Concrete-Filled Tube Bridges for Accelerated Bridge Construction

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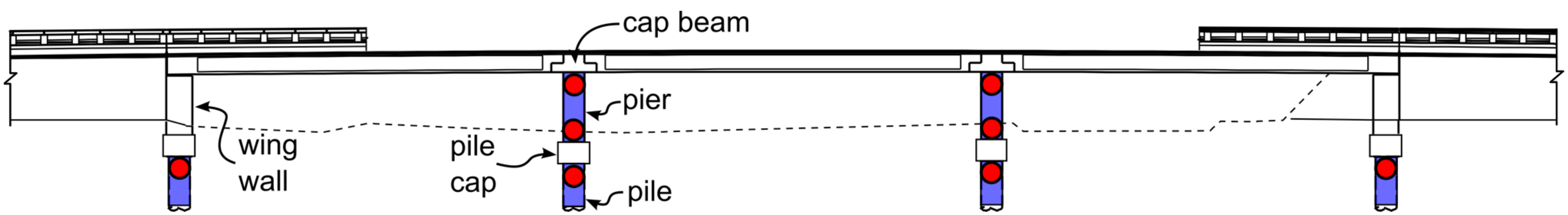
What is a Concrete-Filled Steel Tube?

- Concrete-Filled Steel Tube (CFST) elements are circular (most common) or rectangular steel tubes filled with concrete.
- They are fully composite members maximizing the benefits of the steel and concrete:
  - Steel tube confines the concrete
  - Concrete increases stiffness and compressive strength
  - Local buckling is delayed
- CFT elements are <u>not</u> simply RC columns with steel jackets, as is commonly used in seismic retrofit

Application of CFST

- CFST can be used as foundation elements (piles, shafts) and piers in elevated bridges

- Under extreme loads, inelastic deformation must be isolated to CFST component. Surrounding concrete components remain essentially elastic for large reversed cyclic displacement demands



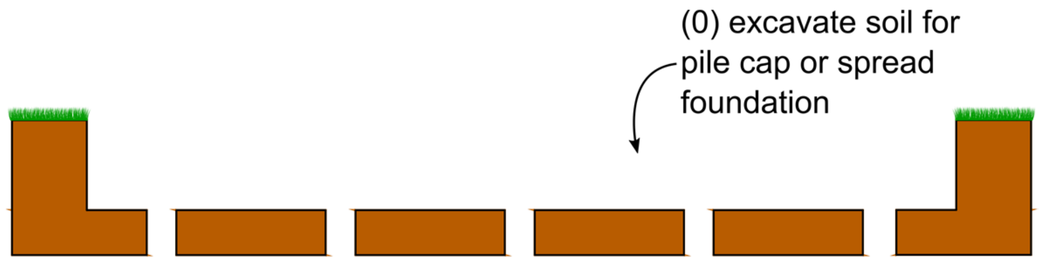
Advantages of CFST in ABC

- **Relative to RC columns:**
  - No formwork to construct, tear down or store
  - Internal reinforcement not required
  - Self-consolidating concrete
  - Smaller diameters

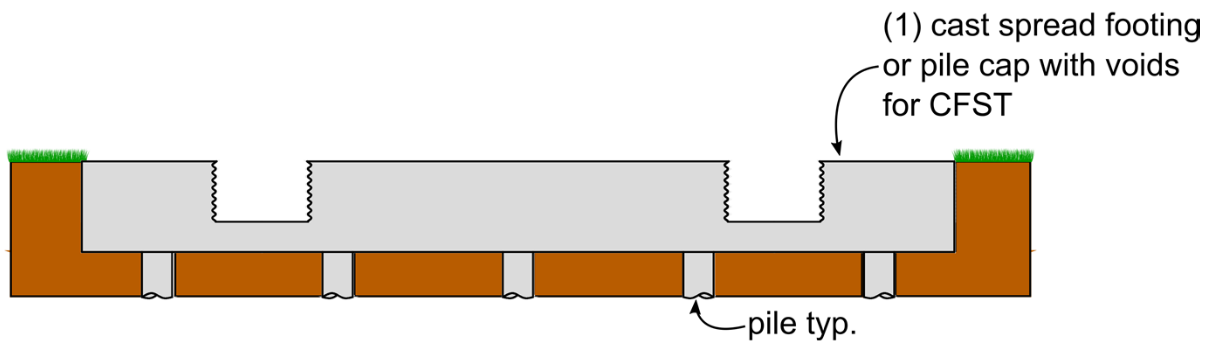
- **Relative to precast columns:**
  - Lighter facilitating placement
  - Length and diameters can easily vary within a structure
  - Smaller diameters than RC columns
  - Can also be integrated with precast cap beams.

Photo Courtesy of MDT

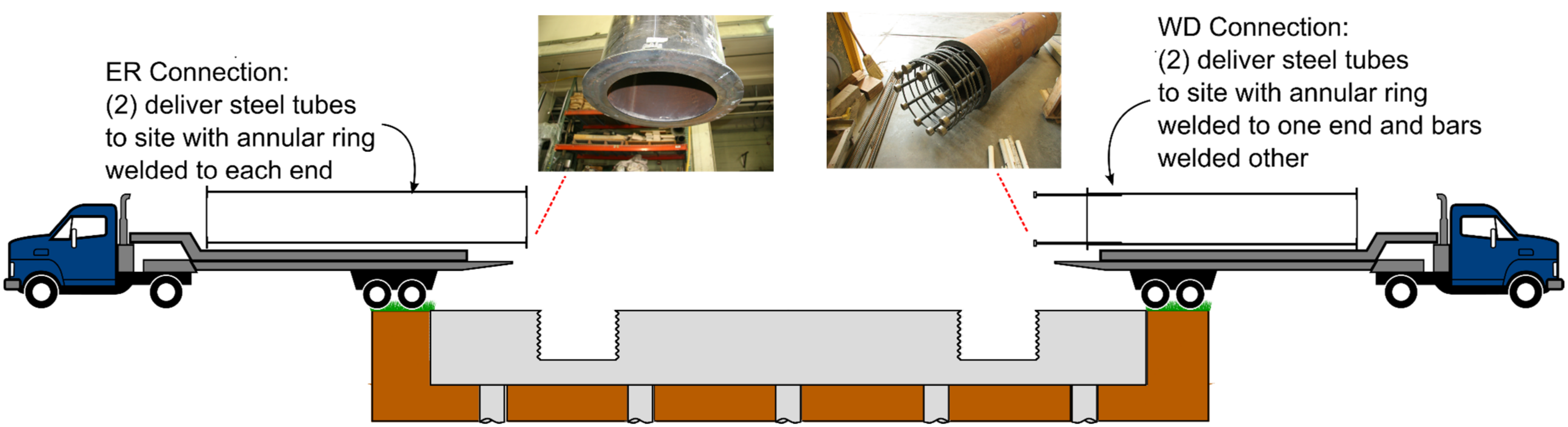
Accelerated Construction Sequence



Accelerated Construction Sequence



Accelerated Construction Sequence



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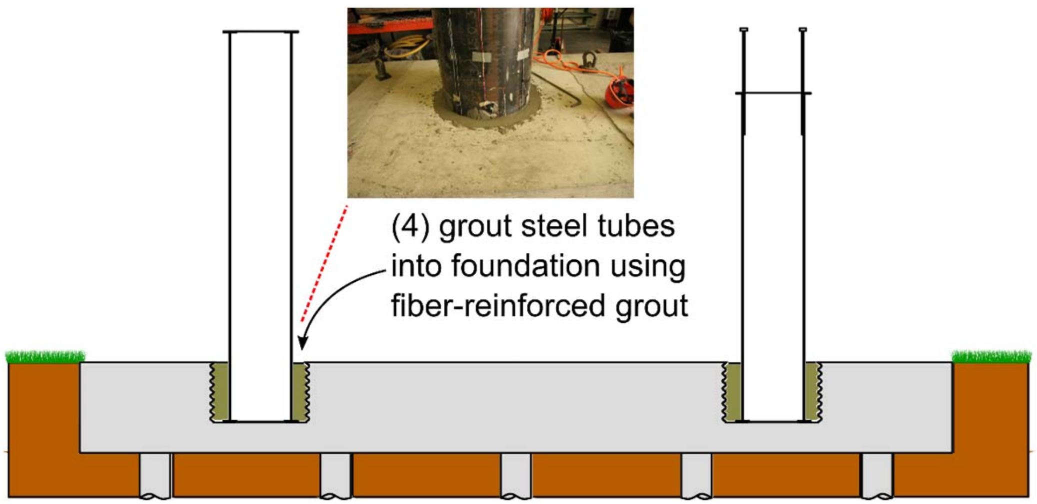
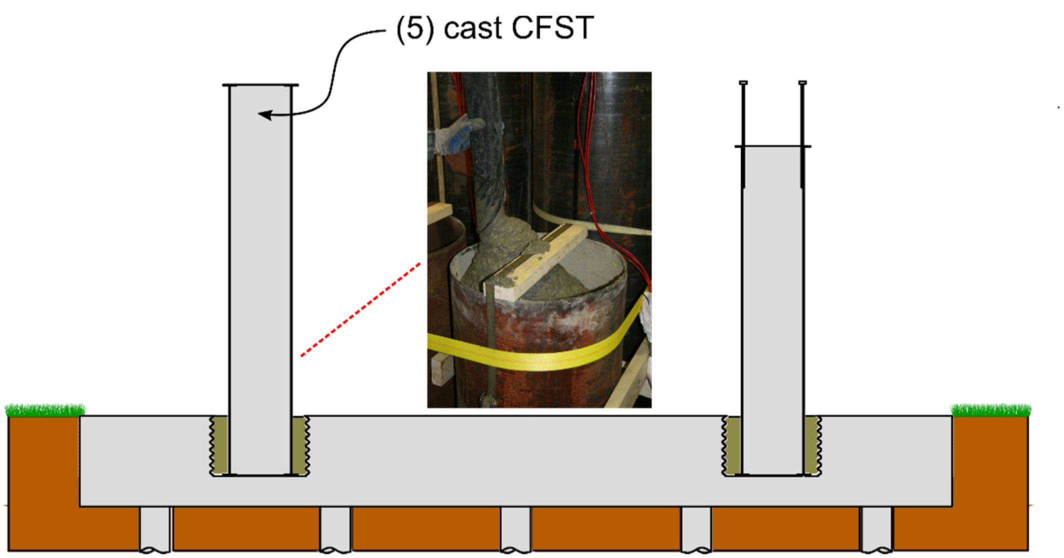


Accelerated Construction Sequence



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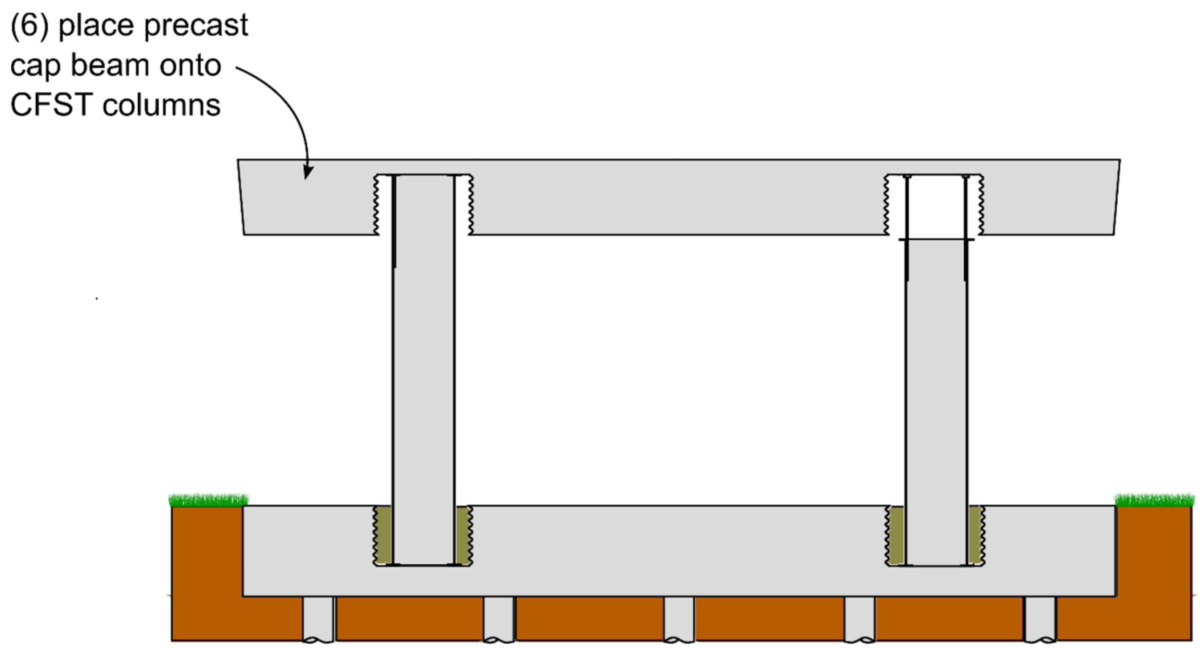
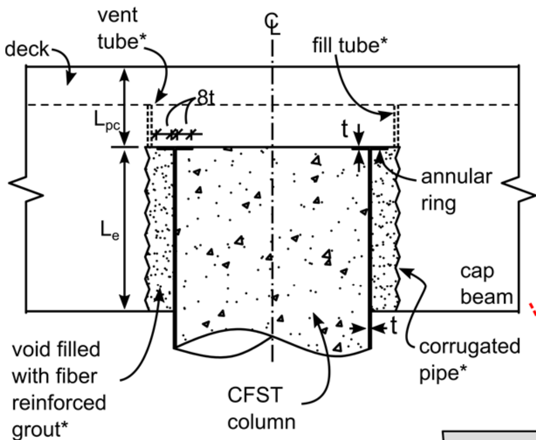
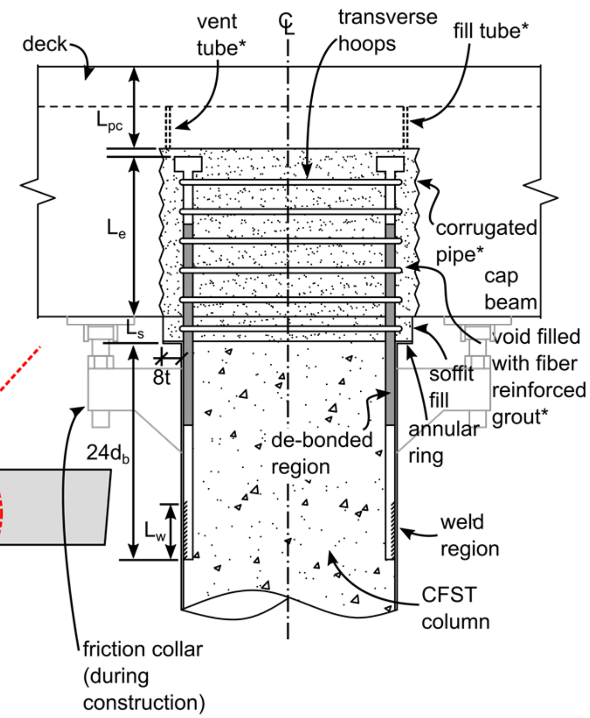


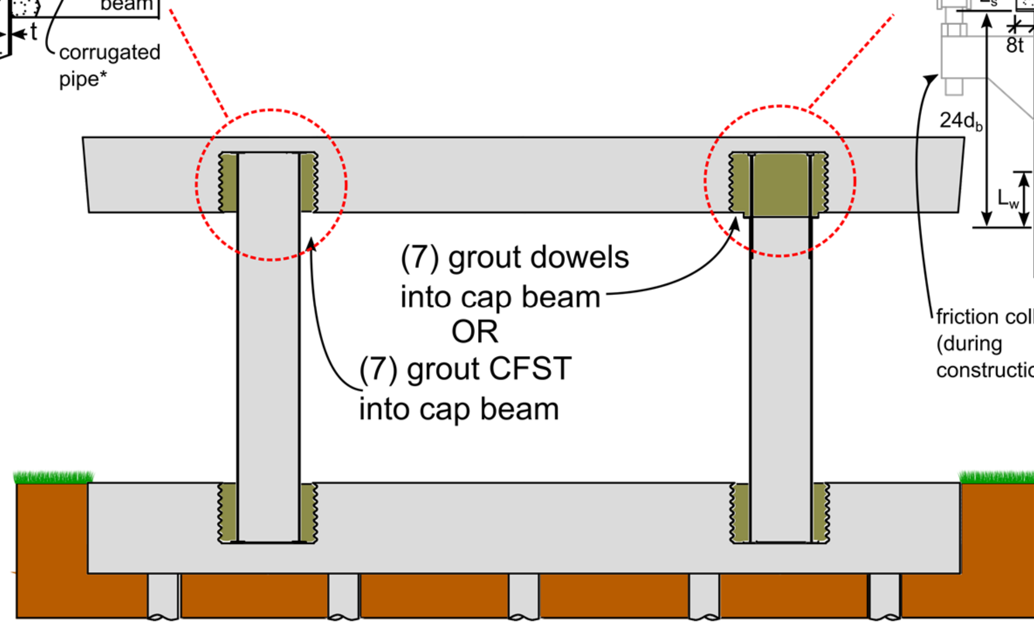
Accelerated Construction Sequence

Embedded Ring (ER)

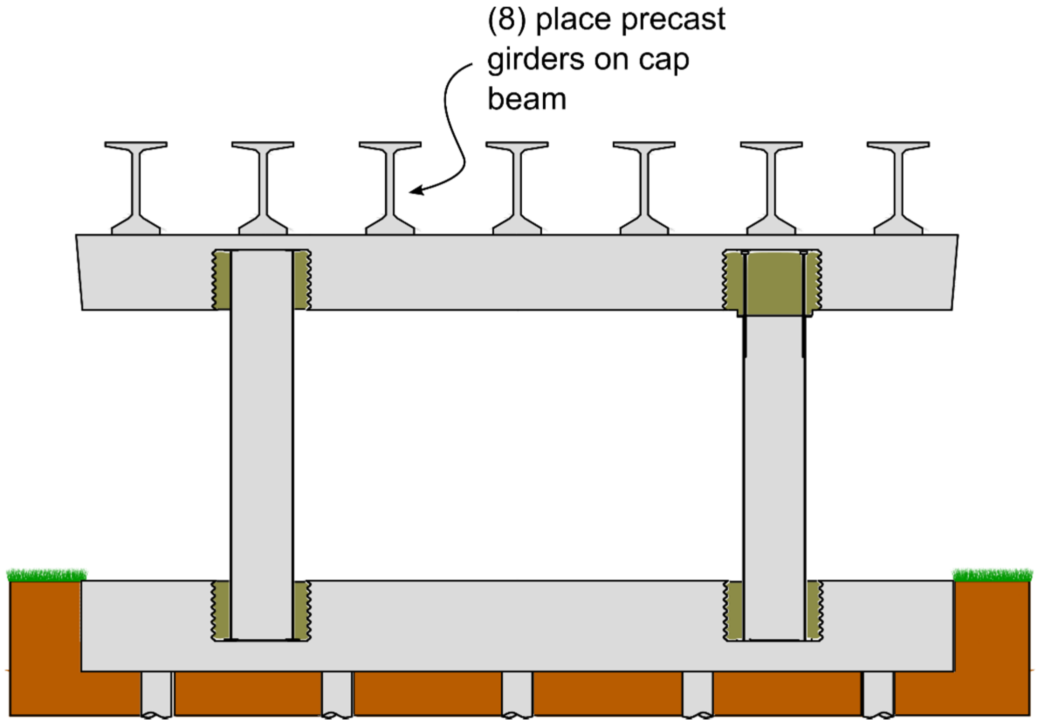


Welded Dowel (WD)

