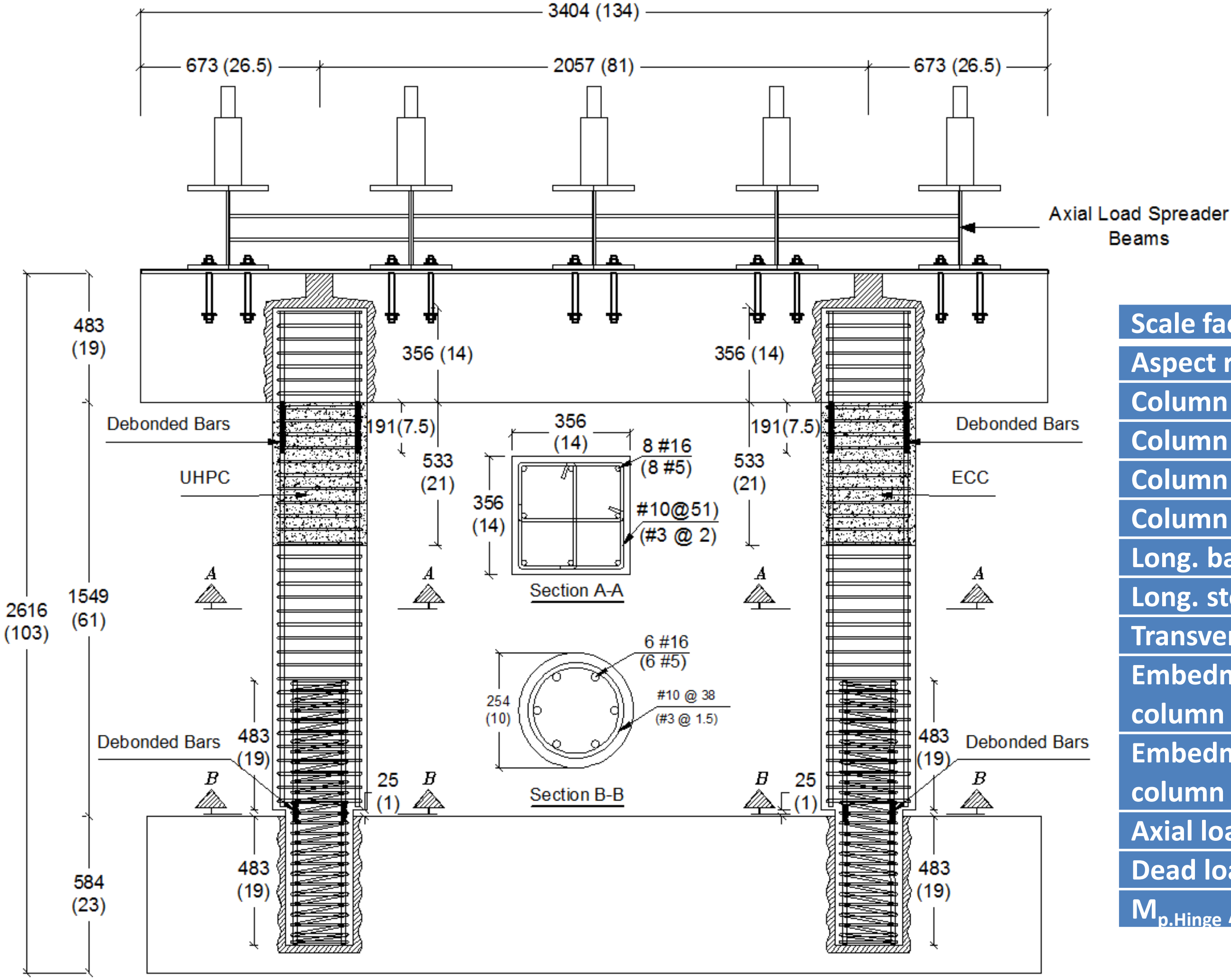
Pier Model

Novel Aspects

- Precast column and footing with pocket connection in:
  - Cap beam
  - Rebar hinge
- Engineered cementitious composite (ECC) in plastic hinge zone
- Ultra-high performance concrete (UHPC) in plastic hinge



