PERFORMANCE LIMIT STATES OF RCFST DRILLED SHAFTS

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Outline

1. Introduction
2. Experimental Program
3. Analytical Studies
4. Performance Limit States
5. Conclusions
1. Introduction

Reinforced Concrete Filled Steel Tube (RCFST) Drilled Shafts

OMalley Bridge (Courtesy, AKDOT)

RCFST Cross Section

Pile-Column System Elevation

Seismic Force
Long. Direction

Moment Distribution

Max.
1. Introduction

Past Research: Brown et al. (2015)

- 12 Large-scale tests
- D/t ratios of 33 to 160
- D/t ratio
- Equilibrium and strain compatibility
1. Introduction

Past Research: Brown et al. (2015)

Progression of Buckling for “Thin Wall” Tubes
1. Introduction

Past Research: Brown et al. (2015)

Progression of Buckling for “Thick Wall” Tubes
1. Introduction

2. Experimental Program

3. Analytical Studies

4. Performance Limit States

5. Conclusions
2. Experimental Program

Test Setup

Soil Surcharge System (Soil Sandwich)
2. Experimental Program

Test Setup

100-kip, 70-in Stroke Hydraulic Actuator
RCFST Specimen
PT Bars
Hydraulic Jacks
RC Top Plates
2. Experimental Program

Test Setup

Optotrak Sensor
RCFST specimen
Top RC plates
Example: Test #11 – August 18, 2016

Test # 11

Reinforced Concrete Filled Steel Tube in Soil

- Outer diameter: \( D = 12.75 \text{ in} \)
- Tube Thickness: \( t = 0.129 \text{ in} \)
- Nominal D/t ratio: \( D/t = 95 \)
- Above ground height: \( L_1 = 7.24 \times D \)

Test Day: August 18, 2016
2. Experimental Program

Failure Mechanism

- Cracks parallel to rupture
- Rupture along half of section perimeter
- Local buckling
- Fracture initiation

SOUTH SIDE

TOP

BOTTOM

NORTH SIDE
2. Experimental Program

Tensile Strains Prior Fracture:

![Graph showing longitudinal tensile strain vs. D/t ratio]

- **2.5% limit**
- **X**: Brown et al. (2015)
- **△**: La/D = 5.5 (No Surcharge)
- **□**: La/D = 7.5 (No Surcharge)
- **○**: La/D = 5.5 (Surcharge = 46 kPa)
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Analytical Model: finite element, fiber-based approach (OpenSees)

Bridge Bent Example

Pinned-Head Shaft
Longitudinal

Fixed-Head Shaft
Transverse

RCFST

Cap Beam

Column

Pile

Fiber-based elements

p-y springs
Parametric Study: general considerations

Simulations on single RCFST specimens

Internal reinforcement: $\rho = 2\%$ and $\rho_v = 1\%$

Material properties:
- Concrete: $f_{ce} = 36.4$ MPa (5.2 ksi)
- Steel tube: $f_{yte} = 396$ MPa (57.2 ksi)
- Reinforcement: $f_{yre} = 462$ MPa (66 ksi)

Basic parameters:

<table>
<thead>
<tr>
<th>Head Fixity</th>
<th>Diameter (mm)</th>
<th>ALR (%)</th>
<th>D/t Ratio</th>
<th>La/D Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinned</td>
<td>610</td>
<td>5</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>Fixed</td>
<td>1,220</td>
<td>10</td>
<td>64</td>
<td>8</td>
</tr>
</tbody>
</table>

Performance Limit States of RCFST Drilled Shafts
3. Analytical Studies

**Parametric Study:** soil considerations

- Uniform soil layer
- Deep enough to achieve zero rotation at shaft tip
- Undrained conditions for clay – Matlock
- Dry or moist conditions for sand – API + Reese and Van Impe

**Soil parameters:**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Soil Profile</th>
<th>Soil Strength and Stiffness</th>
<th>Sand</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>γ (kN/m³)</td>
<td>Ø (°)</td>
<td>n_h (kN/m³)</td>
</tr>
<tr>
<td>Sand</td>
<td>Flexible</td>
<td>15.7</td>
<td>30</td>
<td>9500</td>
</tr>
<tr>
<td>Clay</td>
<td>Medium</td>
<td>17.3</td>
<td>35</td>
<td>27200</td>
</tr>
<tr>
<td></td>
<td>Stiff</td>
<td>18.9</td>
<td>40</td>
<td>61100</td>
</tr>
</tbody>
</table>
3. Analytical Studies

System Behavior

Eklutna River Bridge (echoak.com)
3. Analytical Studies

System Behavior: fixed-head RCFST
3. Analytical Studies

**System Behavior:** fixed-head RCFSTs

- Top plastic hinge
3. Analytical Studies

**System Behavior:** fixed-head RCFSTs

- Inground plastic hinge
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4. Performance Limit States

Equivalent Cantilever Plastic Hinge Model

Pinned-Head RCFSTs: Aguirre et al. 2017

\[ \Delta_y = c_1 \phi_y L_e^2 \]
\[ \Delta_p = \theta_p L_e = (\phi - \phi_y) L_p L_e \]
4. Performance Limit States

**Performance Limit States:** pinned-head shafts

**In-ground plastic hinge:** RCFST

\[
\phi_{LS, t} = \frac{\varepsilon_t}{D' - c}
\]

\[
D' = D - t
\]

**Note:** steel tube provides confinement and flexural strength

### Inground plastic hinge strain limits

<table>
<thead>
<tr>
<th>Strain</th>
<th>Serviceability</th>
<th>Damage Control</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\varepsilon_t = 0.021 - \frac{D}{9100t} \geq \varepsilon_{y(tube)} = 0.025
\]
4. Performance Limit States

Equivalent Cantilever Plastic Hinge Model

Fixed-Head RCFSTs: Aguirre et al. 2017

\[ \Delta_y = c_1 \phi_{y\text{ (top)}} L_e^2 \]

\[ \Delta_p = \theta_p \beta L_e = \left( \phi_{\text{(top)}} - \phi_{y\text{(top)}} \right) L_{p\text{(top)}} \beta L_e \]
4. Performance Limit States

Performance Limit States: fixed-head shafts

Top plastic hinge: RC

\[
\phi_{LS, t} = \frac{\varepsilon_t}{d - c}
\]

\[
d = D_{conc} - c_{bl} - \frac{d_{bl}}{2}
\]

Note: steel tube provides confinement only

Top plastic hinge strain limits (POLA, 2010)

<table>
<thead>
<tr>
<th>Strain</th>
<th>Performance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serviceability</td>
<td>Damage Control</td>
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<tr>
<td>Tension</td>
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Pinned-Head Shafts:

- Displacement capacity up to $\mu_3$ (even for $D/t = 95$)
- Controlling LS: **tube tensile strain of 2.5%**
- **PJP** spiral welds *negatively influence performance*
5. Conclusions

Fixed-Head Shafts:

- Displacement capacity up to $\mu_4$
- Controlled by **top plastic hinge only**
- Controlling LS: **bar tensile strain of 8%** (POLA, 2010)
- In-ground hinge has reserved capacity
Acknowledgements: