Seismic Evaluation of Beam-Column Assemblages Strengthened with FRP and Anchored with Spike Anchors

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Presentation Outline

- Research Objectives
- Experimental Program
- Material Properties
- Loading Protocol
- Experimental Results
- Conclusions

Research Objectives

- To evaluate the seismic performance of RC frame elements reinforced with modern code requirements and strengthened in flexure with CFRP fabric for increased demand
- To examine the delay or control of CFRP debonding using different arrangements of spike anchors and full wraps

RC Column Ductility Improvement

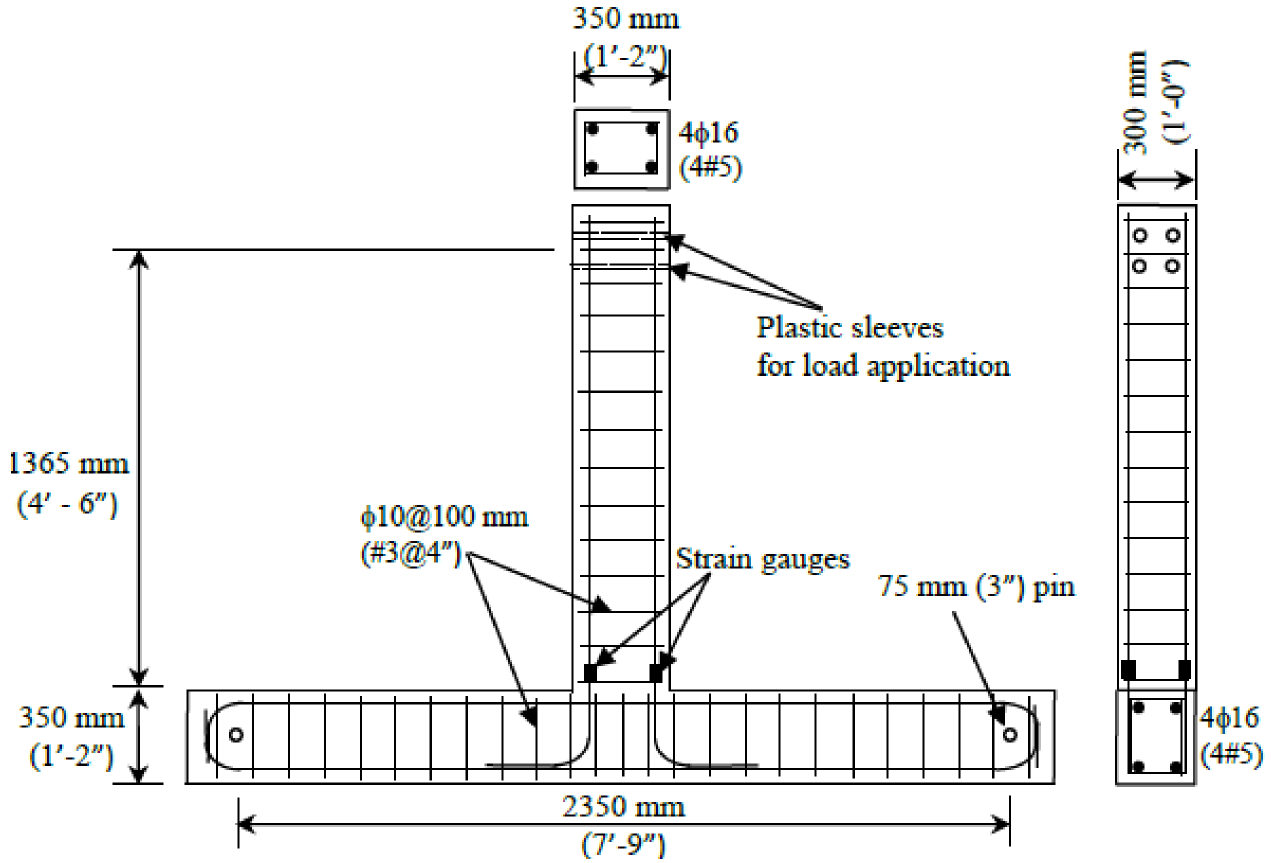
Experimental Program

- Five large scale beam-column assemblages were built
- All specimens had same steel reinforcement details
- One control specimen (BCA-1)
- One specimen strengthened with CFRP fabric and anchored with full wraps (BCA-2)
- Three specimens strengthened with CFRP fabric and anchored with different arrangements of spike anchors

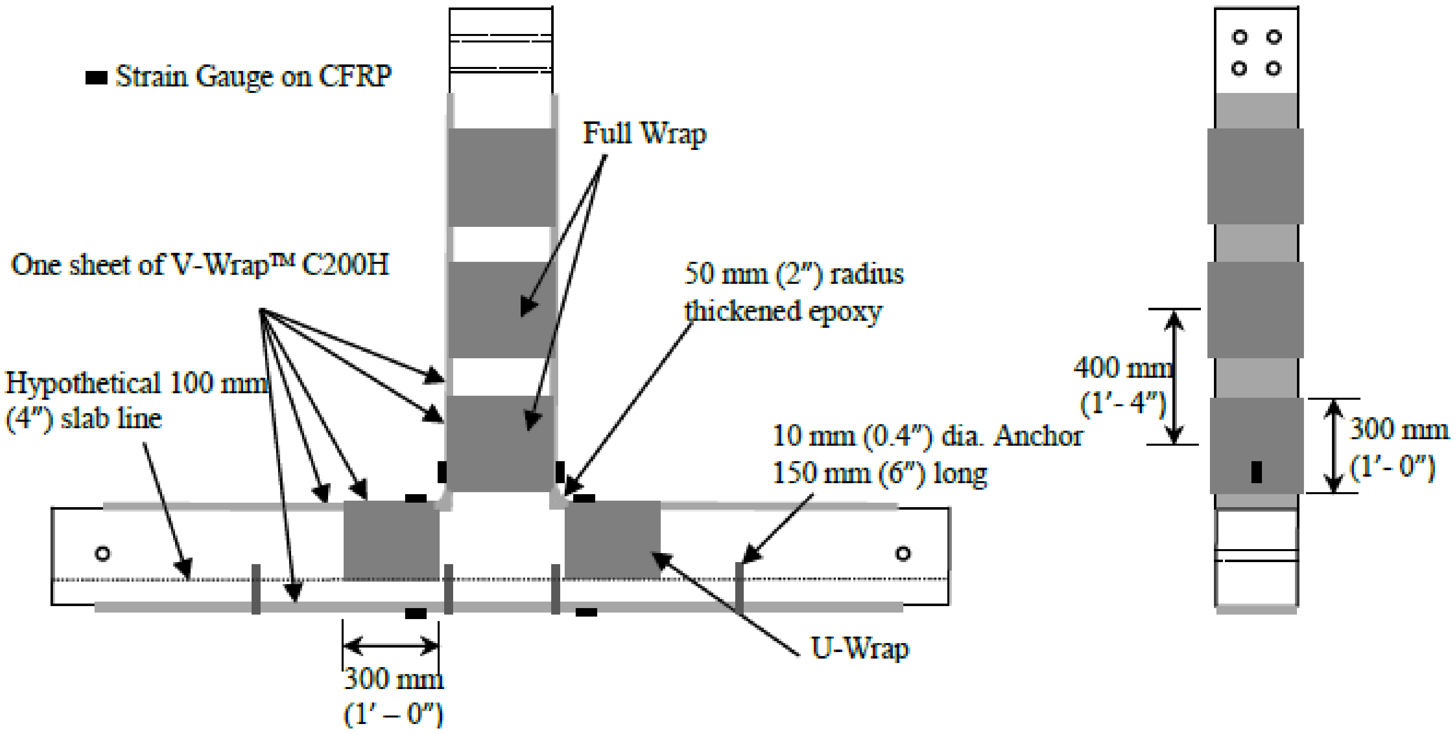
Experimental Program

- One specimen strengthened with CFRP fabric and anchored with a single spike anchor replacing each full wrap (BCA-3)
- One specimen strengthened with CFRP fabric and anchored with five spike anchors in plastic hinge region "dense arrangement" (BCA-4)
- One specimen strengthened with CFRP fabric and anchored with a parallel spike anchor confined with full wraps (BCA-5)

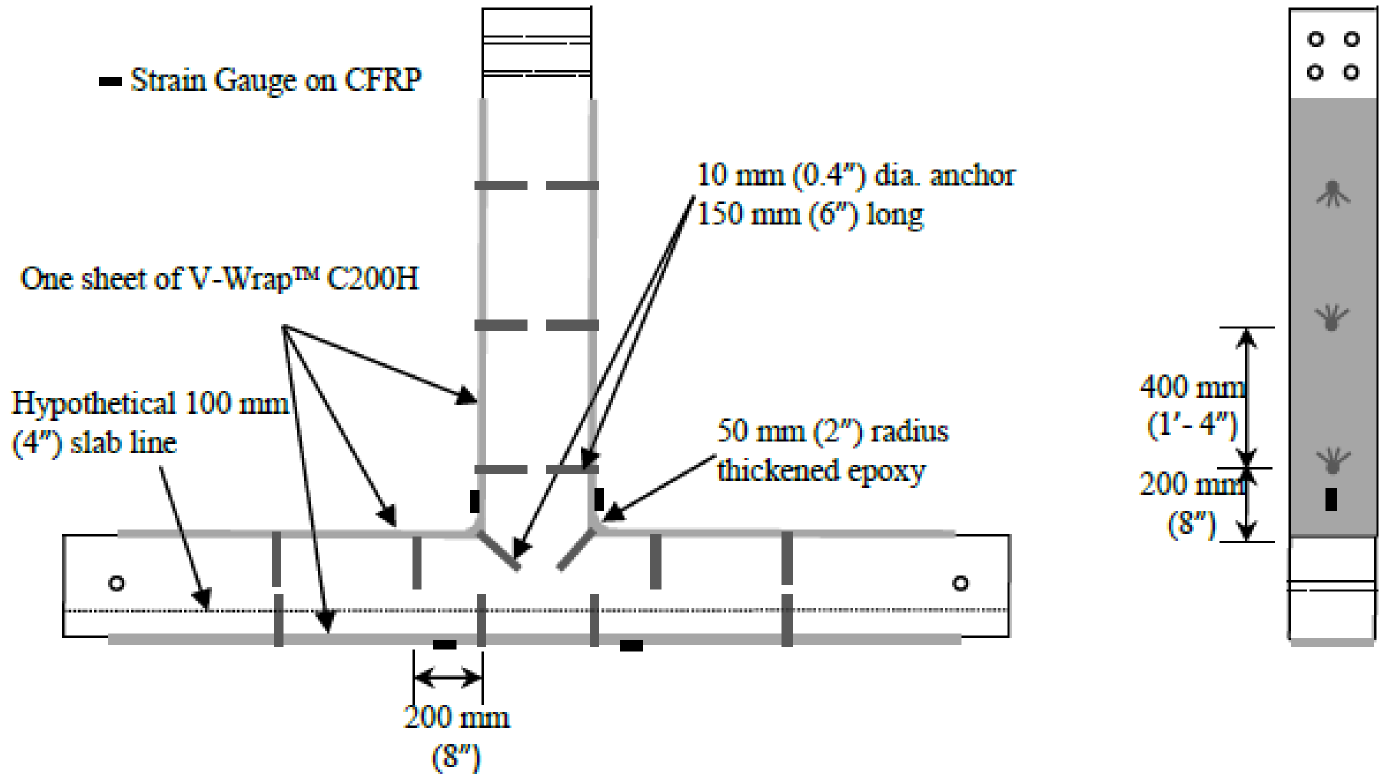
Specimens Dimensions and Internal Reinforcement



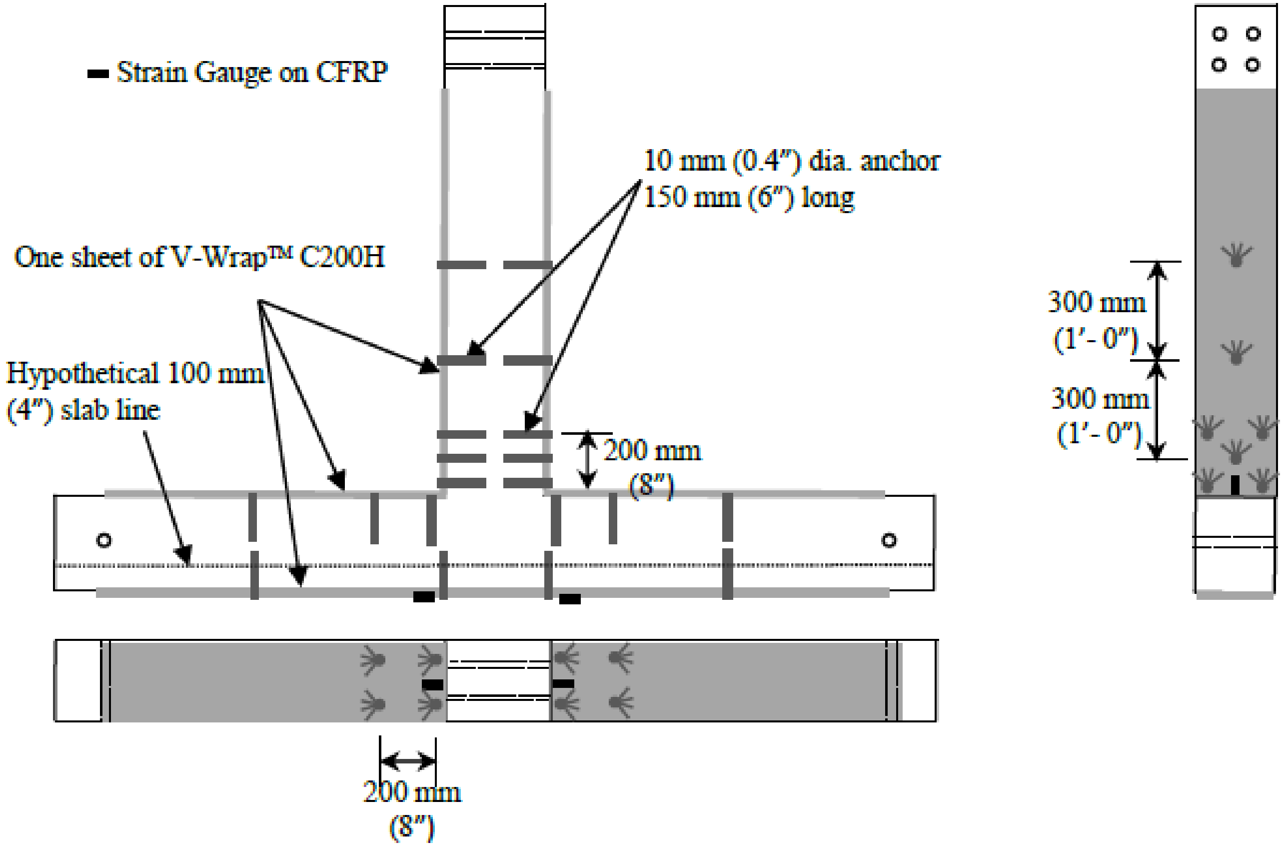
Strengthened with CFRP Fabric and Full Wraps BCA-2



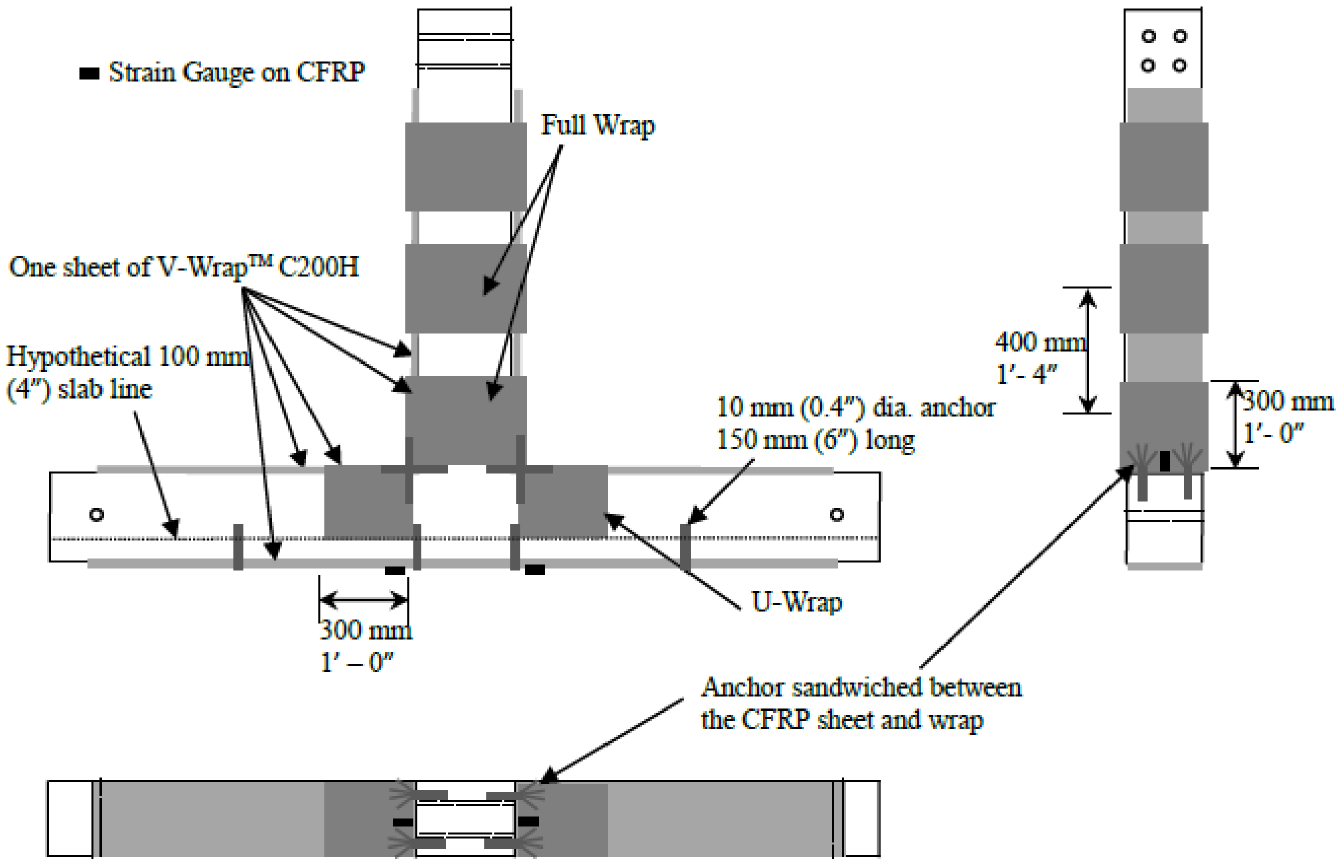
Strengthened with CFRP Fabric and Arrangement 1 Spike Anchors – BCA-3