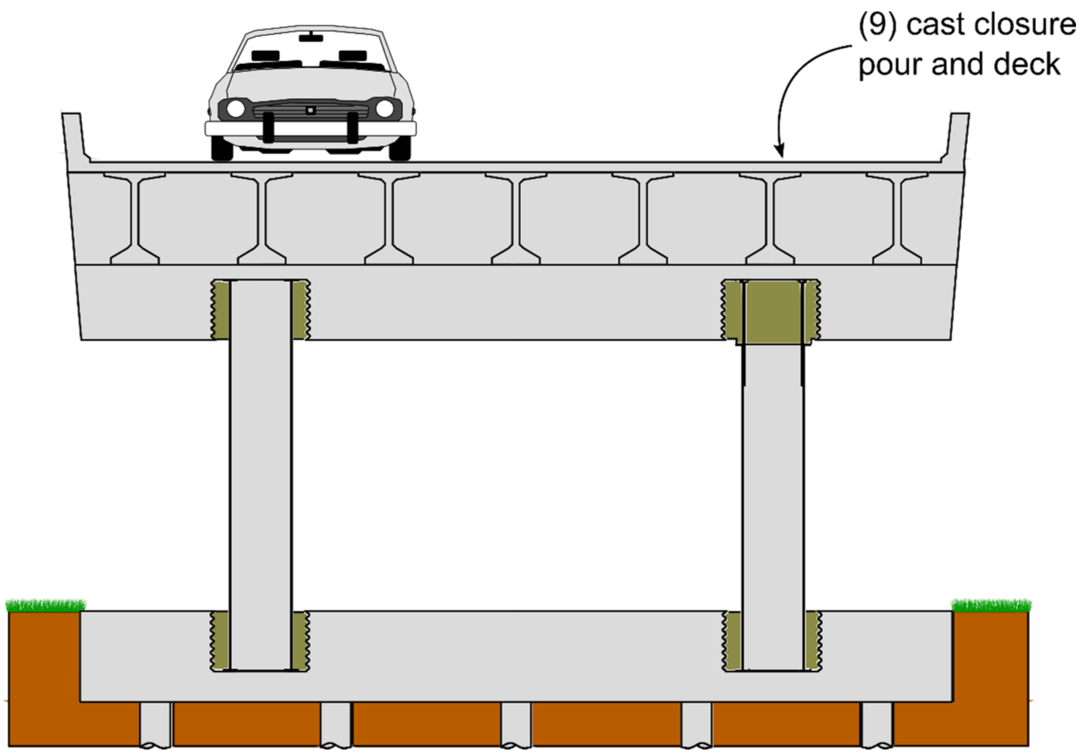




Accelerated Construction Sequence

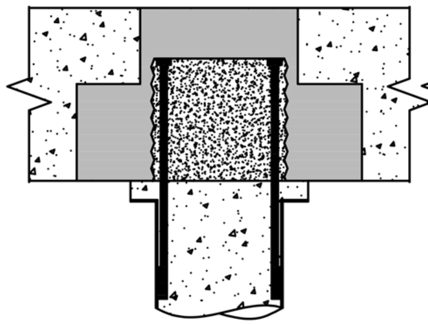


Accelerated Construction Sequence

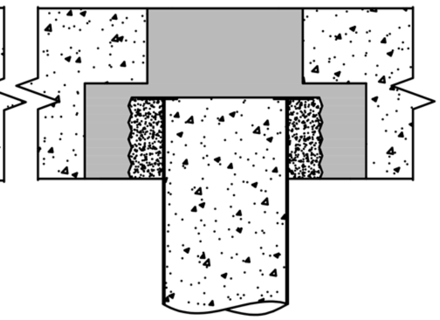


CFST Bridge System (Funding Agency)

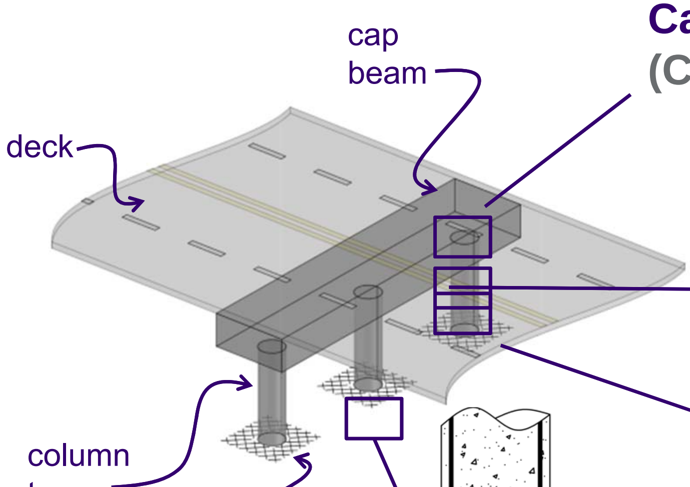
Welded Dowel (WD)

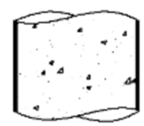


Embedded Ring (ER)



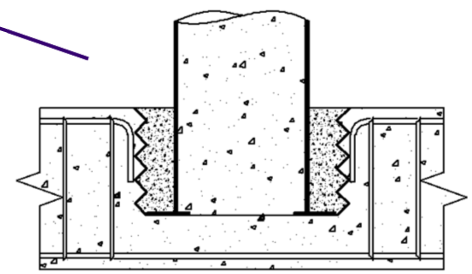
Cap Beam Connection (7)
(Caltrans)





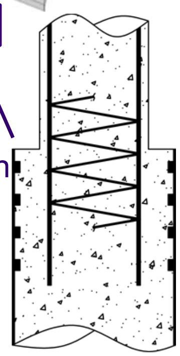
CFST Component:
(WSDOT, ARMY)

- > Flexural Strength **(6)**
- > Shear Strength **(21)**
- > Deformation Capacity



Foundation Connection (17):
(Caltrans, WSDOT, ARMY)

Embedded Ring (ER)



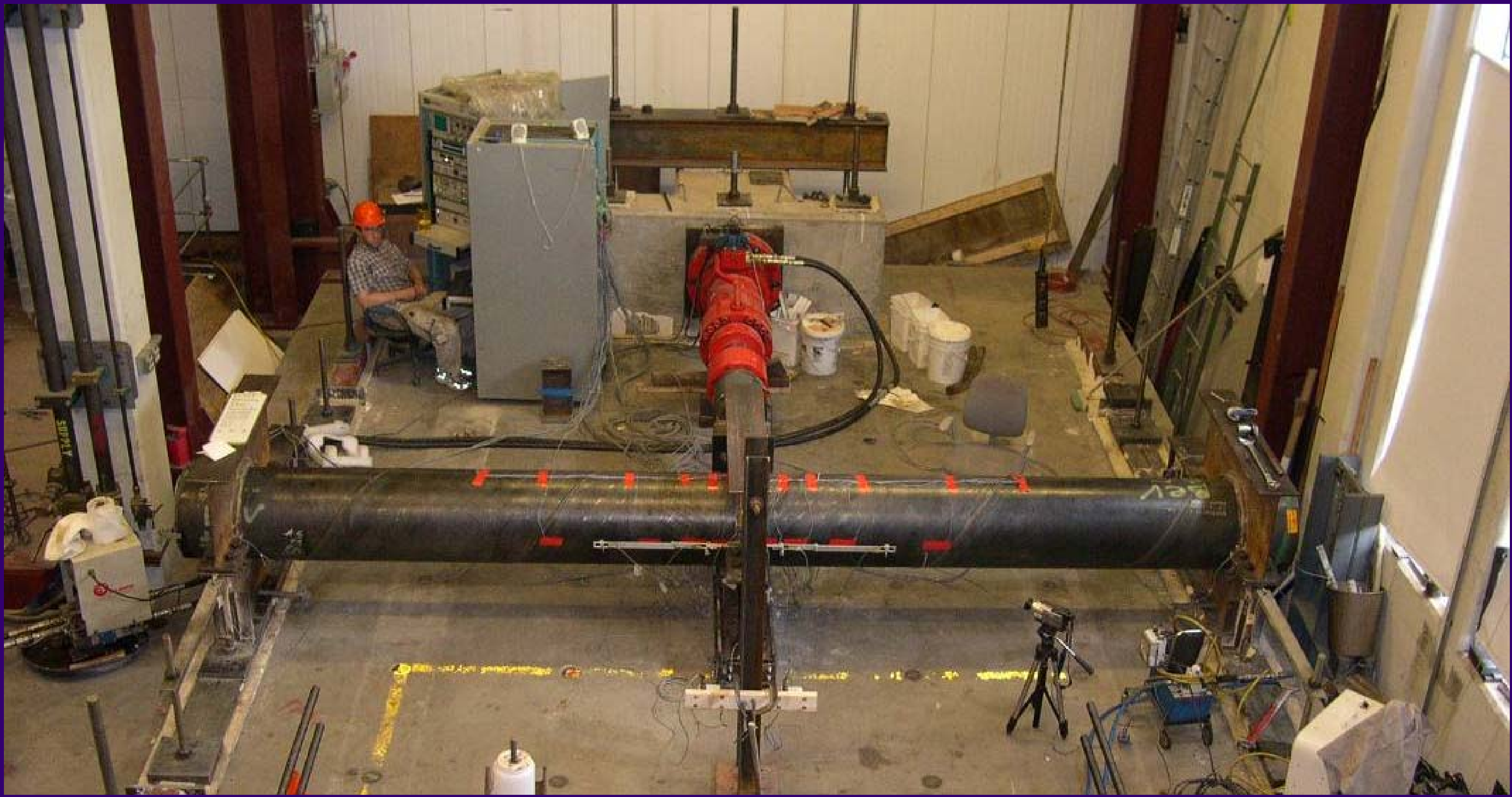
Deep-Foundation Connection
and Soil-Structure Interaction (Proposed)

Design & Implementation

- Combined Loading: Flexure and Axial Strength
- Shear Strength
- Connections

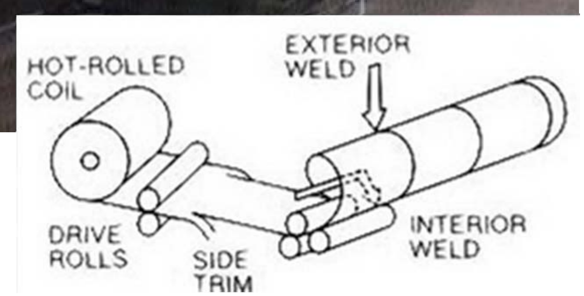
Alaskan Way Viaduct (CFST piles)

CFST Component Testing



Steel Tubes

- **Spiral Weld Tubes**
  - Economical, widely available, larger diameters and lengths than straight seam tubes
  - Fabricated by running a coil of steel through a machine that spins the coil into a spiral
  - Double submerged arc weld is used to seal the spiral; continuous x-ray of weld
  - Weld provides mechanical bond
- **Straight Seam Tubes**
  - Thicker tubes available; as such typically used for driven piles
  - No mechanical bond; low-shrinkage concrete or binding through bending required for composite action.



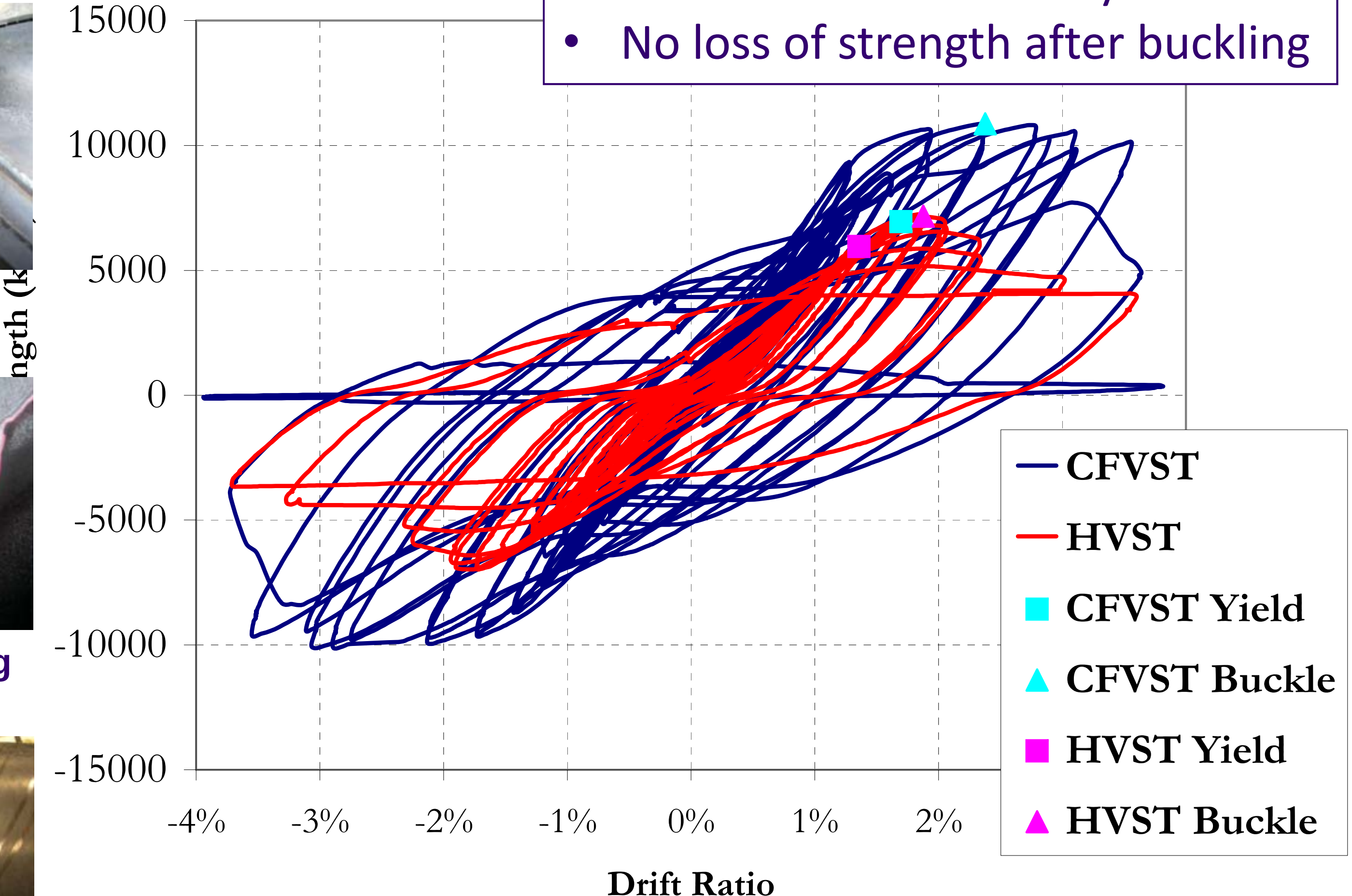
Flexural Response

- Increased Stiffness
- Increased Strength
- Increased Deformability
- No loss of strength after buckling

Initial Buckling (~2.3% drift)

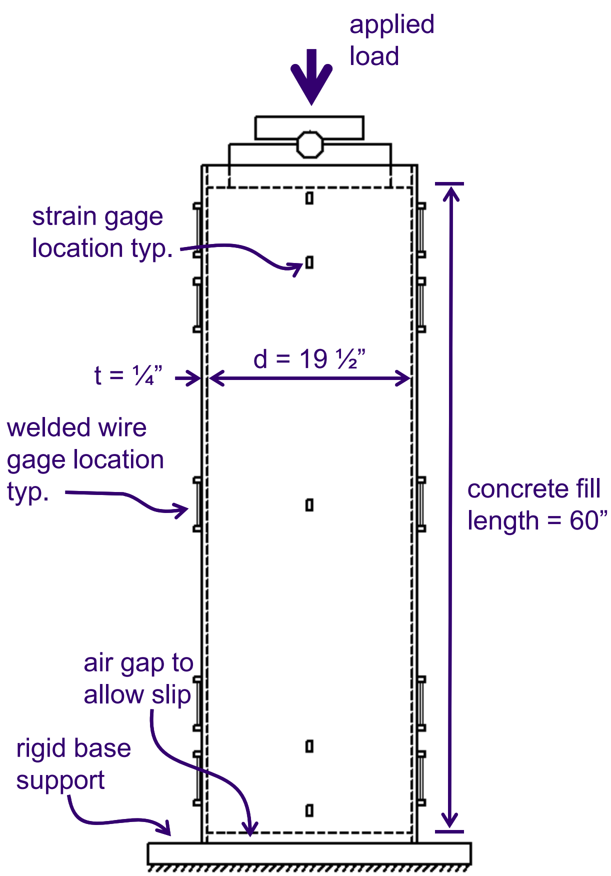
Initial Tearing (~2.7% drift)

Complete Tearing (3% drift)



Composite Action in CFST

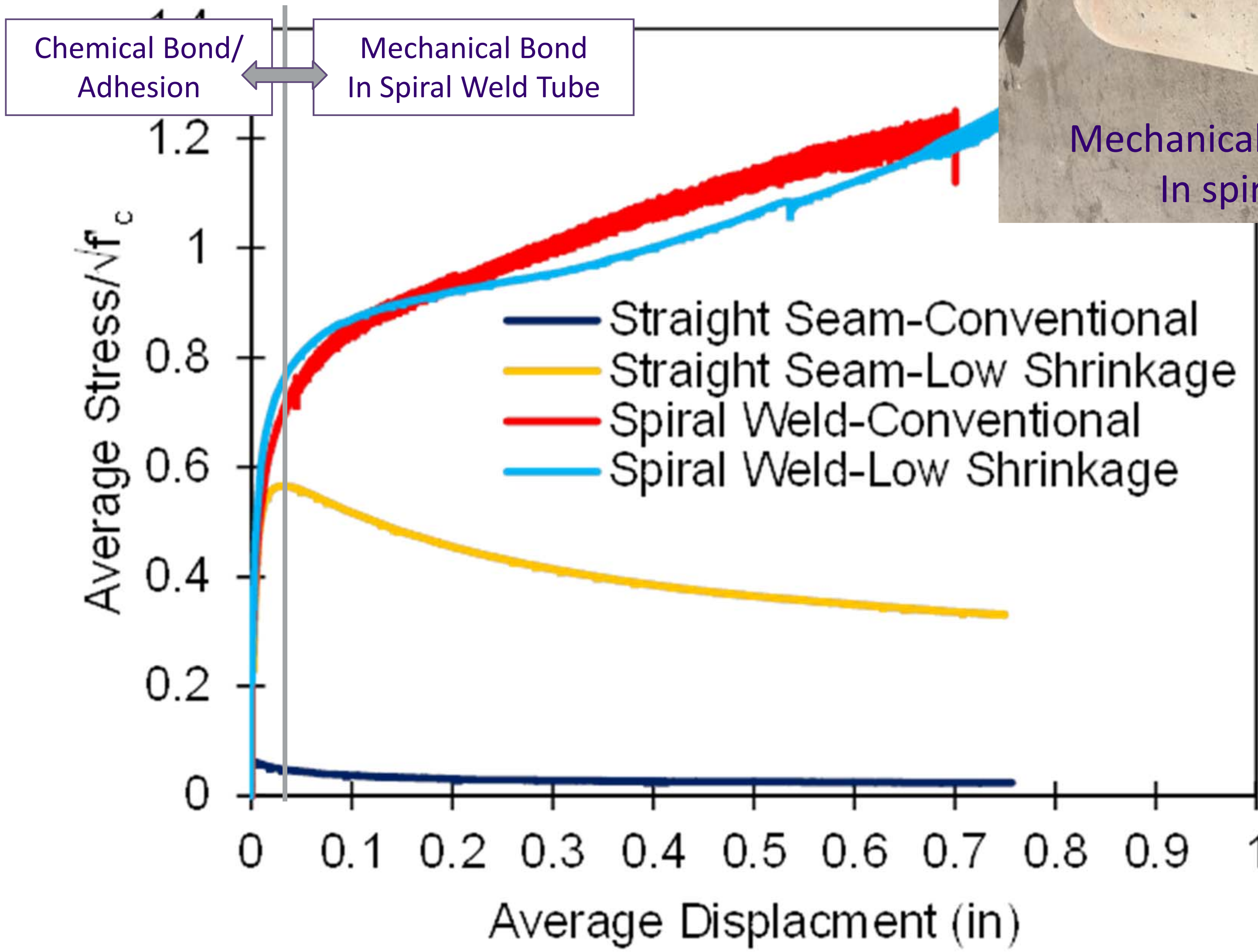
Simple, filled-tube push-through tests and 3-point bending tests



4-Test Matrix

Tube	Concrete
Straight Seam	Conventional
	Low Shrinkage
Spiral Weld	Conventional
	Low Shrinkage

Composite Action



Shear Strength of CFST

21 tests on CFST specimens conducted. New expression proposed.

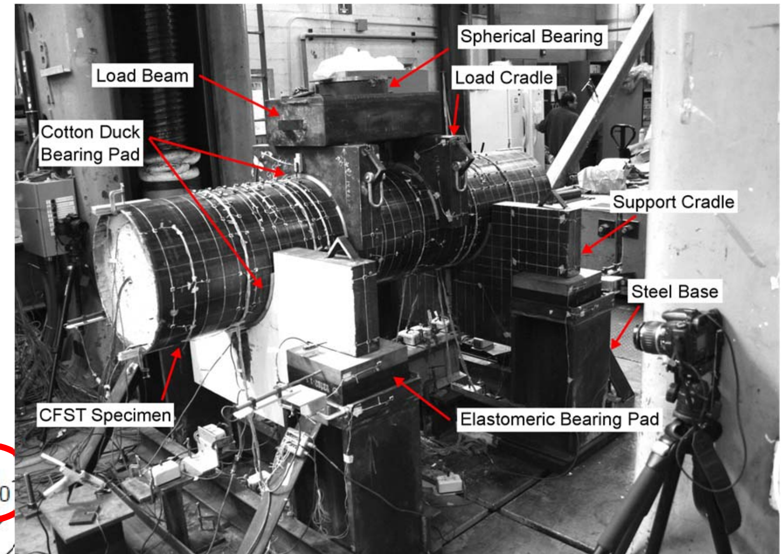
> Current design expressions include **steel tube only** (V_s) or treat CFST as an **RC section** with $V_n = V_s + V_c$. Neither approach is correct.

