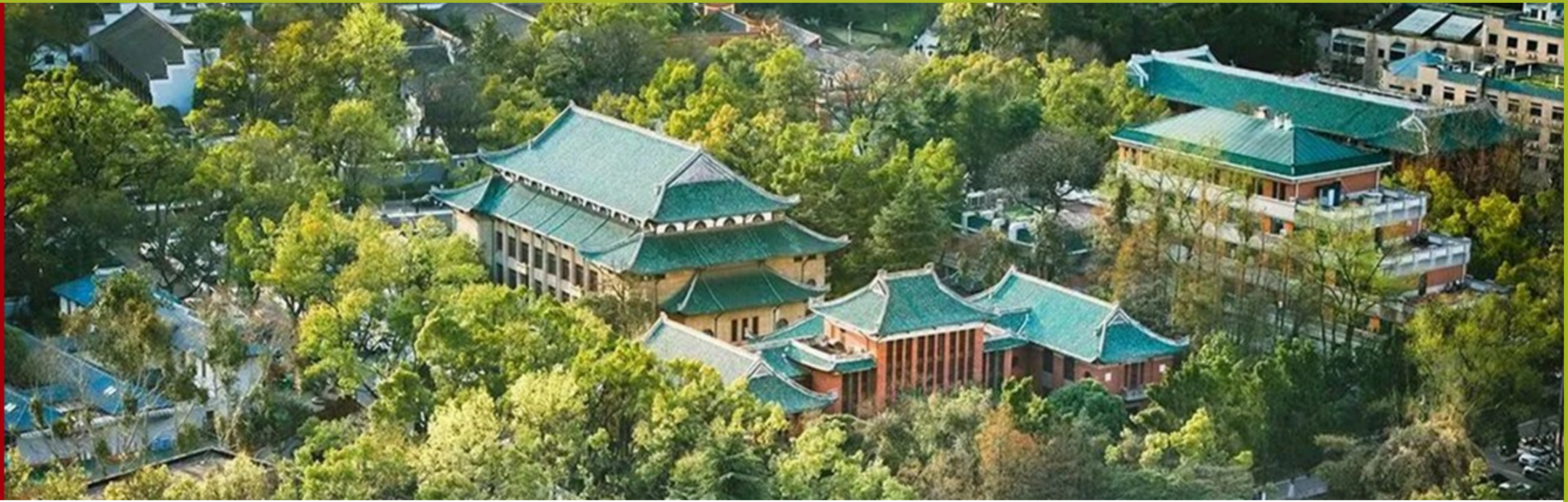
5IBSW

5TH INTERNATIONAL BRIDGE SEISMIC WORKSHOP

Changsha, China

5-8, June 2026



Seismic Resilience of Bridge Components Constructed with Concrete Filled Steel Tubes (CFST)

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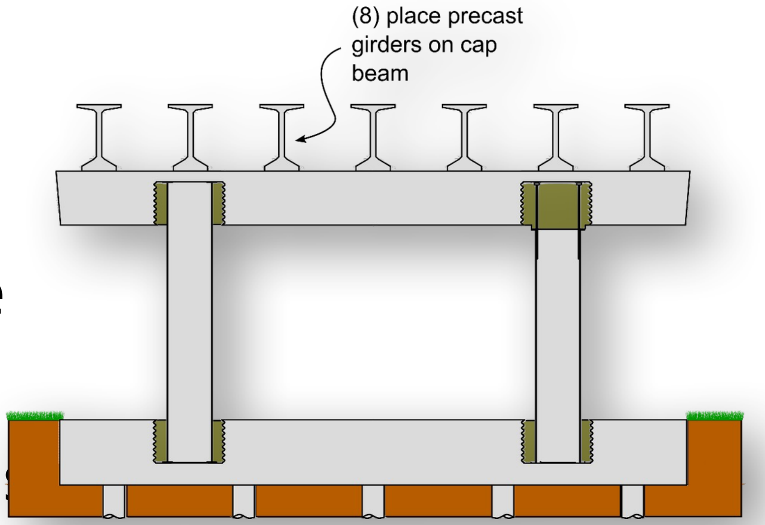
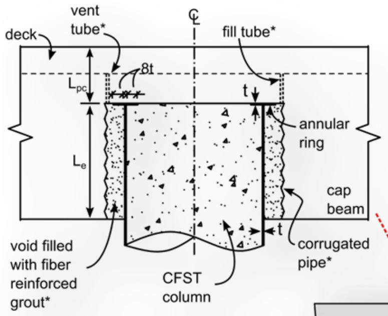
Adjunct Professor, Saint Martin’s University, WA

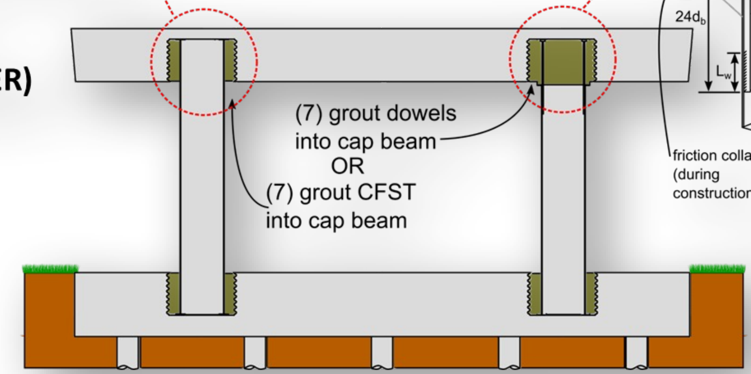
Presentation Outline:

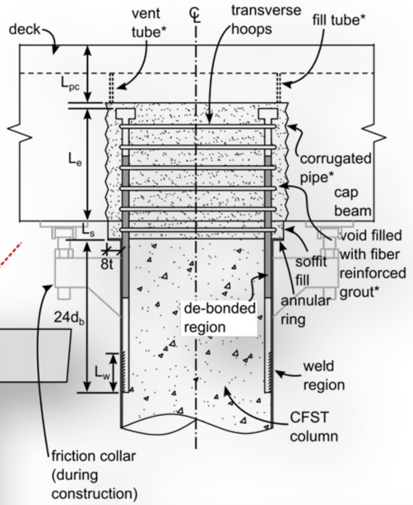
- Applications of CFST
- CFST Component Testing
- CFST ER and WD Connection Performance
- Seismic Resiliency of CFST
- Design Expressions and Standard Drawings



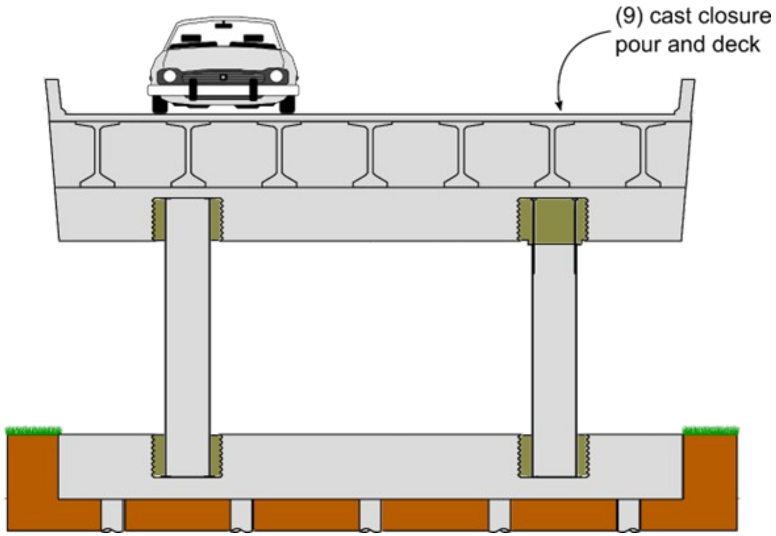


Embedded Ring (ER)



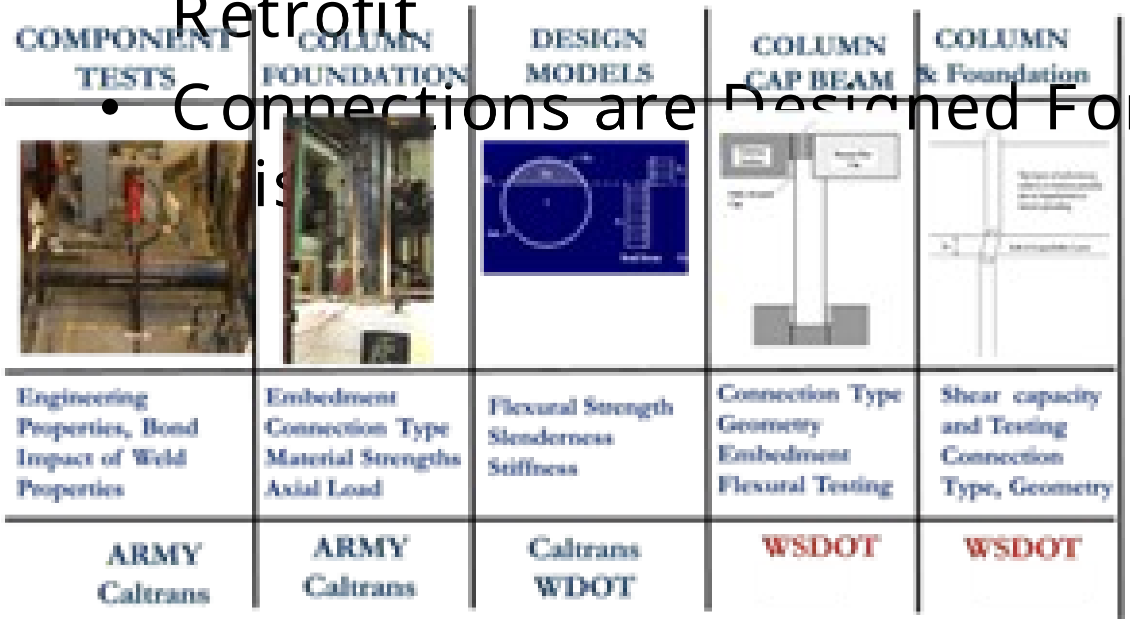


Welded Dowel (WD)



CFST Advantages and Applications

- Used for Bridge Piers/Columns, and Piles and Shafts
- Superior Strength, Stiffness with Delayed Local Buckling
- Superior Seismic Resilience for Design and Retrofit
- Connections are Designed For Strength and



COMPONENT TESTS	COLUMN FOUNDATION	DESIGN MODELS	COLUMN CAP BEAM	COLUMN & Foundation
Engineering Properties, Bond Impact of Weld Properties	Embedment Connection Type Material Strengths Axial Load	Flexural Strength Slenderness Stiffness	Connection Type Geometry Embedment Flexural Testing	Shear capacity and Testing Connection Type, Geometry
ARMY Caltrans	ARMY Caltrans	Caltrans WDOT	WSDOT	WSDOT

WSDOT-UW Research Project: Professors Charls Roader and Dawn Lehman) – followed by WSDOT BDM and AASHTO Adoption)

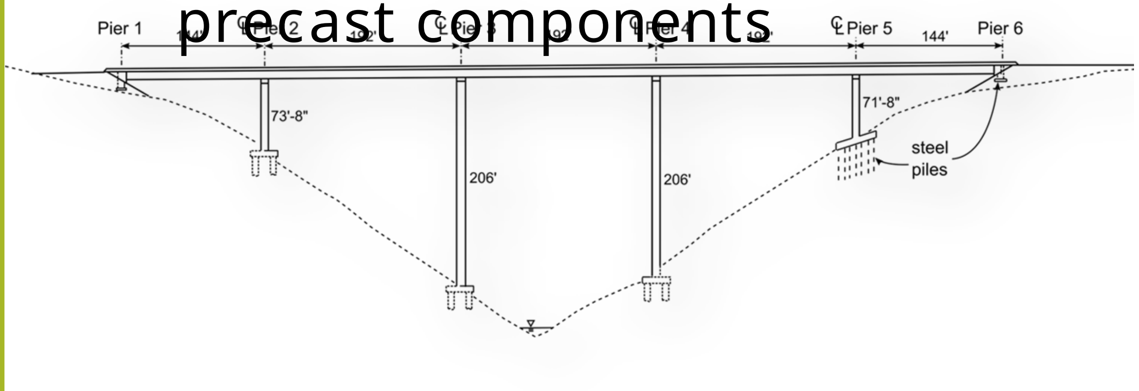
US-Japan Workshop

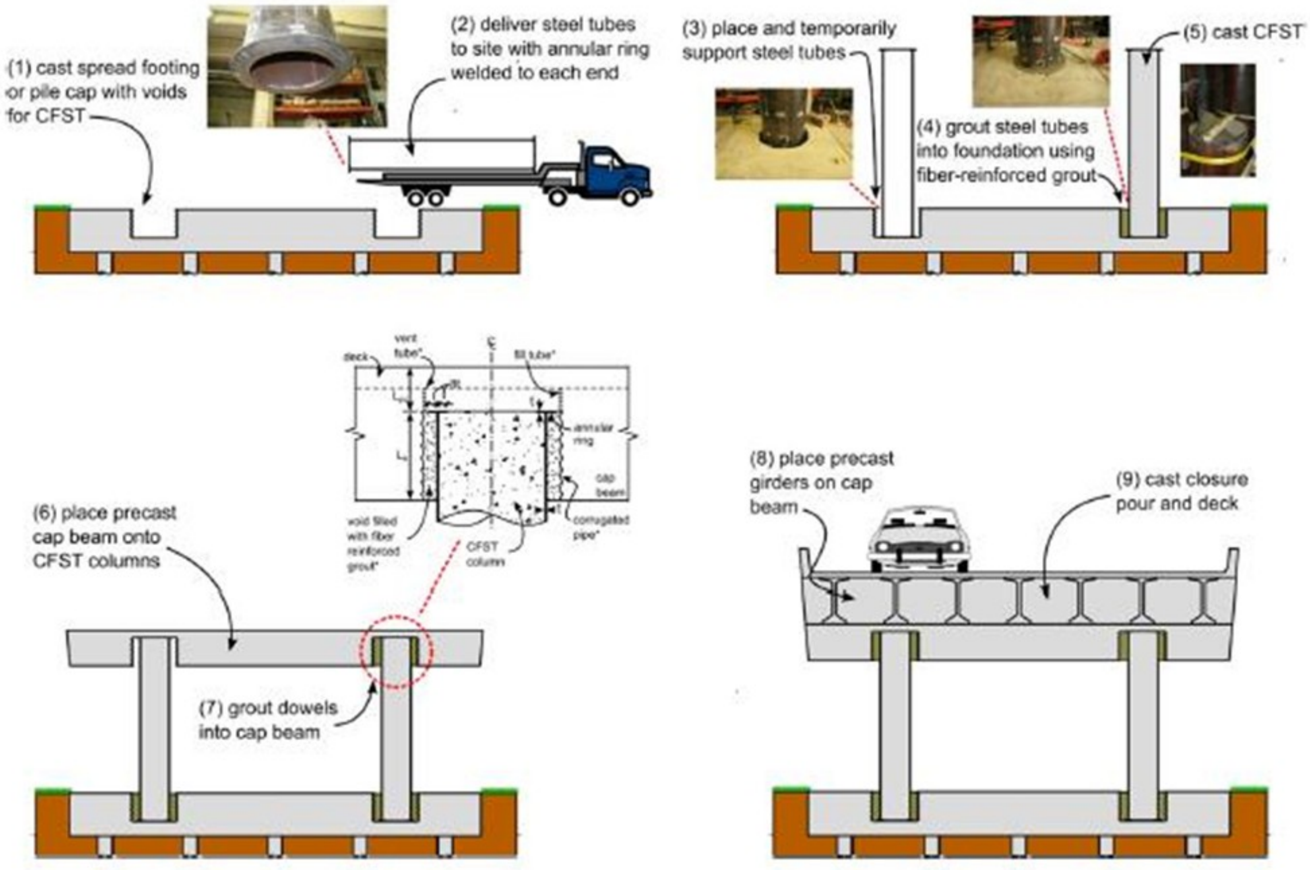
Tenpo-zan Ohashi Bridge Foundation Seismic Retrofit

