Seismic Resilient Substructures

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Concrete Filled Steel Tubes (CFST) Vertical Components in Transportation Structures

- CFSTs can be used as foundation elements (piles, shafts) and piers in elevated transportation structures (CFSTs are indicated in blue).
- Under extreme loads, inelastic deformation must be isolated to CFST component. Surrounding concrete components remain essentially elastic for large reversed cyclic displacement demands (Plastic hinges idealized in red).
- In ground hinging is NOT detrimental to post-earthquake performance.
CFST is a Composite Solution

Advantages
> Improved seismic performance, blast and collapse resistance
> Reduced size relative to RC
> Design eliminates labor and time associated with formwork and reinforcement
> Integration with precast superstructure. Lighter columns for placement.

Disadvantages
> Unknown deformation capacity
> Wide variation in design expressions
> No standard connections
Advantages of Using CFST Components in Seismic Regions

> Larger shear and flexural strength for a given cross section.
> Increased deformability prior to loss of lateral strength.
> Increased deformation corresponding to replacement (partial or full) of the component.
> Flexural response results in no damage prior to observable tube buckling, therefore repair of hinges (particularly in ground) is not needed.
> Components are never “shear critical” because shear is a ductile response mechanism.
Example of material and cost savings

<table>
<thead>
<tr>
<th></th>
<th>Original RC Pier</th>
<th>CFST Pier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Strength (ksi)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Steel Strength (ksi)</td>
<td>60.0</td>
<td>50.0</td>
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<tr>
<td>Diameter (in.)</td>
<td>72</td>
<td>50</td>
</tr>
<tr>
<td>Tube Thickness (in.)</td>
<td>-</td>
<td>0.625</td>
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<tr>
<td>Concrete Area (in.$^2$)</td>
<td>4072</td>
<td>1866</td>
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<tr>
<td>Steel Area (in.$^2$)</td>
<td>92</td>
<td>96.94</td>
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<tr>
<td>Weight/ft of Pier (kips)</td>
<td>4.4</td>
<td>2.2</td>
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<tr>
<td>Total Pier Weight (kips)</td>
<td>209</td>
<td>104</td>
</tr>
<tr>
<td>Difference in Pier Weight</td>
<td>50% Reduction</td>
<td></td>
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</table>
CFST System: Current study

- **Welded Dowel (WD)**
- **Embedded Ring (ER)**

**Cap Beam Connection (7)** (Caltrans)

**Deep-Foundation Connection and Soil-Structure Interaction** (Initiated)

**CFST Component:** (WSDOT, ARMY)
- Flexural Strength (6)
- Shear Strength (21)
- Deformation Capacity

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

- **Deck**
- **Column typ.**
- **Foundation typ.**
- **Cap Beam**
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)

Drift Ratio

Length (k)

Flexural Strength (k-in)

CFVST

HVST

CFVST Yield

CFVST Buckle

HVST Yield

HVST Buckle
Composite Action in CFST

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

4-Test Matrix

<table>
<thead>
<tr>
<th>Tube</th>
<th>Concrete</th>
</tr>
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<tbody>
<tr>
<td>Straight Seam</td>
<td>Conventional, Low Shrinkage</td>
</tr>
<tr>
<td>Spiral Weld</td>
<td>Conventional, Low Shrinkage</td>
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</tbody>
</table>

Instrumented 20 in. Dia. Tube

applied load

strain gage location typ.

t = ¼”

d = 19 ½”

welded wire gage location typ.

air gap to allow slip

rigid base support

concrete fill length = 60”

Applied Load 2.4m lb. UTM
Composite Action

Chemical Bond/Adhesion

Mechanical Bond In Spiral Weld Tube

Mechanical bond of concrete In spiral weld tube
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.
## Test Matrix

> Primary study parameters: 
> \( D/t \) ratio, \( a/d \), \( f'_c \), tail length, \( \rho_{\text{int}} \)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>D (in)</th>
<th>a/D</th>
<th>t (in)</th>
<th>a (in)</th>
<th>D/t</th>
<th>( f_{ym} ) (ksi)</th>
<th>( f'_{cm} ) (ksi)</th>
<th>N/N_0</th>
<th>Tube Type</th>
<th>Tail Length (in)</th>
<th>( \rho_{\text{int}} )</th>
<th>Interface</th>
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<td>SW</td>
<td>90</td>
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Testing Apparatus

Load beam
Load cradle
Cotton duck bearing pad
Machined radius
Elastomeric bearing
Steel base
Spherical bearing
CFT
Support cradle

Diagram:
- Shear Span
- Tail
- Constant Moment
- Testing Apparatus
Shear Response (Tested and Simulated with FEA)

Specimen 16
(a/D = 0.375, F_{ytm} = 56.8 ksi, f'_{cm} = 8.61 ksi, flex-shear)

Steel Tube Deformations

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

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

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

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

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

$V_c = 0.0316A_c\sqrt{f'_{c}}$ (ksi)

Testing demonstrated that engineers were underestimating the shear capacity by a factor of 2.5
Connection Tests
CFST Column to RC Component (CIP or Precast) Connections

Embedded Ring Connection

Reinforced Concrete Connection

Welded Dowel Connection

Weld Details

Section A-A
Response of Embedded Ring 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

buckling visible
initiation of tearing

①

②

③

④

① ② ③ ④
Performance of Debonded Welded Dowel 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
Performance of RC Connection