Strengthened with CFRP Fabric and Arrangement 2 Spike Anchors – BCA-4

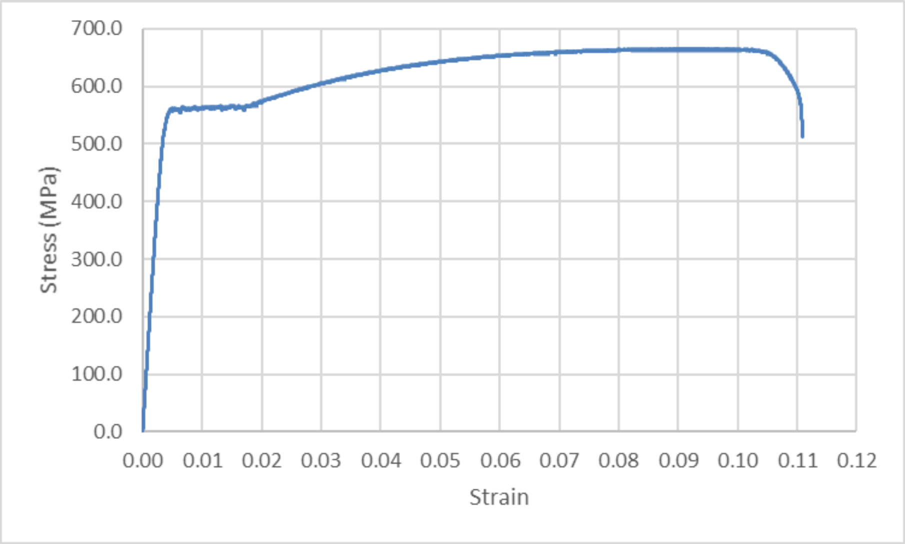


Strengthened with CFRP Fabric and Arrangement 3 Spike Anchors and Wraps– BCA-5



Material Properties

Specimen	Day of testing concrete strength (MPa)
Control – BCA-1	32.0
Wraps – BCA-2	31.9
Spike Anchors 1 – BCA-3	35.1
Spike Anchors 2 – BCA-4	34.5
Spike Anchors 3 – BCA-5	29.2

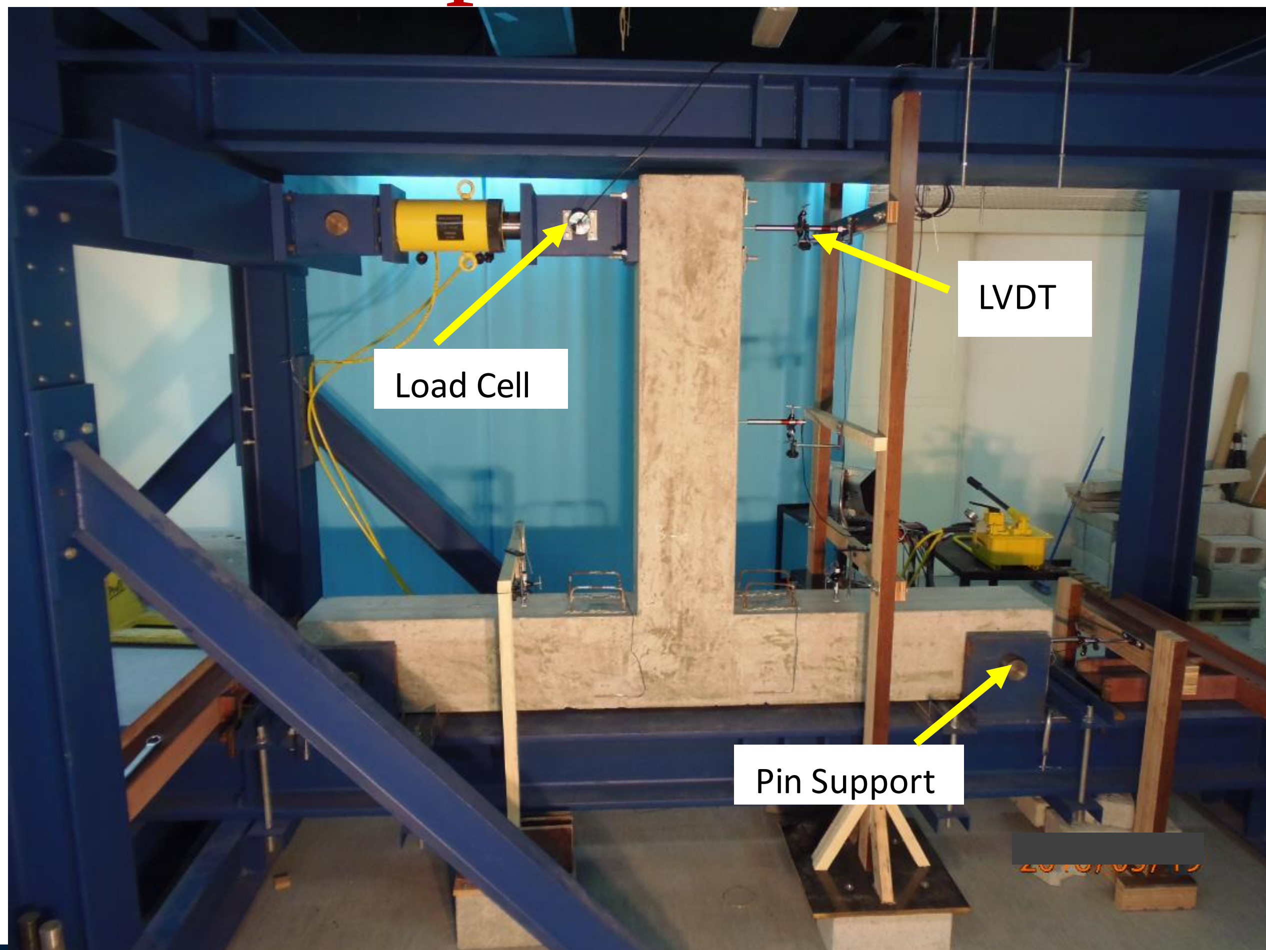


CFRP Properties*

Fiber Type	Nominal Thickness or Diameter t_f (mm)	Ultimate Tensile Strength f_{fu} (MPa)	Elongation at Break ε_{fu} (%)	Modulus of Elasticity E_f (GPa)
Carbon Dry Fiber Fabric	0.33	4830	2.1	227.5
Carbon Cured Laminate	1.0	1240	1.7	73.77