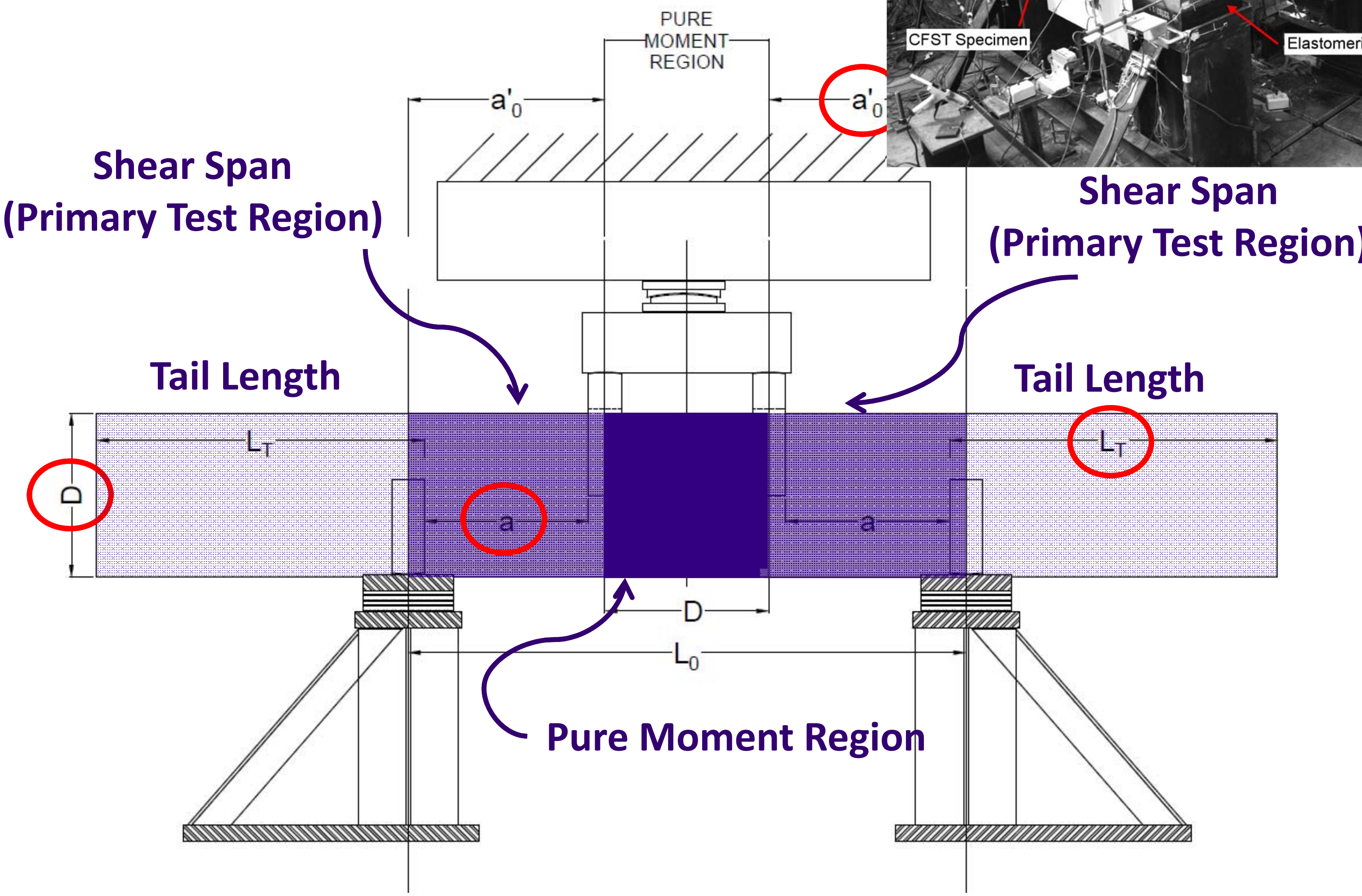
> Both underestimate the shear strength by a factor of at least two.

> Testing investigated: (a) aspect ratio, (b) D/t, (c) concrete strength, (d) internal reinforcement ratio, (e) tail (anchorage) length, (f) axial load ratio.

> Results show that CFST sections are very strong in shear.

Experimental Setup





Test Matrix (21 Specimens)

Specimen	a/D	t (in)	a (in)	D/t	F_{yt} (ksi) [1]	f'_c (ksi)	P/P_0	L_T (in.)	ρ_{int}	Interface [3]
10 [1]	0.375	0.25	7.5	80	42	6.0	0 %	2D	0 %	Clean
1	1.0	0.25	20	80	42	6.0	0 %	2D	0 %	Clean
2	0.5	0.25	10	80	42	6.0	0 %	2D	0 %	Clean
3		0.25	10	80	42	6.0	0 %	D/2	0 %	Clean
4		0.25	10	80	42	6.0	0 %	D	0 %	Clean
5		0.25	10	80	42	6.0	0 %	2D	0 %	Muddy
6		0.25	10	80	70	6.0	0 %	2D	0 %	Spiral
9		0.25	10	80	42	6.0	0 %	2D	0 %	Greased
12		0.25	10	80	42	6.0	0 %	2D	1.13 %	Clean
17		0.25	10	80	42	12	0 %	2D	0 %	Clean
18		0.375	10	53.3	42	12	0 %	2D	0 %	Clean
19		0.375	10	53.3	42	12	0 %	2D	1.07 %	Clean
7	0.375	0.25	7.5	80	42	6.0	0 %	2D	1.04 %	Clean
8		0.25	7.5	80	42	6.0	0 %	2D	2.01 %	Clean
11		0.25	7.5	80	42	6.0	0 %	D/2	0 %	Clean
13		0.25	7.5	80	42	6.0	8.5 %	D/2	0 %	Clean
16		0.25	7.5	80	42	12	0 %	2D	0 %	Clean
21		0.25	7.5	80	42	gravel	0 %	2D	0 %	Clean
14	0.25	0.25	5	80	42	12	0 %	2D	0 %	Clean
15		0.25	5	80	42	12	0 %	5/8D	0 %	Clean
20		0.25	5	80	42	2.5	0 %	2D	0 %	Clean

[1] Specimen 10 is the baseline test in the entire series. The test parameters that differ from this specimen are highlighted.

[2] All tube steel conformed to both API 5L X42 and ASTM A53B standards, except Specimens 6 and 22 which conformed to ASTM A1011 HSLAS Gr 70 C1/C2.

[3] All specimens were constructed with straight-seam tubes unless noted otherwise.

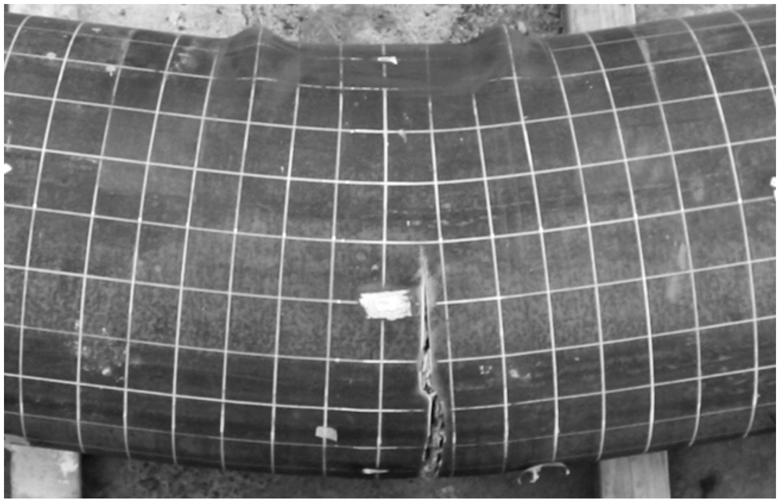
Parameters

- **a/D**
- **L_T**
- **D/t**
- **Tube type**
- **f_c'**
- **Tube-to-Concrete interface condition**
- **ρ_{int}**
- **P/P_0**

Test Results: **Flexural Response**

Specimen 17	
a/D = 0.5	f_{cm}' = 9.5 ksi
L_T = 2D	ρ_{int} = 0%
D/t = 80	clean interface

Midspan



- Typical shear span ratios: 1.0 and 0.5
- Flexural buckling of steel tube
- Vertical tube tear in constant moment region
- Concrete fill crack patterns:
  - Dense transverse flexural cracking in
  - midspan region
  - Minor to no diagonal cracking in shear spans

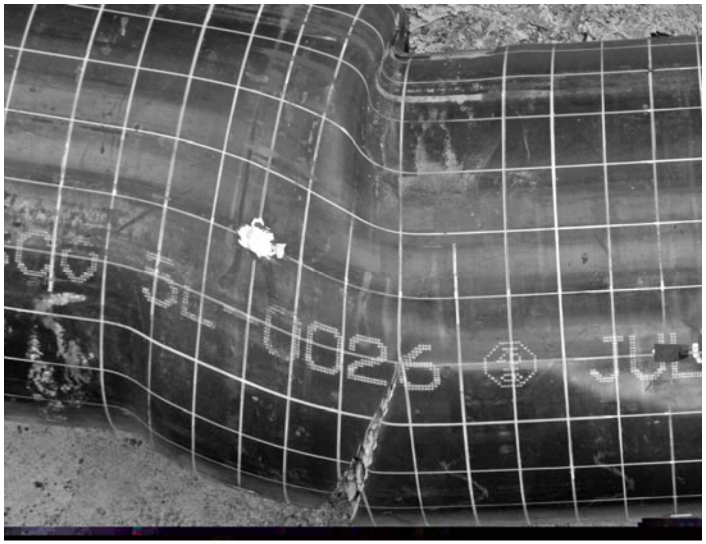
Shear Span

Test Results: **Shear Response**

Specimen 14/8

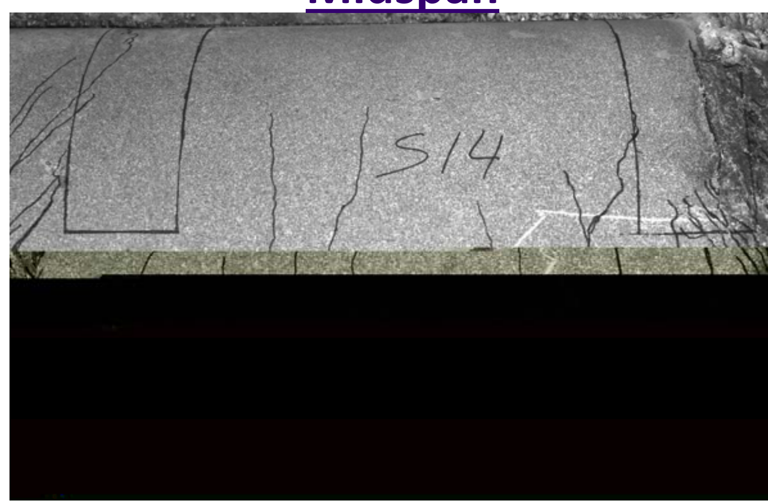
a/D = 0.25	f'_{cm} = 8.6/6.5 ksi
L_T = 2D	ρ_{int} = 0%/2%
D/t = 80	clean interface

Shear Span



- Typical shear span ratios: 0.375 and 0.25
- Evident shear strain in shear span
- Inclined tube tear in shear span region
- No visible deformation of steel tube in pure moment region
- Concrete fill crack patterns:
  - Minor flexural cracking in midspan region
  - Extensive diagonal cracking in shear spans

Midspan

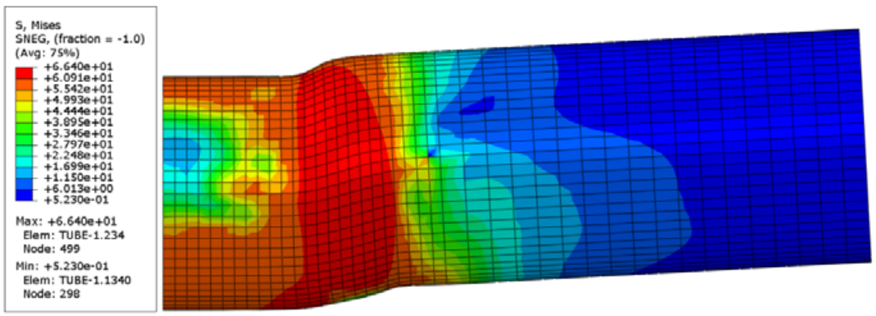


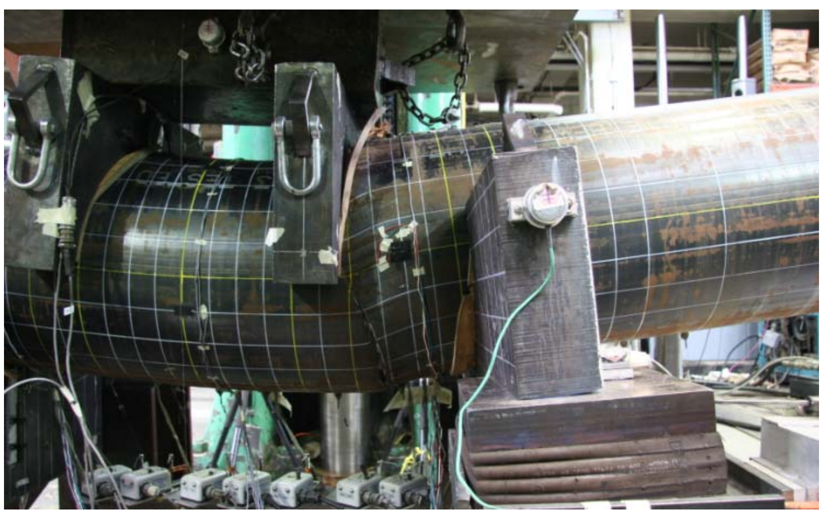
Simulation of Shear Response

Specimen 16

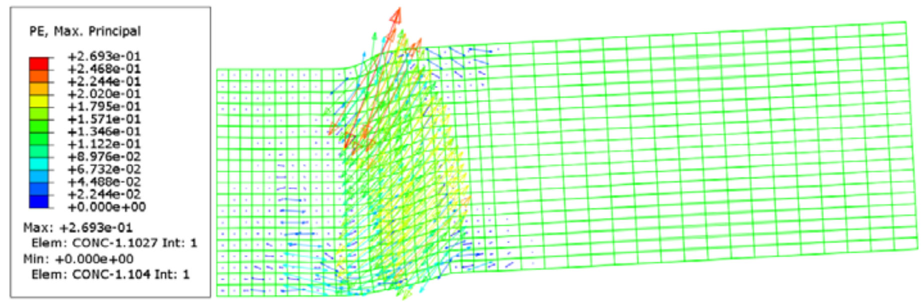
(a/D = 0.375, F_{ytm} = 56.8 ksi, f'_{cm} = 8.61 ksi, flex-shear)

Steel Tube Deformations





Concrete Cracking



Parameter Studies

Crushing Capacity:

$$P_0 = A_{st}F_{yt} + A_{srl}F_{yrl} + 0.95A_cf'_c$$

> Axial Load Ratio, P/P_0

> Internal Reinforcement Ratio, ρ_{int}

New developments

> Tube Diameter-to-Thickness Ratio, D/t

> Concrete Strength, f'_c

> Tube Steel Yield Strength, F_{yt}

Confirmed experimental conclusions

Proposed Shear Design Expression, $V_{n(prop)}$

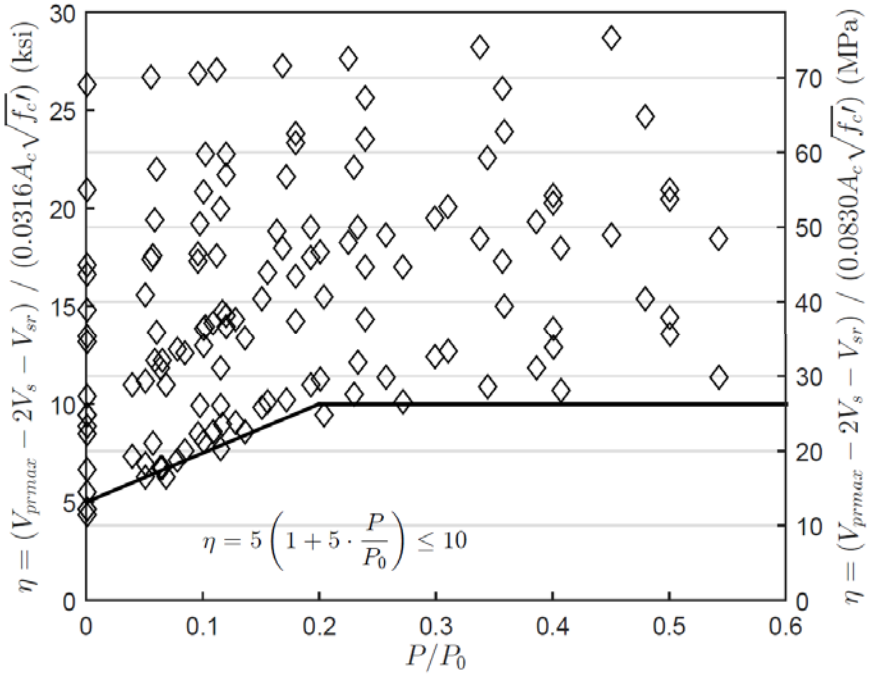
$$V_{n(prop)} = 2V_s + V_{sr} + \eta V_c$$

$$\text{where: } \eta = 5\left(1 + 5\frac{P}{P_0}\right) \leq 10$$

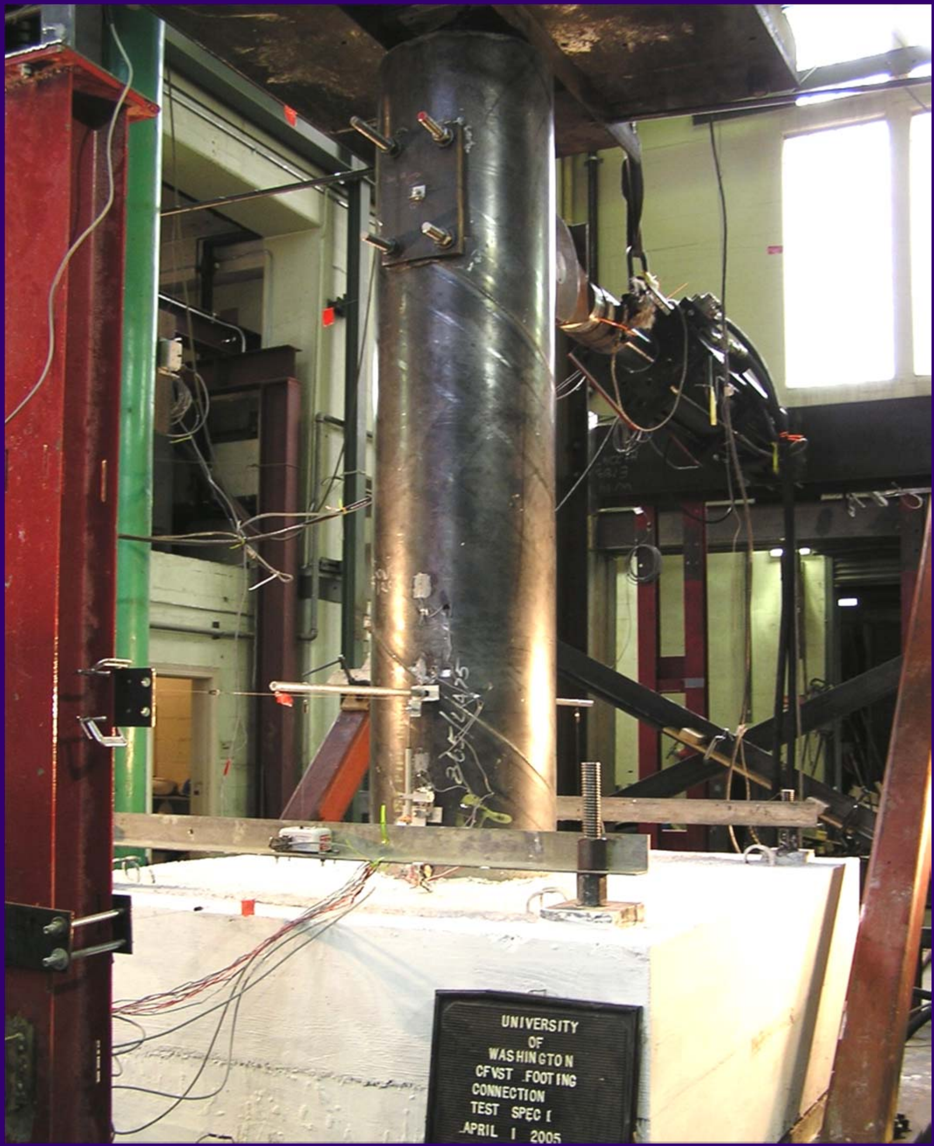
$$V_{st} = 0.6F_{yt}(0.5A_{st})$$

$$V_{srl} = 0.6F_{yrl}(0.5A_{srl})$$

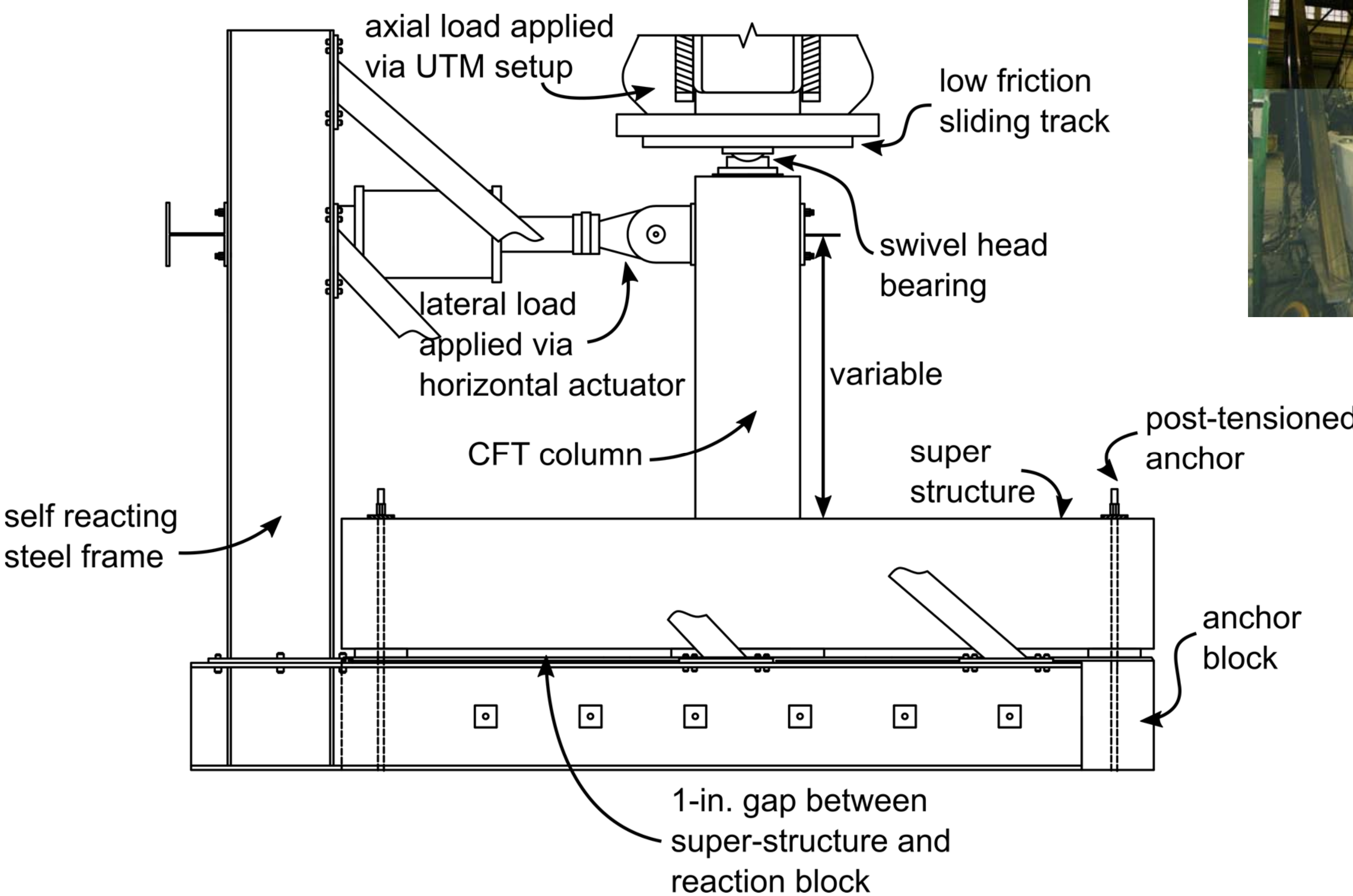
$$V_c = 0.0316A_c\sqrt{f_c'}\ (ksi)$$



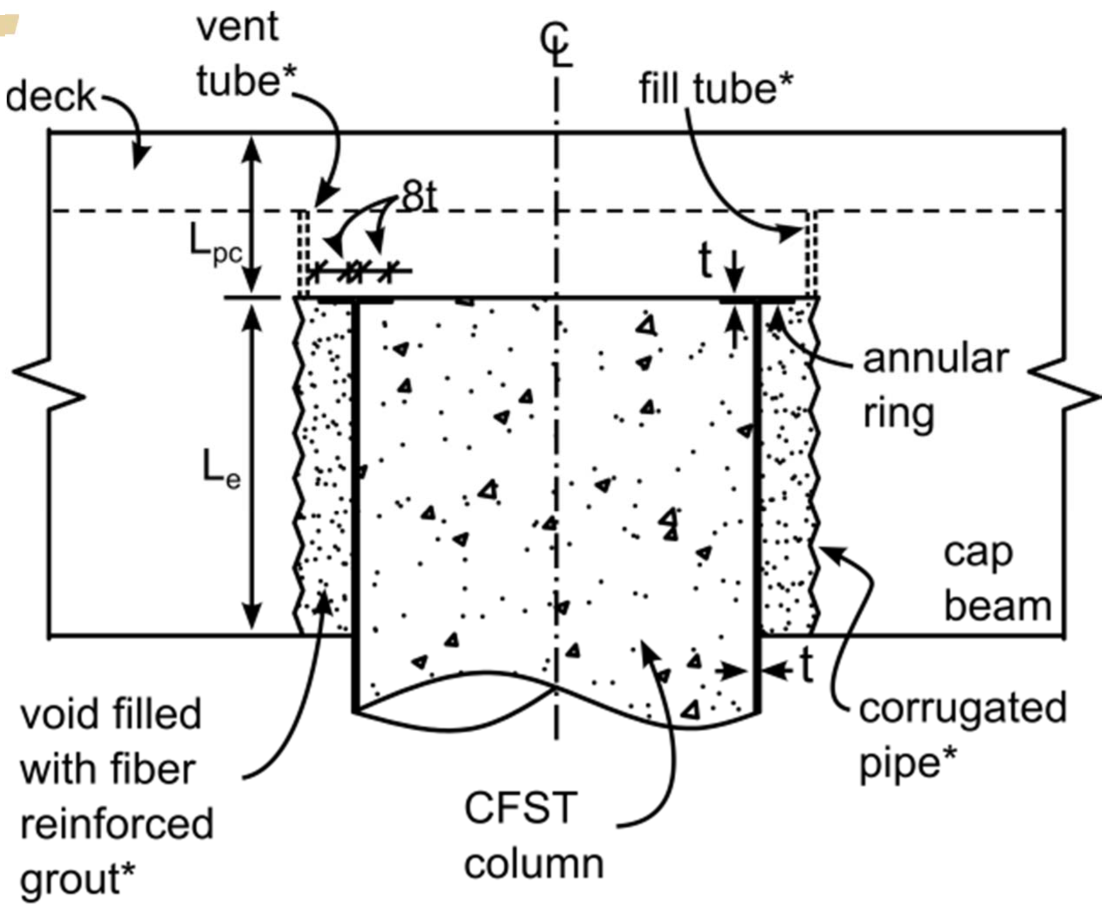
Connection Tests



Test Apparatus – Long.



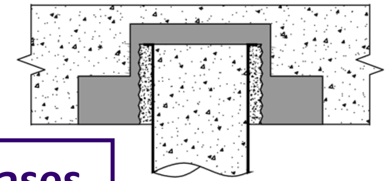
Embedded Ring (ER) Connection

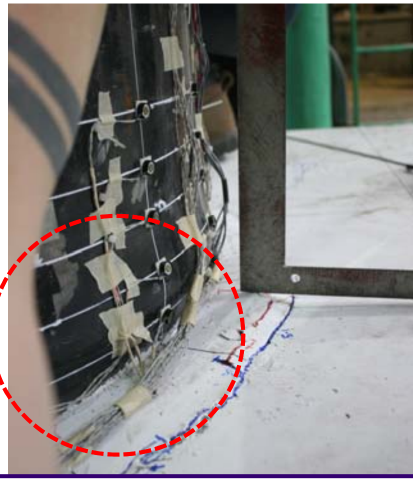


Note: Cap beam reinforcing not shown
* Used for precast construction

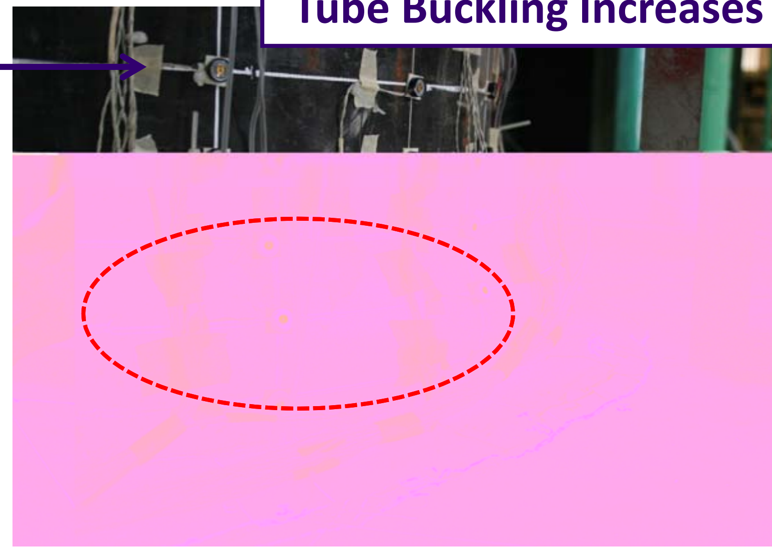
D (in)	t (in)	D/t	P/P_o	Tube Type	Tube Steel	ρ (%)	$(f_y/f'_c)\rho$
24	0.25	96	0.05	Straight Seam	APIX42	4	0.3

Performance of ER Connection

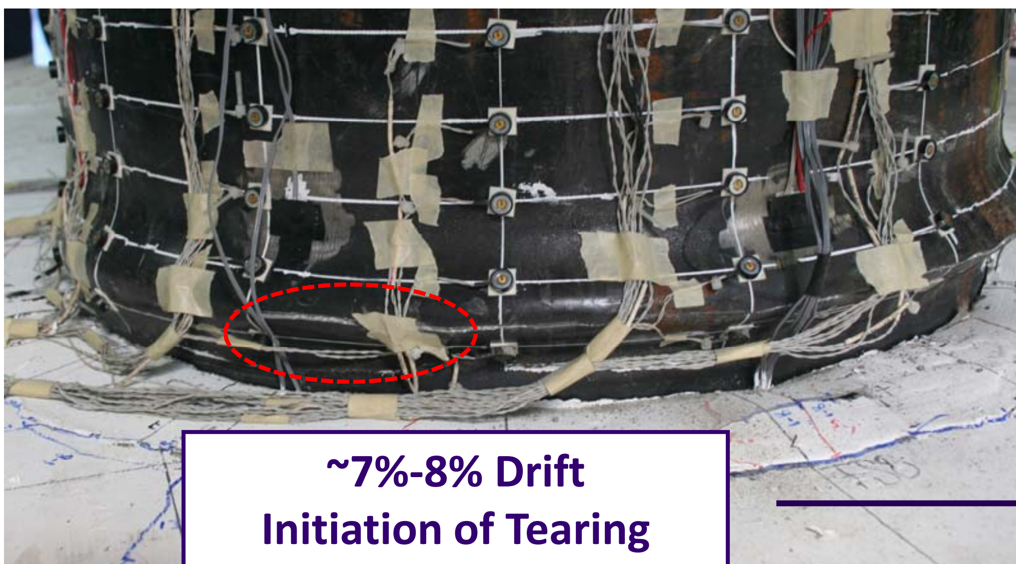




~3.5%-4% Drift
Tube Buckling Develops



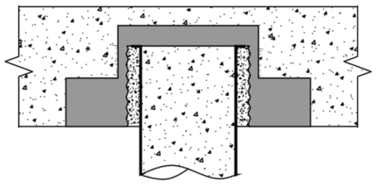
Tube Buckling Increases

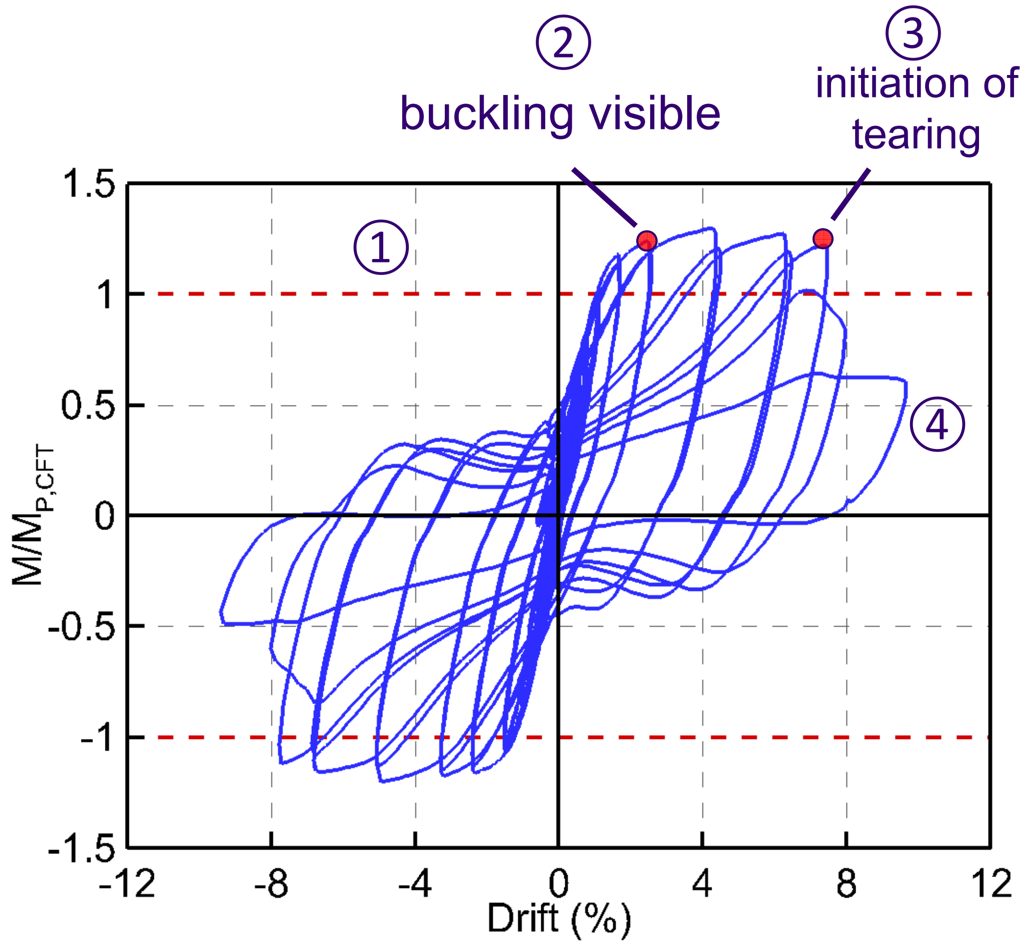


~7%-8% Drift
Initiation of Tearing

Final State

Response of ER Connection

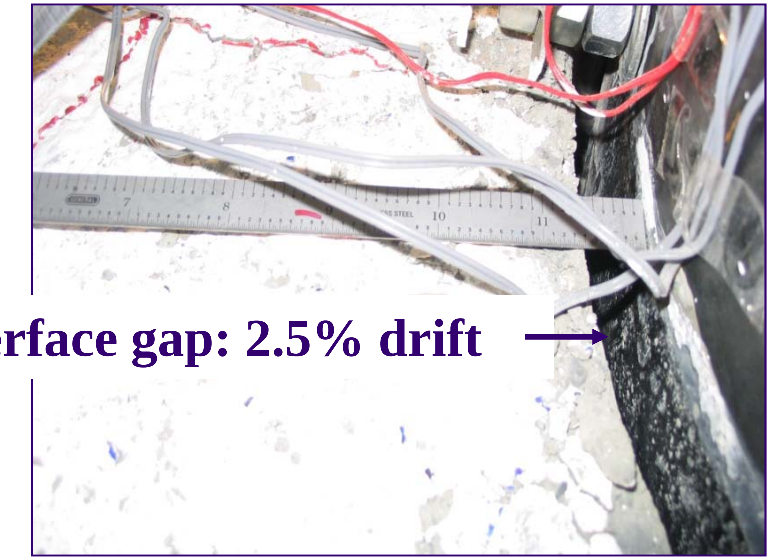




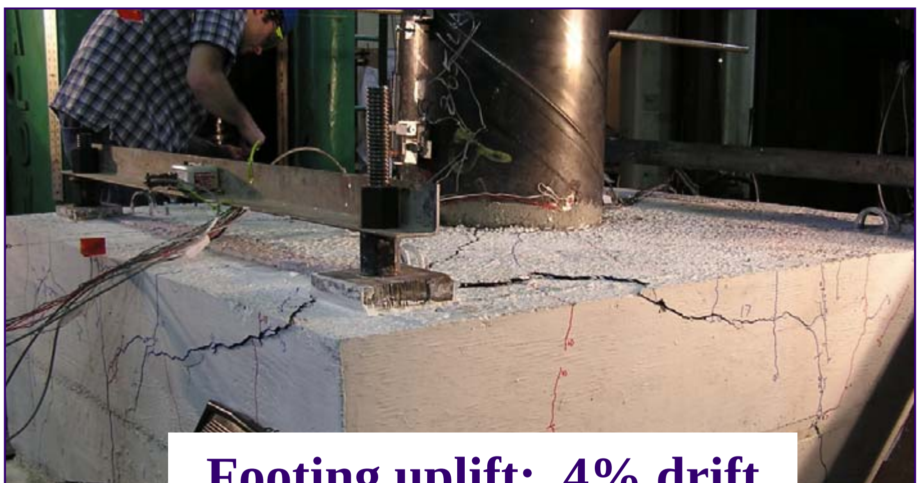
1. Failure mode and loss of lateral load initiated by ductile tearing of steel tube
2. Buckling does not impact performance
3. Theoretical plastic moment capacity achieved
4. Axial load capacity maintained after tearing

Observed Behavior ~ Inadequate Embedment

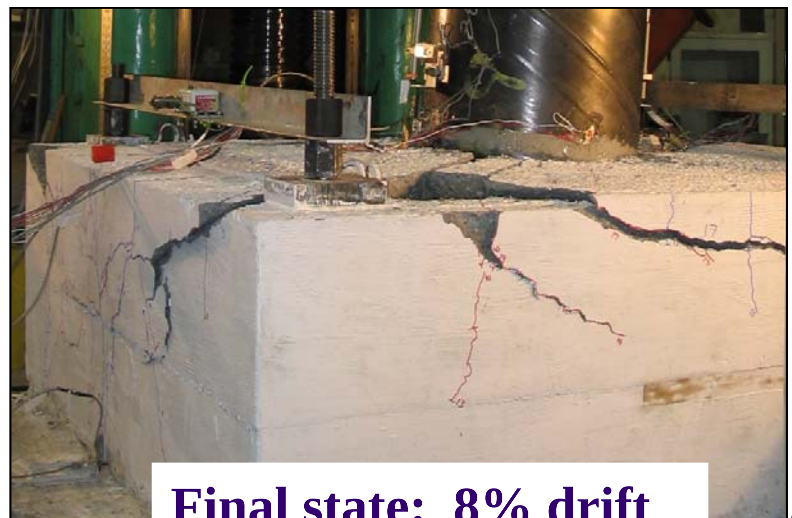
Bisecting cracks: 0.75% drift



Interface gap: 2.5% drift →

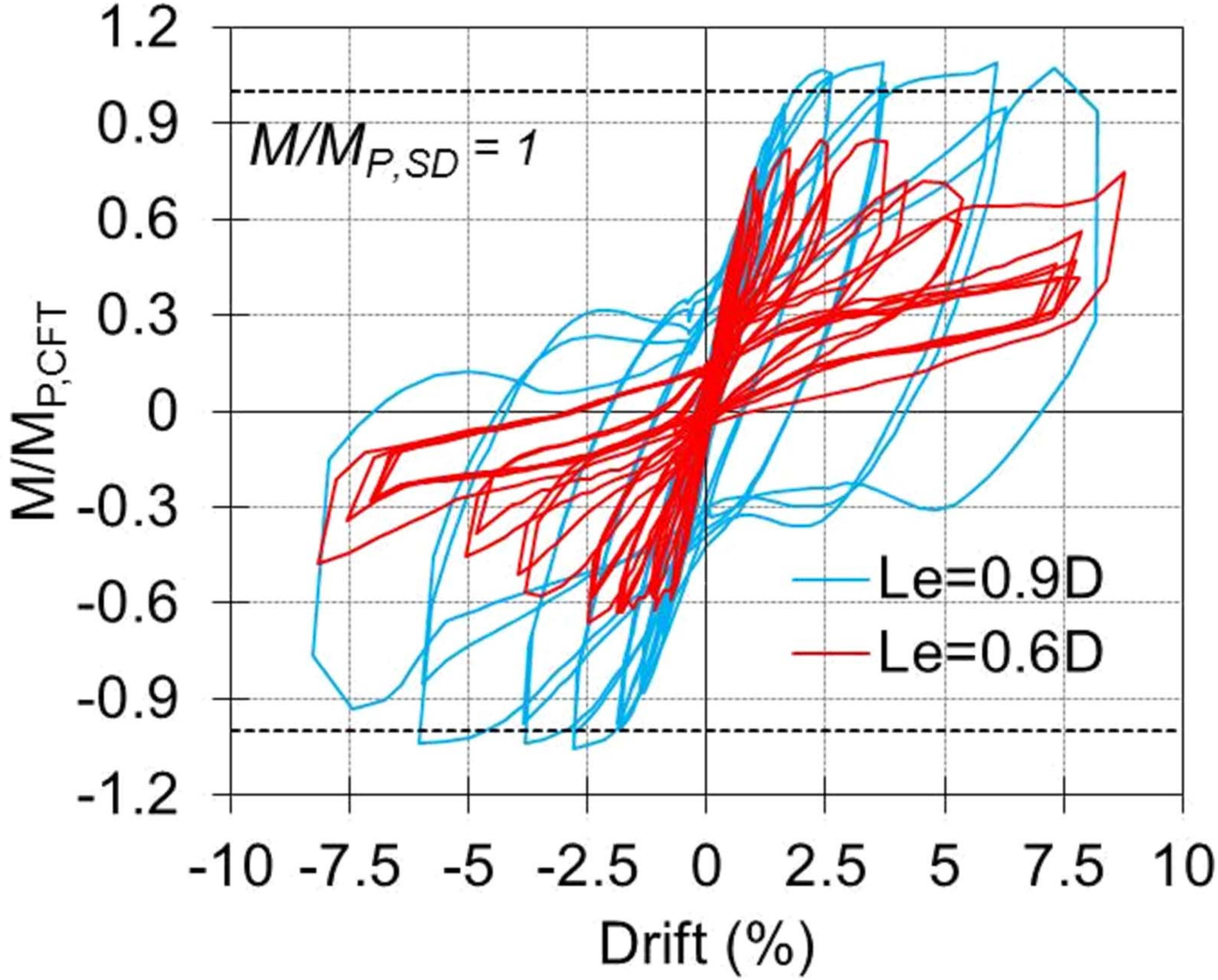


Footing uplift: 4% drift



Final state: 8% drift

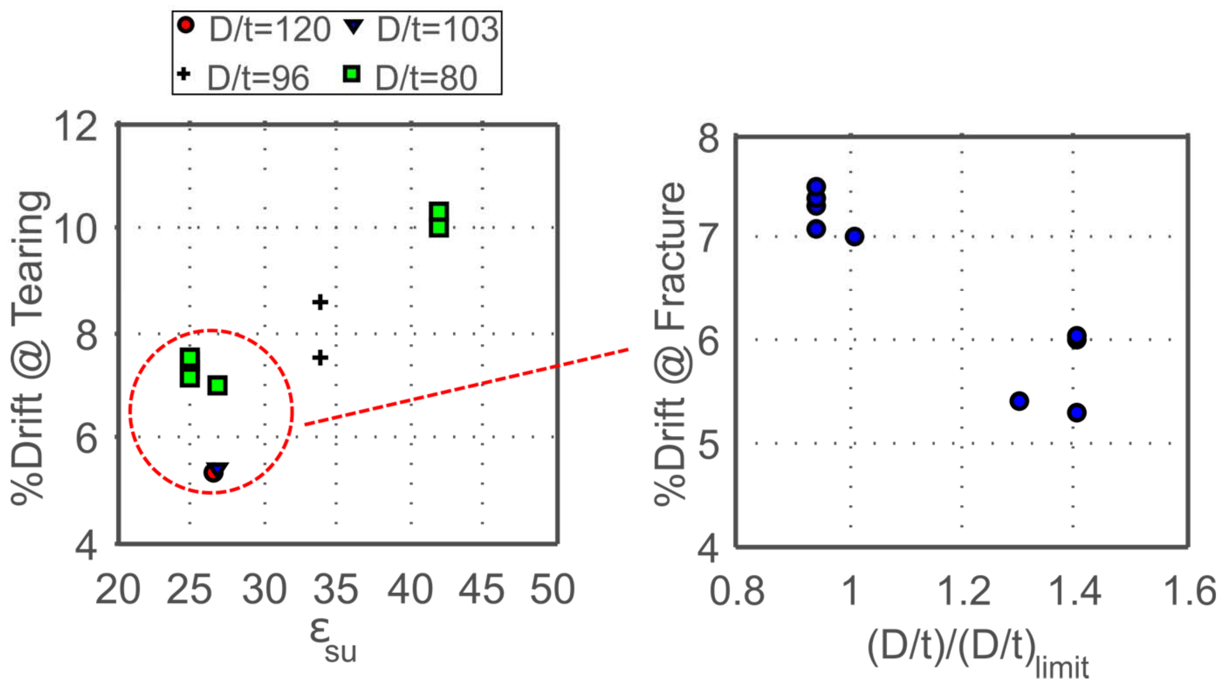
Comparison of ER Specimen: With and Without Adequate Embedment



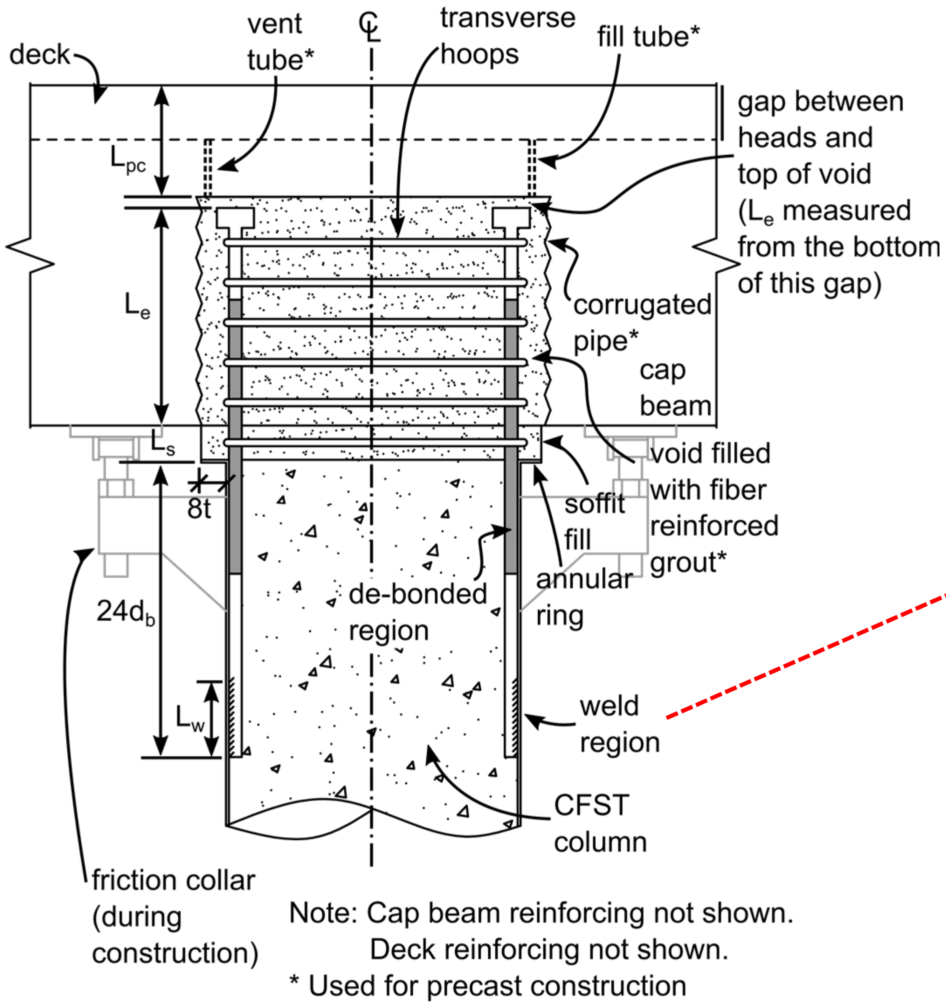
Key Takeaways – ER Connection

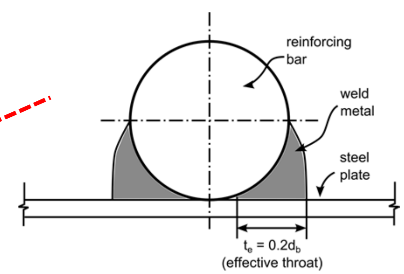
> **Utilizing steel tubes which exceed the AASHTO LRFD slenderness limit buckled at earlier drifts**
>
> > $\frac{D}{t} < 0.15\frac{E}{F_y}$

> **Utilizing steel tubes with larger ultimate strain capacities develop tearing at larger drifts even for large D/t ratios**



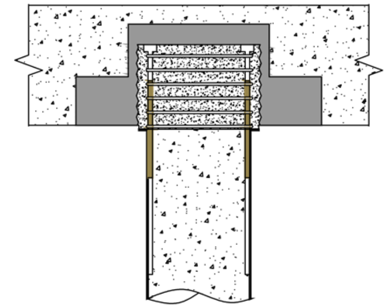
Welded Dowel Connection (WD103L)

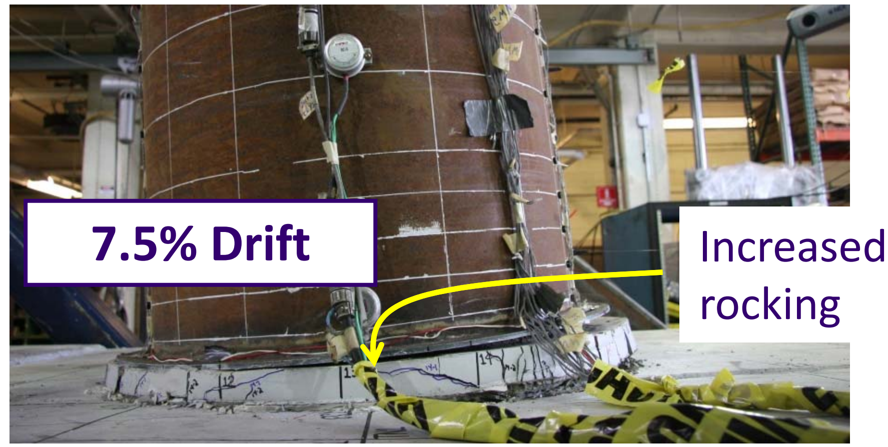


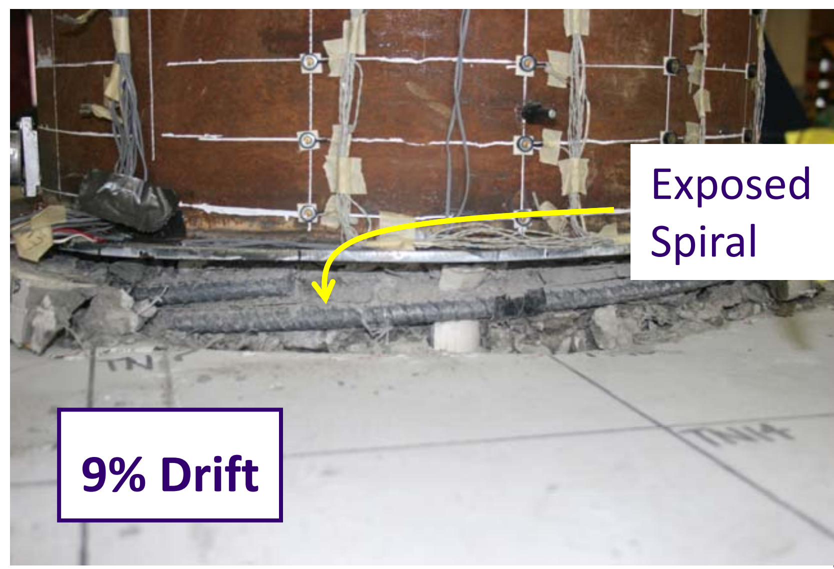


D (in)	t (in)	D/t	P/P_o	Reinforcing Steel	Fy (ksi)	f'_c (ksi)	ρ_L(%)	$(f_y/f'_c)\rho_L$
25.75	0.25	103	0.10	A706 Grade 60	68	7.7	3	0.3

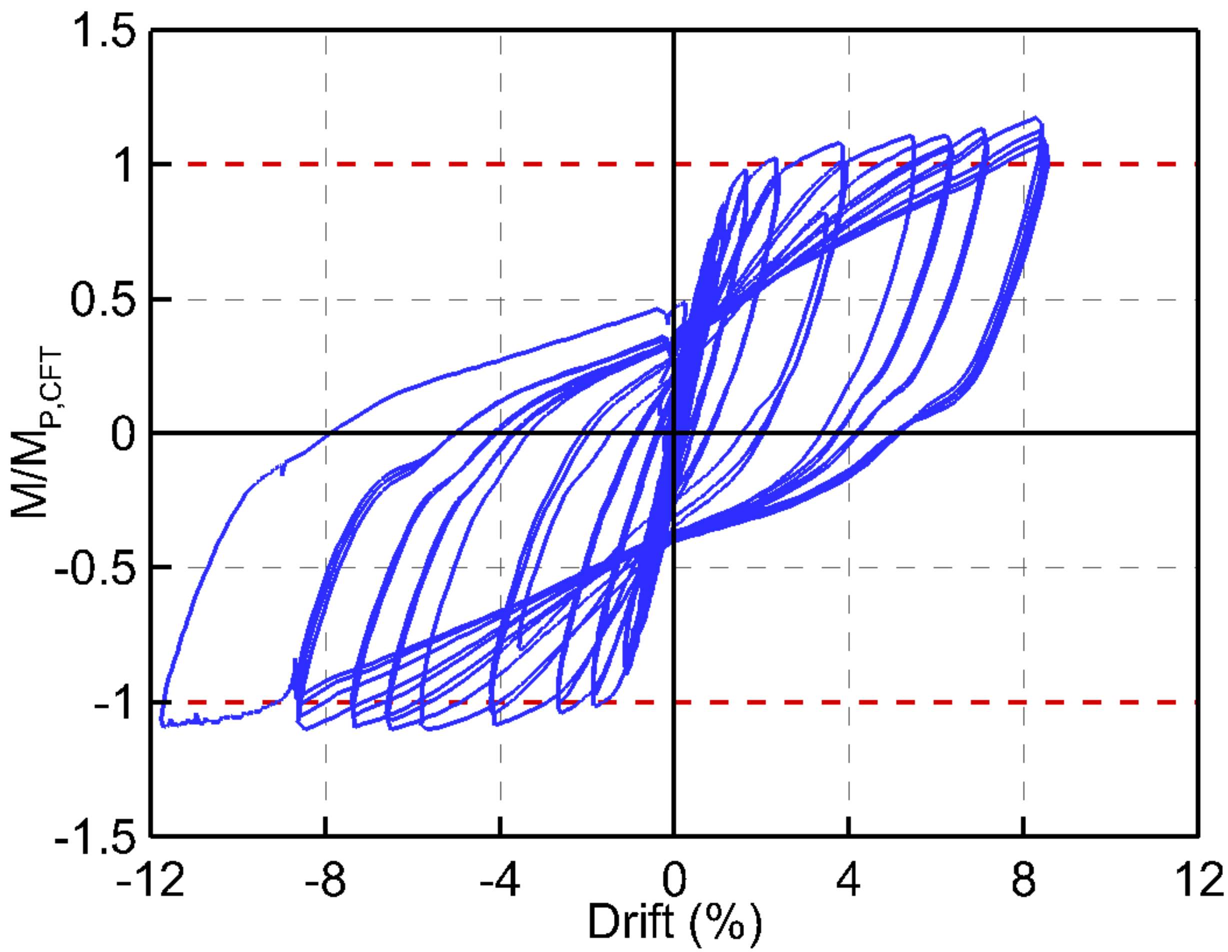
Performance of WD(db) Connection







Performance of WD Connection



① Achieved symmetric drifts of up to 9% with no degradation

② Theoretical plastic moment capacity of CFT achieved due to similar mechanical reinforcing ratio

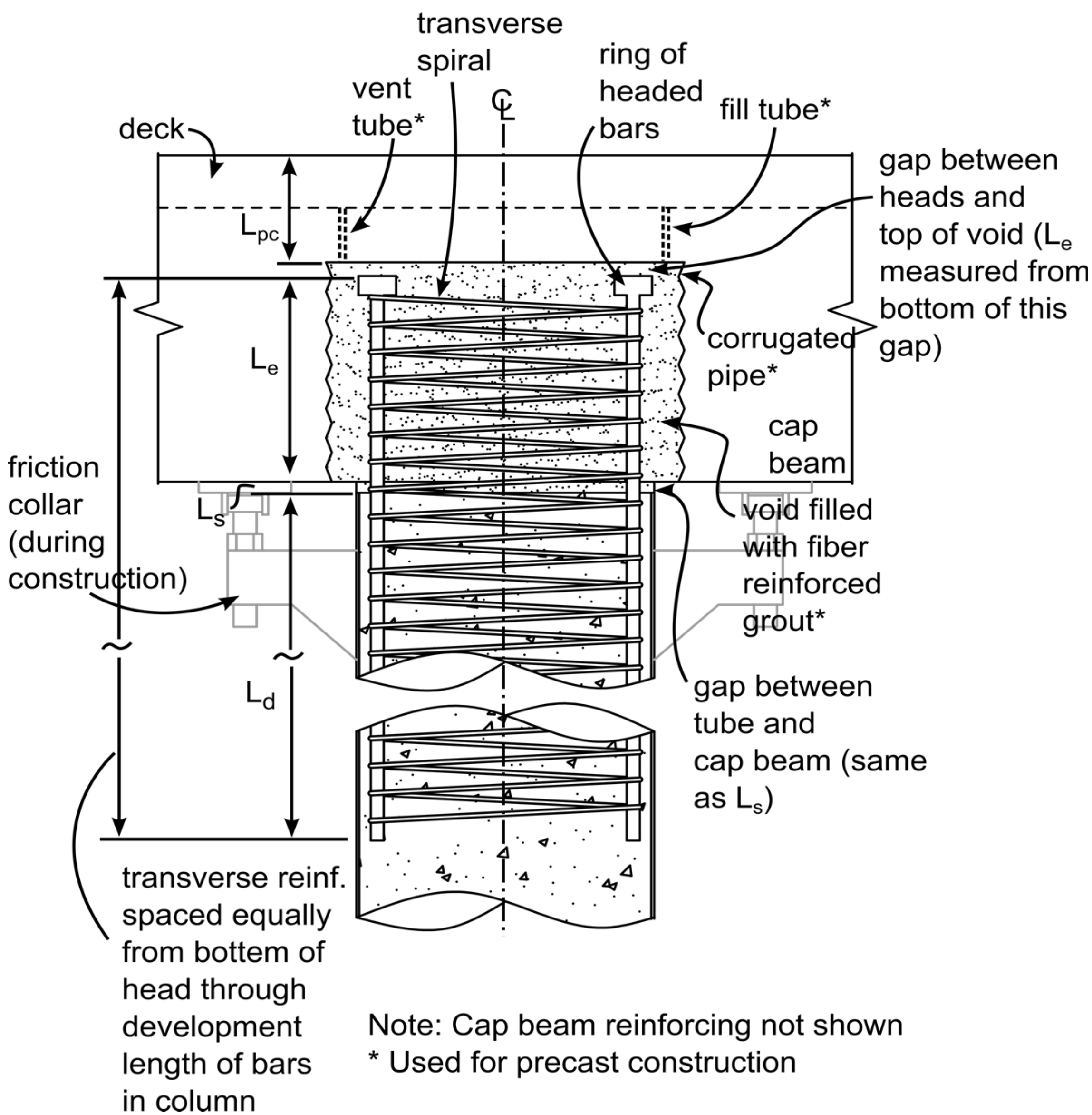
Key Takeaways WD Connection

- Debonding longitudinal dowels **decreases** damage to cap beam
- Including transverse joint reinforcing in the joint improves confinement in soffit

