Ultra-High-Performance Concrete and Advanced Manufacturing Methods for Modular Construction

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Self-consolidating Ultra-High Performance Concrete (UHPC)

• A new type of UHPC which features a compressive strength higher than 150 MPa.

• Self-consolidating characteristics

• Desired for SMR modular construction
  • Facilitate rapid construction of steel plate-concrete (SC) beams and walls
  • Thinner and lighter modules
  • Withstands the harsh environments and mechanical loads anticipated during the service life of nuclear power plants
Previous Work and Gaps

• More than two decades of research work on high strength concrete with $f_{c'}$ more than 100 MPa.

• Direct application in nuclear power plant construction does not yet exist.

• Attaining compressive strengths over 150 MPa without special treatment such as high pressure curing, heat curing and extensive vibration, has remained a challenge

• Lack of standardized processing and quality control methods to produce robust HPC materials in large quantities has limited its application in factory prefabrication.
Experimental Program

• The UHPC material development approach integrates
  • Micromechanics theory
  • Hydration chemistry
  • Rheology tailoring methods
  • Time-dependent computed micro-tomography (Micro-CT)

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**Fundamental Principles for developing UHPC**

- Optimum packing density by selecting ingredients such that all the voids are densely packed.
- A low w/b ratio.
- Pozzolanic ingredients (e.g. fly ash) with spherical particles to improve workability.
- Application of round quartz crystalline silica as high strength aggregates.
- Achieving an optimum amount of HRWR.
Materials

- The UHPC developed in this study contains cement, silica fume, fly ash, fine sand, aggregates, fine grain silica, high-range water reducer (HRWR) and water.

- **Cement:** Type I Portland cement (ASTM C150) and Class-H cement
  - Class-H has zero Calcium Aluminate (C₃A) content
  - Class-H has coarser particle size compared to Type I ordinary Portland cement
  - Type I ordinary Portland cement has higher (C₅S) content

- **Silica Fume:** regular densified silica fume (DSF), undensified silica fume (USF) and white silica fume (WSF)

- **Fly ash:** Low calcium Type-F

- **Aggregates:** round quartz crystalline silica that is chemically inert with >99.7% silicon dioxide content.
  - Unground silica passing the sieve size of 850 micron is used as coarse sand
  - Ground silica (GS) passing the sieve size of 212 micron is used as fine sand

- **Fine grain silica (FGS):** Median diameter of the fine ground silica is 1.6 micron, and 96% of the powder has a diameter smaller than 5 micron

- **HRWR (High-range water reducer):** Three different types of Polycarboxylate-based HRWR that are commercially available in the U.S. were investigated, with different amounts of dosage
Experimental Results (Continued)

Particle size distribution of mixtures with 0.25 silica fume, 0.25 FGS, and (a) 5% fly ash, (b) 0% fly ash to cement ratio by weight, compared with PSD models.
Developed Ultra-High Performance Concrete

- 150 MPa (22 ksi) compressive strength
- Self-consolidating property
- High durability
- No special (curing) treatment required

Optimum mixture proportions:

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>1</td>
</tr>
<tr>
<td>Silica Fume (Undensified)</td>
<td>0.200</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>0.050</td>
</tr>
<tr>
<td>Silica Powder</td>
<td>0.200</td>
</tr>
<tr>
<td>w/b</td>
<td>0.210</td>
</tr>
<tr>
<td>Superplasticizer (HRWR)</td>
<td>0.060</td>
</tr>
<tr>
<td>Sand 1 (0.212mm)</td>
<td>0.28</td>
</tr>
<tr>
<td>Sand 2 (0.85mm)</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Test Results

<table>
<thead>
<tr>
<th>Spread Value (cm)</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c'$ (ksi)</td>
<td>23.24</td>
</tr>
</tbody>
</table>
UHPC Microstructure Characterization

UHPC

Conventional Mortar

Calculated porosity: 6.91%
Calculated porosity: 14.57%
Self-Consolidating Characterization

• Small scale, 5 Qt. capacity

ASTM C230
ASTM C1437

• Large scale, 11 ft$^3$ capacity

ASTM C143, ASTM C1611
Self-consolidating UHPC

V-funnel test

Passing ability test (J-ring)