* As provided by the manufacturer

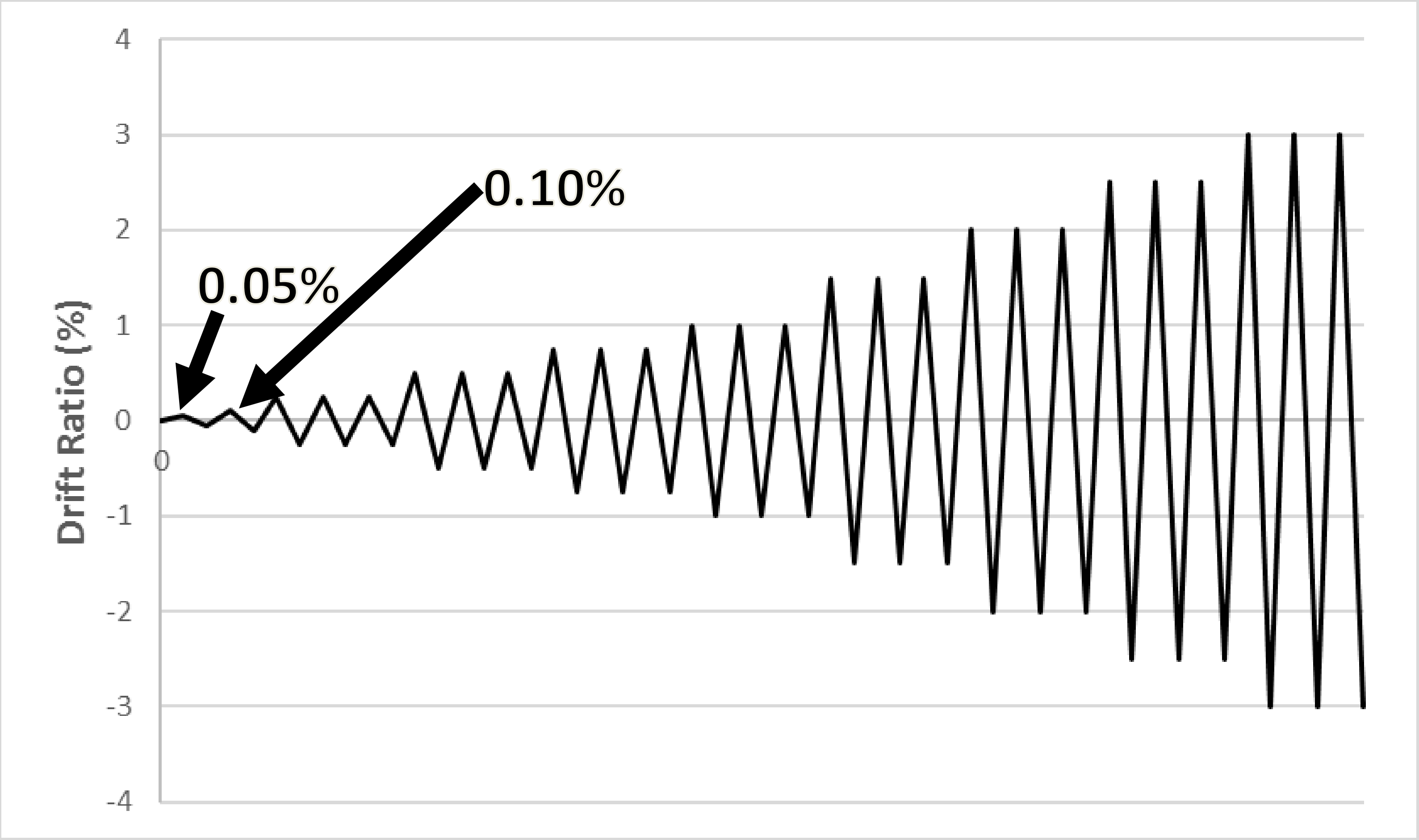
Control Specimen – BCA-1



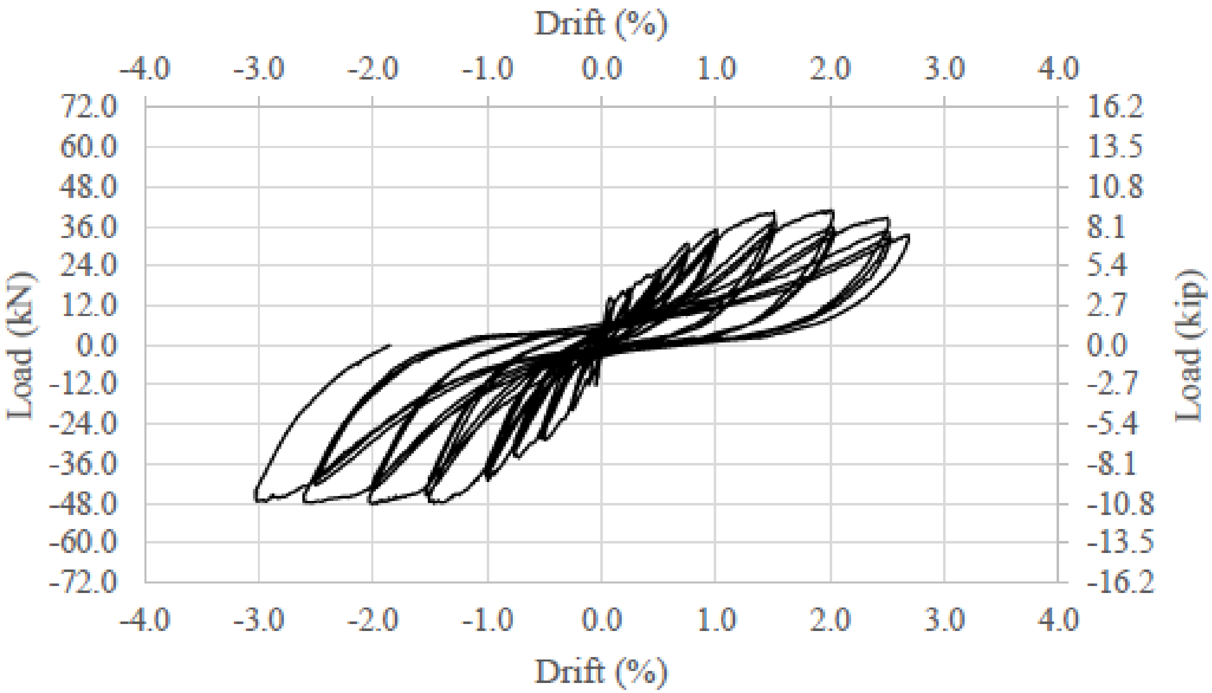
Specimen Anchored with Wraps – BCA-2

Specimen Anchored with Spike Anchors 2 – BCA-4

Loading Protocol

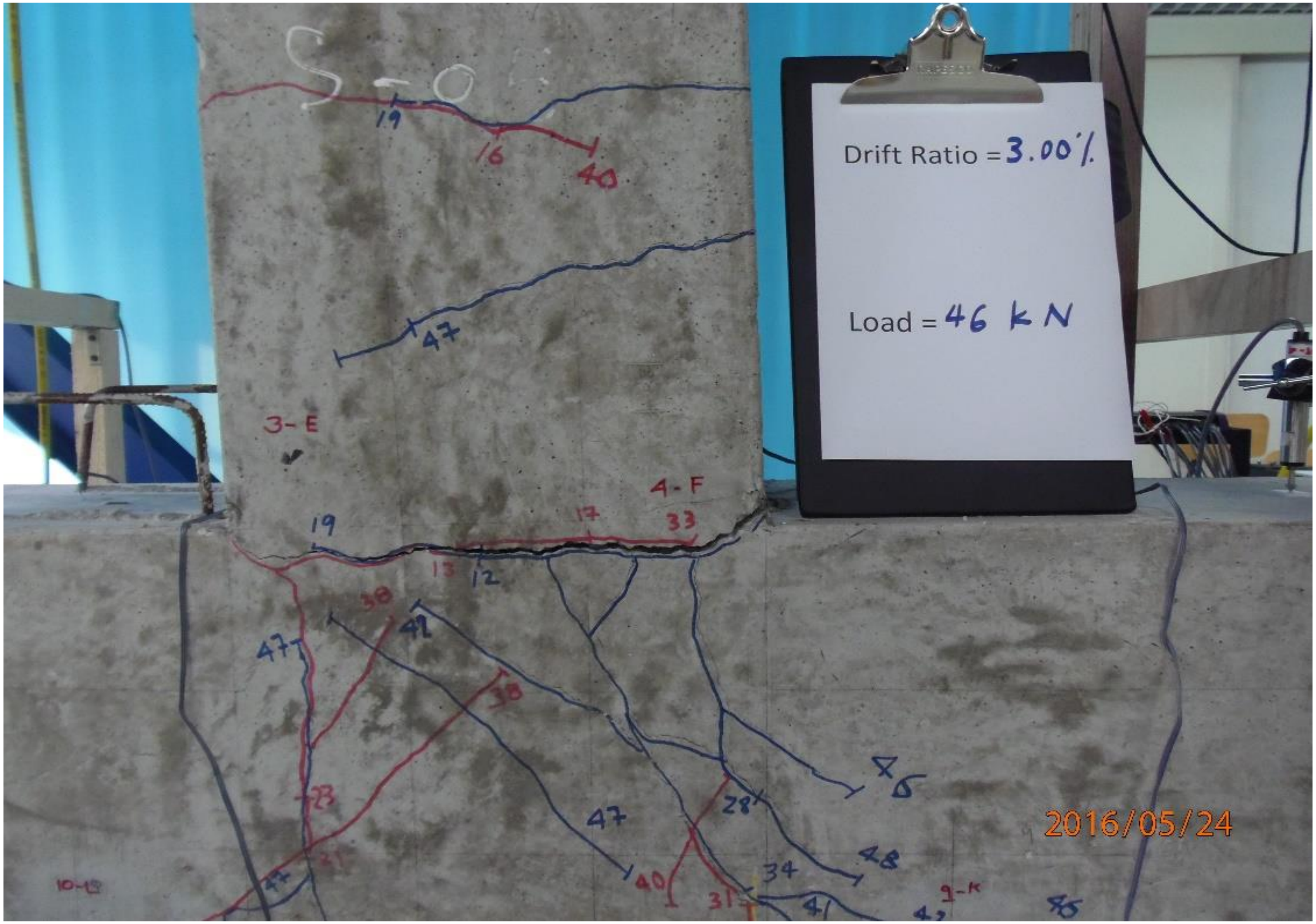