Application of CFST to Accelerated bridge construction

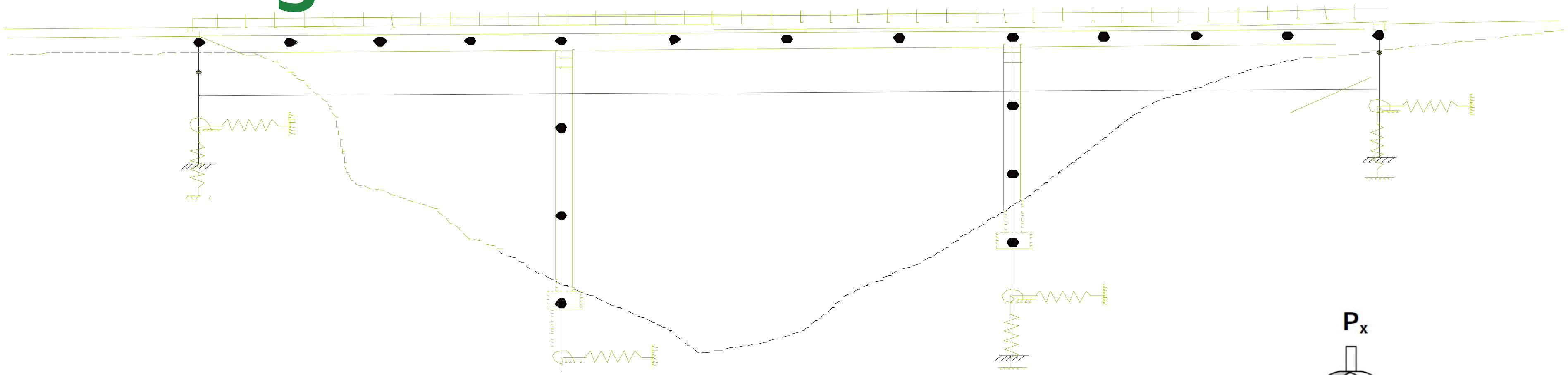
ABC Benefits include:

- Decreased construction costs an time,
- Increased safety and Improved quality,
- CFST columns fulfill ABC objectives providing adequate seismic resistance
- CFST Can be integrated with precast components

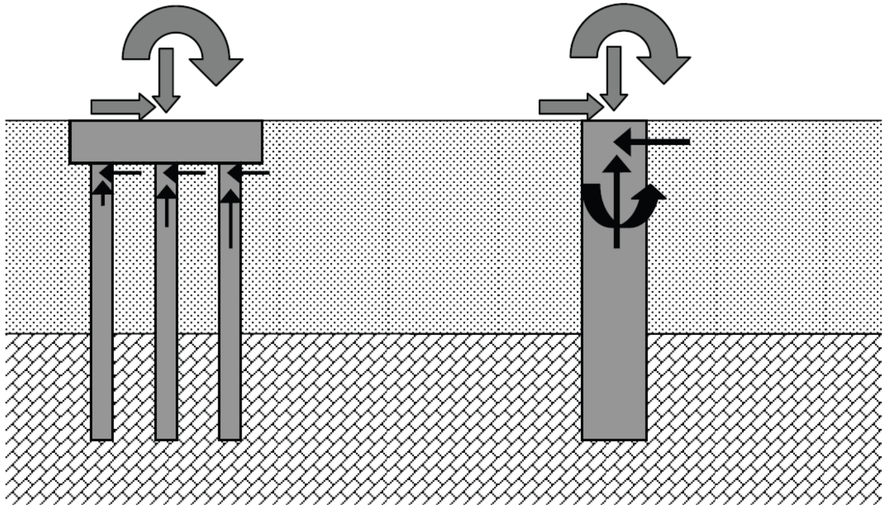




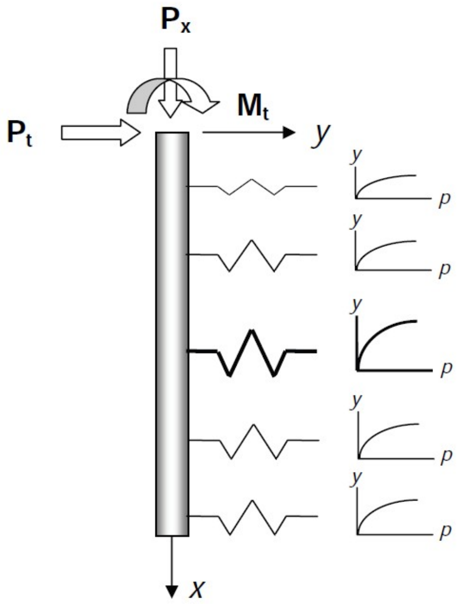
CFST Piles and Shafts - SSI Advantage



Ductility



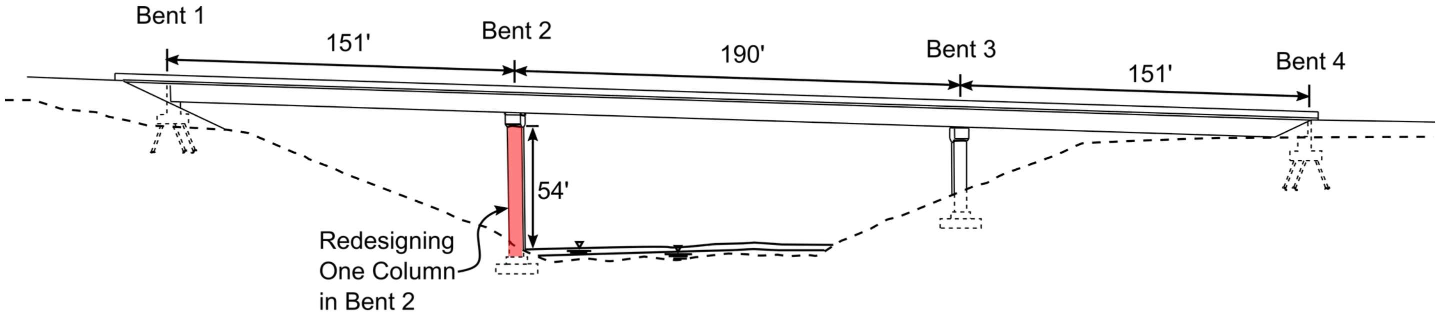
Deep Foundation

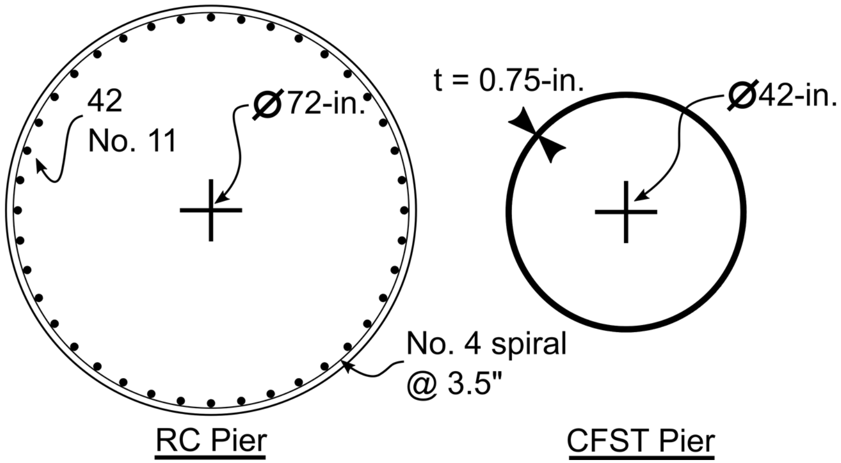


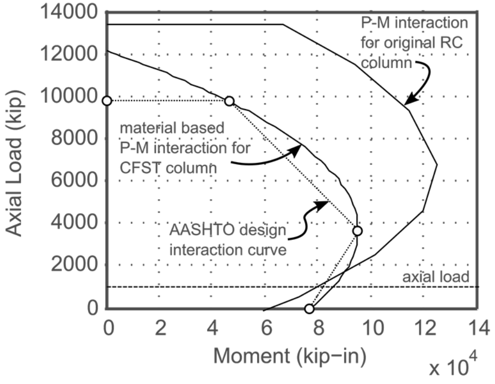
Lateral EQ Load

Bridge Comparison Example & Practical Design Solution

- CFST Offers smaller diameter columns and foundation resulting in less Materials
- CFST Reduce construction time a



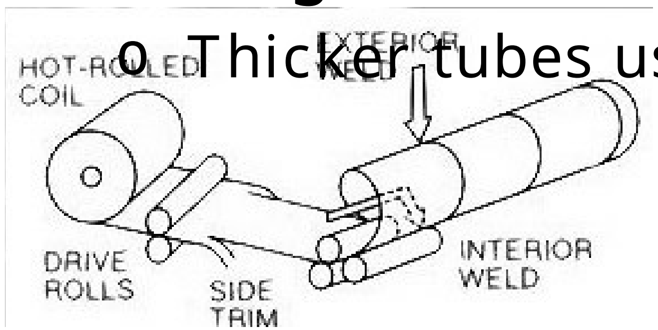




	Original RC Pier	CFST Pier
Concrete Strength (ksi)	4.0	4.0
Steel Strength (ksi)	60.0	50.0
Diameter (in.)	72	50
Tube Thickness (in.)	-	0.625
Concrete Area (in.^{2})	4072	1866
Steel Area (in.^{2})	92	96.94
Weight/ft of Pier (kips)	4.4	2.2
Total Pier Weight (kips)	209	104
Difference in Pier Weight	50% Reduction	

Steel Tube Types for CFST

1. **Spiral Weld Tubes**
   - Economical, widely available in larger diameters and lengths
   - Fabricated by running a coil of steel to spiral
   - Submerged arc weld is used to seal the spiral
   - Weld provides mechanical bond
2. **Straight Seam Tubes**
   - Thicker tubes used for driven piles



Steel Tubes:

- ASTM A252 Gr. 2 or 3
- ASTM A572 or A588
- API 5LGrade 42 or 52

- For primarily flexural members:

$$\frac{D}{t} \leq 0.22\frac{E}{F_y}$$

- For primarily to axial loading members:

$$\frac{D}{t} \leq 0.15\frac{E}{F_y}$$

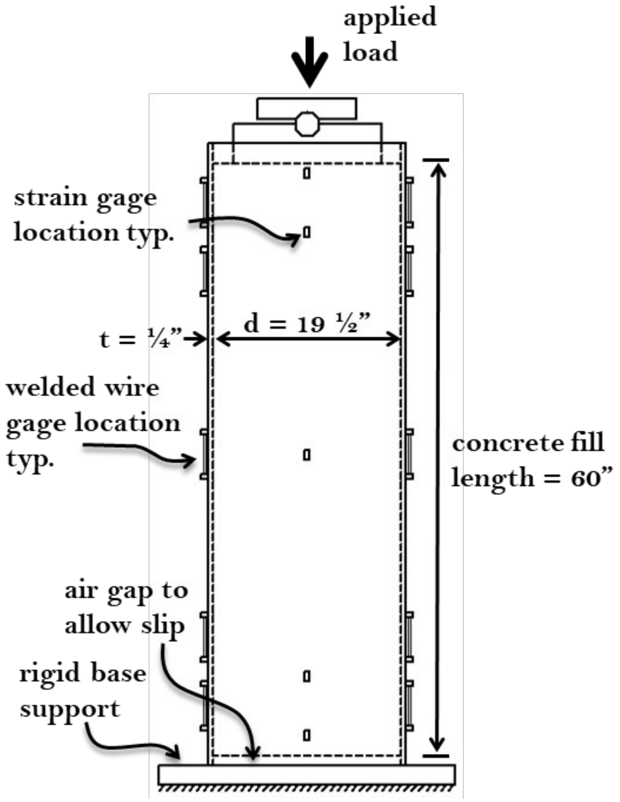
- Effective stiffness of CFT,

$$EI_{eff} = E_s I_S + C'E_c I_c$$

$$C' = 0.15 + \frac{P}{P_0} + \frac{A_s}{A_s + A_c} \leq 0.9$$

Axial Specimen Testing - Composite Action in CFST

CFST push-through tests



Applied Load 2.4m lb.