- north bar fracture
- northwest and northeast bar fracture
- Failure mode fracture of reinforcing bars (~8% drift)
- Strength limited by reinforcing ratio and moment arm
## CFT vs. RC Damage Comparison

<table>
<thead>
<tr>
<th></th>
<th>3% Drift</th>
<th>5% Drift</th>
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<tbody>
<tr>
<td>Reinforced Concrete</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Concrete Filled Tube</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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</table>
Pile-to-Caisson Connections for Transportation Systems
Current Research

Funded by FIU (through FHWA) and PEER Center

- Initial study to use high-resolution FEA to study different connections
- Testing to investigate use of ribs or other methods to mechanically enhance bond between RC or CFT pier and CFT pile
Research Plan: Direct Pile-to-Caisson Connection

Objective: Develop new, economical connections

> Testing will utilize large-scale specimens to investigate:
  – Type of tube: Straight seam or Spiral weld tube
  – Pier/pile diameter ratio
  – New, mechanical bond connectors: Rings, Tabs, Welds
    > Will investigate dimensions and spacing as function of bar size and pier/pile diameter ratio
  – D/t ratio

> Simulation of:
  – Full system response (including soil) to determine post-earthquake damage and functionality

> Results to be used for:
  – Cost comparison, improved seismic performance, implementation into codes and practice.
Historical WSDOT Practice
Recent Projects Using Steel Casing

2009

2012

2015

now
Nooksack River Bridge – 539/860W
Nooksack River Bridge – 539/860W
Puyallup River Bridge – 167/20E
CFST Design Equations

• General Dimensions

1. For members subjected to elastic forces:
   \[ \frac{D}{t} \leq 0.22 \frac{E}{F_y} \]

2. For members subjected to plastic forces:
   \[ \frac{D}{t} \leq 0.15 \frac{E}{F_y} \]

   Minimum wall thickness of 3/8”

AASHTO LRFD Equation:

\[ \frac{D}{t} \leq 0.15 \frac{E}{F_{yst}} \]
CFST Design Equations

- Flexural and Axial Resistance

\[ P_0 = 0.95f_f A_f + F_{y,at} A_{at} \]

\[ M_n(y) = \left( c(r_1^2 - y^2) - \frac{c^2}{3} \right) + 0.95f_f + 4c \frac{r_n}{r_1} F_y \]

- Similar to AASHTO

Figure 6.9.6.3.4-1
CFST Design Equations

- Shear Resistance

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

Where:
- \(A_x\) = cross-sectional area of the steel tube
- \(A_c\) = area of concrete within the steel tube
- \(g_1\) = coefficient for the shear capacity of the steel tube = 2.0
- \(g_2\) = coefficient for the effective shear area of steel tube = 0.5
- \(g_3\) = coefficient for the effect on concrete strength in shear due to confinement from the steel tube = 3.0
- \(g_4\) = coefficient for bond development between the concrete and steel tube = 1.0

(WSDOT BDM)

- AASHTO states that the shear resistance is the nominal shear resistance of the steel tube alone

\[
V_n = 0.5 F_{cr} A_g
\]

(6.12.1.2.3c-1)
Mukilteo Ferry Terminal

- Embedded flange/annular ring connection:
WSDOT BDM CFST Annular Ring Requirements

Plan View

1” diameter vent hole

\[ d_e \geq D \]
Mukilteo & Seattle Ferry Terminals

• Reinforced concrete connection:
Seattle Ferry Terminal

• Reinforced concrete connection:
CFST Design Equations

- **Annular Ring Connection**

\[
l_e \geq \sqrt{\frac{D_o^2}{4} + \frac{3.95DF_y}{\sqrt{f'_{cf}}} - \frac{D_o}{2}}
\]

To ensure full plastic behavior of the CFST, then the embedment length shall satisfy:

\[
l_e \geq \sqrt{\frac{D_o^2}{4} + \frac{5.27DF_y}{\sqrt{f'_{cf}}} - \frac{D_o}{2}}
\]

- **Reinforced Concrete Connection**

The minimum embedment length, \( l_e \), of the reinforcing cage into the cap shall satisfy:

\[
l_e \geq \frac{\psi_{eF_{yb}}}{2\sqrt{f'_{cf}}} d_b
\]

\[
l_e \geq \sqrt{\frac{D^2}{4} + \frac{2F_{yb}A_{st}}{\sqrt{f'_{cf}}} - \frac{D}{2}}
\]
WSDOT Steel Casing Specs

• Casing material per Standard Specifications for steel piling.

• WSDOT Special Provision required:
  – Welding per AWS D1.1 Structural Welding Code; including CVN testing
  – Weld and welders shall be qualified
  – VT and UT inspection of welds required
  – Cleaning of casing

• Design must account for corrosion.
  – Provide sacrificial thickness
WSDOT CFST Special Provisions
II. Corrosion

The design wall thickness for tubes shall be reduced for corrosion over a 75-year minimum design life. Minimum corrosion rates are specified below, except that the design thickness loss due to corrosion shall not be taken to be less than 1/64 inch.

- Soil embedded zone (undisturbed soil): 0.001 inch per year
- Soil embedded zone (fill or disturbed soils): 0.003 inch per year
- Immersed Zone (fresh water): 0.002 inch per year
- Immersed and Tidal Zone (salt water): 0.004 inch per year
- Splash Zone (salt water): 0.006 inch per year
- Atmospheric Zone: 0.004 inch per year

Thank You