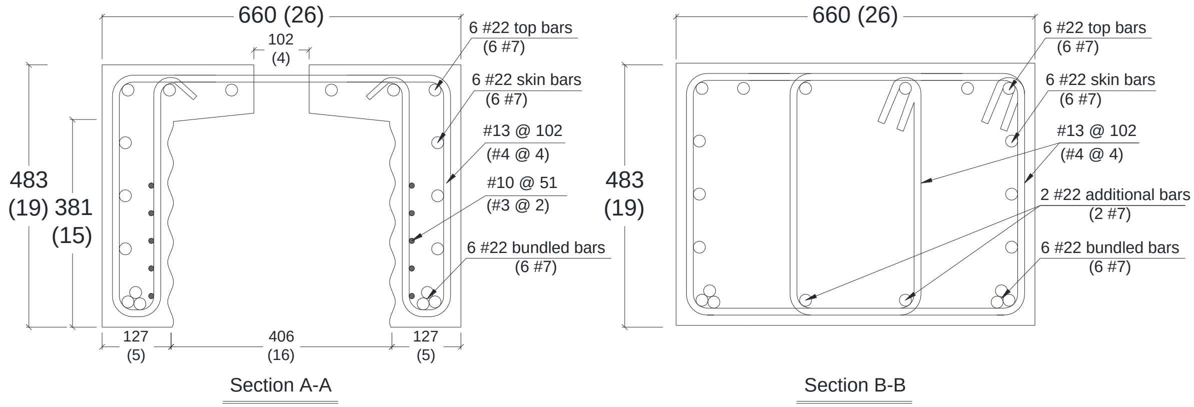
Pier Model



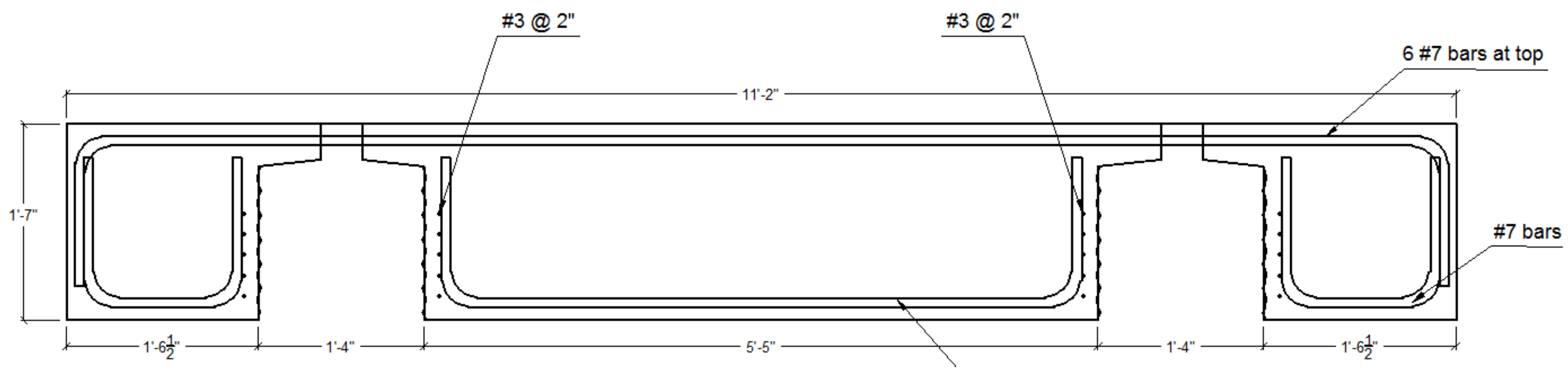
Scale factor	1/3
Aspect ratio	4.35
Column long. bar	8 - #5
Column long. steel ratio	1.26%
Column transverse steel	#3 @ 2.0”
Column transverse steel ratio	2%
Long. bar at hinge section	6 #5
Long. steel ratio at hinge section	2.36%
Transverse steel at hinge section	#3 @ 1.5”
Embedment length of the column at the top (inch)	14.0”
Embedment length of the column at the bottom (inch)	19.0”
Axial load index	6.4%
Dead load (kip)	100.0
$M_{p.Hinge}$ / $M_{p.Col}$	40%