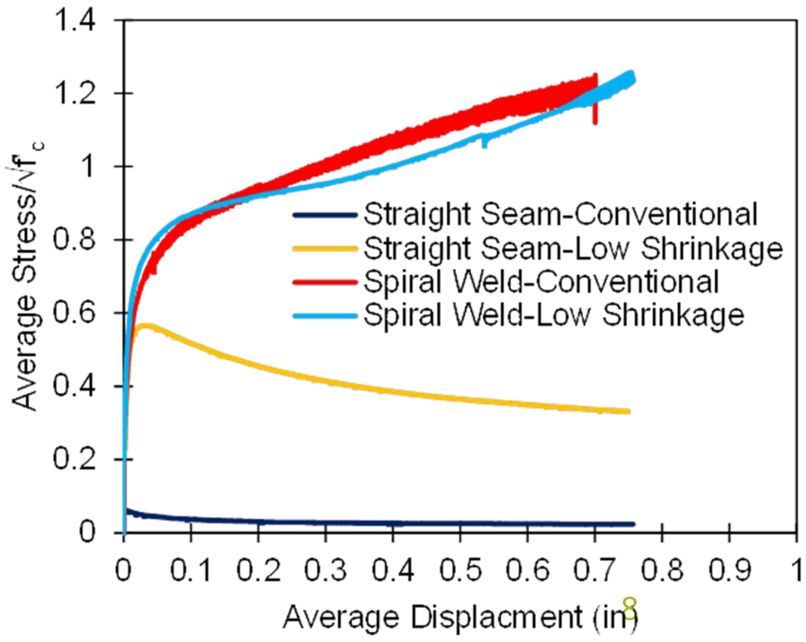
Axial Capacity:

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

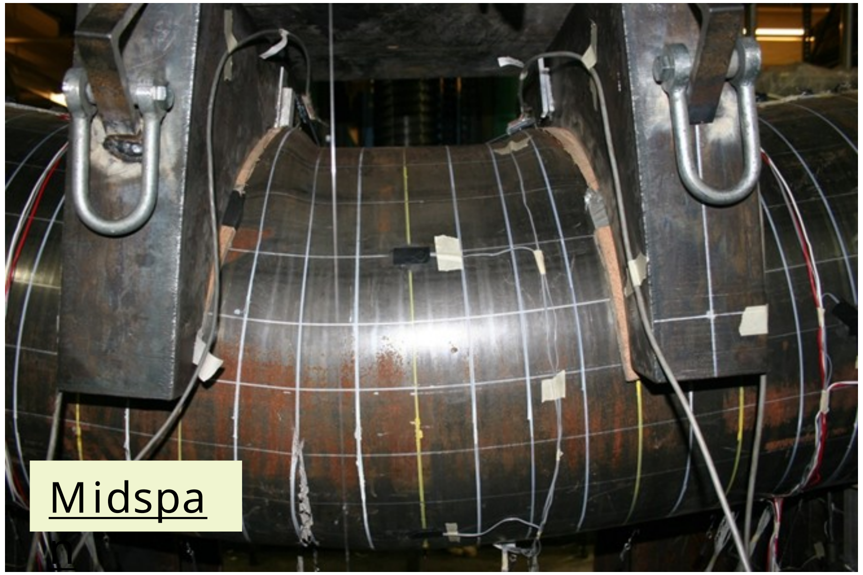
Reinforcement yield strength, Fyrl
Concrete Strength, f'c
Tube Steel Yield Strength, Fyt

4-Test

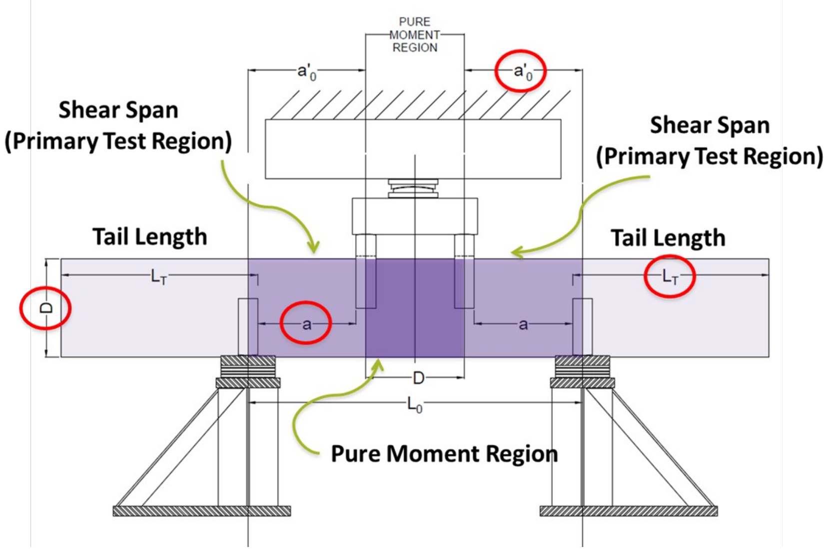
Tube	Concrete
Straight Seam	Conventional
	Low Shrinkage
Spiral Weld	Conventional
	Low Shrinkage



Flexural Response - Test Results:



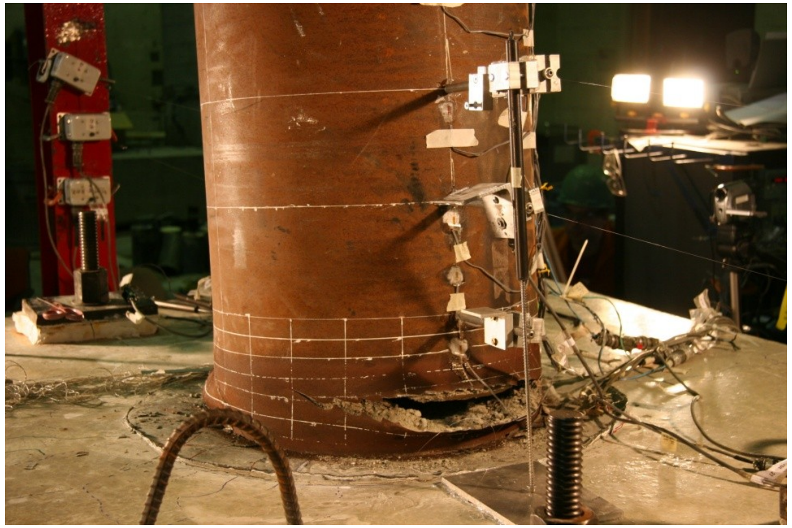
- Flexural buckling of steel tube
- Concrete filled inside the tube crack patterns:
  - Dense transverse flexural cracking in midspan region
  - Minor to no diagonal cracking in shear spans

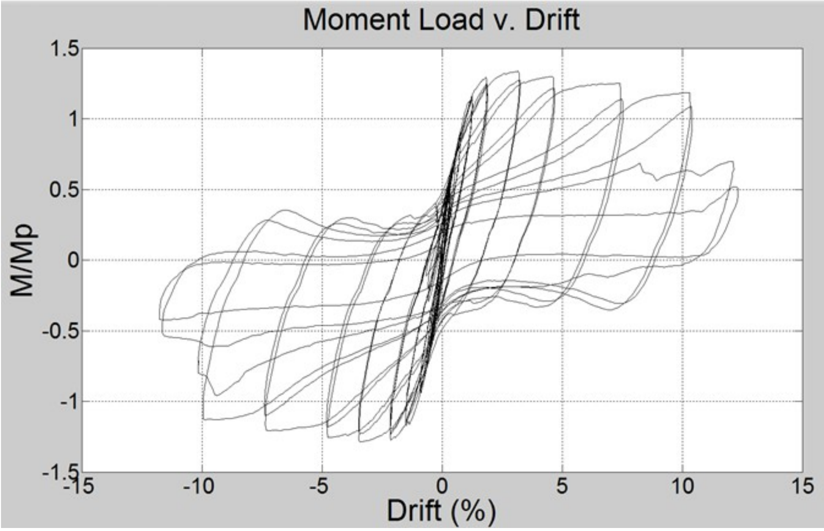


Specimen 17

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

Flexural Seismic -Test Results



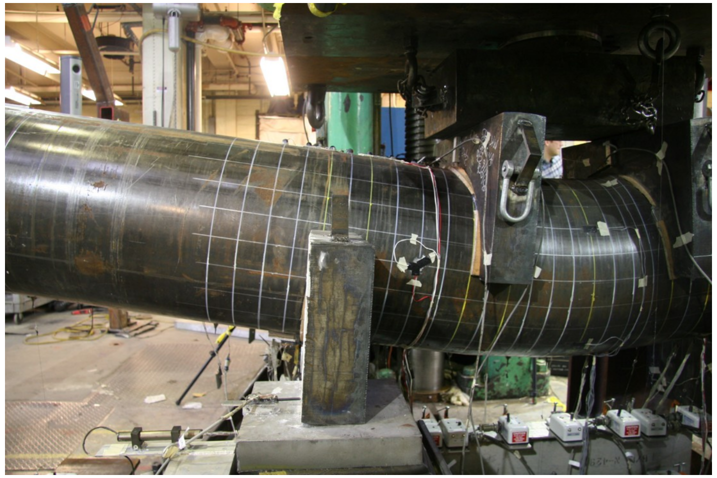


8.9% Drift RC
10% Drift CFST

Shear Strength of CFST

Shear Testing: 21 tests on CFST specimens conducted (a) aspect ratio, (b) D/t, (c) concrete strength, (d) internal reinf. ratio, (e) tail (anchorage) length, (f) axial load ratio.

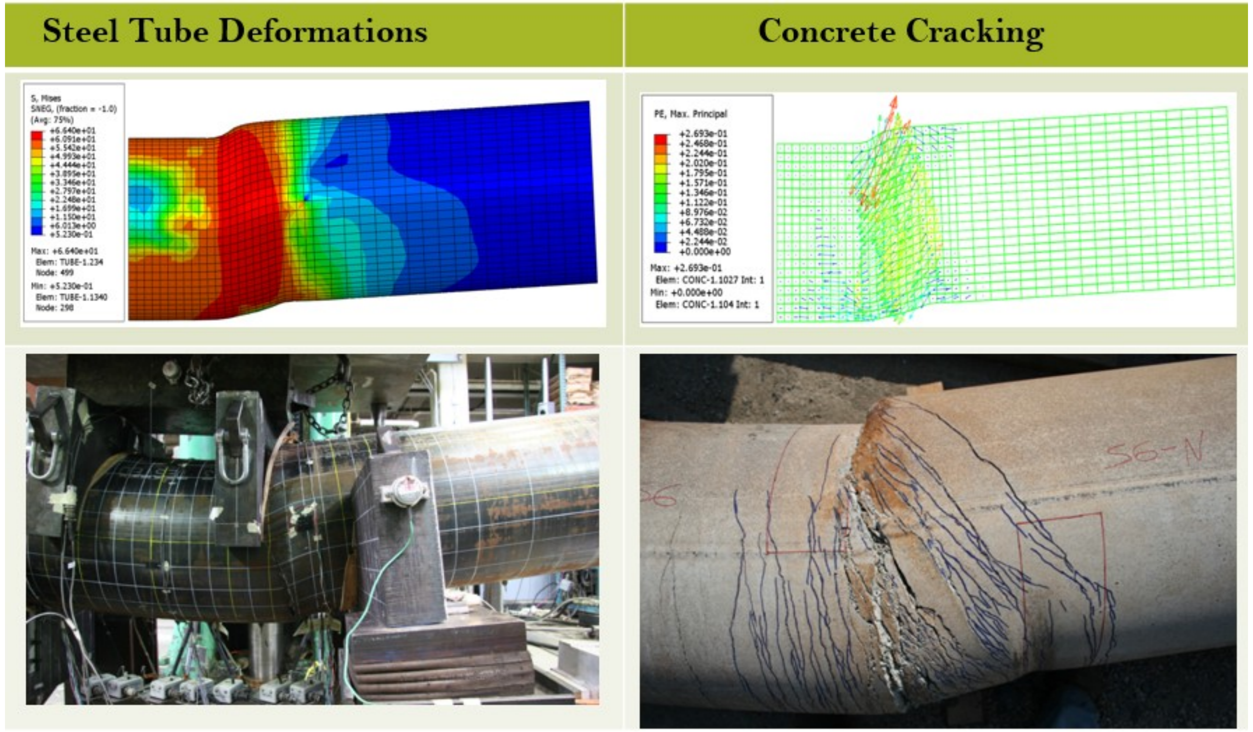
- Results show that CFST sections are very strong in shear.
- Typical shear span ratios: 0.375 and 0.25
- Evident shear strain in shear span with Inclined tube tear in shear span region

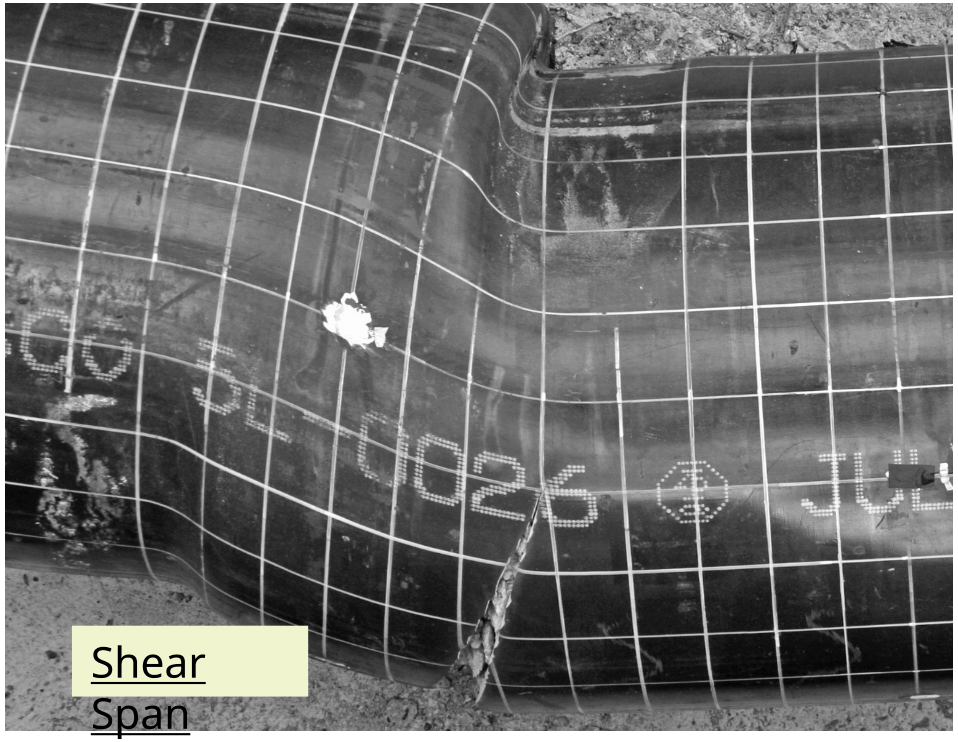


(a/D = 0.375, F_{ytm} = 56.8 ksi, f'_{cm} = 8.61 ksi, flex-shear)