Hysteretic Response

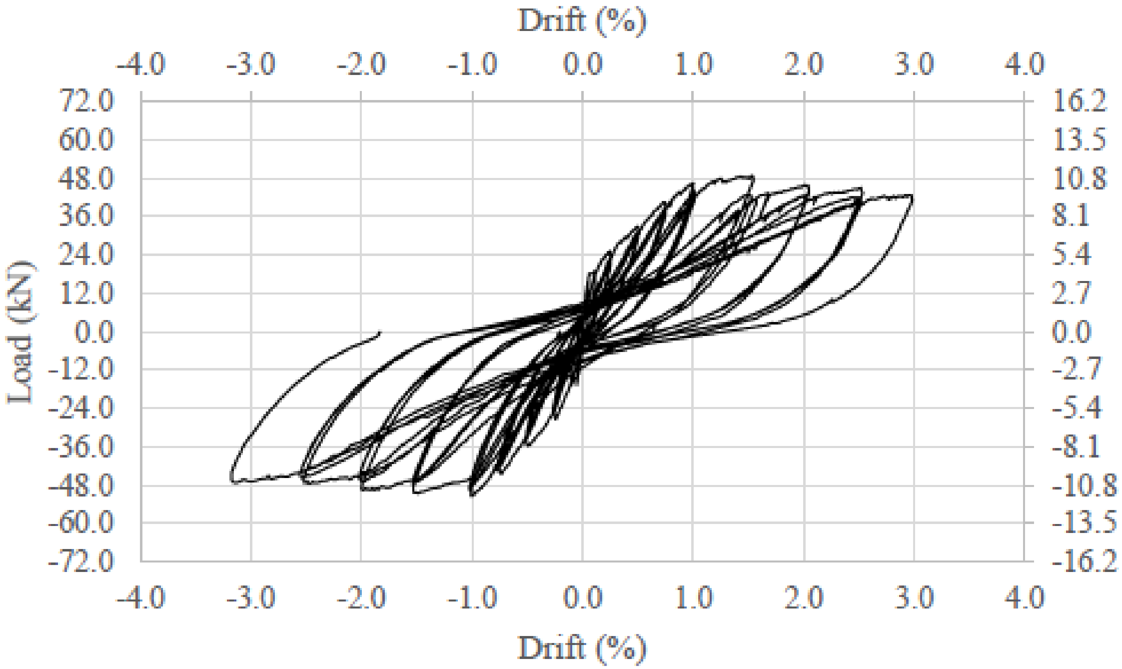


Control – BCA-1

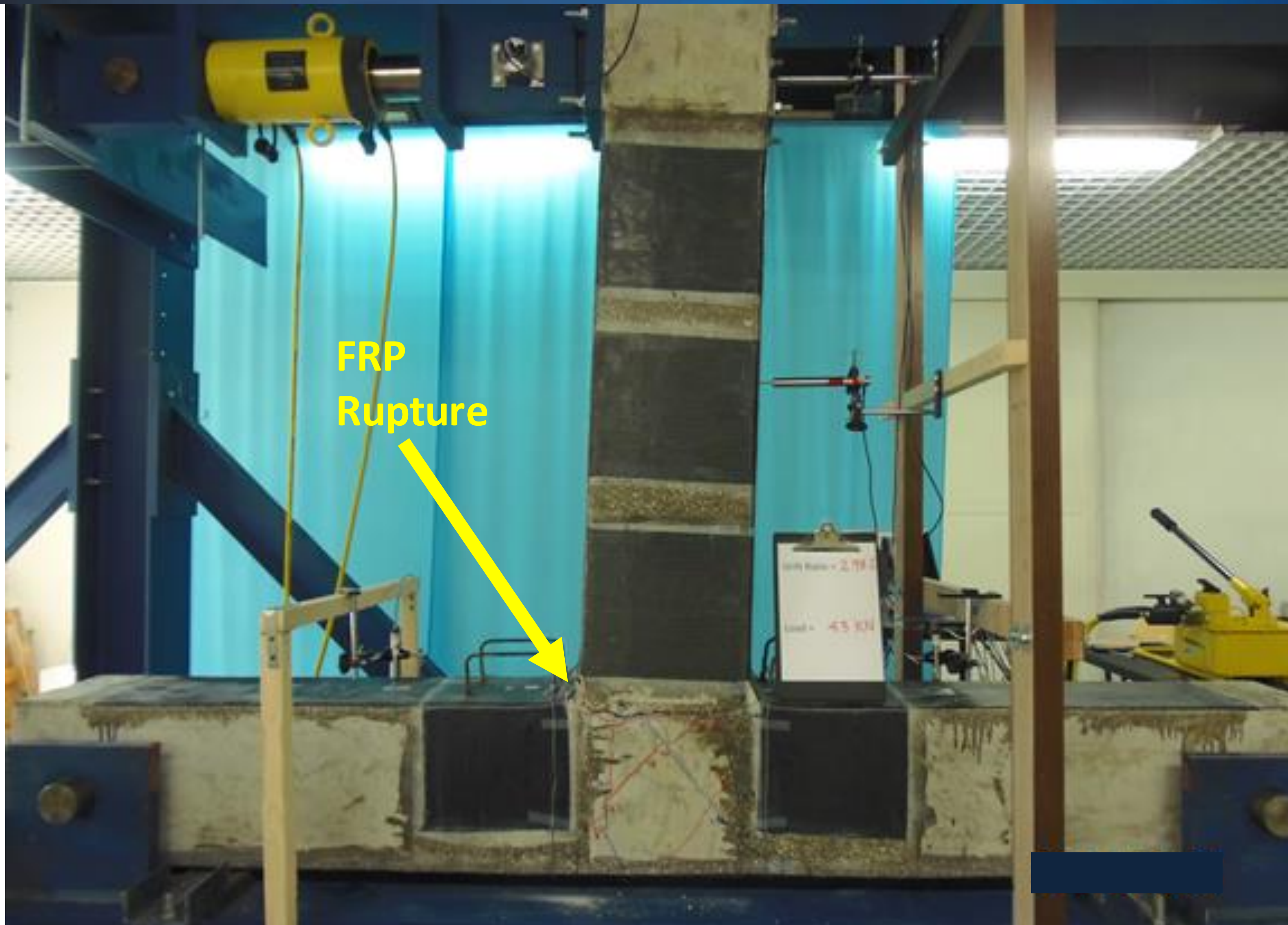

Drift Ratio = 3.00%
Load = 46 kN

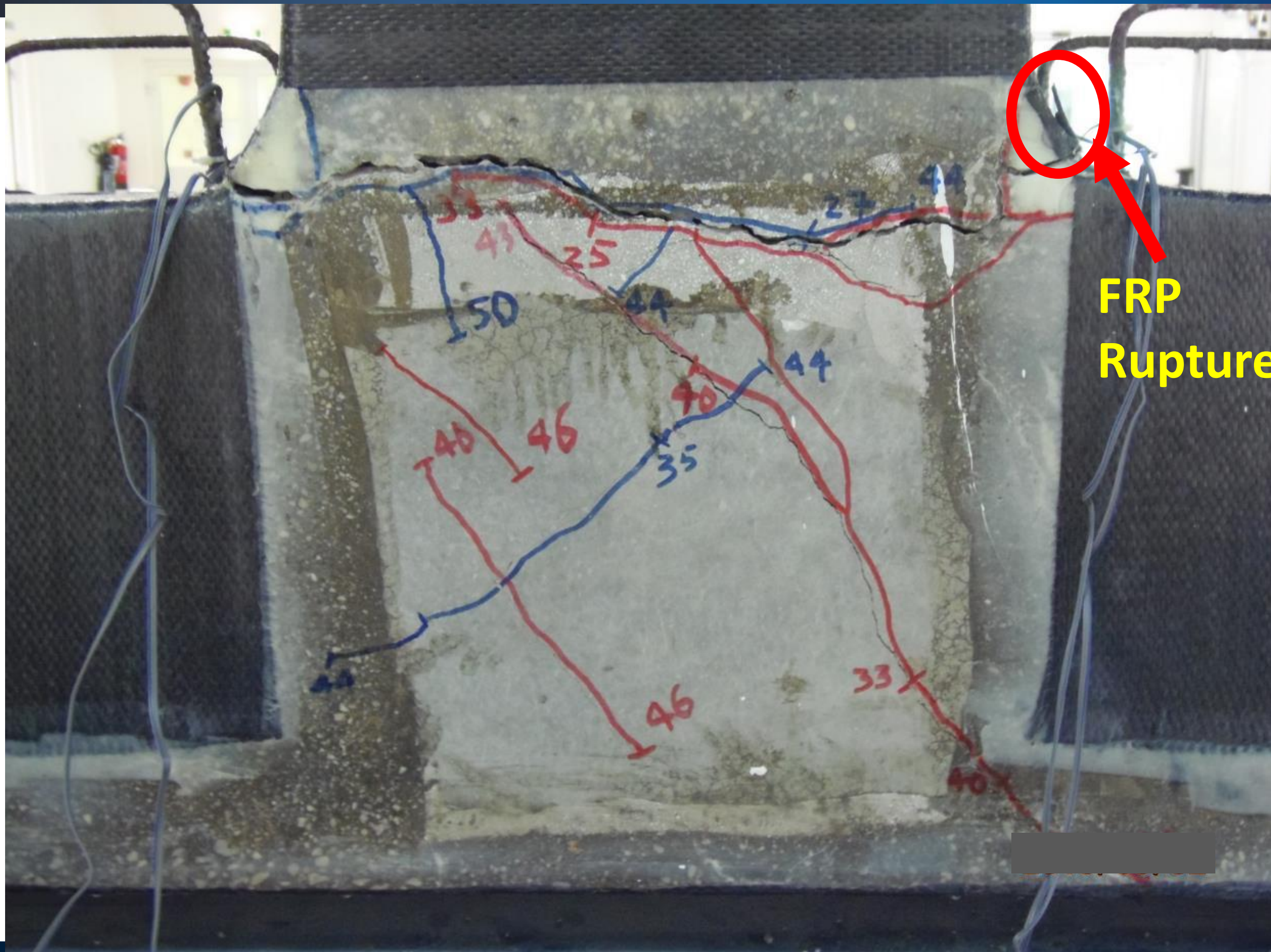

Drift Ratio = 3.00%
Load = 46 kN
2016/05/24

Hysteretic Response