Pier Model-Cap Beam Details

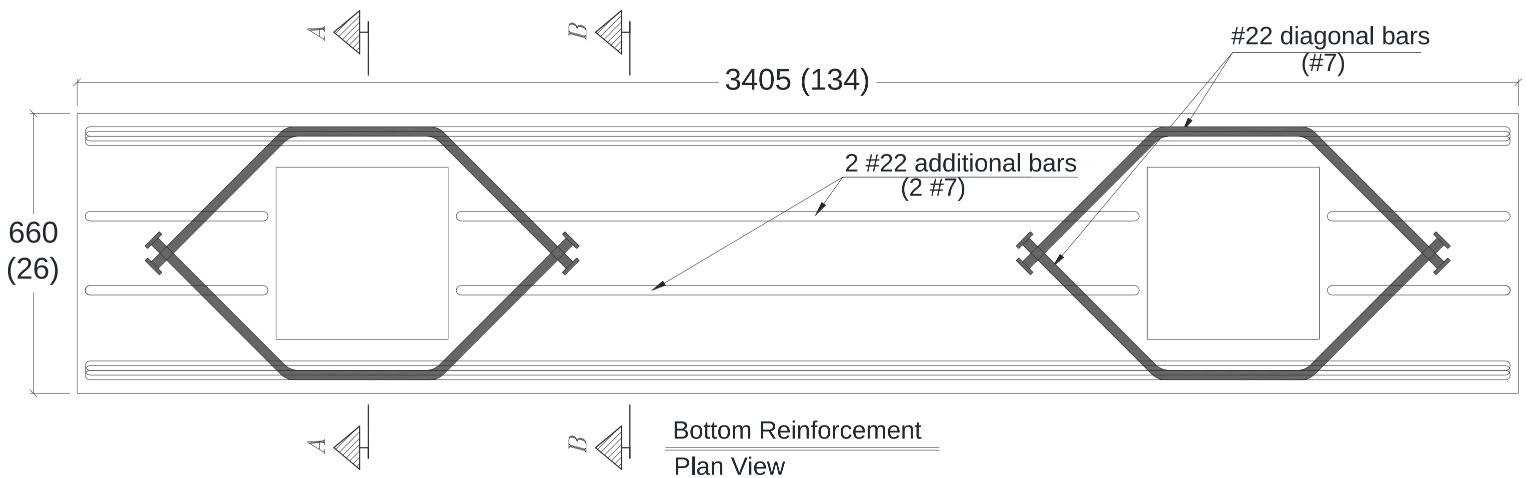
Cross section



Elevation

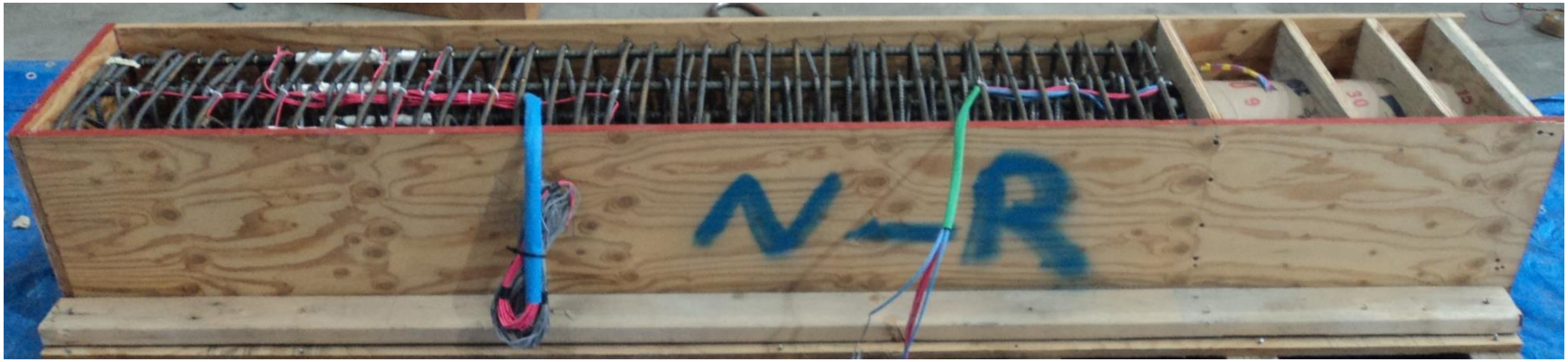


Bottom bars

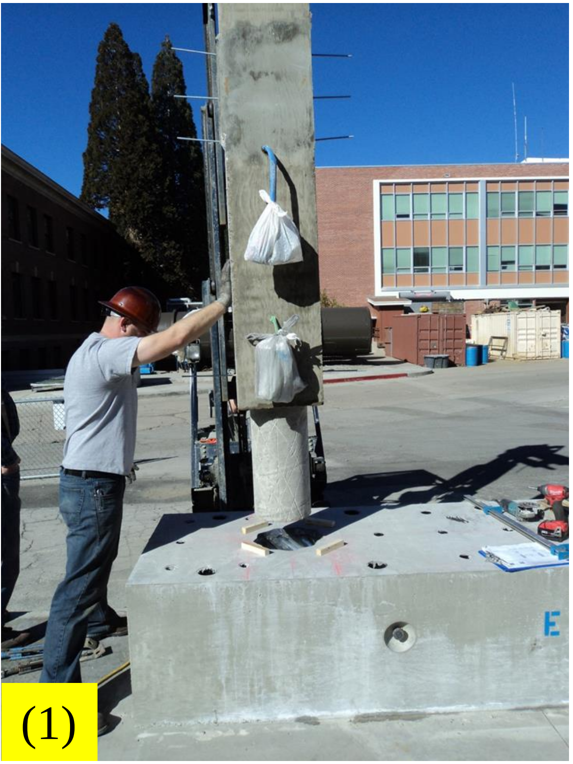


Pier Model-Cap Beam Construction

Column Construction



Pier Model-Assembling


(1)


(2)


(5)


(3)


(4)