WD80T1 @ 10% Drift

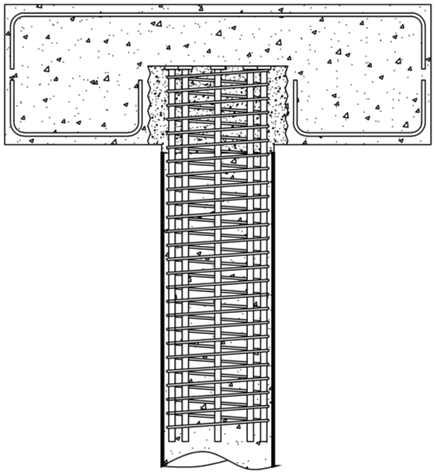
WD80T2 @ 10% Drift

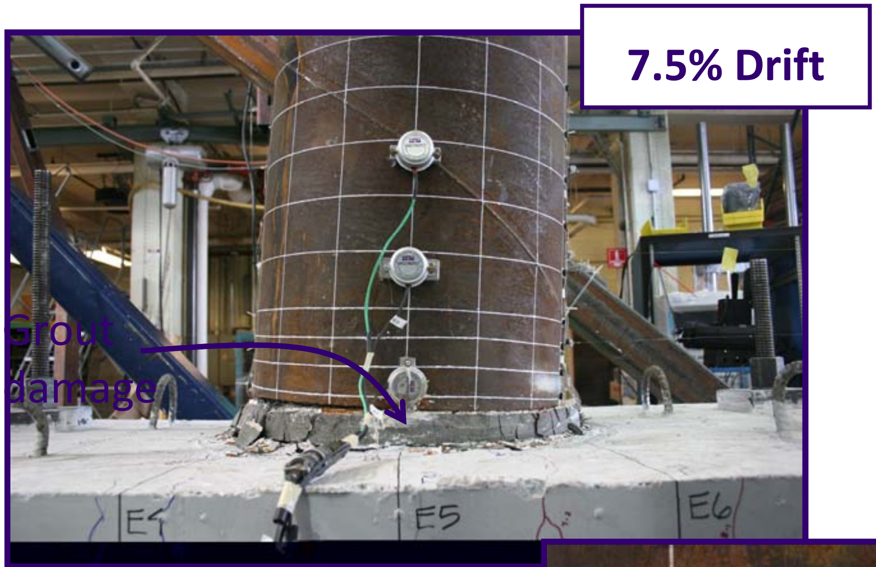
Reinforced Concrete (RC) Connection

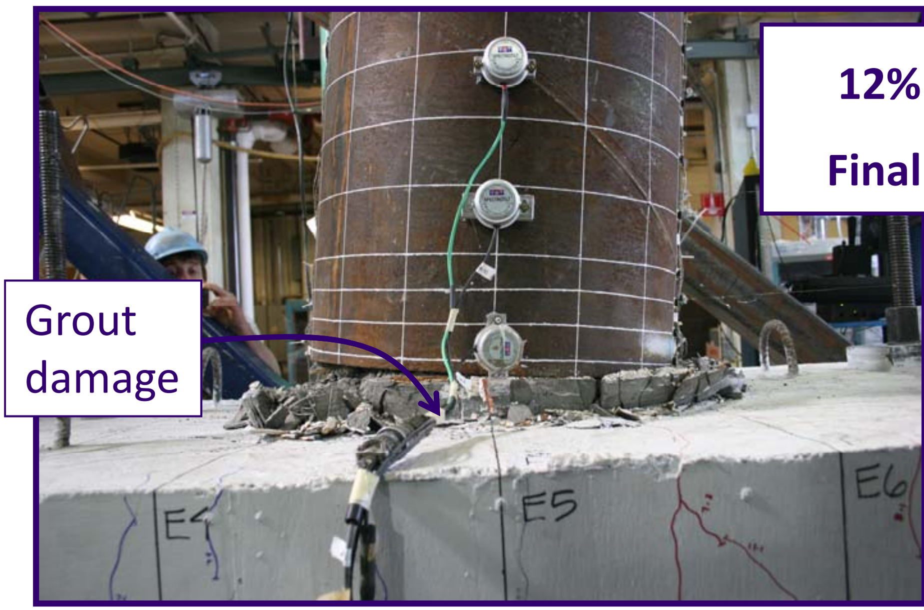


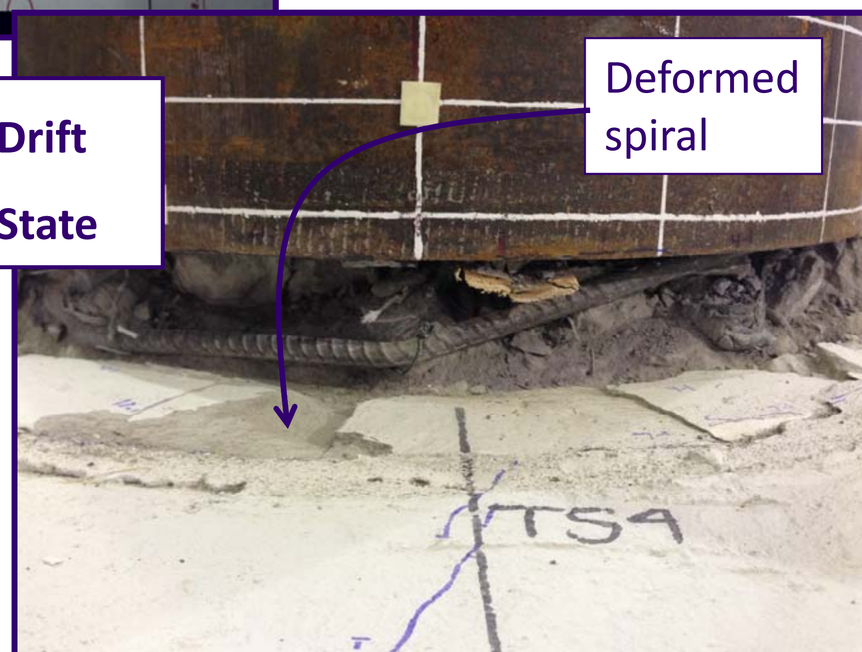
Note: Cap beam reinforcing not shown
* Used for precast construction

Performance of RC Connection

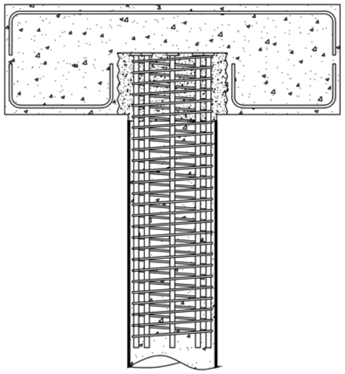


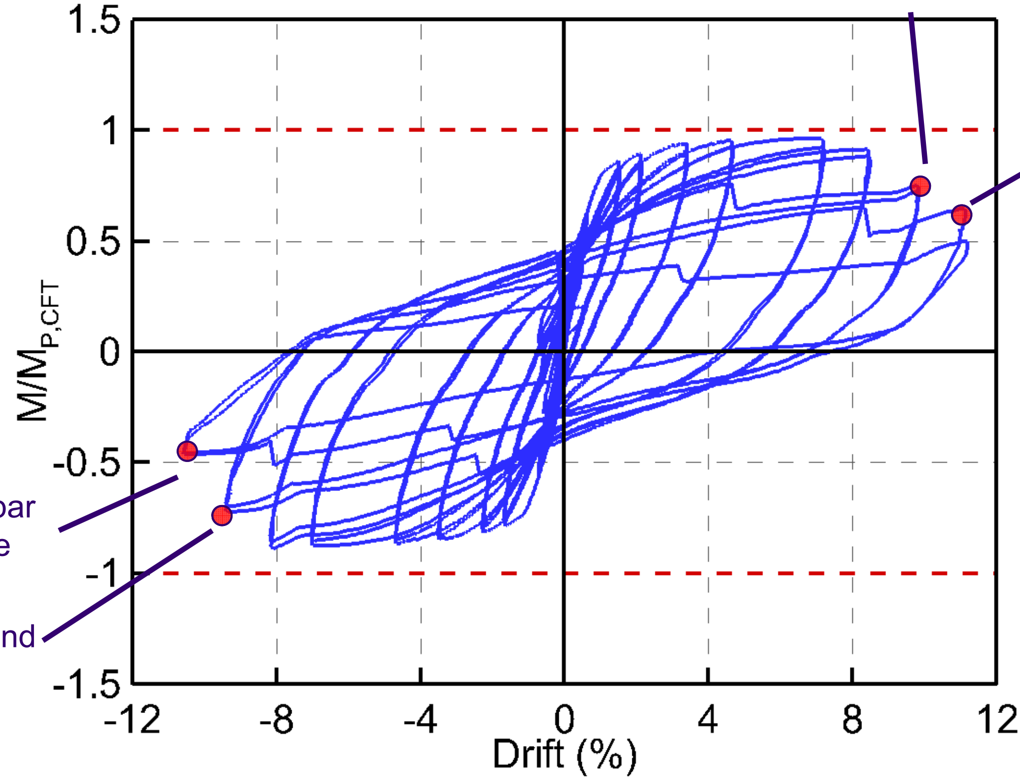






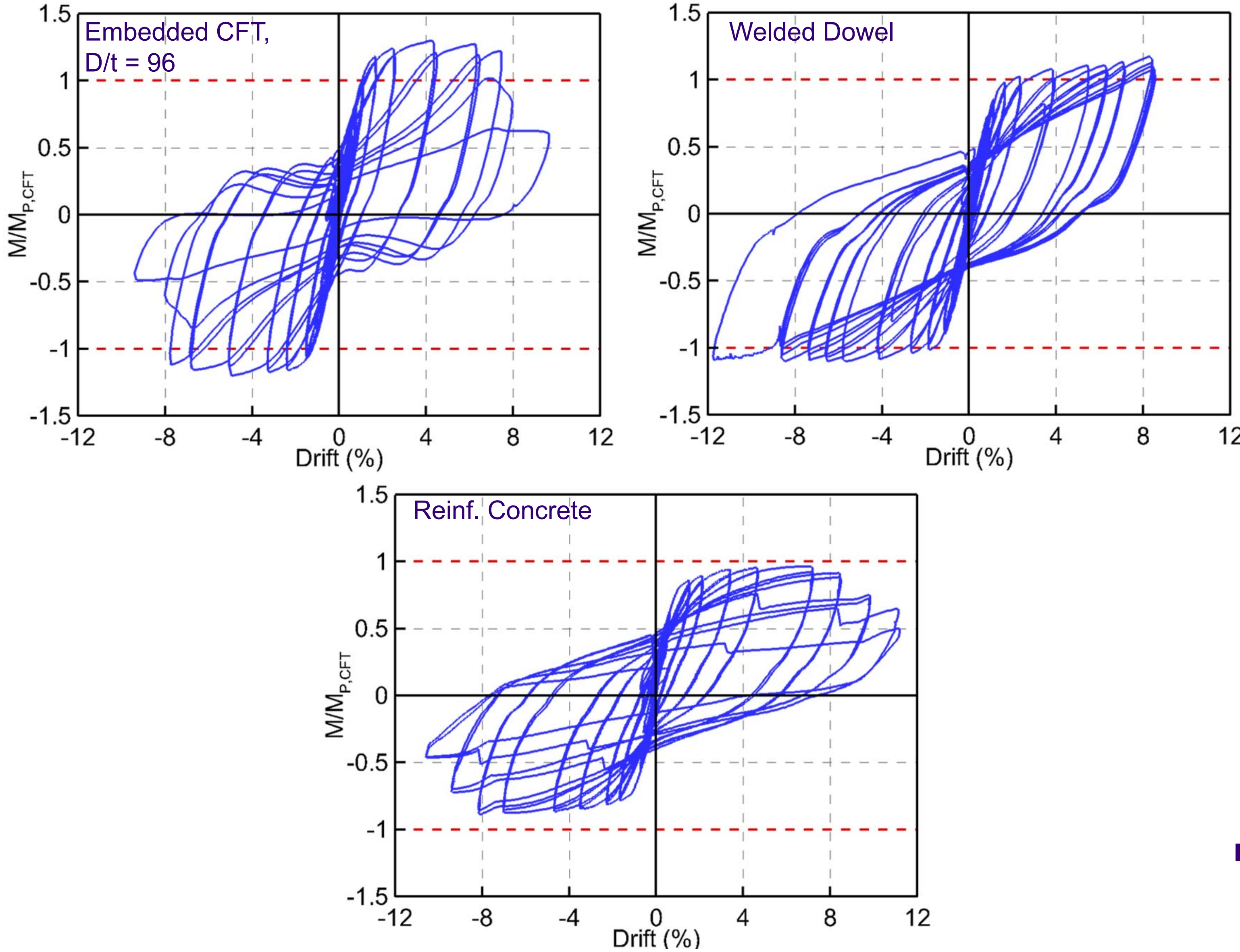
Performance of RC Connection





- ❑ Failure mode fracture of reinforcing bars (~8% drift)
- ❑ Strength limited by reinforcing ratio and moment arm

Hysteretic Comparison



Design/ Construction

Design Expressions

> Strength
  – Flexure
  – Axial
  – Shear

> Connection
  – Embedded Ring
  – Welded Dowel

> Standard Drawings

> Comparison of RC and CFST geometries


Washington State Department of Transportation

Bridge Design Manual (LRFD)

M 23-50.12

August 2012

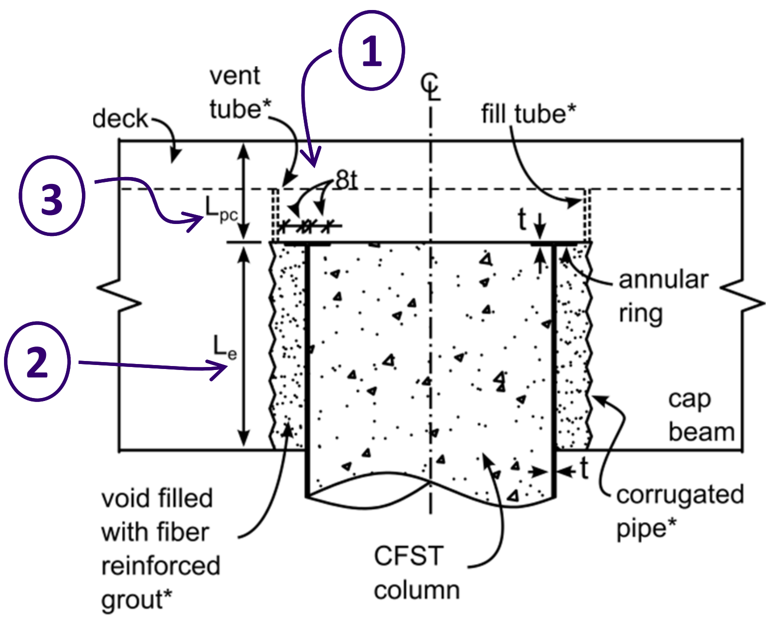
Engineering and Regional Operations
Bridge and Structures Office

Expressions have been implemented in WSDOT Bridge Design Manual

http://www.wsdot.wa.gov/publications/manuals/m23-50.htm

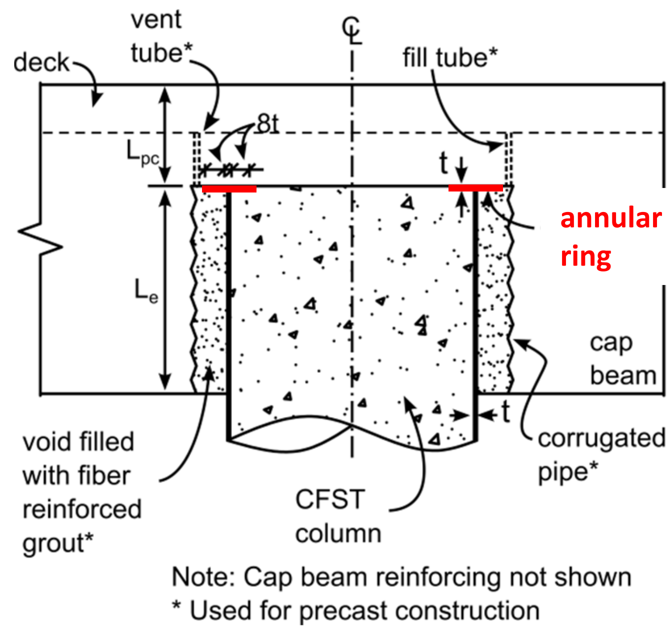
Key Considerations for ER Connection

① **Annular Ring Dimensions & Weld**
② **Embedement Depth of CFST**
③ **Punching Shear above Annular Ring**
④ Cap beam reinforcement



Annular Ring

- Welded to tube to provide anchorage and stress transfer
- Same thickness and strength as steel tube
- Projects inside and outside the tube for a distance 8t
- Welded to the tube using CJP or fillet welds designed to transfer the tensile capacity of the steel tube



minimum fillet weld size →

$$w \geq \frac{1.31 \times F_{u,st} \times t}{F_{exx}}$$

$F_{u,st}$= ultimate strength of steel tube
F_{exx}=tensile strength of weld metal

Embedment Depth

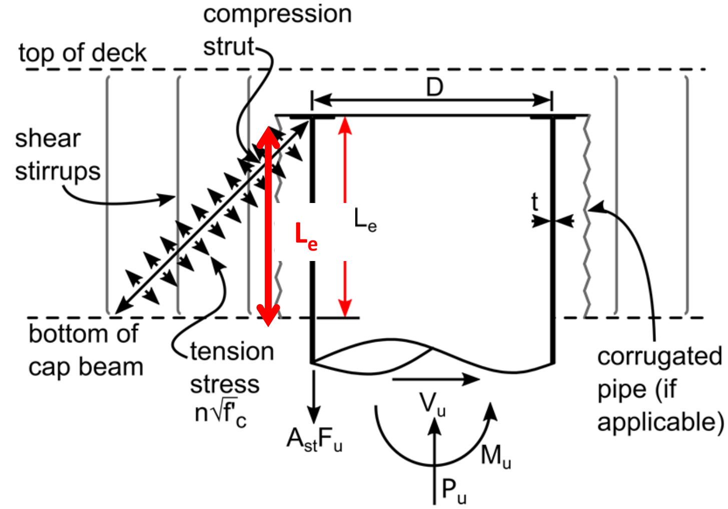
- Adequate embedment must be provided to eliminate pullout from cap beam
- Derived using pullout model with empirical stress limits
  - $6\sqrt{f'_c}$ for seismic
  - $8\sqrt{f'_c}$ for yielding

Yielding:

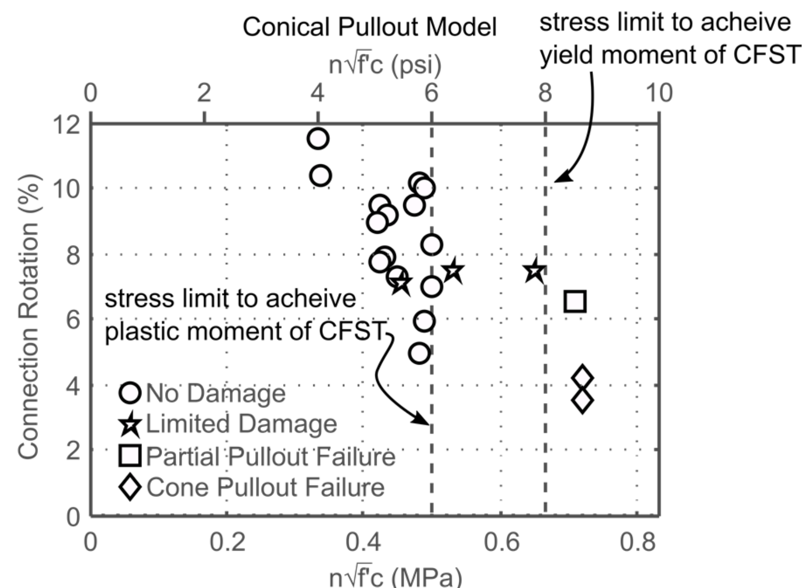
$$L_e \geq \sqrt{\frac{D^2}{4} + \frac{DtF_y}{8\sqrt{f'_{c,cap}}}} - \frac{D}{2}\ (psi)$$

Seismic:

$$L_e \geq \sqrt{\frac{D^2}{4} + \frac{DtF_u}{6\sqrt{f'_{c,cap}}}} - \frac{D}{2}\ (psi)$$



Conical Pullout Model



Evaluation of Stress Demand on Conical Surface

Punching Shear

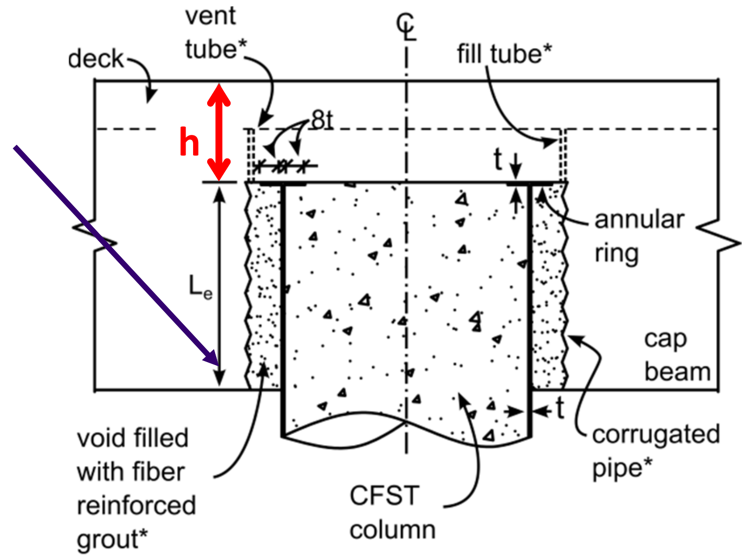
- Adequate depth must be provided above embedded tube to eliminate punching shear
- Derived using ACI procedure for flat slab to column connections