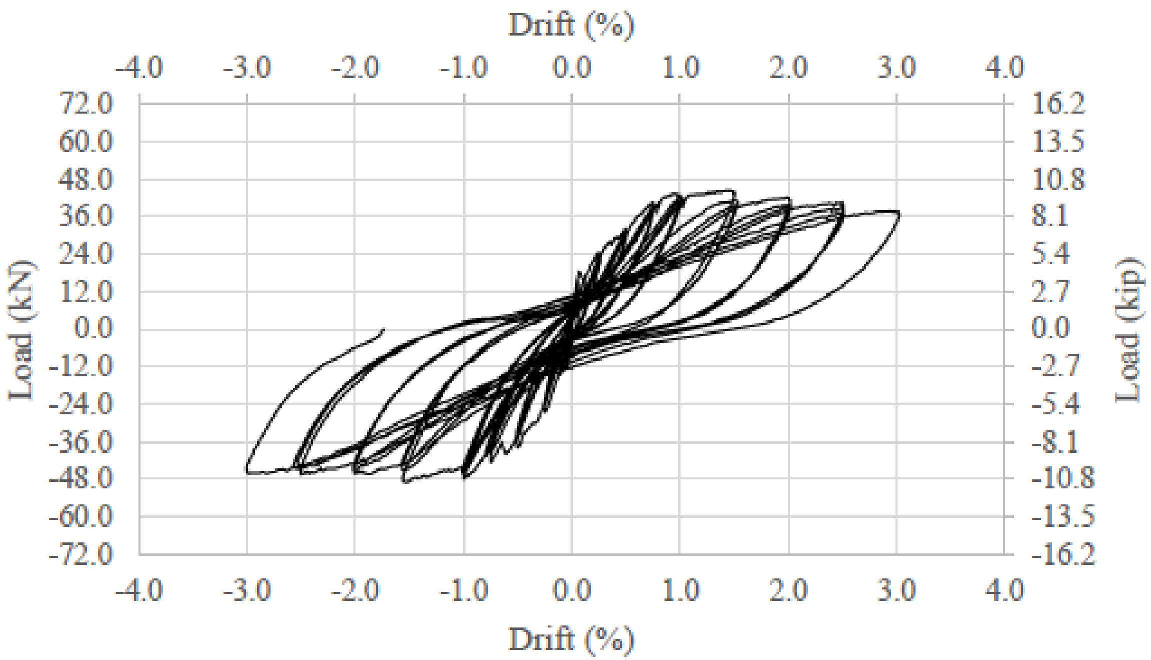


Anchored with Wraps – BCA-2

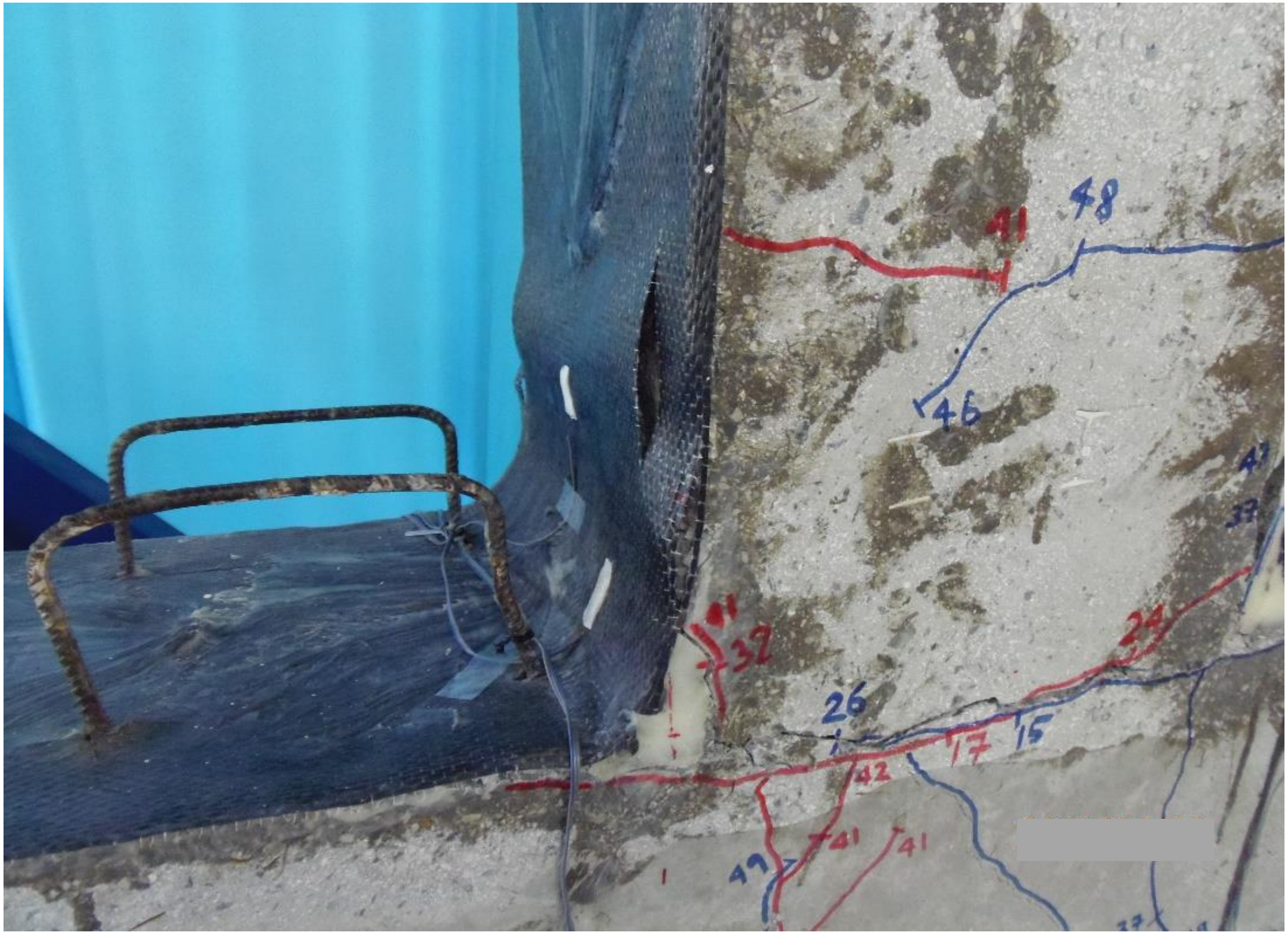

FRP
Rupture


FRP
Rupture

Hysteretic Response



Anchored with Spike Anchor 1 – BCA-3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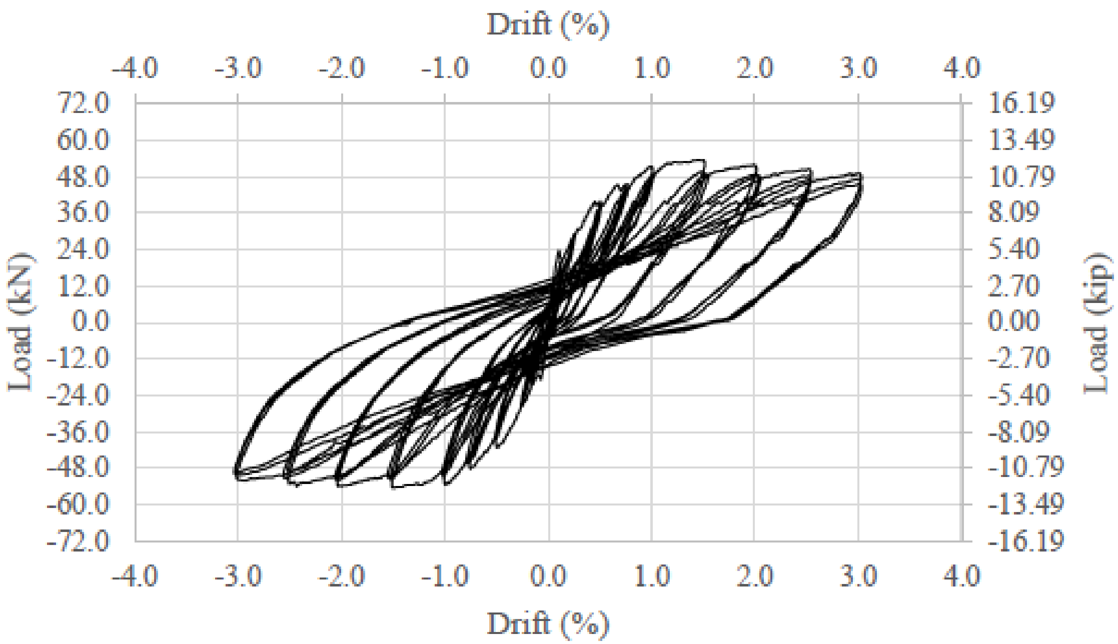