During casting of Steel-plate UHPC beam, good flowability demonstrated without vibration
Self-consolidating UHPC (Continued)

- UHPC self-consolidating properties ($f'_c = 22.34$ ksi)

<table>
<thead>
<tr>
<th>Test</th>
<th>UHPC</th>
<th>EFNARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump flow by Abram’s cone</td>
<td>77 cm</td>
<td>65-85 cm</td>
</tr>
<tr>
<td>$T_{50cm}$ slump flow</td>
<td>4 sec</td>
<td>2-5 sec</td>
</tr>
<tr>
<td>J-ring, height difference</td>
<td>0-2 mm</td>
<td>0-10 mm</td>
</tr>
<tr>
<td>V-funnel</td>
<td>10 sec</td>
<td>6-12 sec</td>
</tr>
<tr>
<td>V-funnel increase time at $T_{5min}$</td>
<td>7 sec</td>
<td>3 sec</td>
</tr>
<tr>
<td>J-ring, spread difference</td>
<td>0 cm</td>
<td>N/A</td>
</tr>
<tr>
<td>Visual stability index (ASTM C1611)</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Air content</td>
<td>4.8%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: EFNARC: The European Guidelines for Self-Compacting Concrete
Structural Behavior of S-UHPC Modules

• Integrity between two distinct materials (UHPC and steel-plate) is essential.

• Integrity through effective shear transfer mechanism

• Shear transfer mechanisms:
  a) Tie bars (Cross Ties)
  b) Shear studs
  c) J-hook
  d) Profiled and surfaced preparation
Design Codes and Guidelines for minimum shear reinforcement ratio

- No technical document available for design of cross ties.
- Designers use four codes commonly used in design of SC structures: (a) ACI 349 Code (2013), (b) Model Code, (c) Design guide by Steel Construction Institute (Narayan et al. 1994), (d) JAEG (2005)
- Design guidelines (c) and (d) do not specify the minimum shear reinforcement ratio.
- ACI 349 Code adopts ACI 318 Code which is for RC members
- Minimum shear reinforcement ratio for reinforced concrete (RC) specified by ACI 318 Code $\rho_{t,ACI}$ is:

$$\rho_{t,ACI} = 0.75 \frac{\sqrt{f_c}}{f_{yt}} \geq 50 \frac{1}{f_{yt}}$$

- The fib Model Code 2010 requires the minimum shear reinforcement ratio $\rho_{t,fib}$ for RC members, as specified by Eq. 8 (fib 2010; Sigrist et al. 2013).

$$\rho_{t,fib} = 0.08 \frac{\sqrt{f_{ck}}}{f_{yk}} (f_{ck} \text{ and } f_{yk} \text{ in MPa})$$
Experimental Program (S-UHPC Beams)

• A strip of nuclear containment is taken out as the study specimen and it is scaled down by a factor of 4/9.

Two SC beams (S-UHPC1 and S-UHPC2) were tested. The length, width, and depth of each SC beam are 4572 mm (15.0 ft.), 304 mm (12.0 in.), and 406 mm (16.0 in.), respectively. The only test parameter was the Cross ties ratio ($\rho_{t,\text{test}}$).
Test Setup

Loading arrangement

Setup of LVDT
Instrumentation

Typical SC beam and arrangement of strain gauges and SAs
## Experimental Matrix

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$s_{tie}$ (cm)</th>
<th>$f'_c$ (MPa)</th>
<th>$\rho_{t,ACI}$ (%)</th>
<th>$\rho_{t,test}$ (%)</th>
<th>$\rho_{t,test}/\rho_{t,ACI}$</th>
<th>$F_{peak.}$ (kN)</th>
<th>Ductility $\delta^+$</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-UHPC-1 South</td>
<td>25.4</td>
<td>154.0</td>
<td>0.170</td>
<td>0.184</td>
<td>1.08</td>
<td>220.5</td>
<td>1.003</td>
<td>Ductile</td>
</tr>
<tr>
<td>S-UHPC-2 South</td>
<td>17.1</td>
<td>153.89</td>
<td>0.170</td>
<td>0.277</td>
<td>1.63</td>
<td>345.6</td>
<td>2.650</td>
<td>Ductile</td>
</tr>
<tr>
<td>S-UHPC-2 North</td>
<td>14.6</td>
<td>153.89</td>
<td>0.170</td>
<td>0.323</td>
<td>1.90</td>
<td>381.7</td>
<td>4.010</td>
<td>Ductile</td>
</tr>
</tbody>
</table>