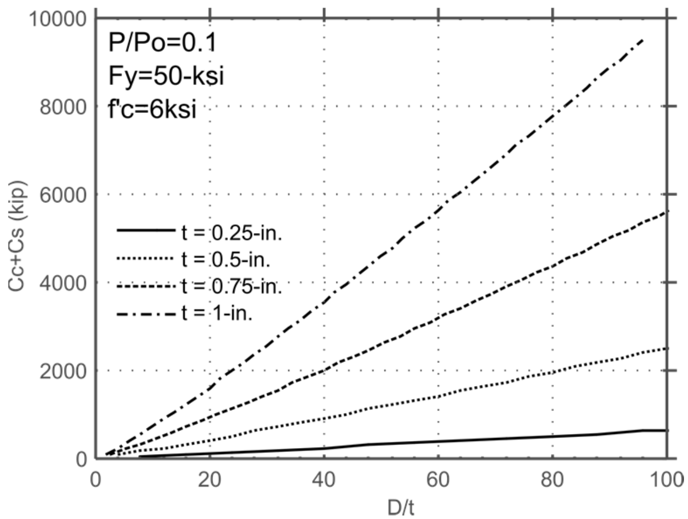
$$h \geq \sqrt{\frac{D^2}{4} + \frac{C_c + C_s + P_{axial}}{3*0.0316*\pi\sqrt{f'_{c,cap}}}} - \frac{D}{2} - L_e \geq 8t$$

$$(f'_{c,cap}\ in\ ksi)$$

C_c= compressive force in concrete

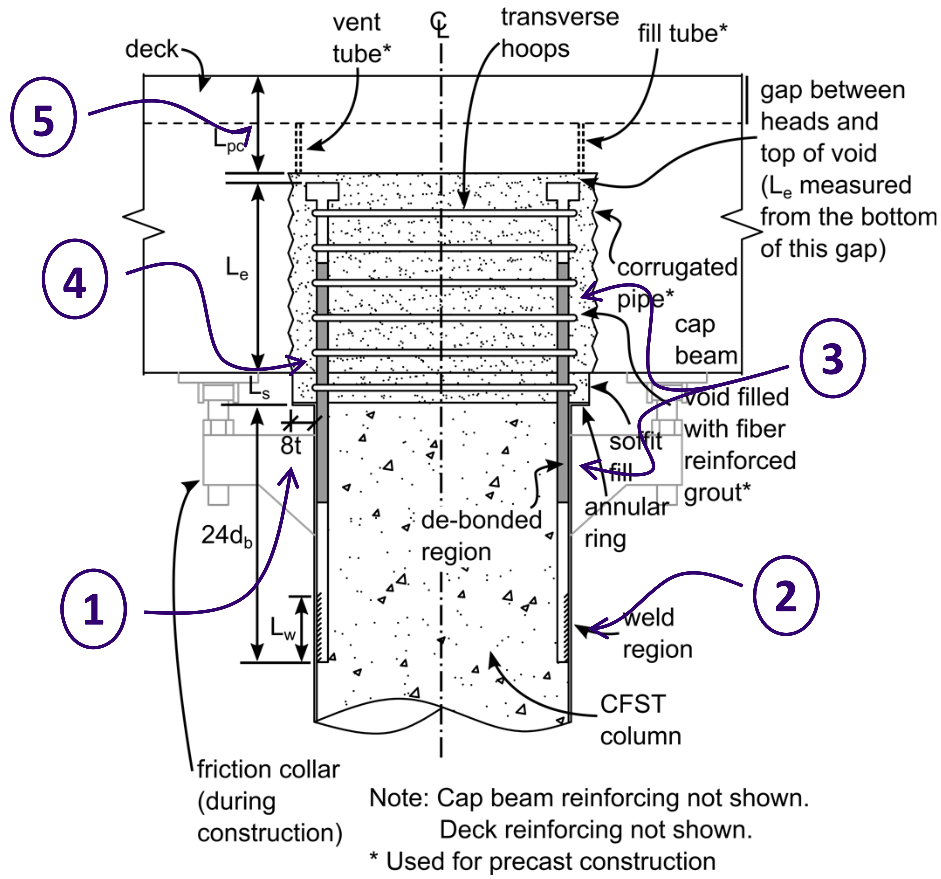
C_s=compressive force in steel





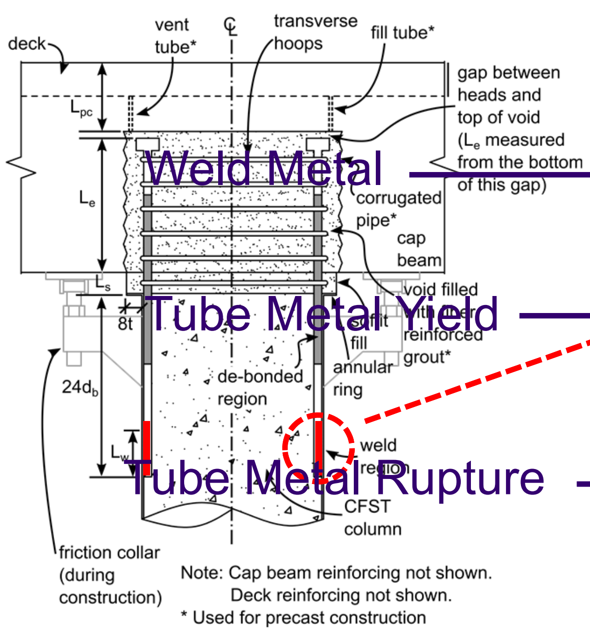
Key Considerations for WD Connection

1. Flange dimensions
2. **Dowel weld length**
3. Anchorage depth of headed bar
4. Dowel debonded length
5. Punching shear above headed dowels
6. Cap Beam Reinforcing
7. Cap Beam Width



Dowel to Steel Tube Welds

- Longitudinal dowels are welded to the inside of the steel tube
- Weld type is flare bevel groove weld as specified in AWS D1.5
- Required weld lengths based on typical limit states for flare bevel groove welds
- Strength reduction factors have been incorporated into the equations



Weld Metal →

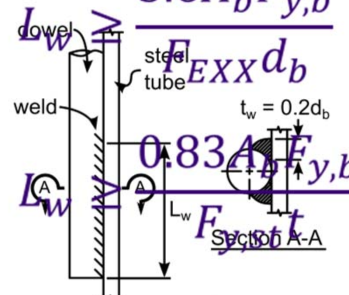
$$L_w \geq \frac{5.6 A_b F_{y,b}}{F_{EXX} d_b}$$

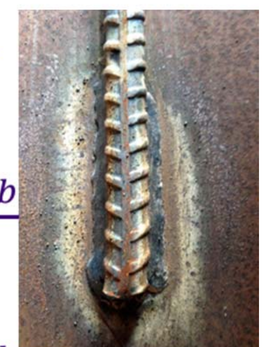
Tube Metal Yield →

$$L_w \geq \frac{0.83 A_b F_{y,b}}{F_{y,st} t}$$

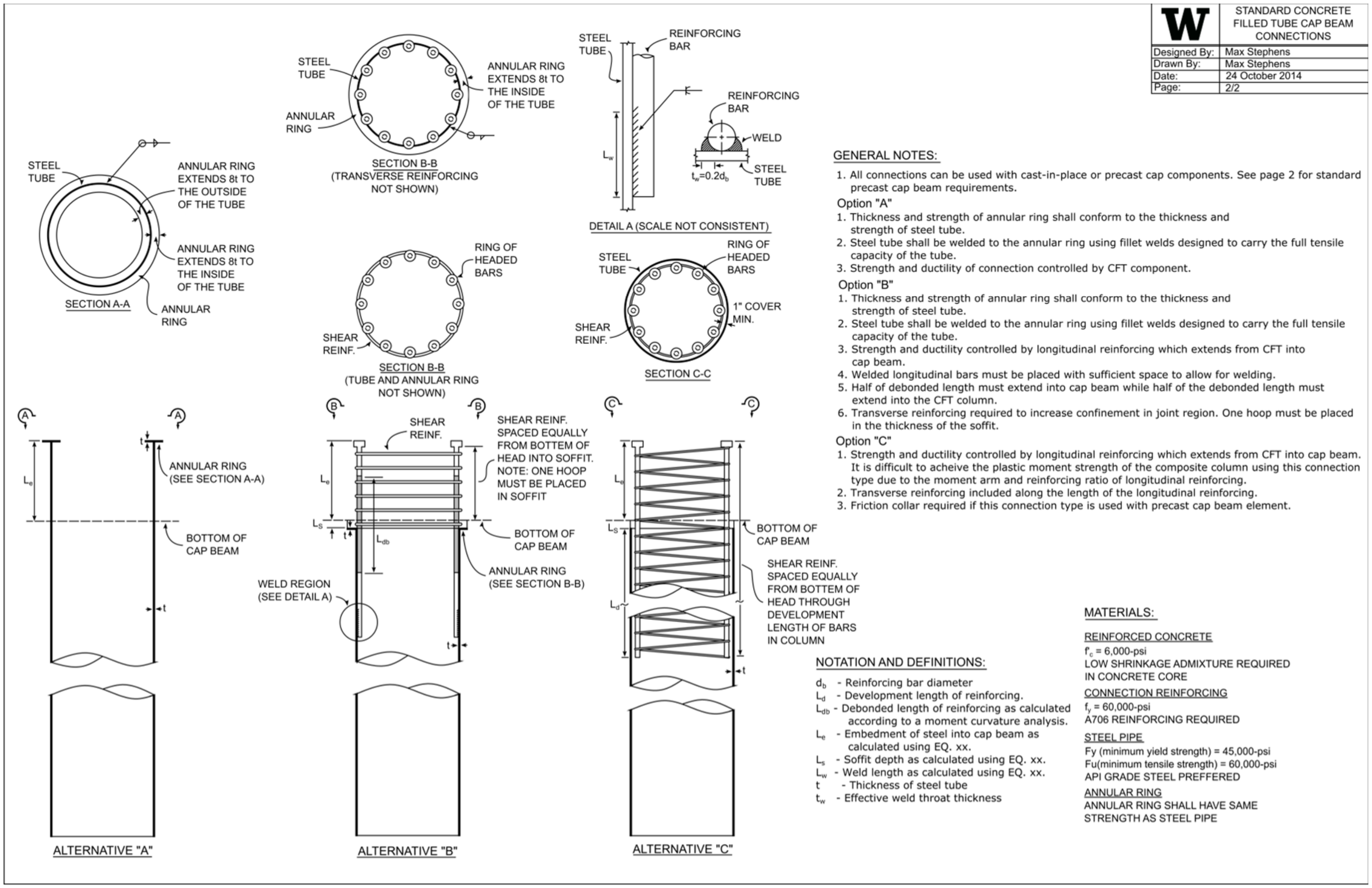
Tube Metal Rupture →

$$L_w \geq \frac{1.11 A_b F_{y,b}}{F_{u,st} t}$$

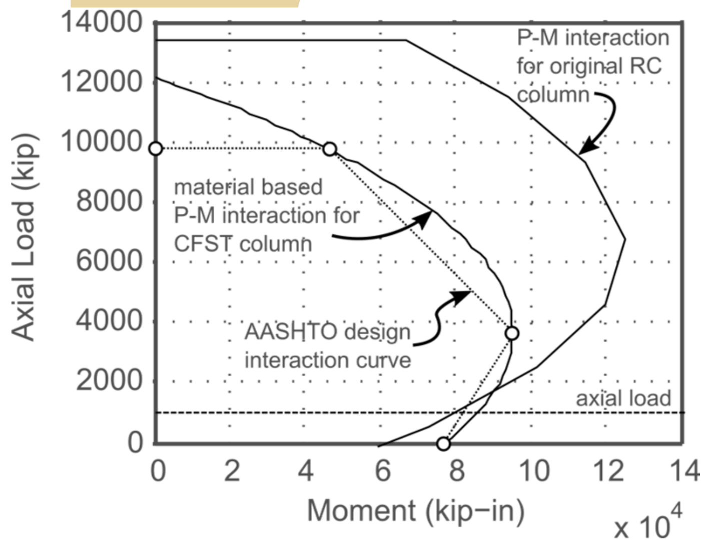


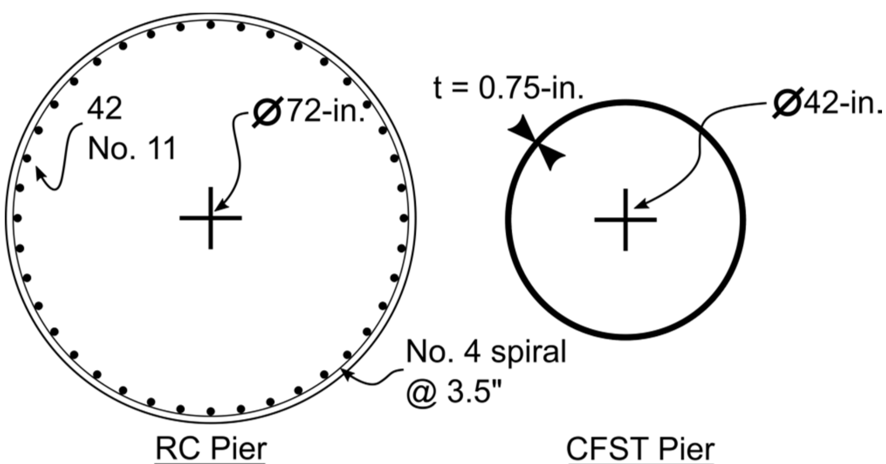


Standard Drawings



Redesign of RC Bridge (Cold Water Creek Bridge)



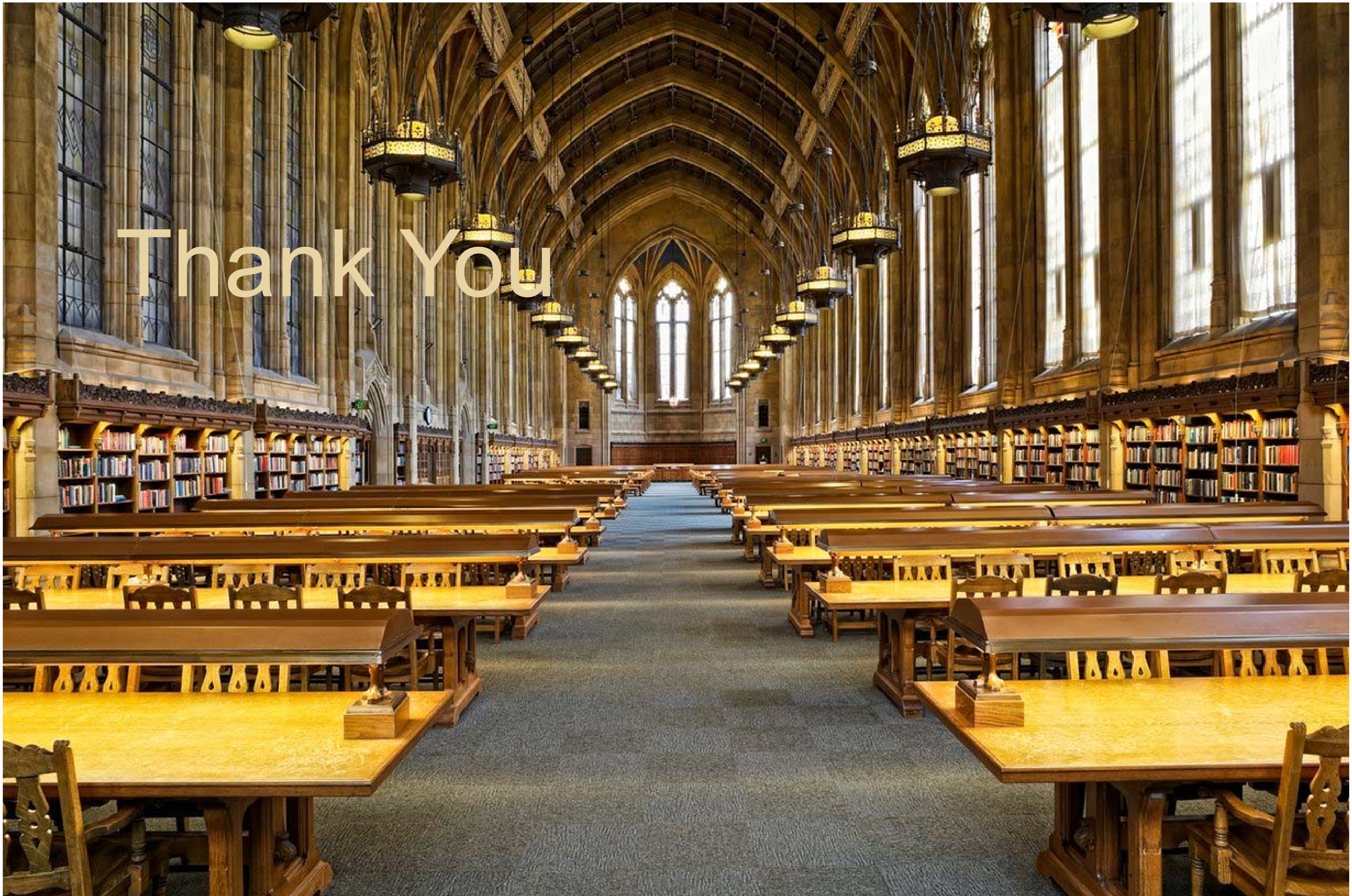


	Original RC Pier	CFST Pier
Concrete Strength (ksi)	4.0	4.0
Steel Strength (ksi)	60.0	50.0
Diameter (in.)	72.0	42.0
Tube Thickness (in.)	-	0.75
Concrete Area (in.^{2})	4000.0	1288
Steel Area (in.^{2})	101	97.19
Weight/ft of Pier (kips)	4.4	1.63
Total Pier Weight (kips)	231	85.4
Difference in Pier Weight	63% Reduction	

Summary and Conclusions

- Spiral weld provides mechanical interlock and superior bond capacity.
- CFST bridge columns and connections are efficient relative to RC. CFST columns are stiffer and stronger for a given cross section. Material savings between 20 and 60%.
- The embedded connection is applicable to cap beam and foundations and capable of developing the full composite flexural strength of the CFT.
- Design expressions have been implemented in the WSDOT Bridge Design Manual (BDM) and AASHTO (strength).
- CFT is a viable solution for rapid construction of bridges.

Thank You



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Bishop, E. (2009). Evaluation of the flexural resistance and stiffness models for circular concrete-filled tube members subjected to combined axial-flexural loading. Master's thesis, University of Washington.

Roeder, C., Lehman, D., and Bishop, E. (2010). Strength and stiffness of circular concrete filled tubes. Journal of Structural Engineering, 135(12):1545-1553.

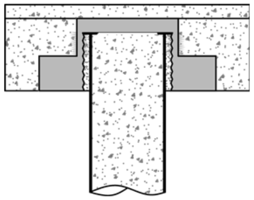
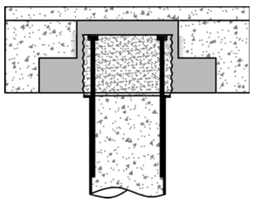
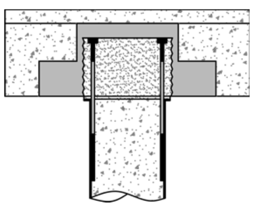
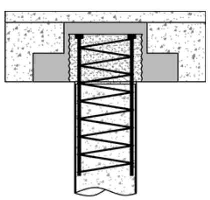
Hannesson, G.1, Kuder, K.2, Shogren R. and Lehman, D. (2012) "The Influence of High Volume of Fly Ash and Slag on the Compressive Strength of Self-Consolidating Concrete" Construction & Building Materials, May 2012, Pages 161-168

Lehman, D., and Roeder, C. (2012). Foundation Connection for Circular Concrete Filled Tubes. *Journal of Constructional Research*, 78:212-225.

Moon, J.1, Lehman, D. E.2, and Roeder, C. W.2 (2012). "Strength of Circular Concrete-filled Tubes (CFT) with and without Internal Reinforcement under Combined Loading." ASCE Journal of Structural Engineering, Permalink: http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0000788

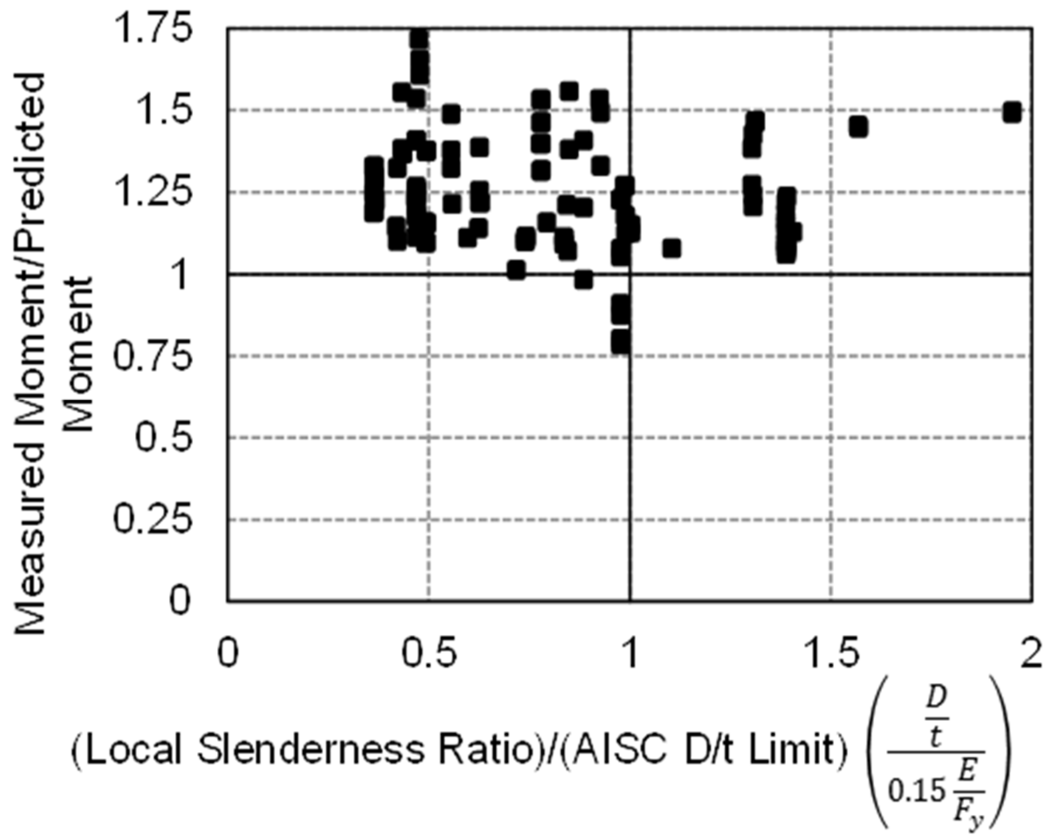
Stephens, M., Berg, L., Lehman, D., and Roeder, C. (2016) "Seismic CFST Column-to-Precast Cap Beam Connections for Accelerated Bridge Construction" ASCE Journal of Structural Engineering, In Press. DOI: 10.1061/(ASCE)ST.1943-541X.0001505

Experimental Matrix

Connection Type	Loading Direction	D (in)	t (in)	Tube Type	Axial Load (P/Po)
Embedded Ring 	Transverse	20	0.25	Spiral Weld	0.1
	Transverse	24	0.25	Straight Seam	0.05
	Longitudinal	25.75	0.25	Spiral Weld	0.1
	Longitudinal	24	0.25	Straight Seam	0.05
Welded Dowel 	Transverse	20	0.25	Straight Seam	0.1
De-bonded Welded Dowel 	Transverse	20	0.25	Spiral Weld	0.1
	Longitudinal	20	0.25	Spiral Weld	0.1
Reinforced Concrete 	Transverse	20	0.25	Spiral Weld	0.1

Slenderness (D/t ratio)

The local slenderness of the tube shall satisfy: $D/t < 0.15E/F_y$



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Axial Resistance

The factored resistance, P_r, of a composite CFST column subject to axial compression shall be determined as: $P_r = \phi_c P_n$.