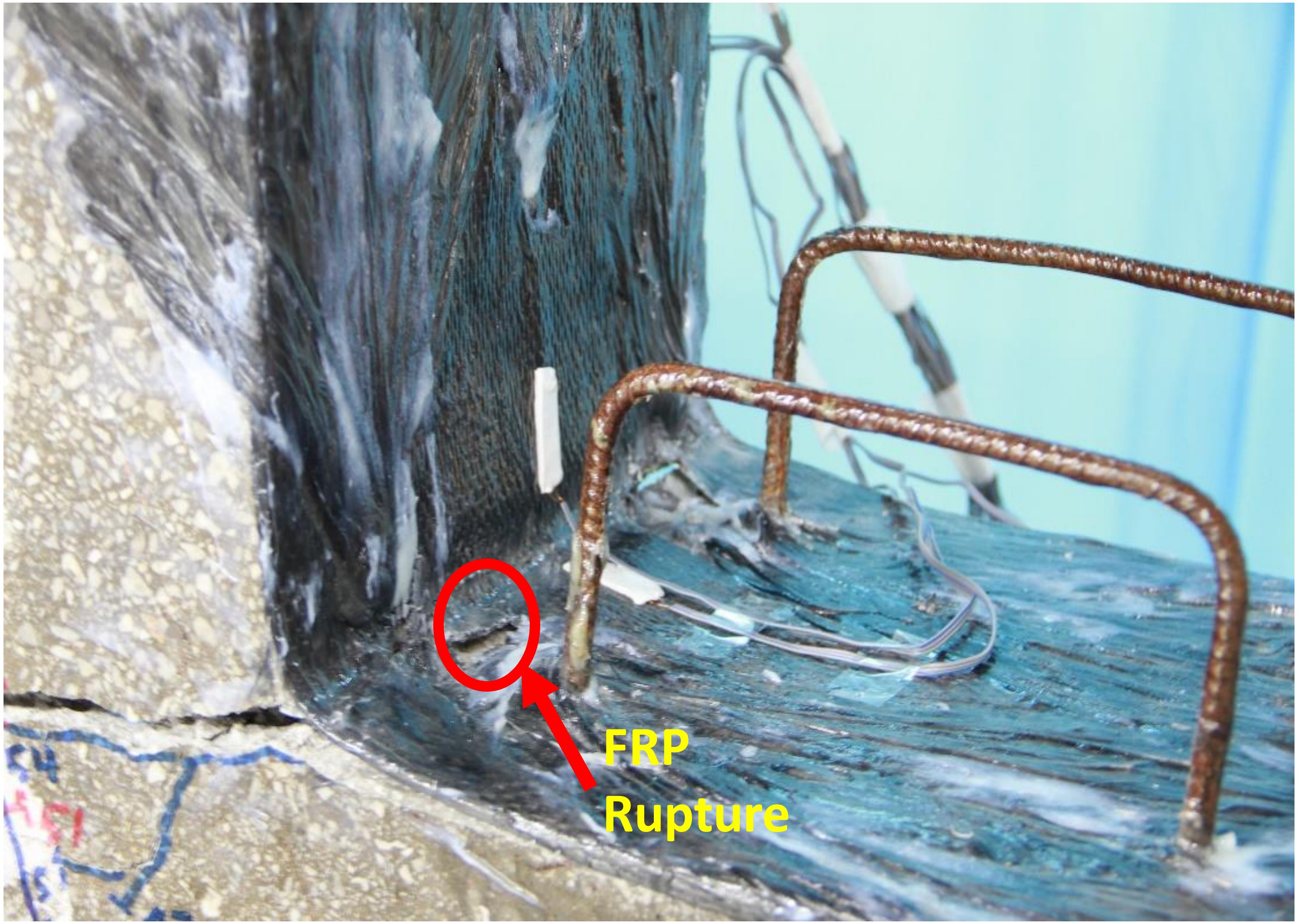
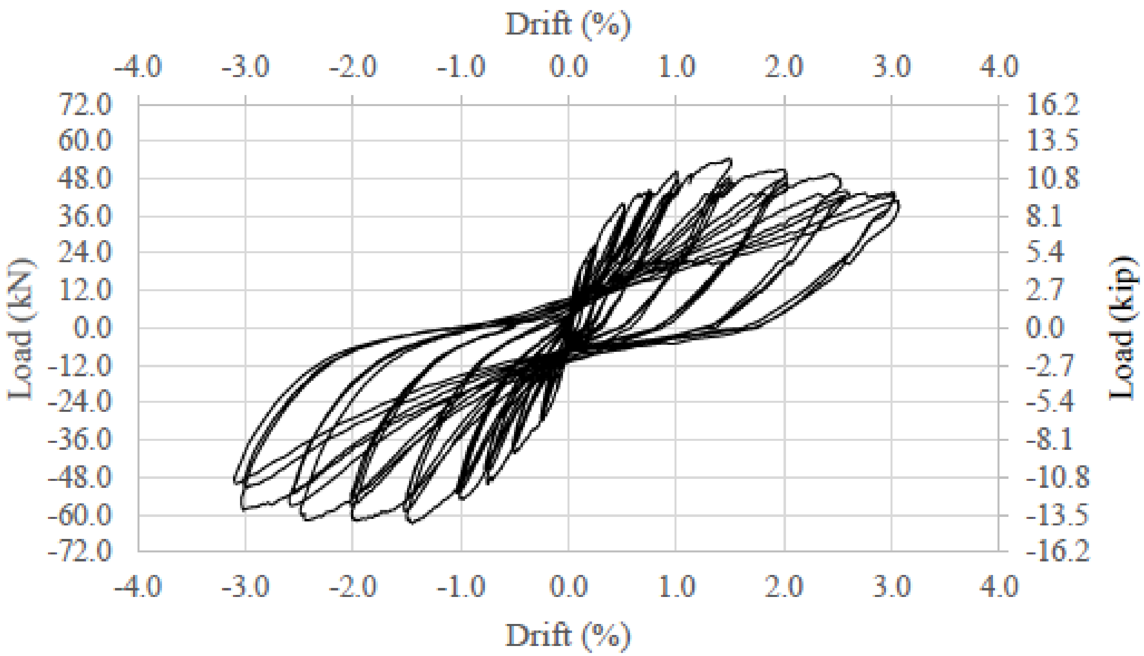
Hysteretic Response



Anchored with Spike Anchor 2 – BCA-4


FRP
Rupture

Hysteretic Response



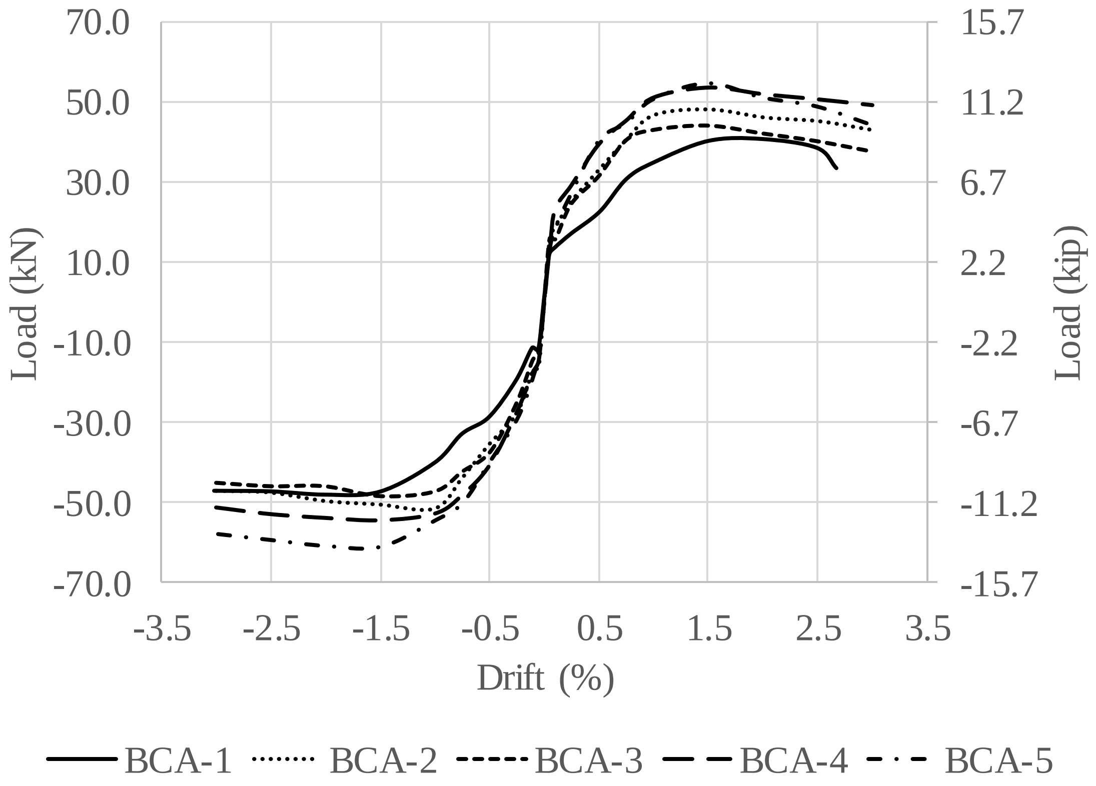
Anchored with Spike Anchor 3 and Wraps – BCA-5