Analytical Study of CFST – Shear Test

- Typical shear span ratios: 0.375 and 0.25
- Evident shear strain in shear span
- Minor flexural concrete cracking in midspan region
- Extensive diagonal Concrete cracking in shear spans

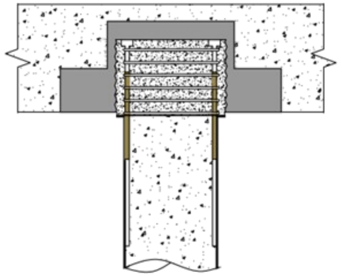




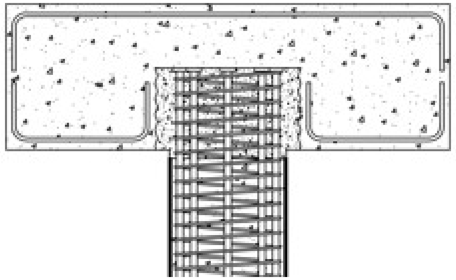
CFST Connection - Experimental Test Matrix

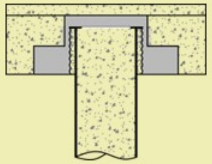
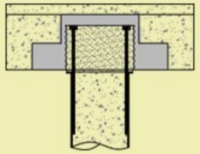
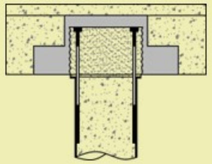
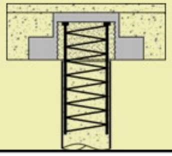
- Embedded Ring (ER)

- Welded Dowel (WD)



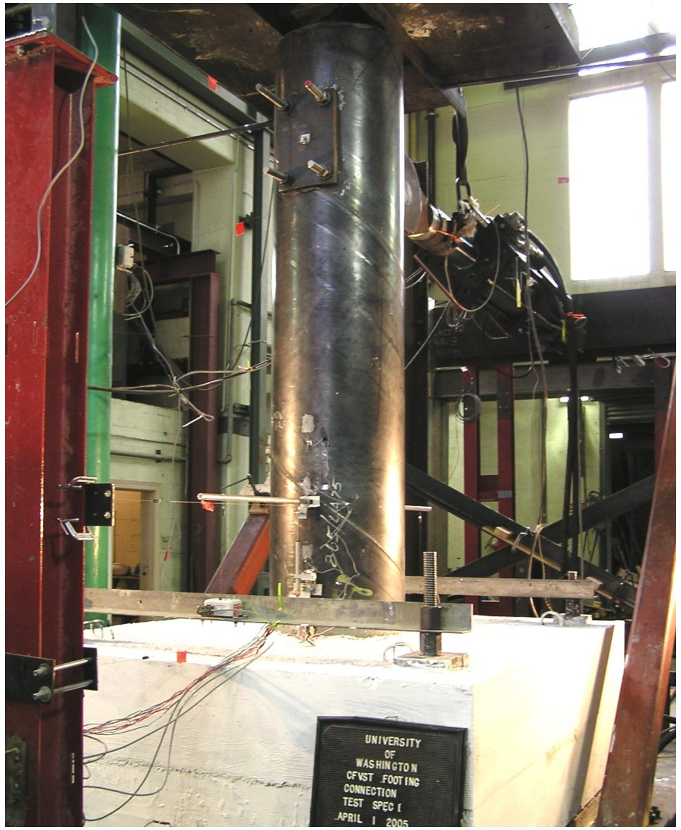
- Reinforced Concrete (RC)

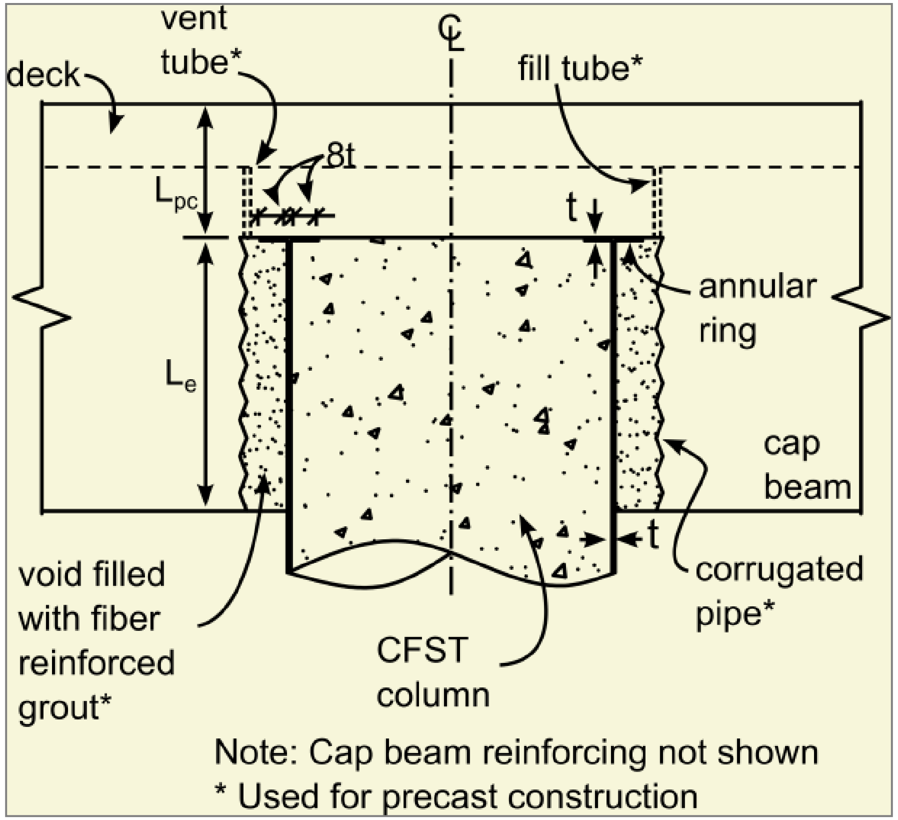


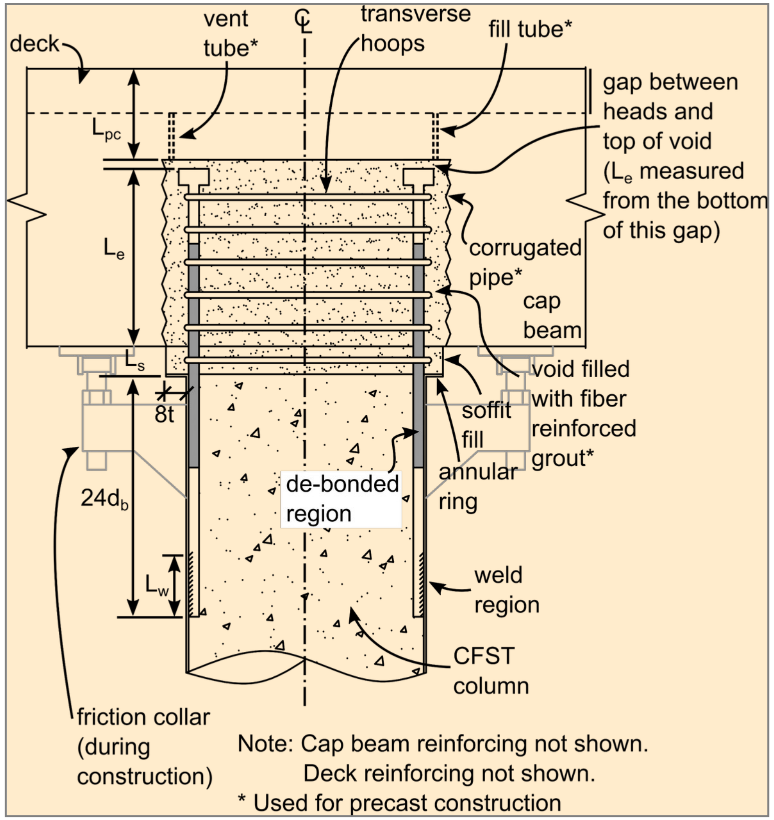
Connection Type	Loading Direction	D (in)	t (in)	Tube Type	Axial Load (P/Po)
Embedded Ring 	Transverse	20	0.25	Spiral Weld	0.1
	Transverse	24	0.25	Straight Seam	0.05
	Longitudinal	25.75	0.25	Spiral Weld	0.1
	Longitudinal	24	0.25	Straight Seam	0.05
Welded Dowel 	Transverse	20	0.25	Straight Seam	0.1
De-bonded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

CFST ER and WD Connection Tests

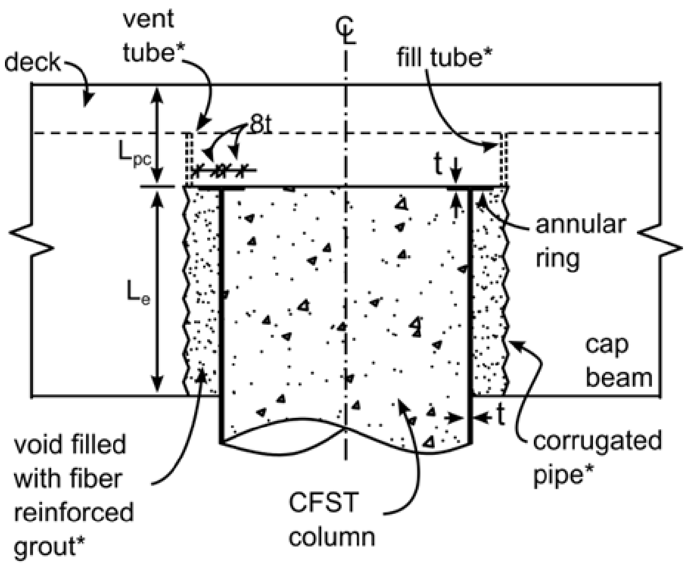
Full Strength CFST ER & Welded Dowel Connection Tests



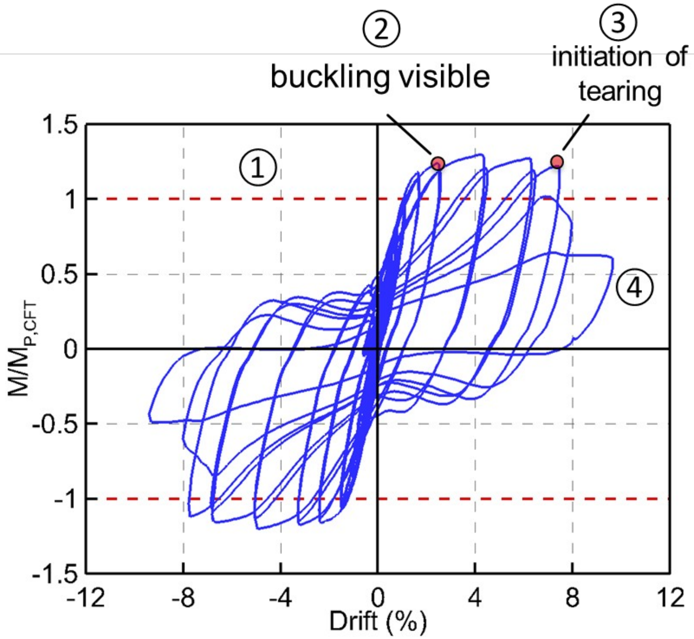


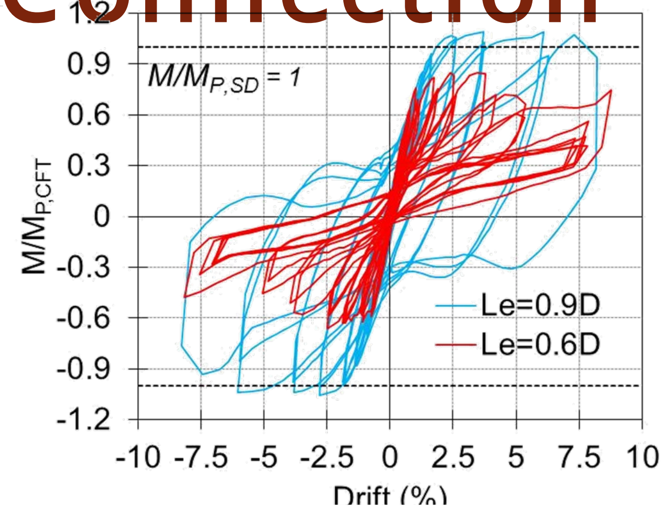


Performance of Embedded Ring (ER) Connection

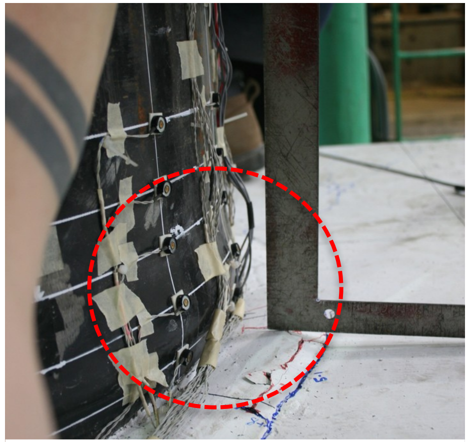


Note: Cap beam reinforcing not shown
* Used for precast construction

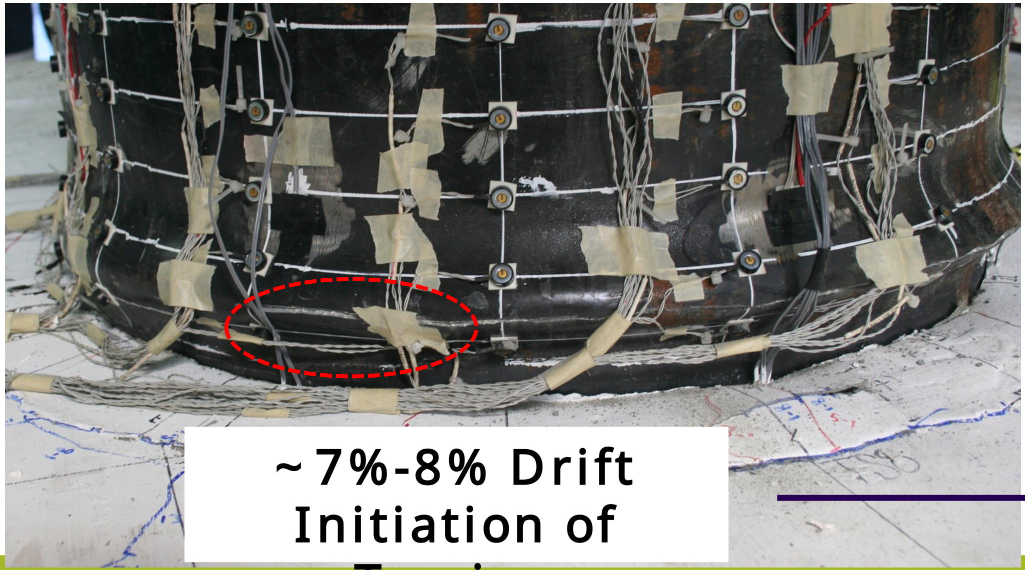




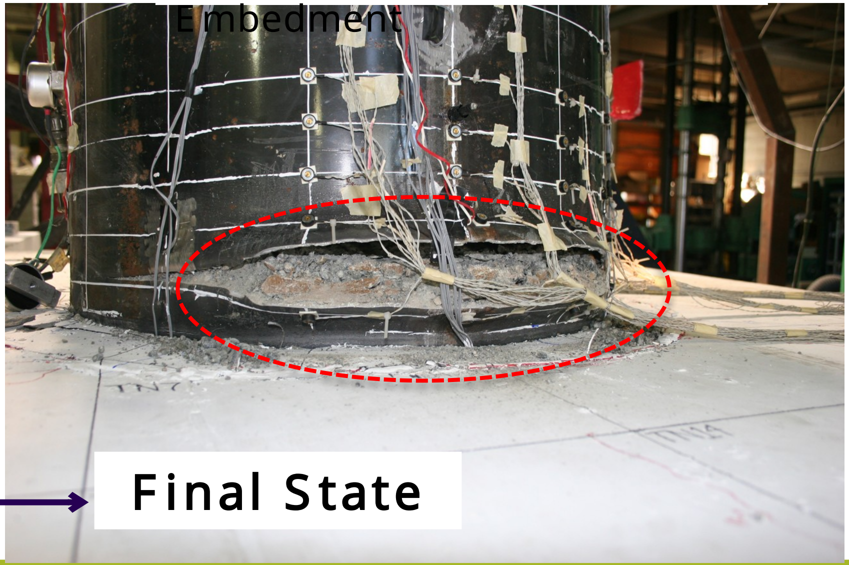
Comparison of ER Connection With and Without Adequate Embedment



3.5%-4% Drift: Tube Buckling Develops

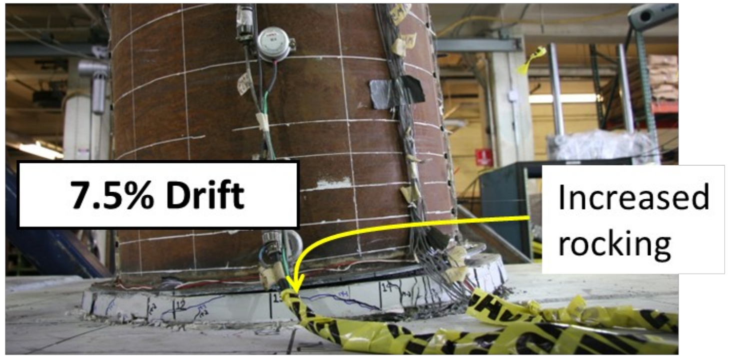


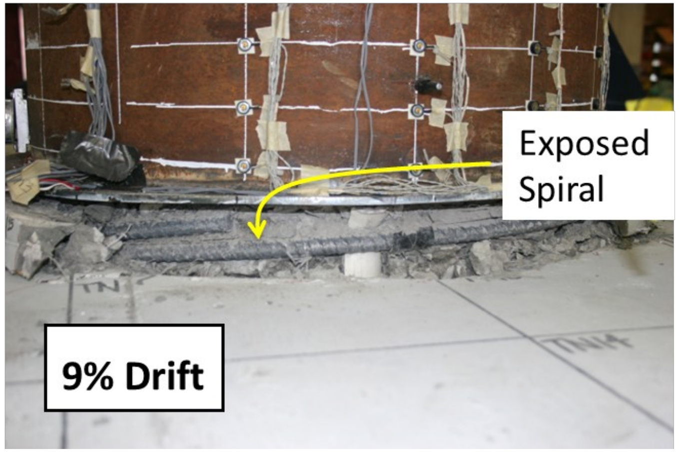
~7%-8% Drift Initiation of Tearing

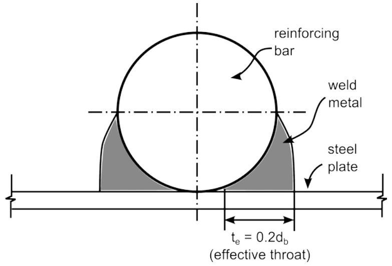


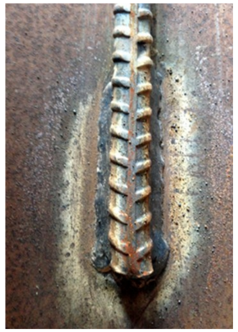
Final State

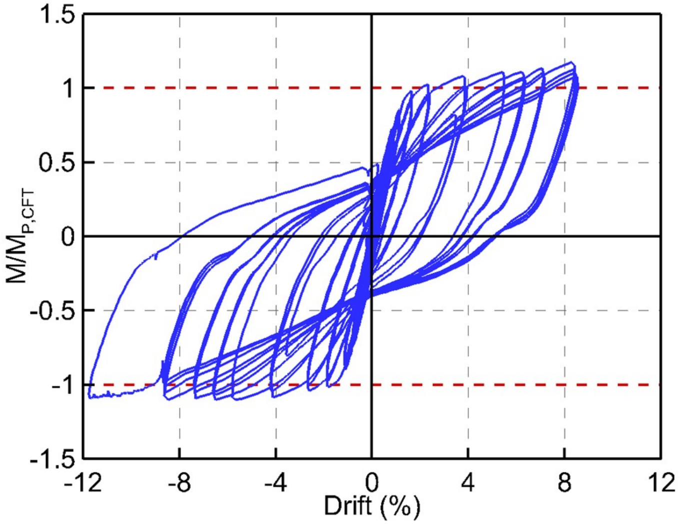
Performance of WD Connection











D (in)	t (in)	D/t	P/P_o	Reinforcing Steel	Fy (ksi)	f'_c (ksi)	ρ_L(%)	$(f_y/f'_c)\rho_L$
25.7 5	0.2 5	10 3	0.1 0	A706 Grade 60	68	7.7	3	0.3

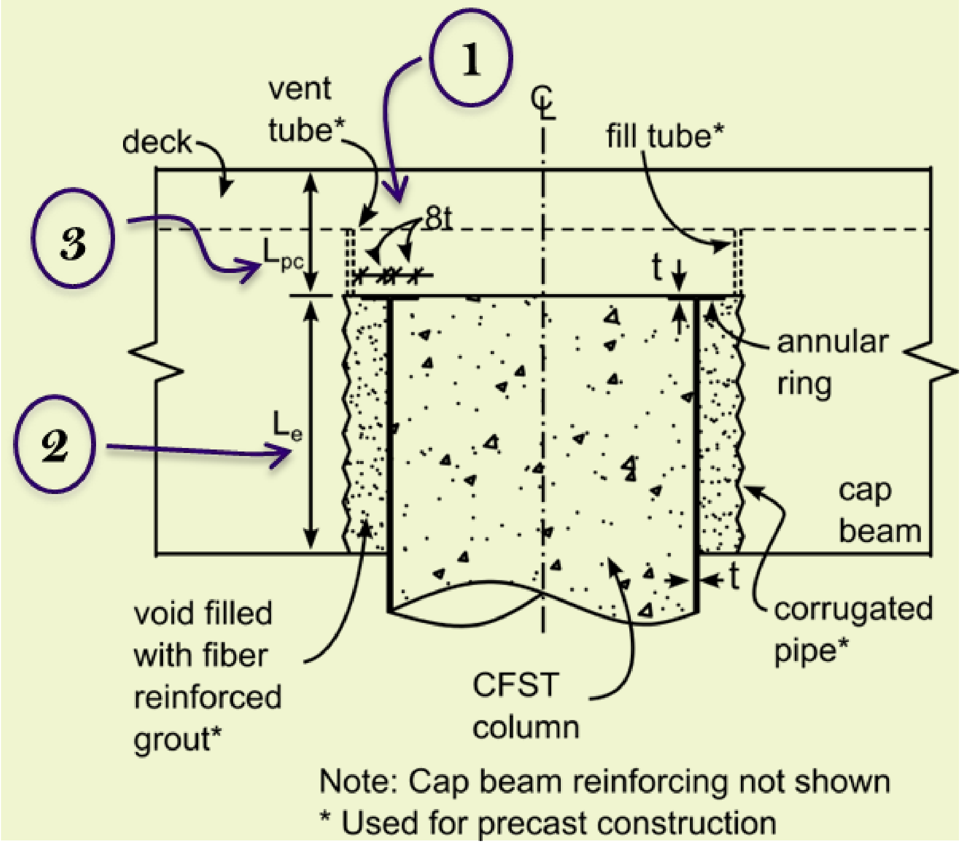
- Failure mode fracture of reinforcing bars (~ 8% drift)
- Strength limited by reinforcing ratio and

Embedded Ring Detail

Key Considerations

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

- ER Welded to tube are the Same thickness and strength as steel tube
- Projects inside and outside the tube for a distance 8t



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

Design Recommendations: Shear

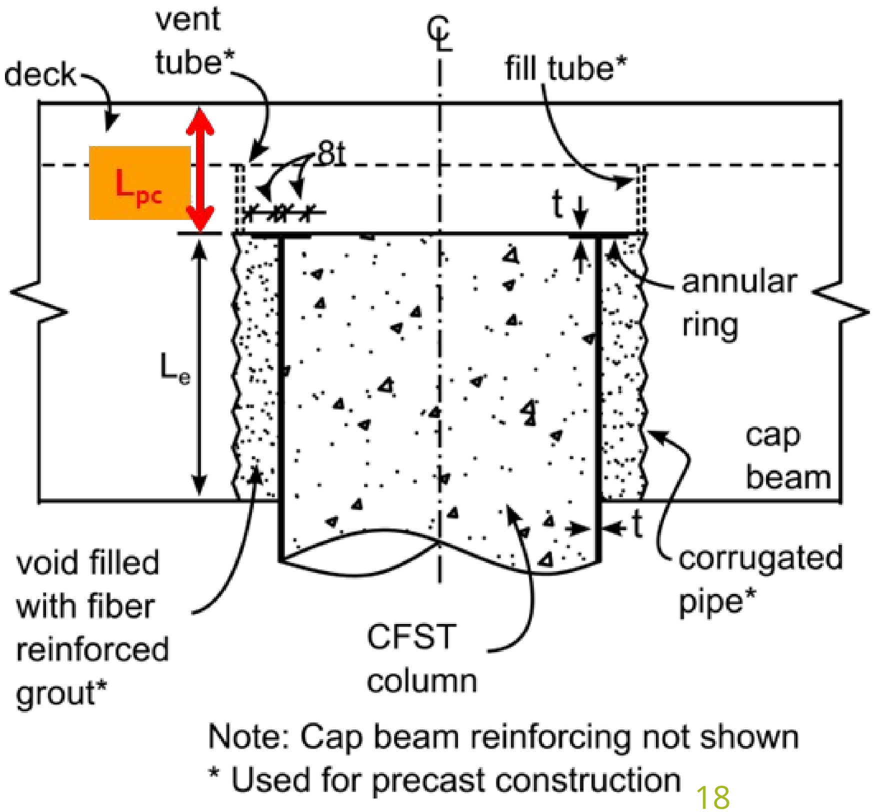
Shear resistance of CFST and RCFST:

$$V_u = \phi V_n = \phi g_4 \left[g_1 \left(0.6 f_y g_2 A_s \right) + 0.0316 g_3 A_c \sqrt{f_c'} \right]$$

Punching Shear Requirements

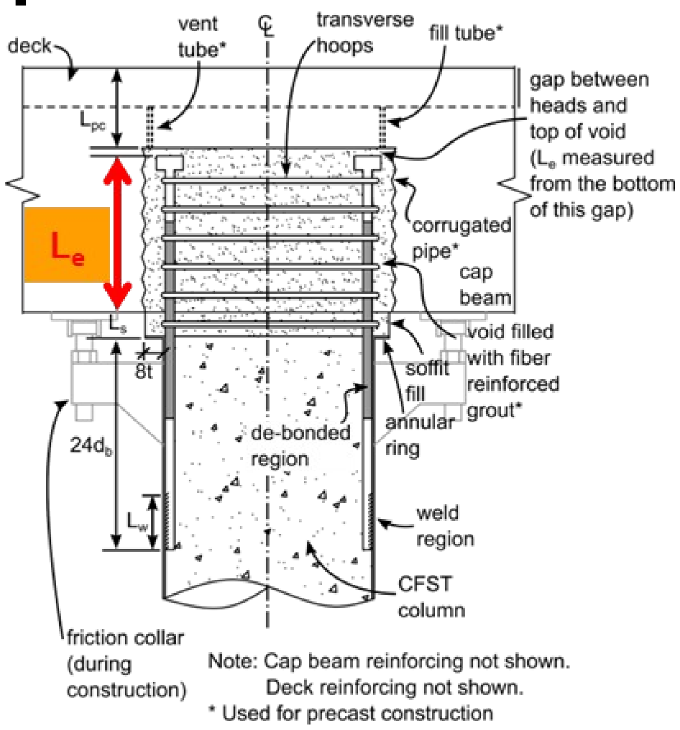
- Adequate depth must be provided above embedded tube to eliminate punching shear
- Derived using ACI procedure for flat slabs

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



Headed bars Embedment Depth Requirement

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

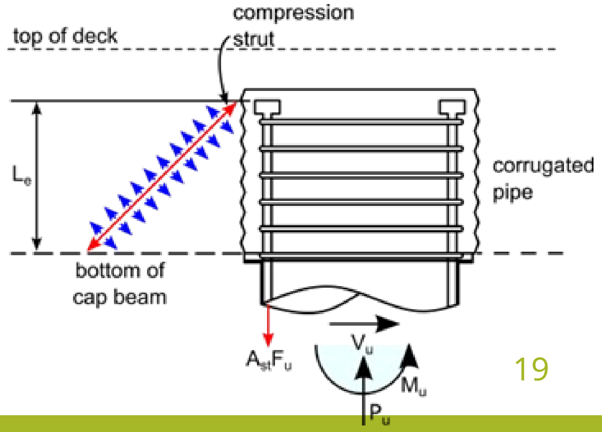


ACI Development of bars with mechanical anchors

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

Length to eliminate conical pullout

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



ER Embedment Depth Requirement

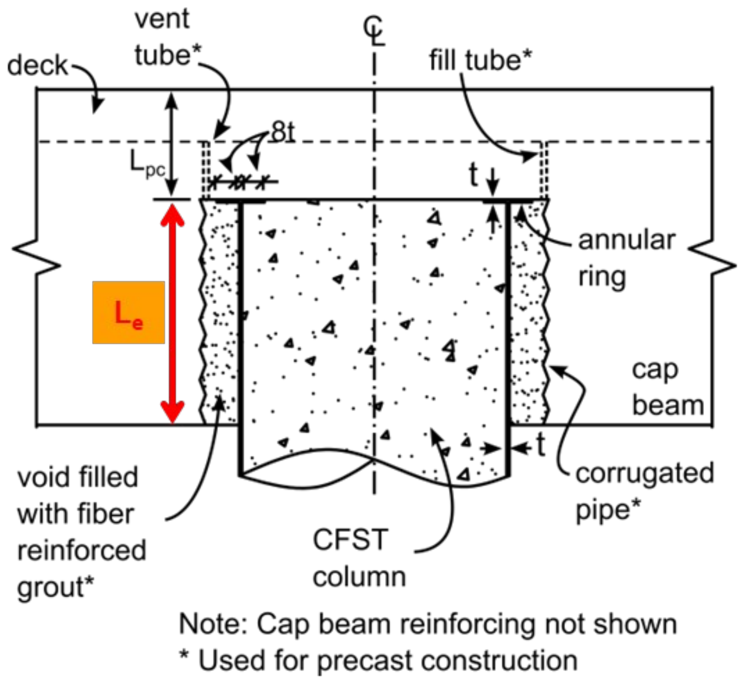
- Adequate embedment must be provided to eliminate pullout from cap beam
- Derived using pullout model with empirical stress limits
  - $6\sqrt{f'_c}$ for seismic
  - $8\sqrt{f'_c}$ for yielding

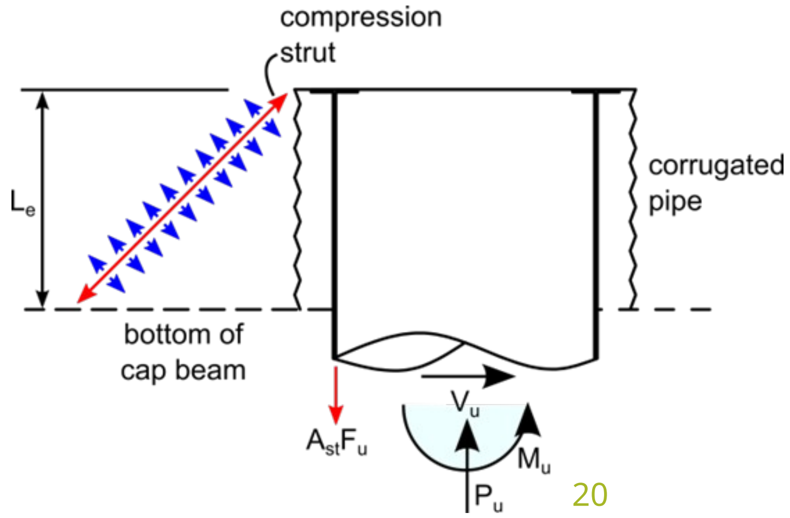
Yielding:

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

Seismic:

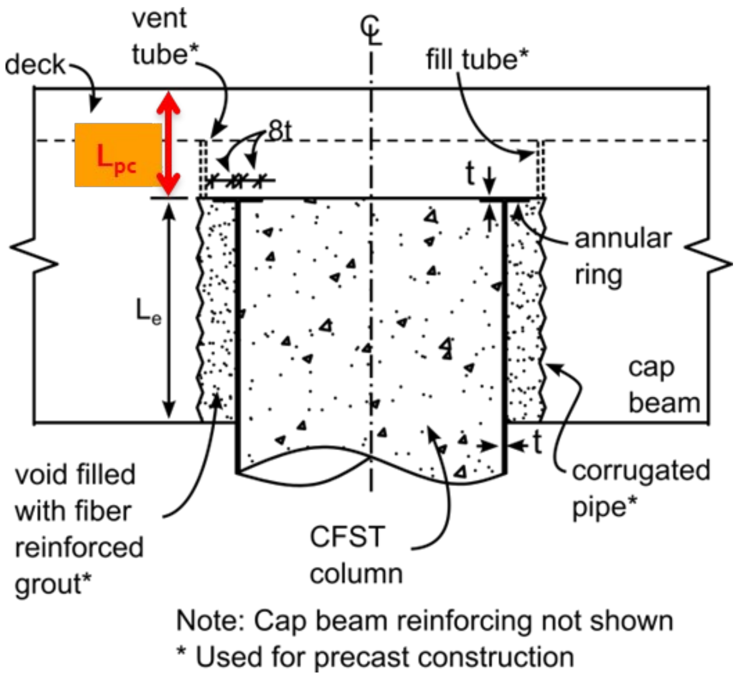
$$L_e \geq \sqrt{\frac{D^2}{4} + \frac{DtF_u}{6\sqrt{f'_{c,cap}}}} - \frac{D}{2}\ (psi)$$





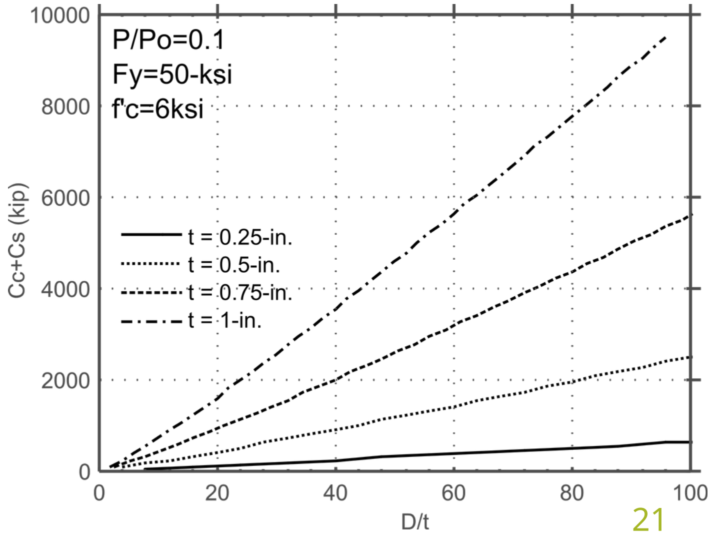
ER Punching Shear

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



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

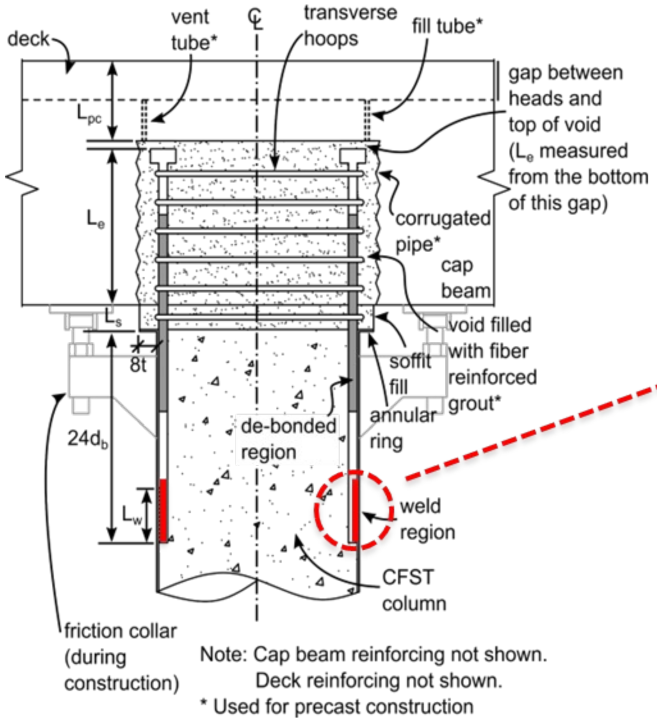
$$(f'_{c,cap}\ in\ ksi)$$

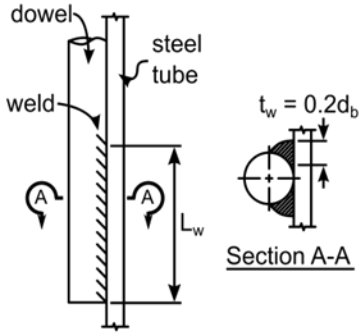


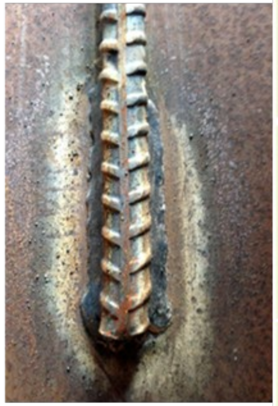
C_c= compressive force in concrete
C_s=compressive force in steel

Dowel to Steel Tube Weld Requirement

- Longitudinal dowels are welded to the inside of the steel tube
- Weld type is flare bevel groove weld as specified in AWS D1.5
- Weld lengths based on typical limit states for flare bevel groove welds





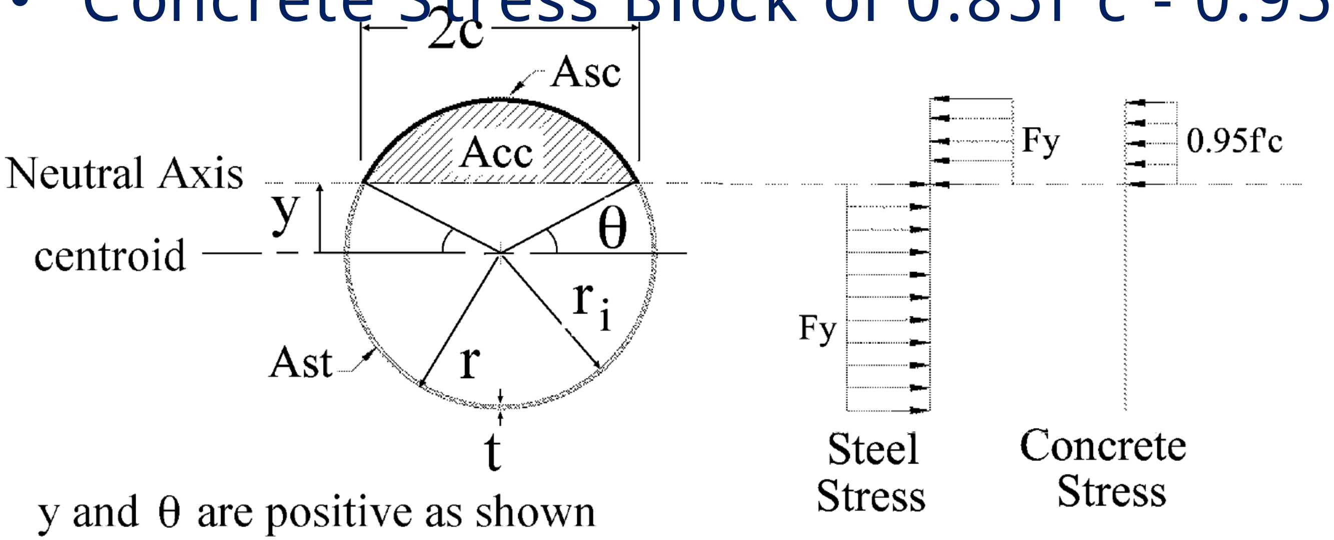


Weld Metal	$L_w \geq \dfrac{5.6 A_b F_{y,b}}{F_{EXX} d_b}$
Tube Metal Yield	$L_w \geq \dfrac{0.83 A_b F_{y,b}}{F_{y,st} t}$
Tube Metal Rupture	$L_w \geq \dfrac{1.11 A_b F_{y,b}}{F_{u,st} t}$

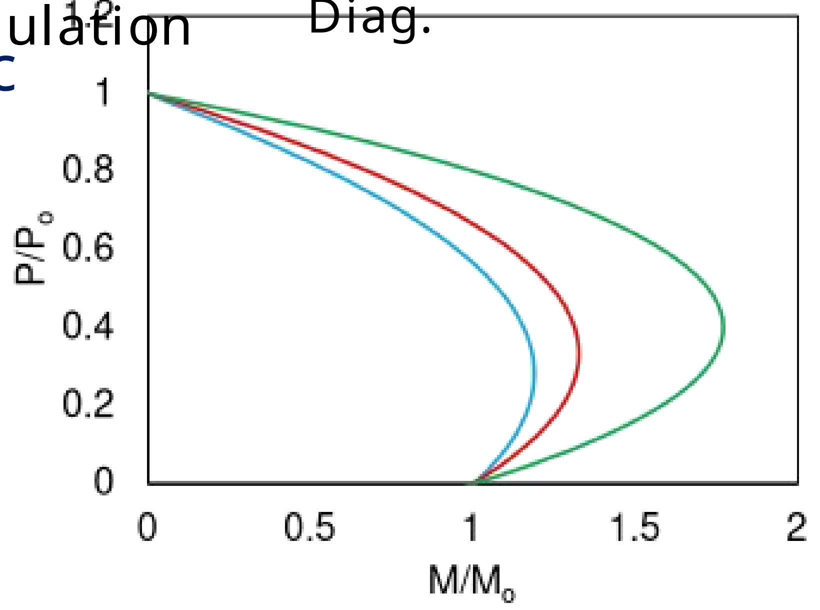
CFST Plastic Stress Distribution

- Capacity to develop Plastic Hinging, Confinement Stress Distribution
- Stress-strain Model For Reinforced Concrete Column with Steel Casing
- Steel is at Yield in Tension & Compression
- Concrete Stress Block of 0.85f’c - 0.95f’c

- Equilibrium-Based Method for flexural strength calculation

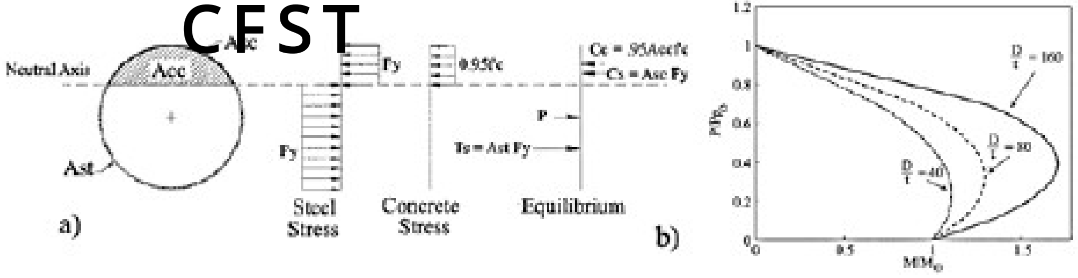


P-M Interaction Diag.