### Experimental matrix, strength, and failure mode

Casting of S-UHPC beam
Results: S-UHPC-1 South

Shear-force deflection curve

Crack Pattern at Failure Mode
S-UHPC-2 (North)

Shear-force deflection curve

Crack Pattern at Failure Mode

Spalling of concrete
S-UHPC-2 (South)

Shear-force deflection curve

Crack Pattern at Failure Mode
(SC Beams) as reference of S-UHPC beams
• To evaluate the effect of concrete strength on the structural performance of Steel plate Concrete (SC) beams with conventional concrete, six SC beams were tested

• Same size as S-UHPC beams

Elevation view of SC beam specimens

Dimensions of SC beam specimens (unit: inch)
Experimental Matrix

Normal strength concrete

<table>
<thead>
<tr>
<th>Specimen</th>
<th>a/d (in.)</th>
<th>$S_{tie}$ (ksi)</th>
<th>$f_c'$ (ksi)</th>
<th>$\rho_{t,ACI}$ (%)</th>
<th>$\rho_{t,test}$ (%)</th>
<th>$\rho_{t,test}/\rho_{t,ACI}$</th>
<th>$F_{ult.}$ (kips)</th>
<th>Ductility</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1 north</td>
<td>2.5</td>
<td>8.00</td>
<td>8.13</td>
<td>0.111</td>
<td>0.102</td>
<td>0.92</td>
<td>27.4</td>
<td>———</td>
<td>Brittle</td>
</tr>
<tr>
<td>SC1 south</td>
<td>2.5</td>
<td>8.00</td>
<td>8.13</td>
<td>0.111</td>
<td>0.102</td>
<td>0.92</td>
<td>26.1</td>
<td>———</td>
<td>Brittle</td>
</tr>
<tr>
<td>SC2 south</td>
<td>2.5</td>
<td>7.00</td>
<td>5.80</td>
<td>0.094</td>
<td>0.117</td>
<td>1.25</td>
<td>26.9</td>
<td>0.730</td>
<td>Brittle</td>
</tr>
<tr>
<td>SC3 north</td>
<td>2.5</td>
<td>6.00</td>
<td>5.82</td>
<td>0.094</td>
<td>0.137</td>
<td>1.45</td>
<td>31.7</td>
<td>1.17</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC3 south</td>
<td>2.5</td>
<td>6.00</td>
<td>5.82</td>
<td>0.094</td>
<td>0.137</td>
<td>1.45</td>
<td>34.9</td>
<td>1.79</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC4 north</td>
<td>2.5</td>
<td>5.00</td>
<td>7.37</td>
<td>0.106</td>
<td>0.164</td>
<td>1.54</td>
<td>42.7</td>
<td>1.58</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC4 south</td>
<td>2.5</td>
<td>4.00</td>
<td>7.37</td>
<td>0.106</td>
<td>0.205</td>
<td>1.93</td>
<td>53.0</td>
<td>1.65</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC5 south</td>
<td>1.5</td>
<td>6.00</td>
<td>8.00</td>
<td>0.110</td>
<td>0.137</td>
<td>1.25</td>
<td>55.9</td>
<td>1.43</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC5 north</td>
<td>1.5</td>
<td>5.00</td>
<td>8.00</td>
<td>0.110</td>
<td>0.164</td>
<td>1.49</td>
<td>64.7</td>
<td>1.48</td>
<td>Ductile</td>
</tr>
<tr>
<td>SC6</td>
<td>5.2</td>
<td>6.00</td>
<td>8.00</td>
<td>0.110</td>
<td>0.137</td>
<td>1.25</td>
<td>29.3</td>
<td>1.99</td>
<td>Ductile</td>
</tr>
</tbody>
</table>
Test Results