Drift Ratio = 3.00%
Load = 59 kN

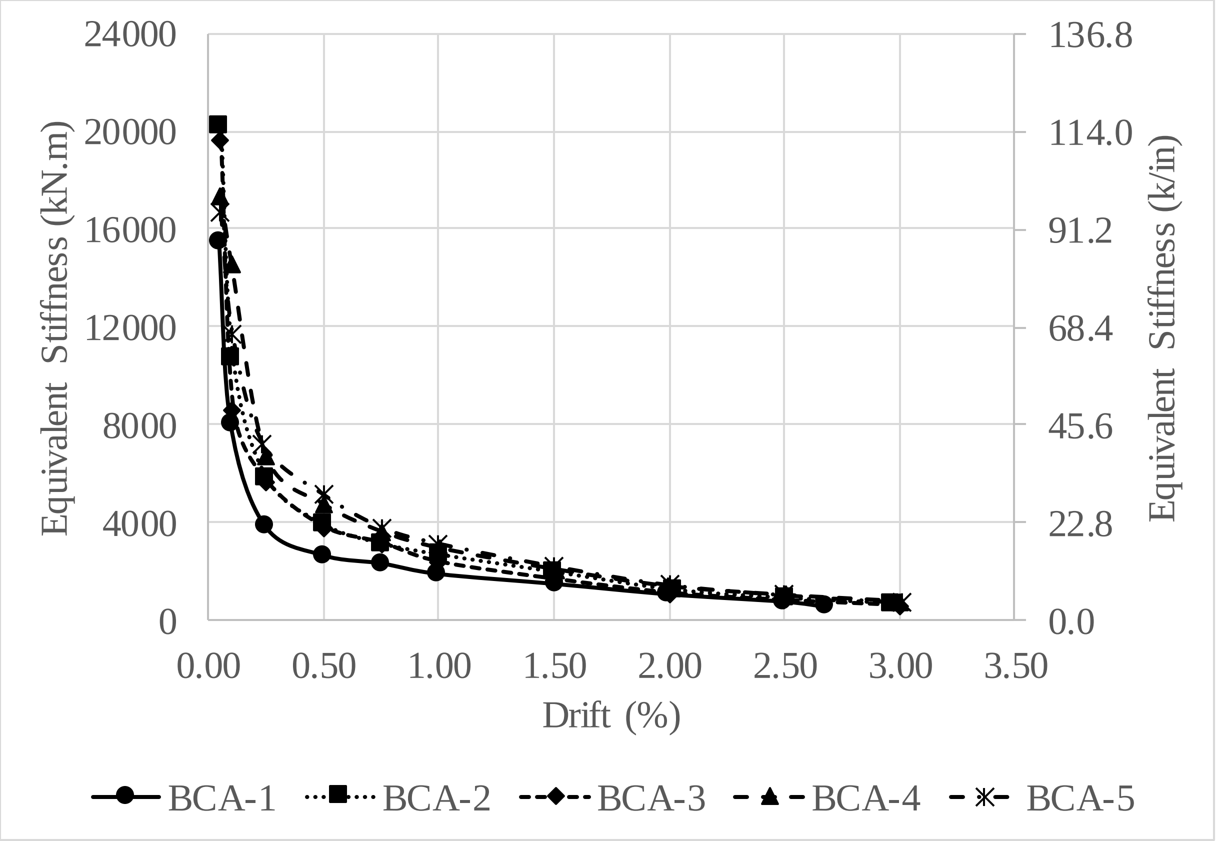
Cracking, Yielding, and Ultimate Loads

Specimen	Cracking Load	Drift ratio	Yielding Load	Drift ratio	Average Ultimate Load	Drift ratio	% increase in strength
	kN (kip)	%	kN (kip)	%	kN (kip)	%	
BCA-1	13.6 (3.06)	0.10	33.4 (7.51)	0.92	40.9 (9.20)	2.00	-----
BCA-2	18.5 (4.16)	0.25	37.9 (8.52)	0.65	48.8 (10.97)	1.50	19.3
BCA-3	17.8 (4.00)	0.06	37.4 (8.41)	0.65	46.5 (10.45)	1.35-1.50	13.7
BCA-4	23.0 (5.17)	0.10	47.5 10.68)	0.85	53.95 (12.12)	1.46-1.50	31.9
BCA-5	20.0 (4.50)	0.13	47.9 10.77)	0.93	58.75 (13.20)	1.45-1.49	43.6

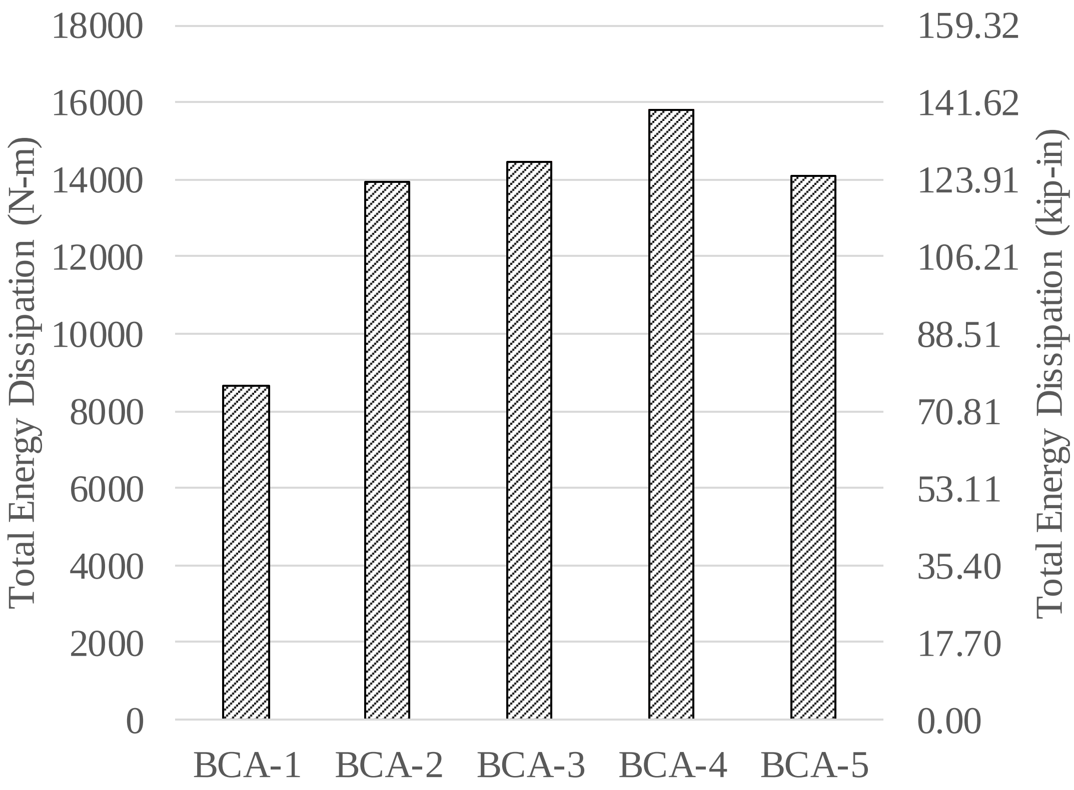
Envelope Curves



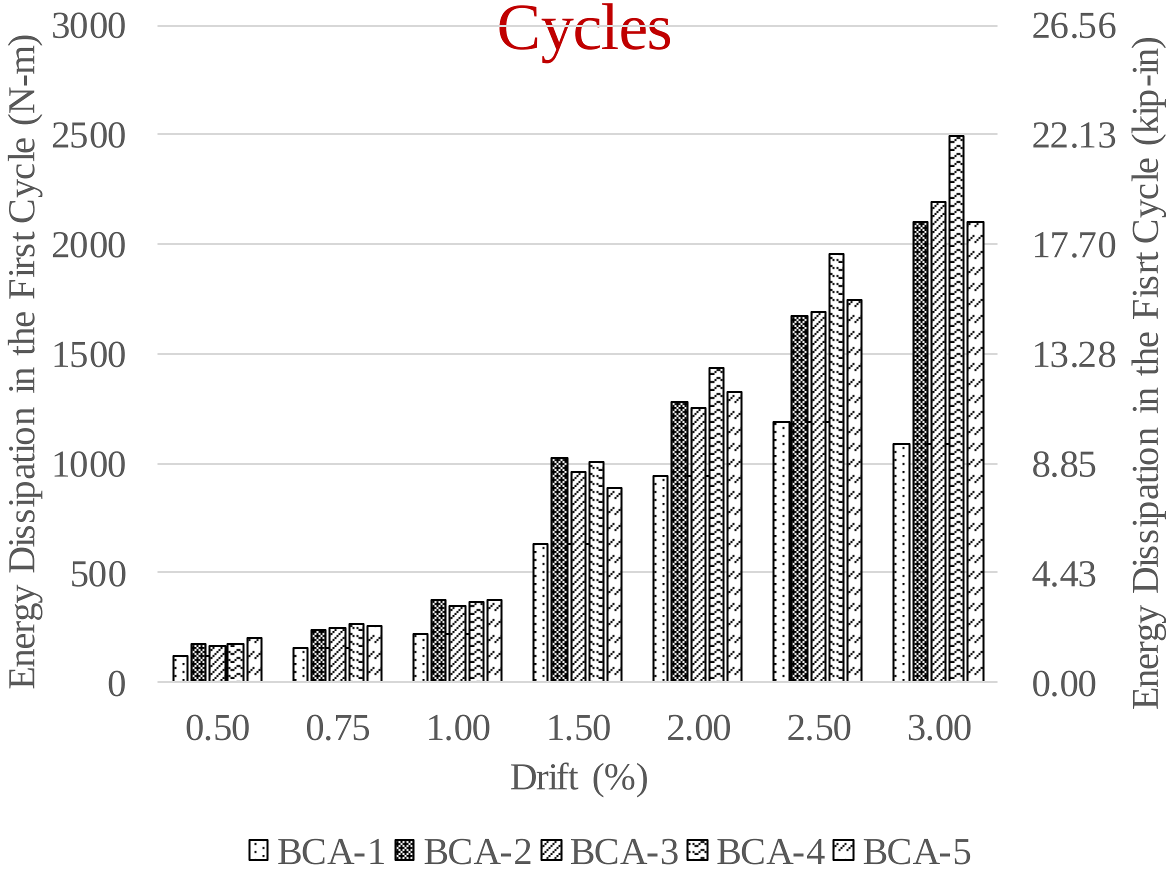
Peak-to-Peak Stiffness Degradation



Total Energy Dissipation



Energy Dissipated in the First Cycle of Each Set of Drift Cycles



Conclusions

- All strengthening schemes improved the behavior compared to that of the control specimen in terms of:
  - Strength
  - Total energy dissipated
  - Stiffness degradation
- Providing dense spike anchors is structurally equivalent to the hybrid scheme combining parallel anchors and full wrapping

Conclusions

- Dense spike anchor scheme out-performed the full wrapping
- The total energy dissipated during the testing was the greatest for the dense spike anchor configuration
- Further studies with various ratios of axial to bending forces are required to better understand the performance of these anchor systems

Acknowledgment

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