CFST Design Expressions

Flexural - CFST



Vacant (7.10.2-5)

$$P_n(y) = \left(\left(\frac{\pi}{2}-\theta\right) r_i^2 - yc\right) * 0.95f'_c - 4\theta t r_m F_y \quad (7.10.2\text{-}6)$$

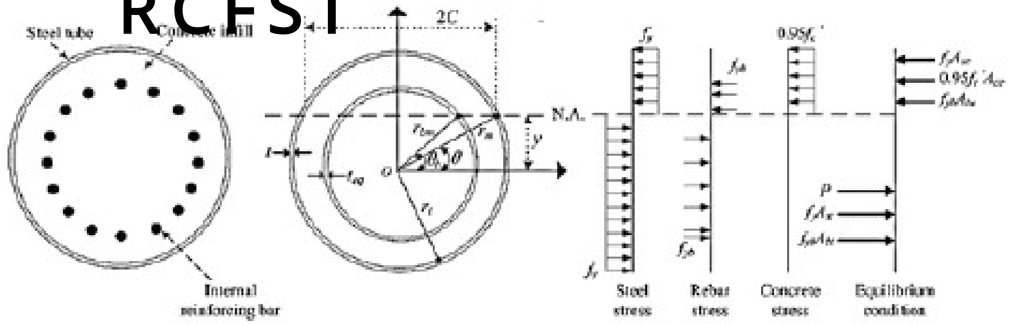
$$M_n(y) = \left(c(r_i^2 - y^2) - \frac{c^3}{3}\right) * 0.95f'_c + 4ct\frac{r_m^2}{r_i}F_y \quad (7.10.2\text{-}7)$$

$$c = r_i cos\theta \quad (7.10.2\text{-}8)$$

$$\theta = sin^{-1}\left(\frac{y}{r_m}\right) \quad (7.10.2\text{-}9)$$

$$r_m = r - \frac{t}{2} \quad (7.10.2\text{-}10)$$

Flexural - RCFST



$$P_n(y) = \left(\left(\frac{\pi}{2}-\theta\right) r_i^2 - yc\right) * 0.95f'_c - 4\theta t r_m F_y - t_b r_{bm}\left(4\theta_b F_{yb} + (\pi - 2\theta_b)0.95f'_c\right) \quad (7.10.2\text{-}11)$$

$$M_n(y) = \left(c(r_i^2 - y^2) - \frac{c^3}{3}\right) * 0.95f'_c + 4ct\frac{r_m^2}{r_i}F_y + 4t_b r_{bm} c_b (F_{yb} - 0.95f'_c) \quad (7.10.2\text{-}12)$$

$$c_b = r_b cos\theta_b \quad (7.10.2\text{-}13)$$

$$\theta_b = sin^{-1}\left(\frac{y}{r_{bm}}\right) \quad (7.10.2\text{-}14)$$

$$t_b = \frac{nA_b}{2\pi r_{bm}} \quad (7.10.2\text{-}15)$$

Axial

$$P_0 = 0.95f'_cA_c + F_{y,st}A_{st}$$

Shear Resistance

$$V_u = \phi V_n = \phi g_4\left[g_1(0.6f_y g_2 A_s) + 0.0316 g_3 A_c\sqrt{f'_c}\right]$$

Embedment

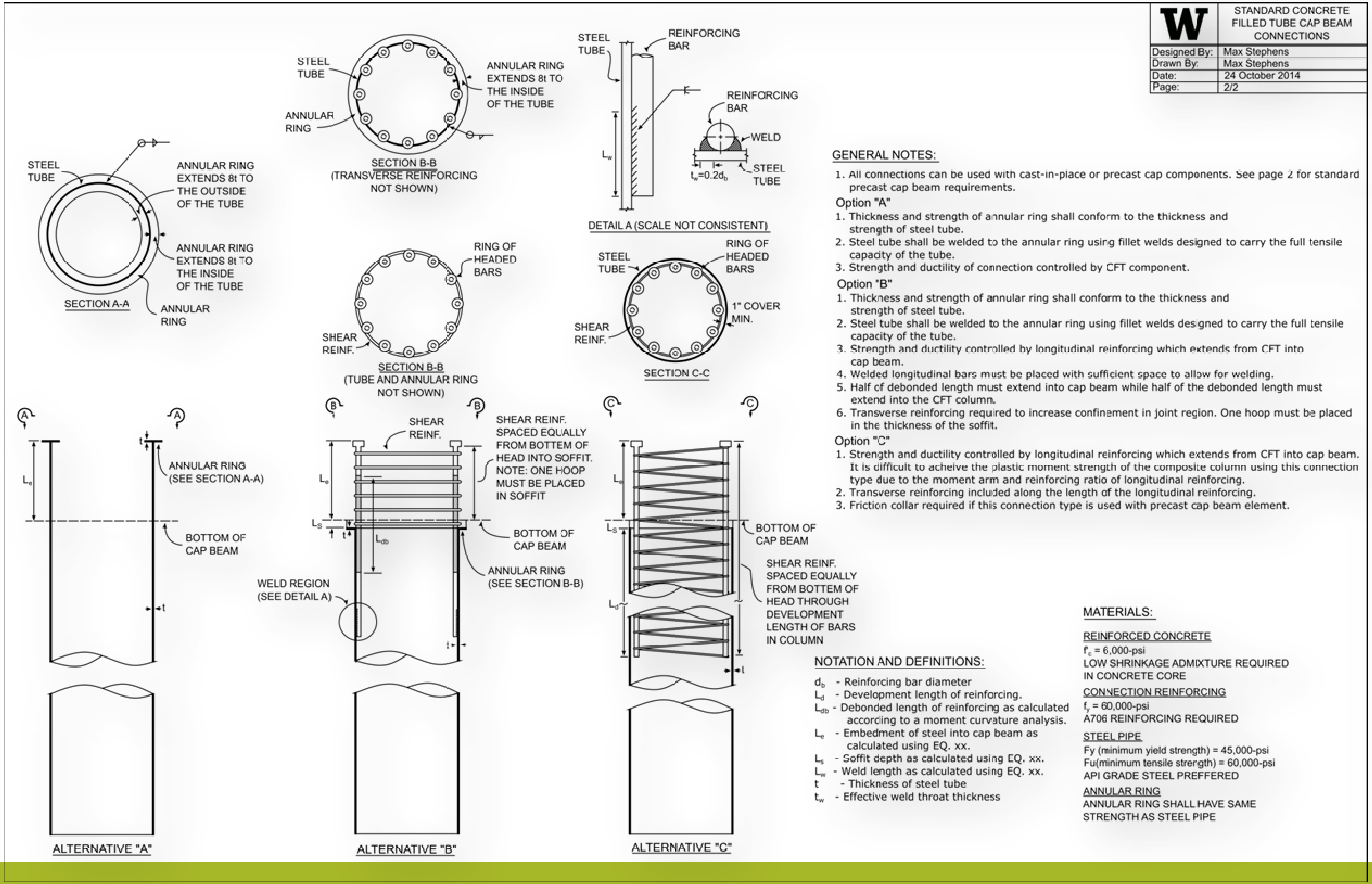
$$l_e \ge \sqrt{\frac{D_o^2}{4} + \frac{3.95DtF_y}{\sqrt{f'_{cf}}}} - \frac{D_o}{2}$$

Stiffnes

$$EI_{eff} = E_sI_s + C'E_cI_c$$

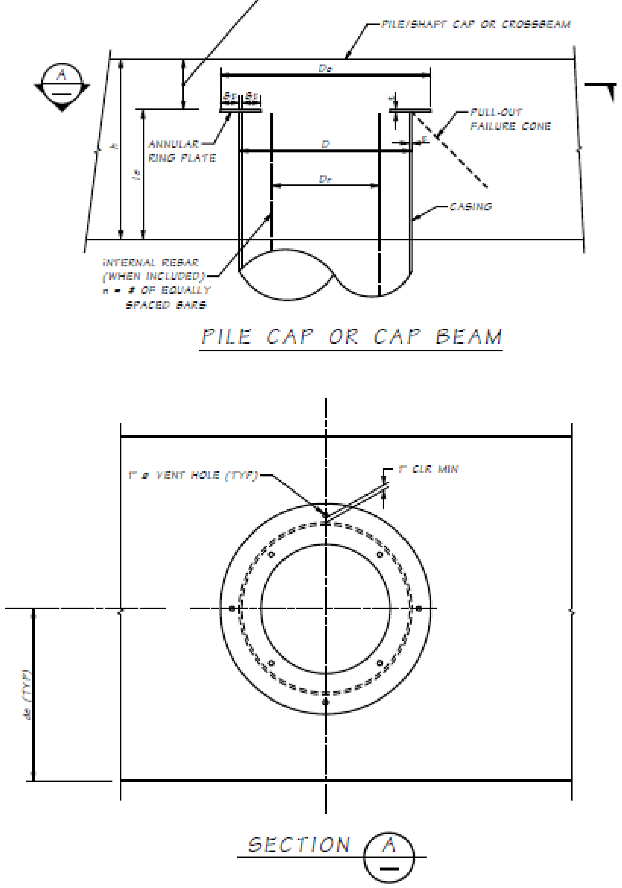
$$C' = 0.15 + \frac{P}{P_0} + \frac{A_s}{A_s+A_c} \le 0.9$$