Specimen SC1

Figure Shear force-deflection curves of SC1

(a) North side

(b) South side

1: Crack (flexural) 2: Crack in north shear span 3: Peak point

1: Crack flexural 2: Crack in the south shear span 3: Crack in the south shear span 4: Ultimate point 5: Lost capacity
Specimen SC2 South

Shear force-deflection curve of SC2 South

1: Crack (flexural) 2: Bond slip 3: Crack in south shear span 4: Ultimate point 5: SM1 yielded
Specimen SC2 South (Continued)

Crack pattern and debonding of SC2 south after test
Specimen SC3
(Cross tie 45% more than that specified in ACI code)

Shear force-deflection curves of SC3

(a) SC3 north
(b) SC3 south
Specimen SC4

Shear force-deflection curves of SC4

(a) SC4 north of cross ties spacing at 5 in. (b) SC4 south of cross ties spacing at 4 in.
Specimen SC4 (Continued)

Critical shear crack and bond slip of SC4 north
Specimen SC5

(a) SC5 south of cross ties spacing at 6 in.
(b) SC5 north of cross ties spacing at 5 in.

Shear force-deflection curves of SC5
Specimen SC6

Shear force-deflection curve of SC6

1: 1st crack (flex.)  2: 2nd crack (flex.)  3: 3rd crack (flex.)
4: 4th crack (flex.)  5: Bottom steel plate yielded
6: ST2 yielded    7: Visible bond slip  8: Ultimate point
Bond slip detection between steel plate and concrete using smart aggregates

• Inaccessibility and invisibility of the interface.

• Piezoceramic-based Smart Aggregates (SAs)
  • Proved applicable to health monitoring and damage detection.
Detection principles

Developed smart aggregate based active sensing approach to detect bond slip between steel plate and concrete
Test details

Two selected SC beams

<table>
<thead>
<tr>
<th>Specimen</th>
<th>a/d</th>
<th>S\text{tie}^# (in.)</th>
<th>f'_c * (ksi)</th>
<th>F_{ult.} ** (kips)</th>
<th>\rho_{t,ACI} (%)</th>
<th>\rho_{t,test} (%)</th>
<th>\rho_{t,test} / \rho_{t,ACI}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1 North</td>
<td>2.50</td>
<td>8.00</td>
<td>8.13</td>
<td>27.4</td>
<td>0.111</td>
<td>0.102</td>
<td>0.92</td>
</tr>
<tr>
<td>SC1 South</td>
<td>2.50</td>
<td>8.00</td>
<td>8.13</td>
<td>26.1</td>
<td>0.111</td>
<td>0.102</td>
<td>0.92</td>
</tr>
<tr>
<td>SC4 North</td>
<td>2.50</td>
<td>5.00</td>
<td>7.37</td>
<td>42.7</td>
<td>0.106</td>
<td>0.164</td>
<td>1.54</td>
</tr>
<tr>
<td>SC4 South</td>
<td>2.50</td>
<td>4.00</td>
<td>7.37</td>
<td>53.0</td>
<td>0.106</td>
<td>0.205</td>
<td>1.93</td>
</tr>
</tbody>
</table>

\# S_{tie} = the spacing of cross ties.

* f'_c = the concrete compression strength from concrete cylinders (152.4 mm × 304.8 mm).

** F_{ult.} = ultimate shear capacity
Installation and location of SAs

Figure Arrangement of SAs in SC1 (unit: inch)

Figure Arrangement of SAs in SC4 (unit: inch)
**Apparatus**

- Function Generator
- Power Amplifier
- Data Acquisition board

[Diagram of apparatus with labeled components: Function generator, Power amplifier, Actuator, Sensor, Acquisition board, Laptop with supporting software.]
Apparatus Setup

SC1 North

SC1 South

Function generator
DAQ board
Power amplifier
Laptop
Sample Test Result (SC4 North)

Bond slip and crack patterns in SC2 north after test
SC4 North

Fig. 32. Shear force-time curves of SC4 north

Figure Damage indexes of sensors installed on SC4 north
Digital Image Correlation-Based Debonding Detection

Instrumentation

DIC system setup, (a) Schematic illustration, (b) Pictorial illustration
Test Setup

The results from DIC is used to compute:

1. Beam deflection
2. Strain contour map
3. Point-to-point average strain
4. Crack opening
5. Steel concrete debonding
6. Final localization with $\pm 5 \ \mu m$ accuracy
Discussion on Debonding

High-resolution images (a) and DIC image (f) of SC3 at north-end corresponding to point 3 in Figs. (c) and (d). (b) and (g) right after point 3 in Figs. (c) and (d).
Discussion on Debonding (Continued)

DIC images of SC3 at north–east side (a–g), showing major strain map with increasing the load.

1. DIC technique is capable of measuring concrete steel-plate bond slip and debonding.
2. Steel–plate concrete in SC beam has perfect bond until the occurrence of the first crack.
Calibrated Finite Element Model for S-UHPC Beam
\[ \Delta L = 0.5d \]

\[ P \]

\[ \text{Steel Plate (Truss Element)} \]

\[ t_s = \frac{3}{16}'' \]

\[ \text{Reinforced Concrete (CSMM Membrane Element)} \]

\[ d = \frac{1}{16}'' \]

\[ b = 12'' \]

\[ L = 164'' \]

\[ a = 2.5d \]

\[ d = 16'' \]

**Finite Element Mesh**

**Cross Section A-A**
Constitutive Model for Concrete

In Compression

\[ f_{cr} = 0.31 \sqrt{f_c'} \text{ (MPa)} \]

\[ \varepsilon_{cr} = 0.00008 \]

In Tension

\[ f_c = f_{cr} \left( \frac{\varepsilon_{cr}}{\varepsilon_c} \right)^{0.4} \]

\[ f_c' \]

= compressive strength

\[ \varepsilon_0 \]

= strain at maximum stress

\[ \zeta \]

= softening coefficient

\[ \zeta = \left( \frac{5.8}{\sqrt{f_c' \text{ (MPa)}}} \right) \left( \frac{1}{\sqrt{1 + 400 \varepsilon_r}} \right) \left( 1 - \left| \frac{\beta}{24} \right| \right) \leq 0.9 \]
Calibration of the maximum bond strength between concrete and steel plate

Equilibrium equation:

\[ V_{\text{max}} \cdot a = jd \cdot T_{\text{max}} \quad \text{(Eq. 1)} \]
\[ T_{\text{max}} = \left( K_1 + 0.8 \rho_{sv} f_{yy} \right) b (z + a) \quad \text{(Eq. 2)} \]

From Eq. (1) & (2) gives:

\[ K_1 = \frac{V_{\text{max}} a}{jdb (z + a) - 0.8 \rho_{sv} f_{yy}} \quad \text{(Eq. 3)} \]

\( K_1 \) = the maximum bond strength between concrete and steel plate
Calibration (Continued)

### S-UHPC Beams

<table>
<thead>
<tr>
<th>Specimen</th>
<th>b (mm)</th>
<th>t (mm)</th>
<th>a/d</th>
<th>ρ (%)</th>
<th>fy (MPa)</th>
<th>fc (MPa)</th>
<th>jd (mm)</th>
<th>Vmax (kN)</th>
<th>0.8ρfy (MPa)</th>
<th>T (kN)</th>
<th>K1 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-UHPC1 South</td>
<td>305</td>
<td>6.350</td>
<td>2.5</td>
<td>0.184</td>
<td>413</td>
<td>154</td>
<td>402</td>
<td>220.47</td>
<td>0.608</td>
<td>612.4</td>
<td>1.060</td>
</tr>
<tr>
<td>S-UHPC2 South</td>
<td>305</td>
<td>6.350</td>
<td>2.5</td>
<td>0.274</td>
<td>413</td>
<td>154</td>
<td>402</td>
<td>345.66</td>
<td>0.905</td>
<td>960.2</td>
<td>1.709</td>
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<tr>
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<td>305</td>
<td>6.350</td>
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<td>0.321</td>
<td>413</td>
<td>154</td>
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<td>382.21</td>
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### SC Beams