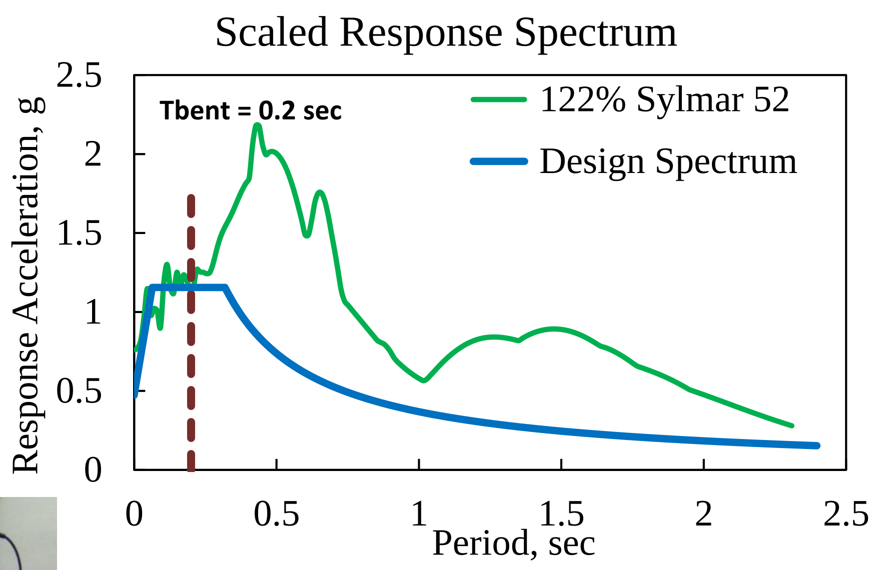
Pier Model

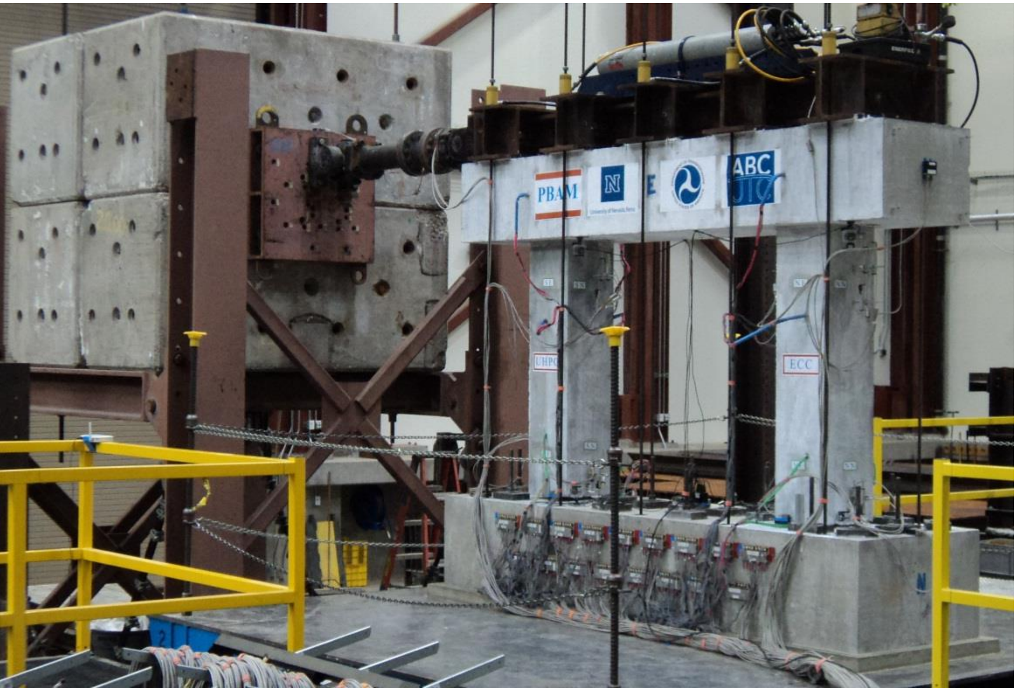
Northridge 1994 (M 6.7), Sylmar Station

Design spectrum

Location: Los Angeles area
Site class: D
A_S=0.473g
S_{DS}=1.15g
S_{D1}=0.637g
Ts=0.552 sec
To=0.11 sec

Video, Run 6
YouTube





Run#	Design EQ
1	10%
2	40%
3	75%
4	100%
5	110%
6	150%

Pier Model

UHPC Column

ECC Column

Design Level
Drift Ratio: 4.4%

150% Design Level
Drift Ratio: 9.6%

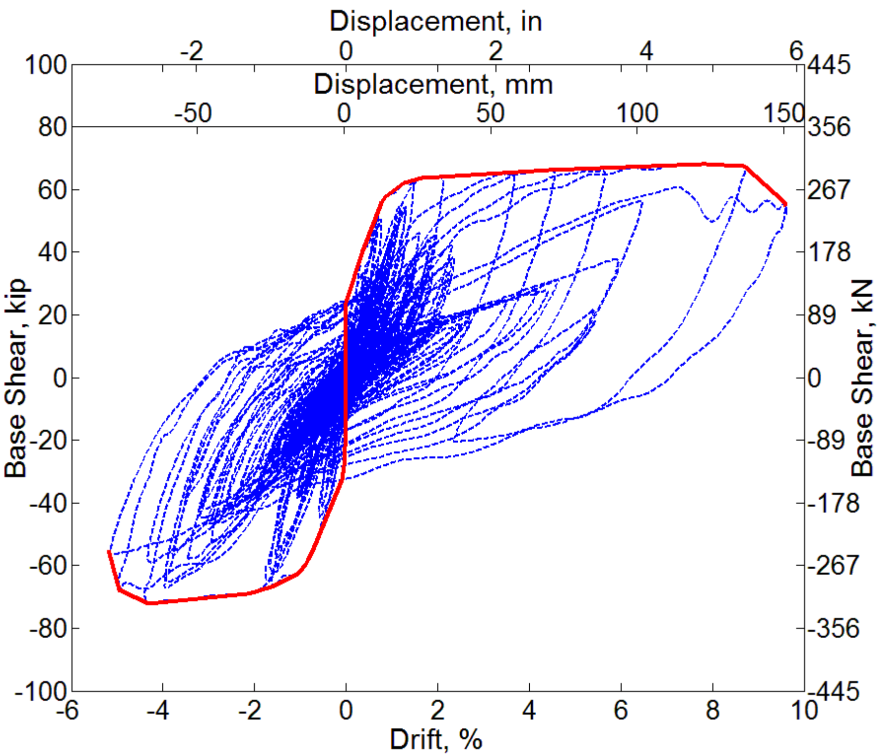
Damage State- (Cont'd)

Rebar Hinge Under
150% Design Level
Drift Ratio: 9.6%

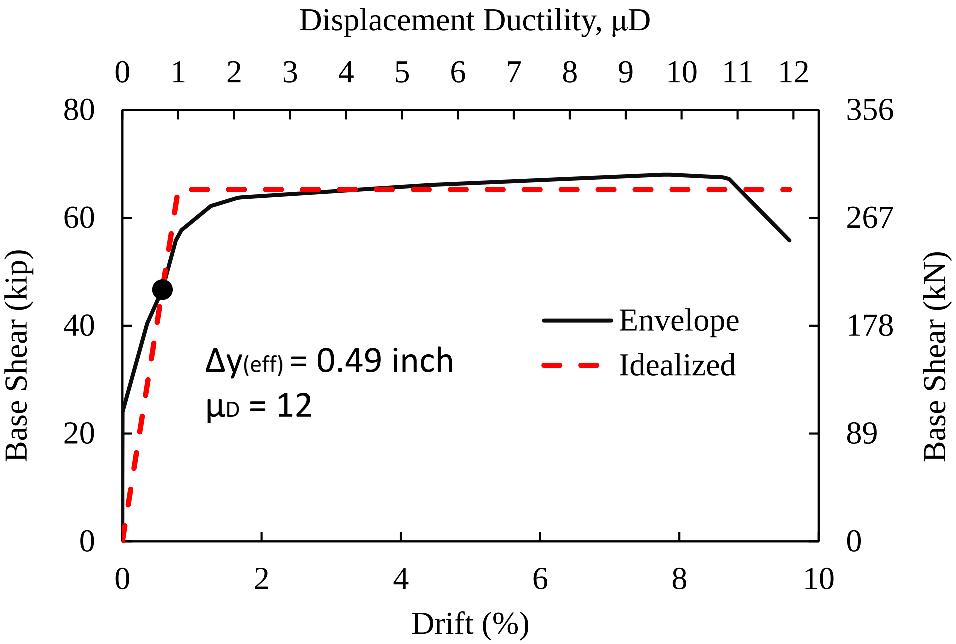
UHPC Column

ECC Column

Pier Model

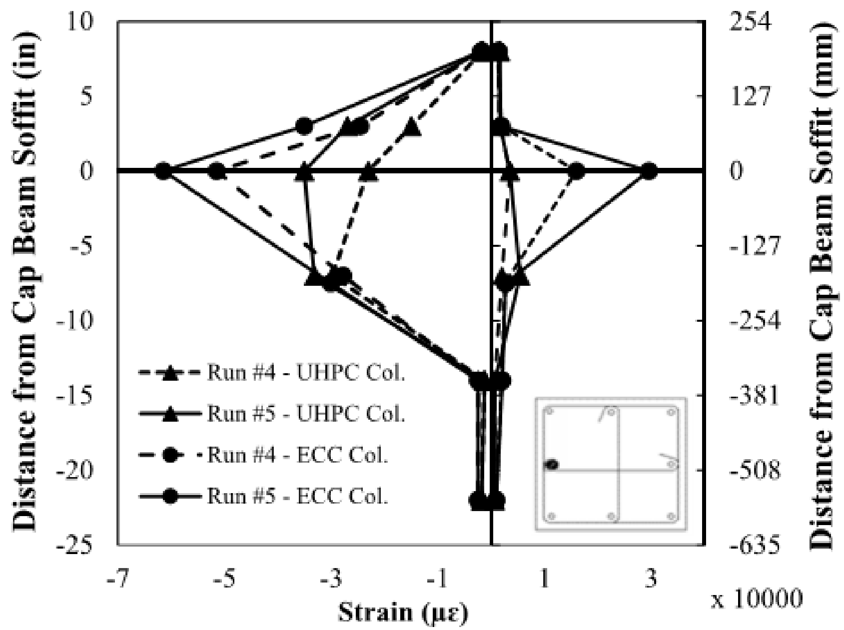


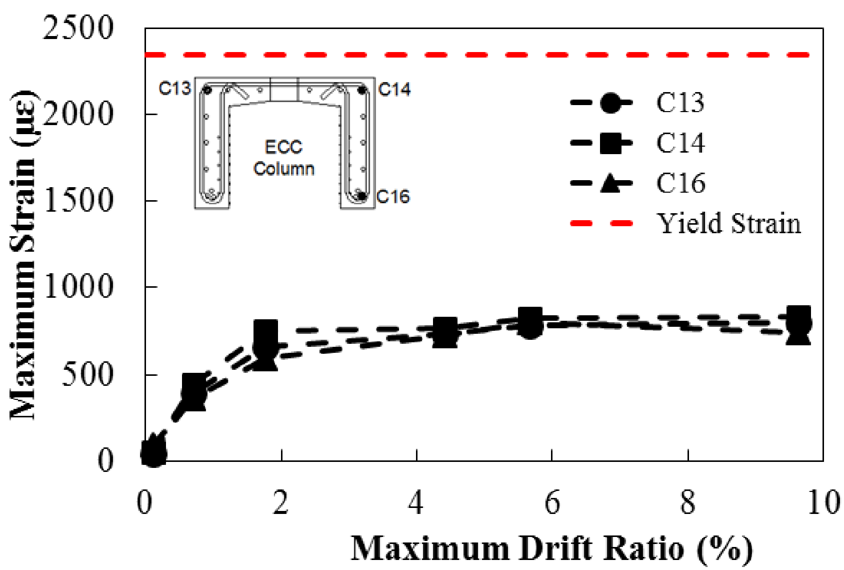
Displacement, in
-2
0
2
4
6
Displacement, mm
-50
0
50
100
150
Base Shear, kip
Base Shear, kN
Drift, %

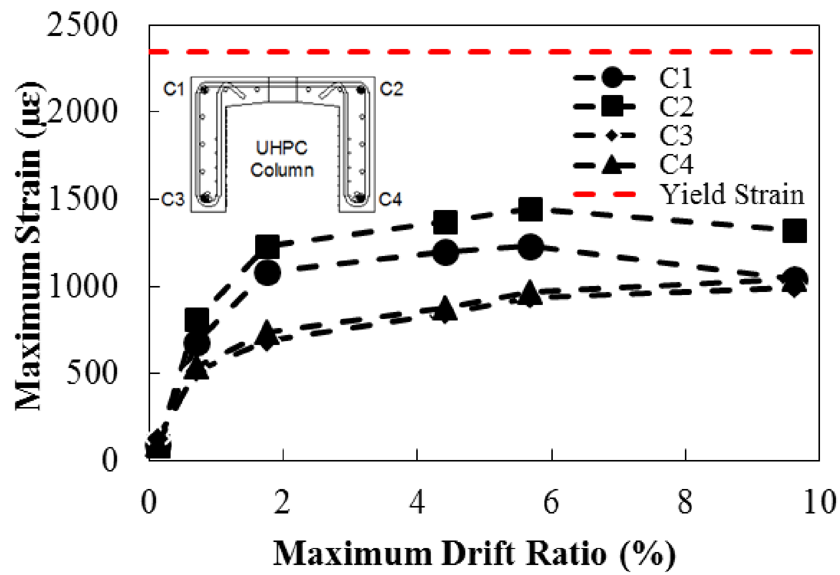


Displacement Ductility, μD
Base Shear (kip)
Base Shear (kN)
Drift (%)
Envelope
Idealized
Δy(eff) = 0.49 inch
μD = 12

Test Results- (Cont'd)