- If $P_e > 0.44P_o$, then:

$$P_n = 0.658^{\frac{Po}{Pe}} P_o$$

- If $P_e \leq 0.44P_o$, then:

$$P_n = 0.877\, P_e$$

$$P_o = 0.95 f_c^{'} A_c + F_{yst} A_{st} + F_{yb} A_{sb}$$

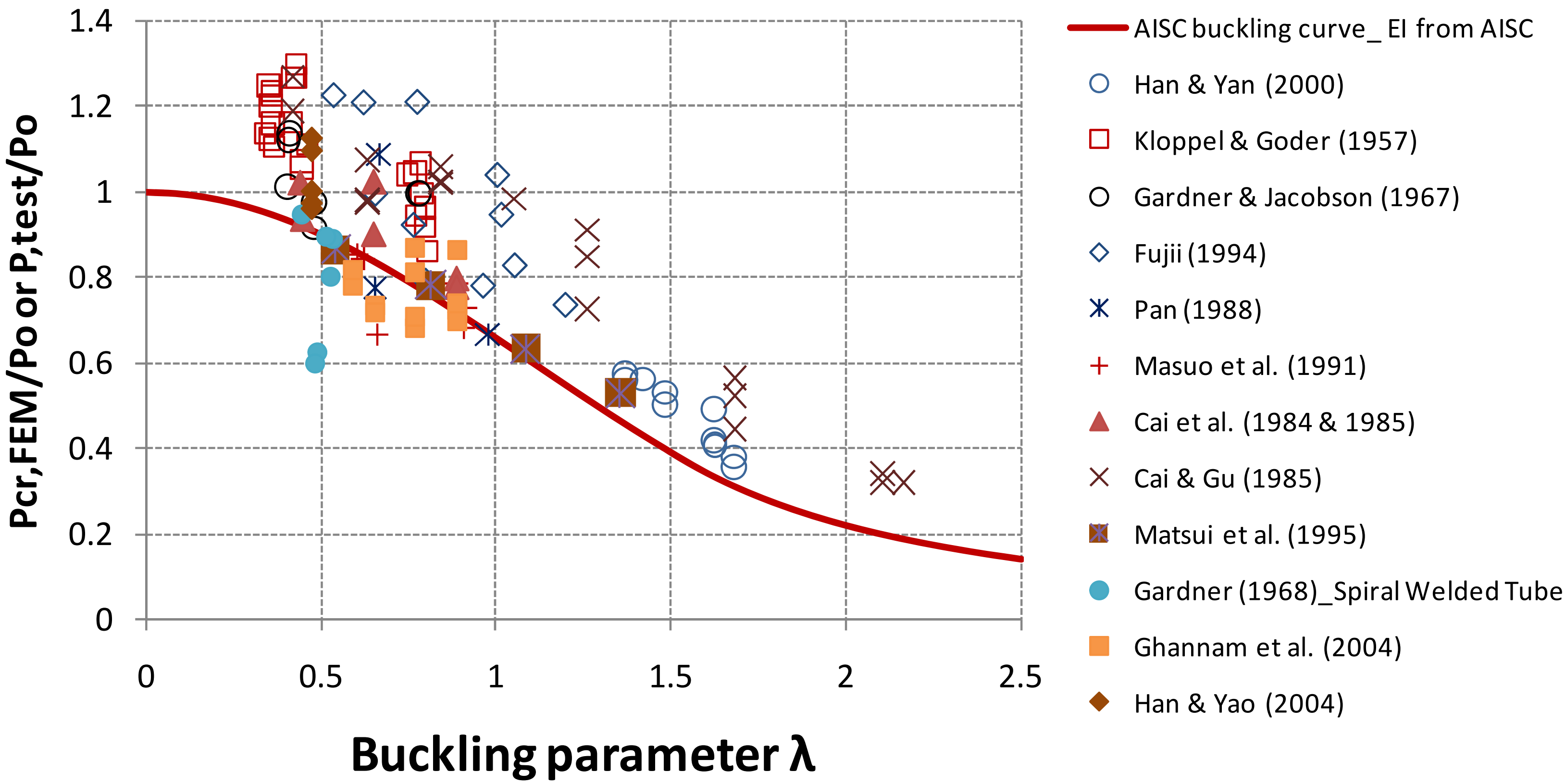
$$P_e = \frac{\pi^2 EI_{eff}}{\left(Kl\right)^2}$$

$$EI_{eff} = E_{st} I_{st} + E_{si} I_{si} + C' E_c I_c$$

$$C' = 0.15 + \frac{P}{P_e} + \frac{A_{st} + A_{sb}}{A_{st} + A_{sb} + A_c} \leq 0.9$$

Comparison with Buckling

Based on AISC Buckling Curve



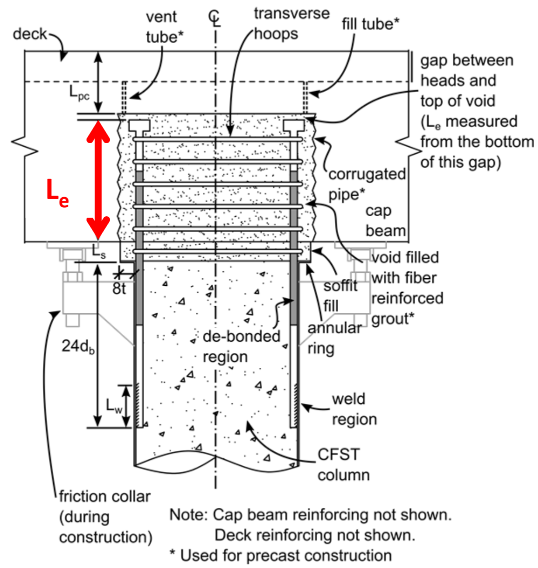
Length Dowels Extend into Cap Beam

The headed reinforcing extends into the cap beam to fully develop the dowels while eliminating the potential for a conical pullout failure

ACI Development of bars with mechanical anchors

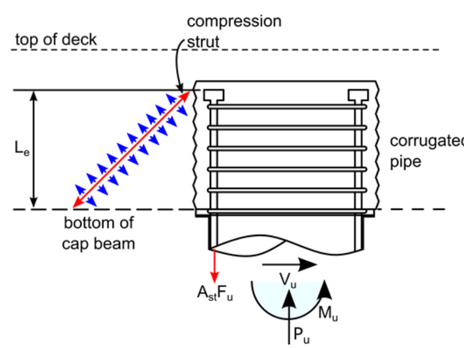
$$L_e \geq \frac{0.016\psi_e F_{y,b}}{\sqrt{f'_g}} d_b$$

f'_g= grout strength
$F_{y,b}$=yield strength of dowel
Ψ_e=bar coating factor
d_b=dowel diameter



Length to eliminate conical pullout

$$L_e \geq \sqrt{\frac{D^2}{4} + \frac{1.2 * F_{y,b} * A_{st,b}}{6\pi\sqrt{f'_{ccap}}}} - \frac{D}{2}$$

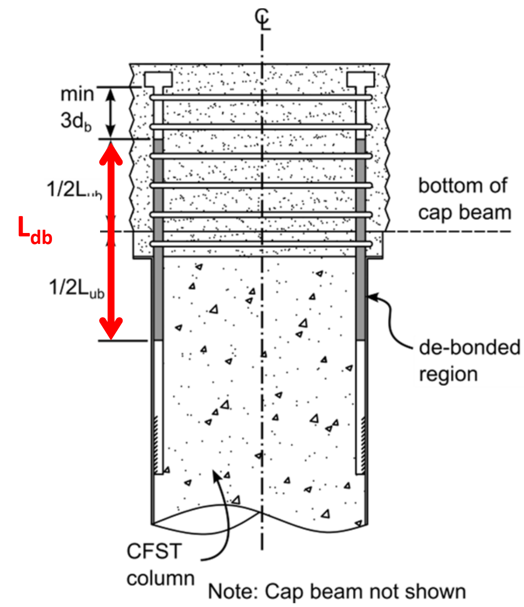


$A_{st,b}$= total area of dowels

Dowel Debonded Length

> **De-bonded with the intent of increasing ductility**
  - **Limits strain in dowels**
  - **Limits damage to cap beam**

> **Two methods to calculated de-bonded length**
  - **Moment-curvature analysis**
  - **Rigid body kinematics**



Moment Curvature Approach

$$L_{db} = \frac{\theta_u}{\phi_u}$$

φ_u= curvature limit corresponding to a maximum steel strain as obtained using a moment curvature analysis

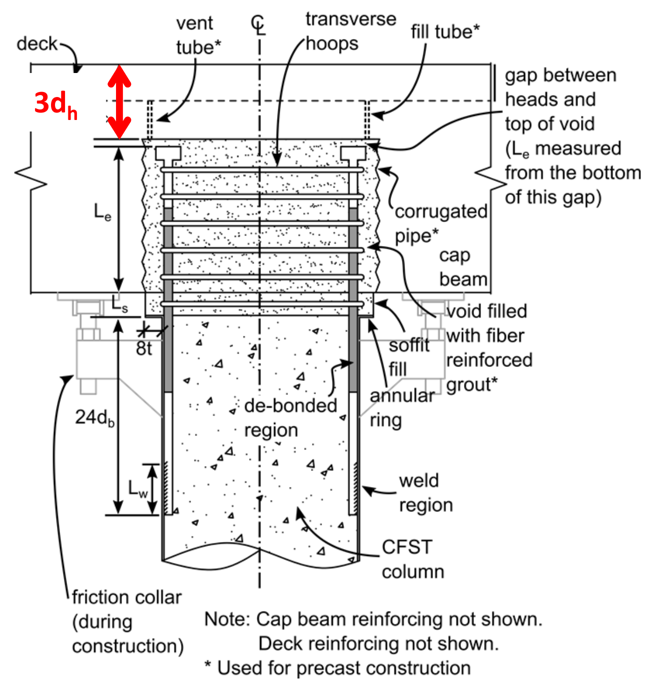
Rigid Body Approach

$$L_{db} = \frac{\tan\theta(D - t - d_b/2)}{0.7\varepsilon_u}$$

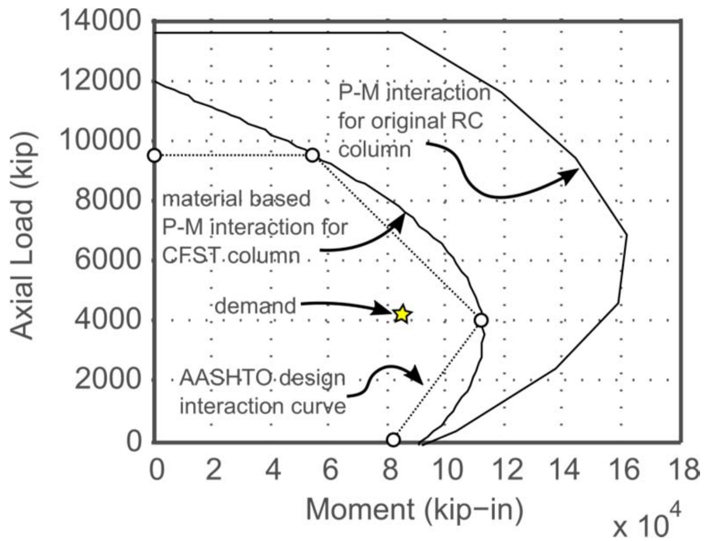
ε_u= ultimate dowel bar strain

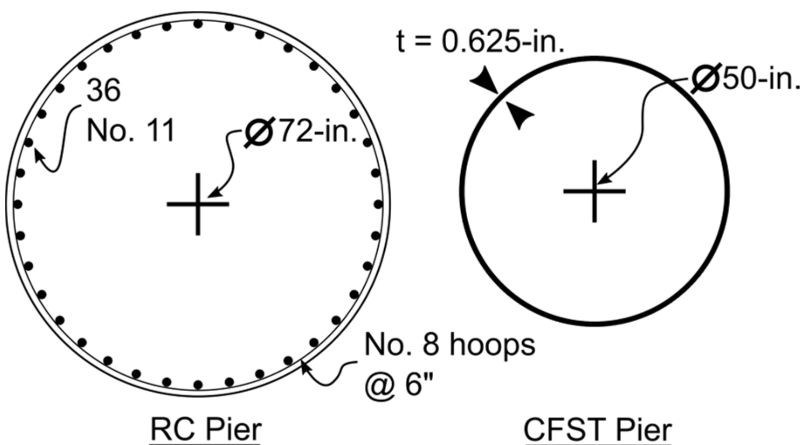
Punching Shear Requirement

- Adequate depth must be provided above the headed dowels to eliminate punching shear
- Experimental research discussed here used $4d_h$
- $3d_h$ may be adequate based on a survey of relevant research



Caltrans Example Bridge

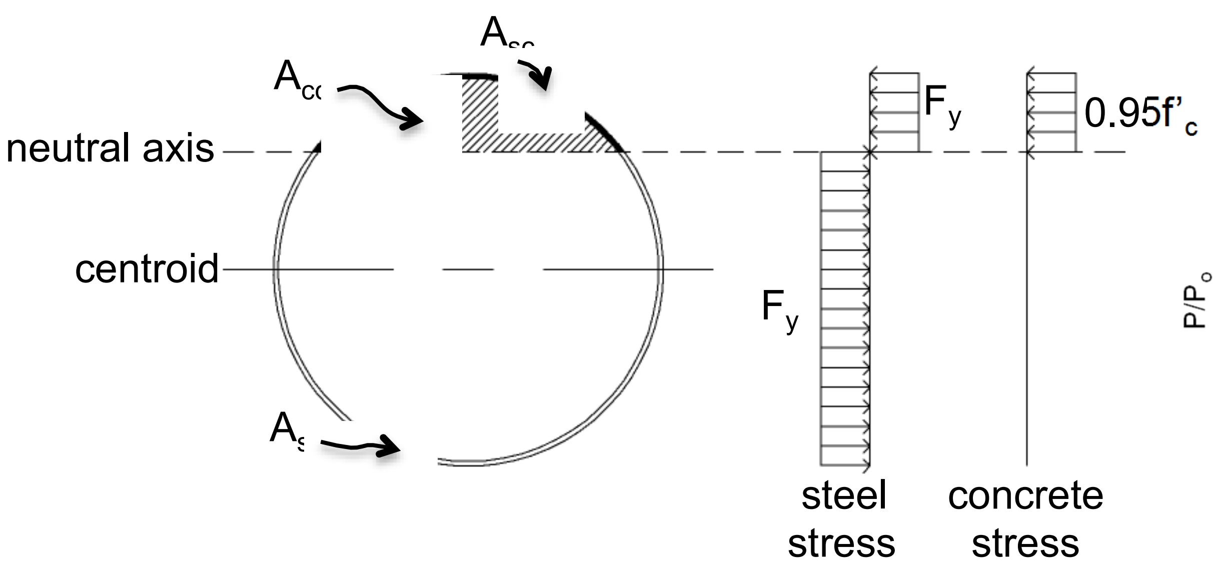




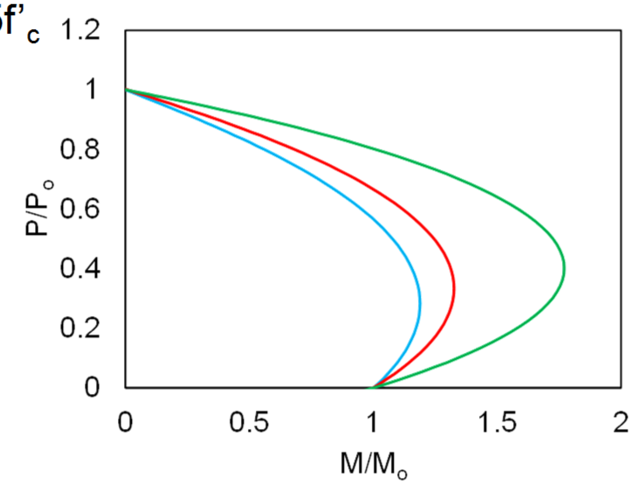
	Original RC Pier	CFST Pier
Concrete Strength (ksi)	4.0	4.0
Steel Strength (ksi)	60.0	50.0
Diameter (in.)	72	50
Tube Thickness (in.)	-	0.625
Concrete Area (in.^{2})	4072	1866
Steel Area (in.^{2})	92	96.94
Weight/ft of Pier (kips)	4.4	2.2
Total Pier Weight (kips)	209	104
Difference in Pier Weight	50% Reduction	

Flexural Strength: Plastic-Stress Distribution Method

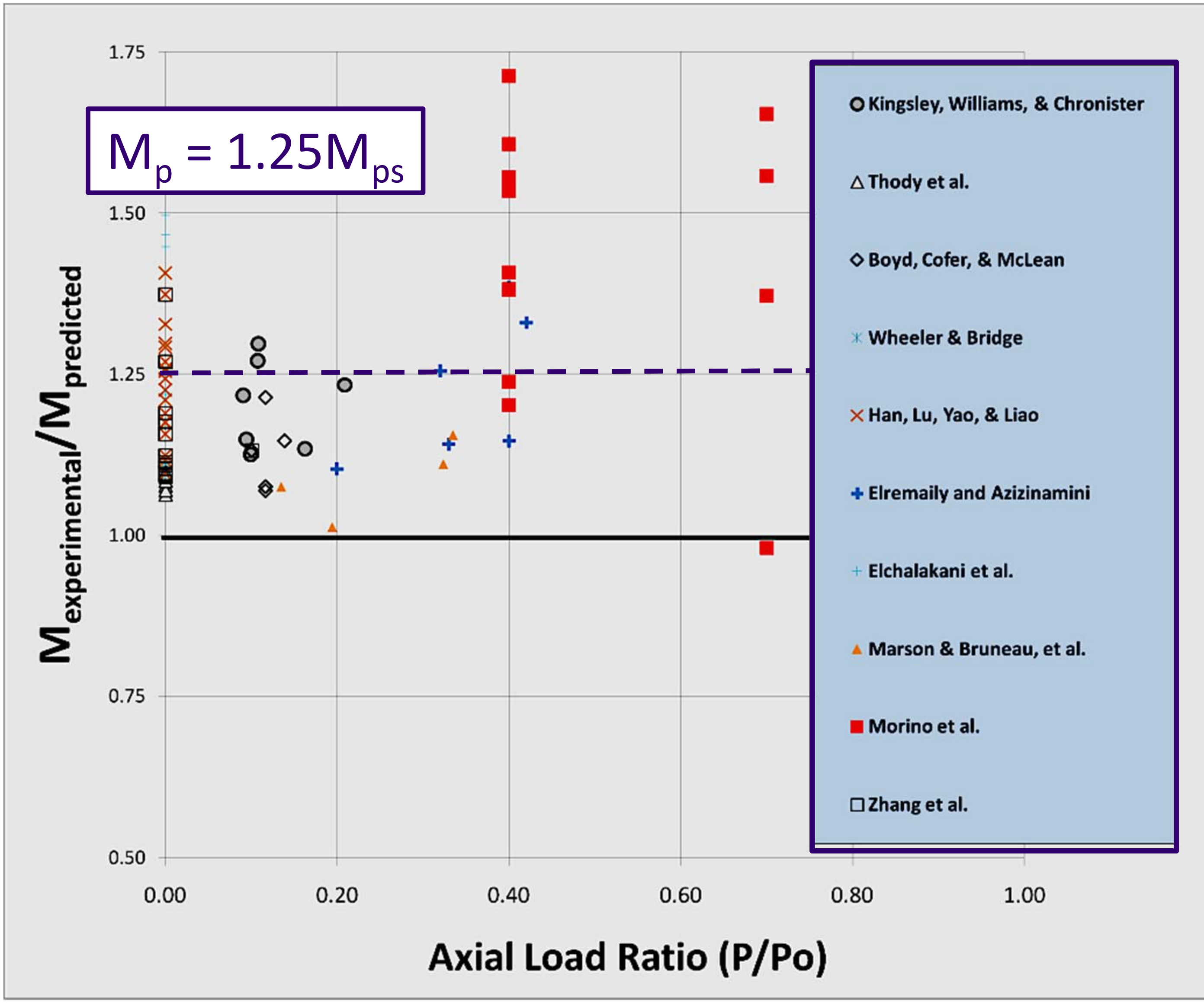
- Method of choice for flexural strength calculation
- Equilibrium-based method



P-M Interaction Diag.



Comparison with Test Data



Embedded Ring Connection

- Fully restrained (Full Strength) CFST moment connection
- Tube embedded in foundation concrete
- Annular ring used to transfer overturning forces