<table>
<thead>
<tr>
<th>Specimen</th>
<th>b (mm)</th>
<th>t (mm)</th>
<th>a/d</th>
<th>ρ (%)</th>
<th>fy (MPa)</th>
<th>fc (MPa)</th>
<th>jd (mm)</th>
<th>Vmax (kN)</th>
<th>0.8ρfy (MPa)</th>
<th>T (kN)</th>
<th>K1 (MPa)</th>
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<tbody>
<tr>
<td>SC1 North</td>
<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.102</td>
<td>413</td>
<td>56</td>
<td>402</td>
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<tr>
<td>SC1 South</td>
<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.102</td>
<td>413</td>
<td>56</td>
<td>402</td>
<td>116.37</td>
<td>0.337</td>
<td>323.3</td>
<td>0.543</td>
</tr>
<tr>
<td>SC3 North</td>
<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.137</td>
<td>413</td>
<td>40</td>
<td>402</td>
<td>155.35</td>
<td>0.453</td>
<td>431.5</td>
<td>0.722</td>
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<tr>
<td>SC3 South</td>
<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.137</td>
<td>413</td>
<td>40</td>
<td>402</td>
<td>143.45</td>
<td>0.453</td>
<td>398.5</td>
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<tr>
<td>SC4 North</td>
<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.164</td>
<td>413</td>
<td>51</td>
<td>402</td>
<td>190.04</td>
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<td>527.9</td>
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<td>305</td>
<td>4.763</td>
<td>2.5</td>
<td>0.205</td>
<td>413</td>
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<td>235.69</td>
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<td>SC5 South</td>
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<td>1.5</td>
<td>0.137</td>
<td>413</td>
<td>55</td>
<td>402</td>
<td>248.77</td>
<td>0.453</td>
<td>414.6</td>
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<td>1.5</td>
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<td>413</td>
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<td>0.453</td>
<td>737.1</td>
<td>0.604</td>
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Calibrated Constitutive Model for Slip Steel Plate

\[ f_{yslip} = \frac{(z + a)}{t} \left( 0.8 \rho_{sv} f_{yv} + K_1 \right) \]

\[ E_{slip} = E_s \left( 0.89 - 0.073 \frac{a}{d} \right) \]

- \( f_{yslip} \) = yielding stress of the slip steel plate
- \( E_{slip} \) = elastic modulus of the slip steel plate
- \( K_1 \) = the maximum bond strength between concrete and steel plate

\[ K_1 = 0.89 \rho_v \sqrt{f_c} \left( \frac{a}{d} \right)^{-0.7} \]

- \( S \)-UHPC Beams
- \( SC \) Beams

- \( a \) = shear span of the beam
- \( d \) = depth of the beam
- \( z \) = distance from center of support to the end beam
- \( \rho_{sv} \) = percentage of transverse steel bar
- \( f_{yv} \) = yielding stress of transverse steel bar
- \( \lambda \) = deterioration rate
Comparison of Analytical Results with Experimental Outcomes
Comparison (Continued)

S-UHPC-1 (South)

S-UHPC-2 (North)

S-UHPC-2 (South)
Comparison (Continued)
Comparison (Continued)

Beam SC4 (North)

Beam SC5 (North)

Beam SC4 (South)

Beam SC5 (South)
Conclusions

• The developed UHPC material can be robustly processed at large scale with commercially available ingredients and equipment.

• It meets self-consolidating and compressive strength requirements.

• Particle size distribution for optimum packing density, the physical and chemical parameters of ingredients, and the resulting microstructure after hydration are considered essential for the design of self-consolidating UHPC.

• Brittle failure if insufficient cross ties are provided. Results show that cross ties can effectively improve interfacial bond condition, ductility and shear strength of SC and S-UHPC beams.
Conclusions

- For S-UHPC Beams: 10% more than that specified in ACI code when $a/d=2.5$.

- For SC Beams:

$$\rho_{t,min} = 1.45 \times \rho_{t,ACI} \quad \text{for } 2.0 < a/d < 4.0, \text{ or}$$

$$\rho_{t,min} = 1.25 \times \rho_{t,ACI} \quad \text{for } a/d \leq 2.0 \text{ and } a/d \geq 4.0.$$  

- DIC technique is capable of measuring concrete steel-plate bond slip and debonding.

- PZT smart aggregates provide early warning about the debonding of the steel plate and the concrete in SC beams before structural failure happens.

- The bond slip based stress-strain curve of steel plate is developed that can be used to accurately predict the shear force deflection relationship of SC beams.
Thank you.