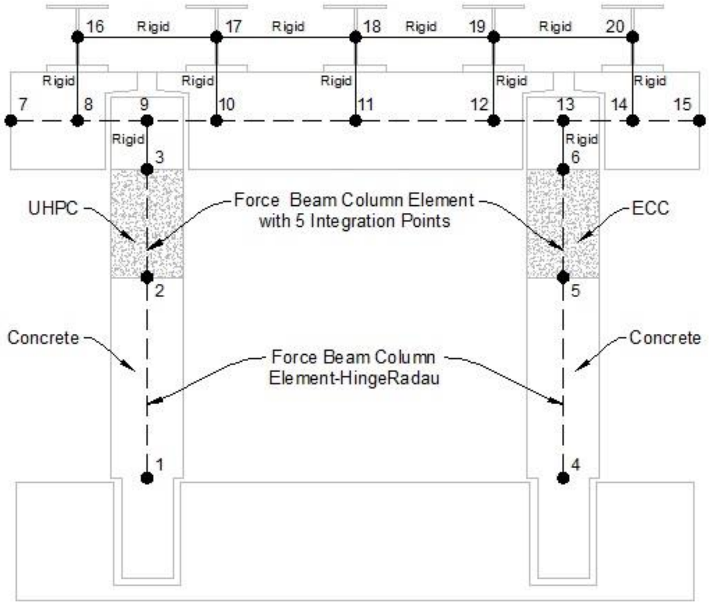


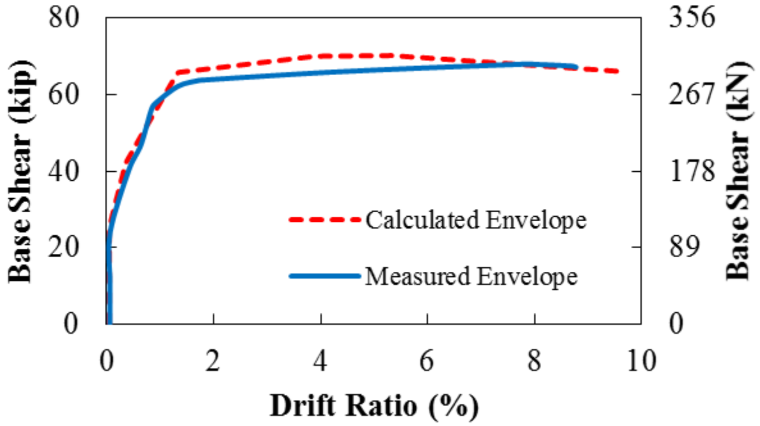


Observations-Pier Model

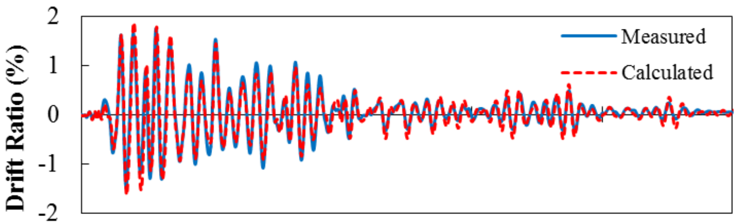
- Pocket connections in the cap beam and footing performed well and the structural integrity was maintained during the entire test.
- Embedment length of 1.0 times the column dimension in the cap beam pocket was adequate to provide the plastic moment at the top.
- UHPC and ECC reduced the seismic damage under design earthquake, although the extent and location of damage for the two materials were different at failure.
- Debonding of the longitudinal bars of the columns for 12d_b below the cap beam was effective to spread plasticity along the bars and increase the drift capacity.
- Diagonal bars in the cap beam were effective around the pocket and reached 37% of the yield strain during the test.

Analytical Study-Pier Model

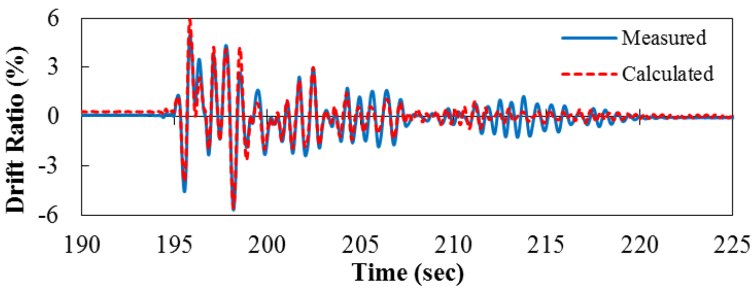




Run3-Moderate Amplitude



Run5-High Amplitude



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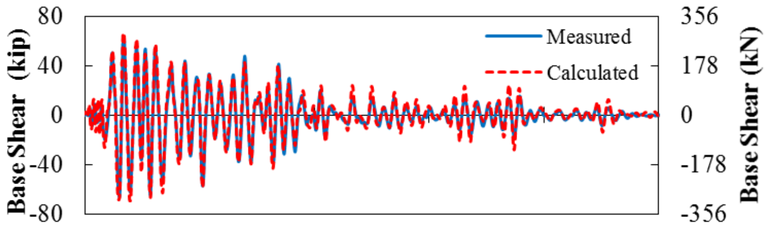
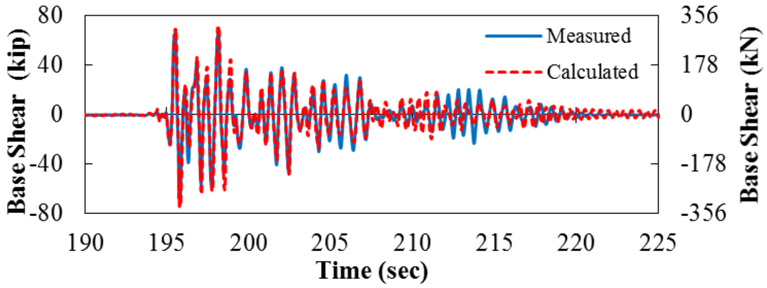
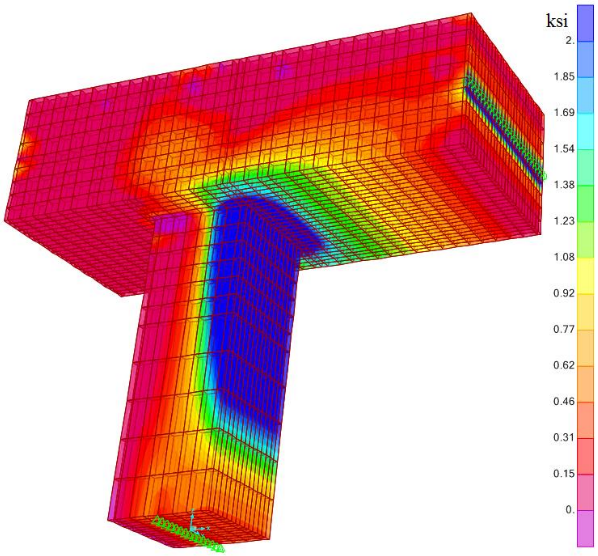
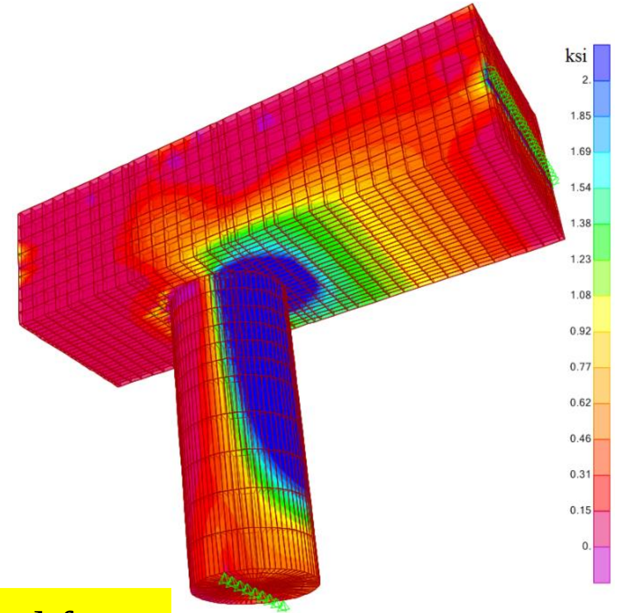