CFST Standard Drawings

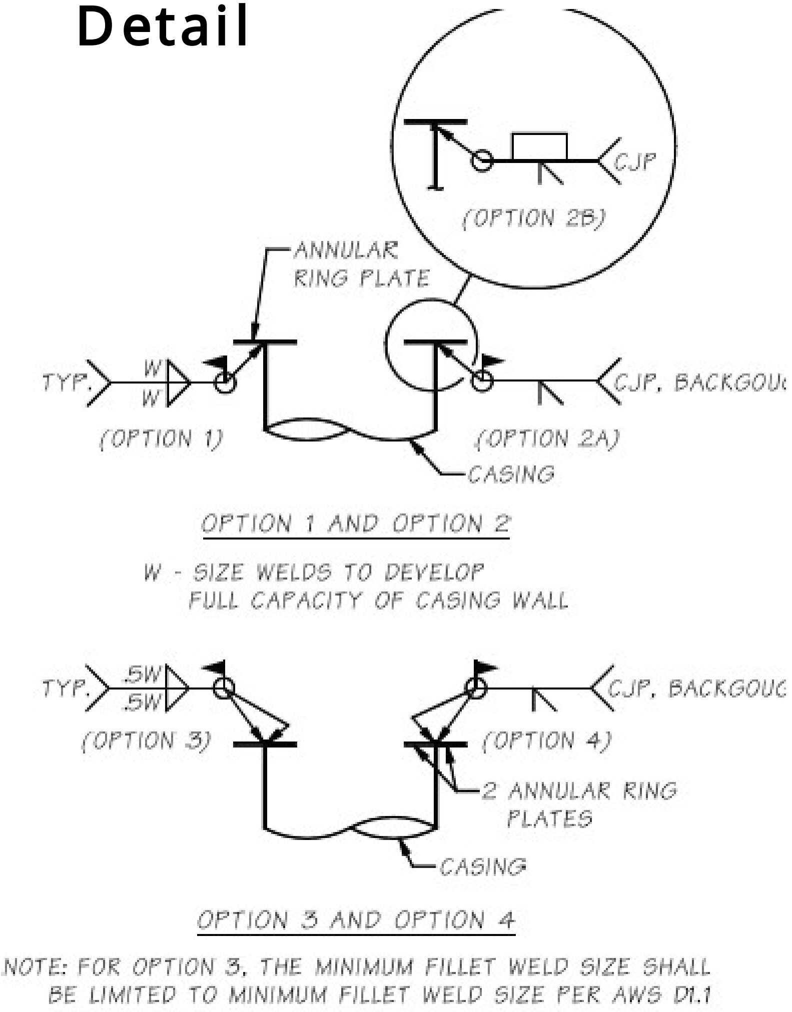


CFST Standard Details

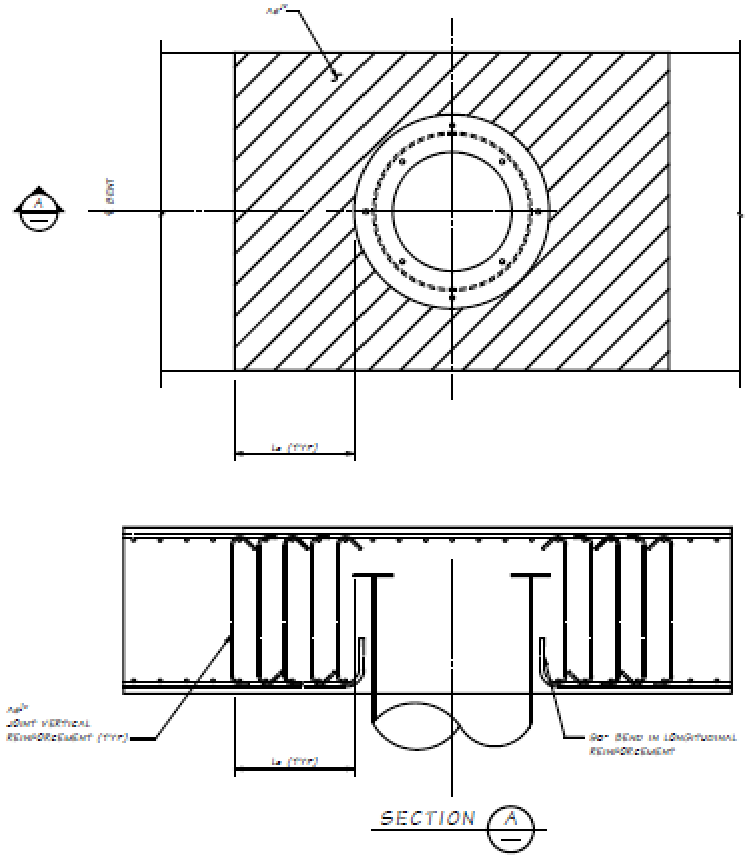
Annular Ring Connection



Annular Ring Weld Detail

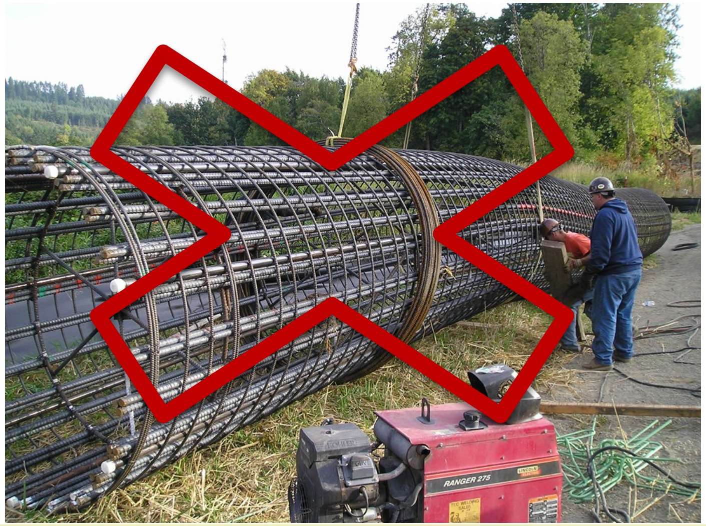


Reinf. Detail at Cap Connection



Eastbound Nalley Valley Highlights

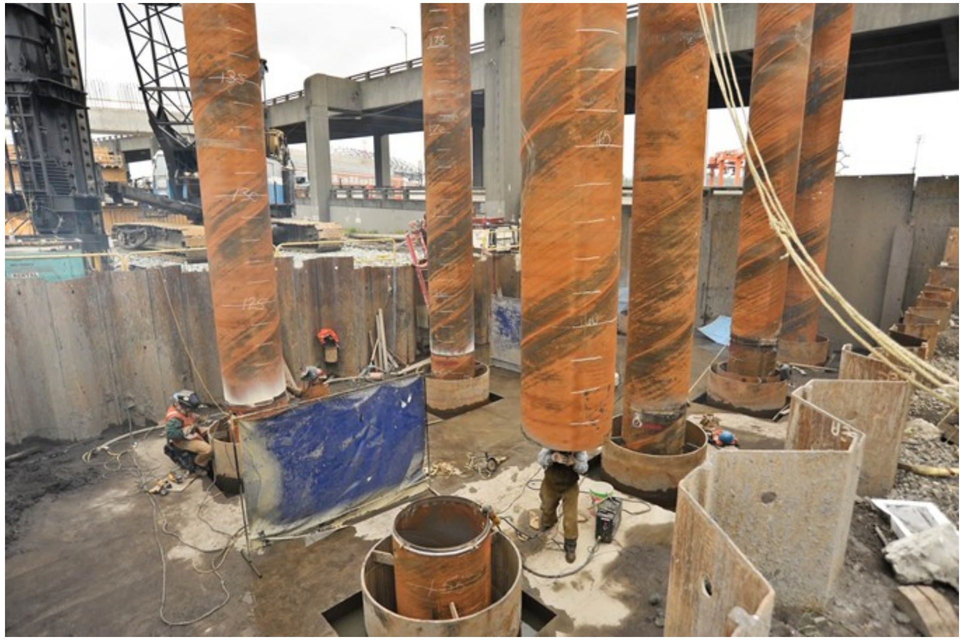
- ***ABC and Practical Design Solution***
- CFST Pile-Column 3 ft dia.
- CFST Ring Connection to Cap
- Driven Pile-Column (no Reinforcement)
- Smaller column and Cap

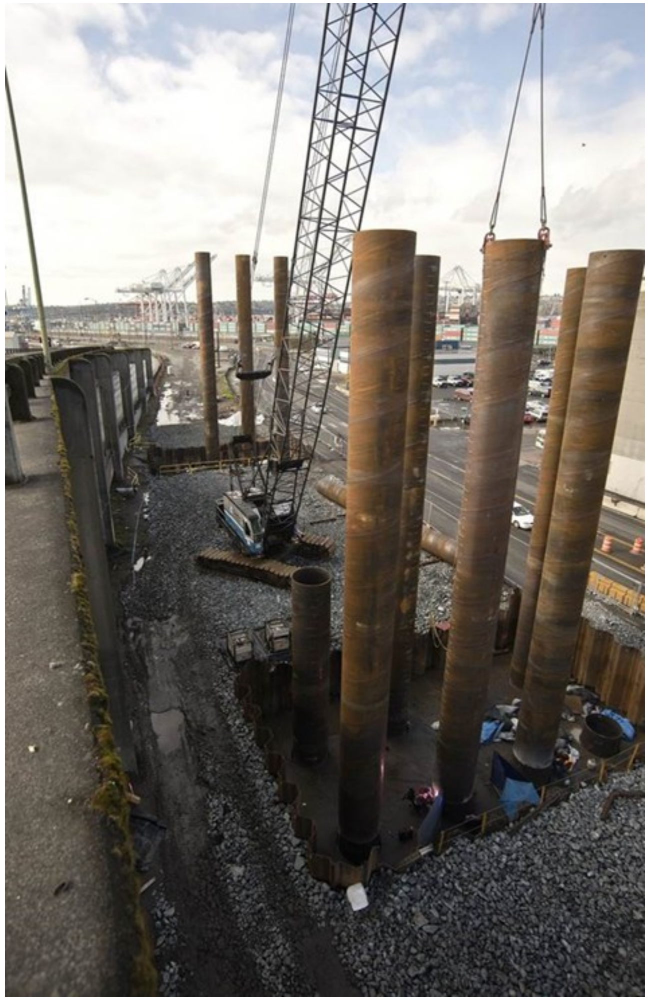


With CFST the Reinforcement could be eliminated

From Research to Practice - Implementation

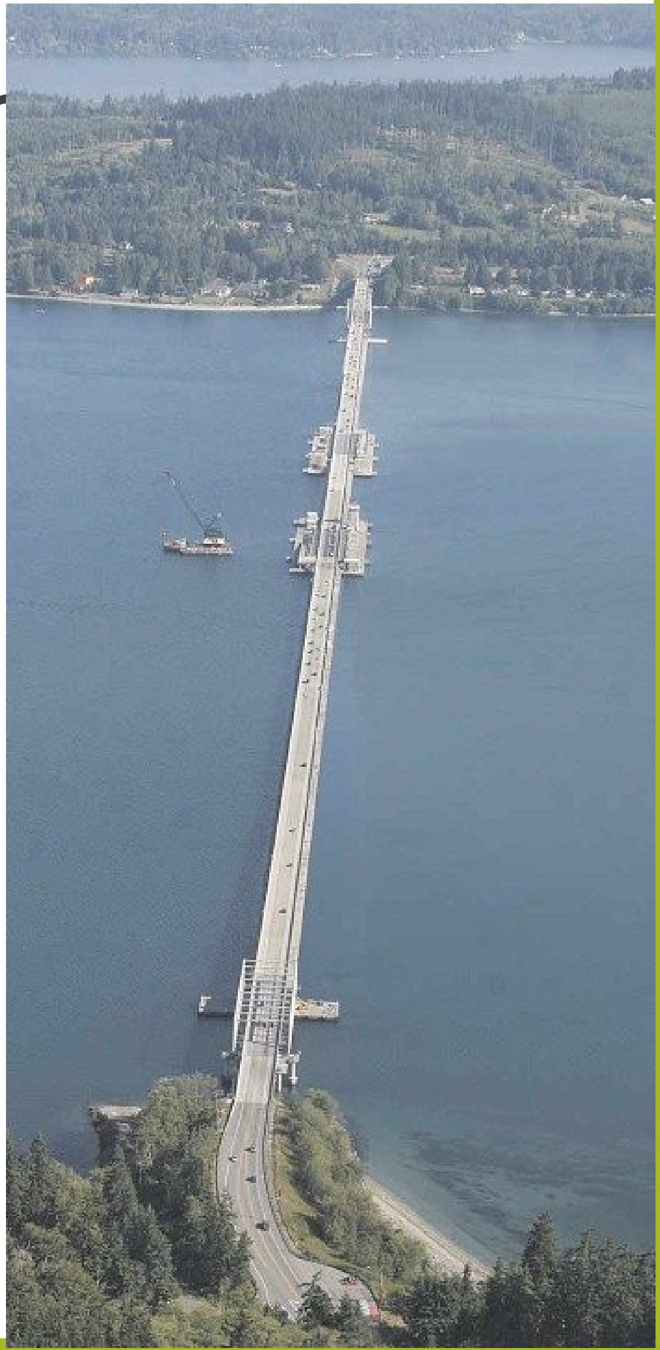
- Nooksack River -539/860W –
- AWV (Holgate to King Stage 2),
- Ebey Slough 539/860W
- Eastbound Nalley Valley
- SR 167 Puyallup River project – DB





HCB – WA Truss Bridge Applicatio

- Length – 7869 feet
  (Longest floating bridge over salt water)
- Floating portion – 6530 feet
- Max water depth – 340 feet
- Tidal Variation – 16.5 feet
- Center draw span opening– 600 feet



Transition Span Truss Fabrication Lifting and SPMT Erection

Concluding Remarks

- CFST bridge columns and connections are efficient relative to RC.
- Spiral weld provides mechanical interlock and superior bond capacity
- CFST material savings between 20 and 60%
- The embedded ring connection is capable of developing the full composite flexural strength of the CFST
- CFST is a viable solution for rapid construction of bridges
- Design expressions have been implemented in AASHTO and BDM

Thank You

References – Webinars, Papers, Reports, Design Policies

Chapter 7 *Substructure Design*

7.10 Concrete-Filled Steel Tubes

7.10.1 Scope

This section shall be taken to supersede LRFD-BDS and LRFD-SGS requirements for concrete-filled steel tubes (or pipes). The use of concrete-filled steel tubes (CFST) and reinforced concrete-filled steel tubes (RCFST) requires approval from the State Bridge Design Engineer when used as a ductile element as part of an earthquake-resisting system.

CFST and RCFST have been shown to offer strength and stiffness beyond a conventional reinforced concrete (RC) member. Recent research has shown that CFST members can sustain large cyclic drifts with minimal damage. The design methods herein regarding concrete-filled steel tubes are largely based on study, testing and recommendations compiled by the University of Washington (UW).

The concrete for CFST members tested at the UW was a low-shrinkage, self-consolidating concrete. The nominal concrete strengths were 6 ksi and 10 ksi. This represents structural concrete with a minimum specified strength of 4 ksi, and an expected strength 25 percent to 50 percent larger.

Prior CALTRANS and ARMY research programs studied fully restrained connections for CFST pier to foundation connections. Two of those connections are further discussed in this section and are shown in Figure 7.10.1-1. The first CFST-to-cap connection type involves an annular ring attached to the top of the CFST, and is partially embedded into the pile cap. This anchored connection resists flexural loading from the pile through strutting action to the bottom of the pile cap (resulting from the portion of tube of the CFST that is in tension) and the top of the pile cap (resulting from the portion of tube of the CFST column that in compression). Tests show this connection is both simple to construct and fully effective in transferring flexure. The current ACI procedure (ACI 318-2011) was recommended by the UW as a conservative approach to design against punching shear in this type of connection.

The second CFST-to-cap connection type requires a circular reinforcing cage with headed longitudinal bars that extend into the concrete cap. The CFST is discontinued just below the cap. This connection type is beneficial for plastic design in that it allows the designer some flexibility in the plastic demand that must be resisted by the cap. Refer to Section 7.10.4 for further discussion.

Transition connections between RC shafts and CFST shafts have not been tested, but considerable analysis has been performed at the UW. Models have been developed to predict the strength of RCFST members, and this RCFST behavior may be used to provide increased strength over a significant length of the pile relative to conventional RC construction. Overstrength factors for capacity protection design of adjacent members and joint shear design at connections were not addressed in the research.

Page 7-98 *WSDOT Bridge Design Manual M 23-50.22 September 2023*

Technical Report Documentation Page

1. Report No. ABC-UTC-2016-C1-UW02-Final	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle New Seismic-Resisting Connections for Concrete-Filled Tube Components In High-Speed Rail Systems		5. Report Date July 2020 6. Performing Organization Code
7. Author(s) Dawn Lehman (https://orcid.org/0000-0002-0823-1167) , Charles Roeder and Muzi Zhao		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Washington More Hall \Seattle WA 98195		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 69A3551747121
12. Sponsoring Organization Name and Address Accelerated Bridge Construction University Transportation Center Florida International University 10555 W. Flagler Street, EC 3680 Miami, FL 33174	US Department of Transportation Office of the Assistant Secretary for Research and Technology And Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 201590	13. Type of Report and Period Covered Final Report (January 2018- January 2020) 14. Sponsoring Agency Code
15. Supplementary Notes Visit www.abc-utc.fiu.edu for other ABC reports.		
16. Abstract In seismic design of transportation structures there are several competing demands that must be met: high strength and stiffness, large ductility, damage resistance and efficient construction. Prior research at the UW demonstrates that concrete-filled tubes (CFTs) can meet these competing demands. This research builds on the prior CFT research to develop connections specific for use in structural systems for high-speed rail (HSR) and other transportation system. While the FIU study focuses on the column-to-cap connection, this study will investigate a new, untested direct column-to-pile connection. This connection is critical to the structural performance and cost of the system, but few studies have focused on it, in particular for ABC. This study will advance design and construction of pile connections for HSR. The research investigated the connection for a bridge or HSR system response using advanced, nonlinear analysis methods. A thorough literature review identified types of connections and document their structural response; the UW team is working with the HSR team to identify one or more connections for further study. Using high-resolution finite element modeling, salient parameters of selected connections, including materials, geometry, and soil-structure interaction, are be studied. The results provide important initial guidelines for the connection design and seismic performance which will provide the basis for a future experimental research study to validate the work.		
17. Key Words Seismic, concrete filled steel tubes, bridges, substructures, accelerated bridge construction		18. Distribution Statement No restrictions.
19. Security Classification Unclassified.	20. Security Classification Unclassified.	21. No. of Pages 82 · 22. Price

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[Concrete Filled Steel Tube Bridge Pier Connections – An ABC Solution]

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