Run5-High Amplitude

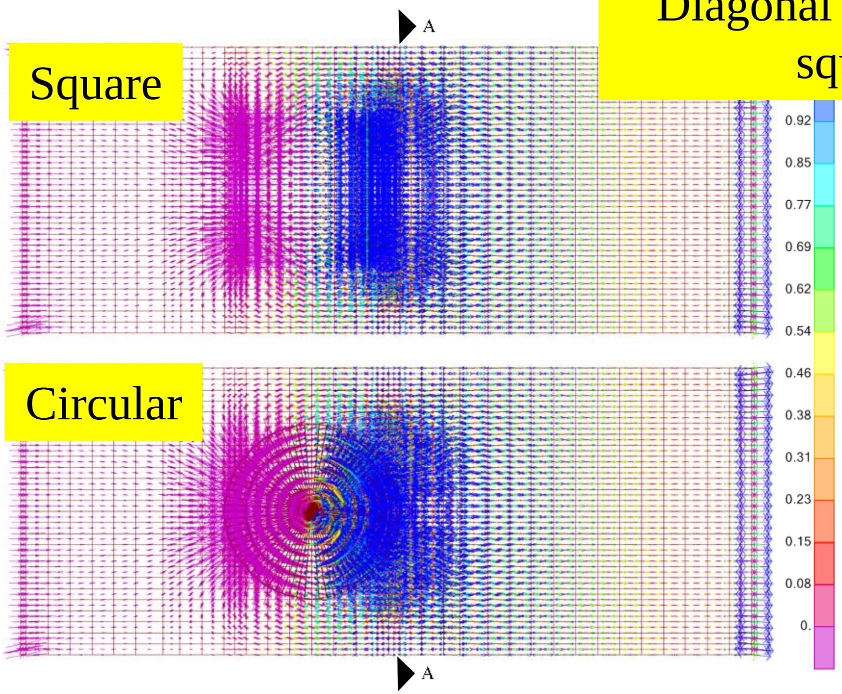


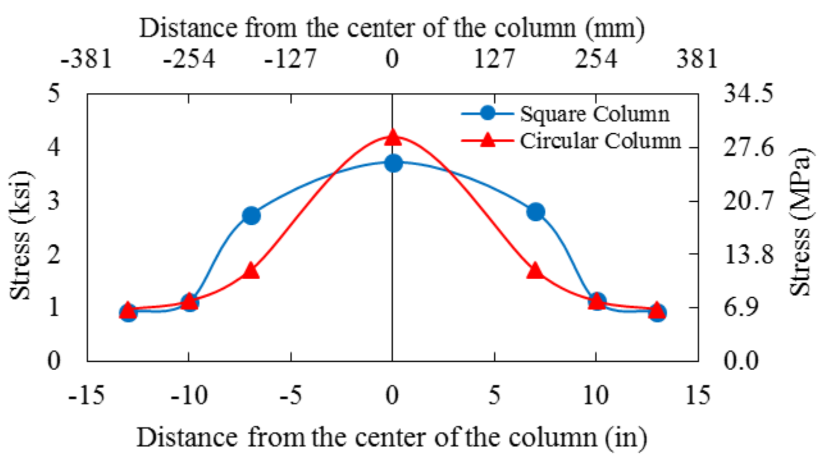
Analytical Study- (Cont’d)





Diagonal bars are required for square columns





Seismic Design Methods

Preliminary seismic design methods for use in accelerated bridge construction (ABC) were developed utilizing the results from this and previous studies integrated with many of the AASHTO provisions for cast-in-place bridges.

- ➢ Design of Square or Rectangular Column-Cap Beam Pocket Connections
- ➢ Design of Square or Rectangular Column-Footing Pocket Connections
- ➢ Design of Unbonded CFRP Tendons for Post-tensioned Bridge Columns
- ➢ Design of Plastic Hinge Zones with UHPC/ECC

✓ The design steps in each method are illustrated in design examples.

Seismic Design Methods- (Cont'd)

Design of Square or Rectangular Column-Cap Beam Pocket Connections

- Step 1. Determine the pocket dimension (B_P): $B_P = B_C + 2Gap$
- Step 2. Determine the minimum pocket depth (D_P)

$$D_p \geq \begin{cases} 1.0\,B_c + \text{Gap} \\ \dfrac{0.79 d_b f_{ye}}{\sqrt{f'_c}} + \text{Gap (AASHTO)} \\ \dfrac{1.56 V_{PO} + \sqrt{4.74 V_{PO}^{\;2} + 6.22 M_{PO} f'_c B_c}}{B_c f'_c} + \text{Gap}\ \ (\text{Motaref et. al., 2011}) \end{cases}$$

- Step 3. Determine the minimum cap beam depth (D_{Cap}): $D_{cap} = 1.25 D_P$
- Step 4. Determine the minimum cap beam width (WCap): $W_{Cap} = B_C + 610\ \text{mm}\ (24\ \text{in}) + 2Gap$
- Step 5. Vent for pumping grout (WV): $W_V \geq 102\ mm\ (4\ in)$
- Step 6. Design of cap beam longitudinal reinforcement (AASHTO): $M_{y(eff)} > M_{Demand}$
- Step 7. Design of cap beam transverse reinforcement (Section 8.13.5.1 AASHTO)
- Step 8. Design of diagonal reinforcement: $A_{s(Diagonal)} \geq (\frac{1}{3} A_{sb(Cap)})$
- Step 9. Principal stress checks

Seismic Design Methods- (Cont'd)

Design of Unbonded CFRP Tendons for Post-tensioned Bridge Columns

- Step 1. Determine the initial post-tensioning stress (f_{pi})

$f_{pi} = 0.25f_u$

- Step 2. Determine the area of CFRP Tendons (A_{CFRP})

The total area of the CFRP tendons for the initial design should be determined such that the initial posttensioning force is equal to the column axial force due to the dead load.

$A_{CFRP} = P/(0.25f_u)$

- Step 3. Pushover analysis

$f_{Max(CFRP)} \leq 0.8f_u$ at the column failure

Seismic Design Methods- (Cont'd)

Design of Plastic Hinge Zones with UHPC/ECC

- The height of UHPC/ECC in the column plastic hinge zones is recommended to be determined such that the moment in the column section with conventional concrete is 75% of the plastic moment of the column section with UHPC/ECC.
- The height of UHPC/ECC should not be less than 1.0 times the column maximum cross-sectional dimension or diameter.
- The debonded length of the longitudinal bars should be determined such that the moment demand at the end of the debonded length in the column is 80% of the column plastic moment.

Conclusions

- The pocket connections in the cap beam and footing performed well and the structural integrity of the both models was maintained during the entire test.

- CFRP tendons eliminated residual drifts under different levels of the earthquake. CFRP tendons can be used as an alternative to unbonded steel tendons. The method to determine the initial post-tensioning force for CFRP tendons was appropriate.

- ECC and UHPC equally reduced the plastic hinge damage under the **100% design earthquake** and no damage was observed at the pocket connection.

- In the column-cap beam connection, the high stiffness and strength of UHPC relative to ECC increased the flexural demand and caused damage at the bottom of the cap beam and around the pocket connection under the **150% design earthquake.**

- In the column-footing connection, UHPC reduced the plastic hinge damage, and damage was limited to minor spalling of UHPC cover even under the **200% design earthquake.**

Conclusions- (Cont'd)

- Debonding the longitudinal bars in the column plastic hinge zones with UHPC/ECC was effective in spreading plastic deformation along the longitudinal bars and eliminating stress concentration at the column to cap beam/footing interface.

- Diagonal bars around the square pockets in the cap beam/footing were effective and should be placed at 45 degree to eliminate cracks due to the stress concentration at the corners.

- To facilitate the use of ABC in practice, preliminary seismic design methods were developed based on the experimental results and the analytical investigations of this study and previous studies integrated with the AASHTO provisions. The design methods were practical as demonstrated in the design examples.

Publications

Journal Papers

- A. Mohebbi, M. Saiidi, A. Itani “Shake Table Studies and Analysis of a PT/UHPC Bridge Column with Pocket Connection”, ASCE Journal of Structural Engineering, 2017 (Accepted).
- A. Mohebbi, M. Saiidi, A. Itani “Shake Table Studies and Analysis of a Precast Two Column Bent Using Advanced Materials”, ASCE Journal of Bridge Engineering, 2017 (Under minor revision).
- A. Mohebbi, M. Saiidi, A. Itani “Seismic Design of Precast Piers with Pocket Connections, CFRP Tendons, and ECC/UHPC Columns”, International Journal of Bridge Engineering, Special Issue, 2017, pp. 99-123.

Refereed Conference Proceedings

- A. Mohebbi, M. Saiidi, A. Itani “Seismic Response of a Precast Bent with Pocket Connections and ECC/UHPC in Plastic Hinges”, National Accelerated Bridge Construction Conference, Miami, FL, 2017 (In progress).
- M. Saiidi, A. Mohebbi, A. Itani, M. Tazarv, S. Varela “New Horizons in Seismic Design of Highway Bridges with Advanced Materials and Construction Methods”, Keynote Paper, No. 10, 14th International Symposium on Structural Engineering, Beijing, China, 2016
- A. Mohebbi, M. Saiidi, A. Itani “Self-centering Bridge Column with CFRP Tendons under Seismic Loads”, 8th International Conference on Bridge Maintenance, Safety and Management, Brazil, 2016
- A. Mohebbi, M. Saiidi, A. Itani “Seismic Evaluation of a Precast PT/UHPC Bridge Column with Pocket Connection and Precast Footing”, National Accelerated Bridge Construction Conference, Miami, FL, 2015.

Reports:

- Mohebbi, A., Saiidi, M., and Itani, A, “Development and Seismic Evaluation of Pier Systems w/Pocket Connections, CFRP Tendons, and ECC/UHPC Columns”, Rep. No. CCEER 17-02 Center for Civil Engineering Earthquake Research, Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada.

Thank you all for your attention

Questions?

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