Outline

• Introduction to Precast Segments
• Strength Design Method for Segments (ULS):
  – Governing Load Cases, Load Factors & Load Combinations
• Methods of Analysis for Governing Load Cases
• Design with Fibers as an Alternative to Reinforcing Bars
• Strength Design Example for FRC Tunnel Segment
• Future Materials to be Added to Document
• Conclusions
Precast Segmental Tunnel Lining

- Serves as both initial ground support & final lining in modern TBM tunnels
- Providing the required operational cross-section
- Controlling groundwater inflow
Governing Loads Cases

• **Production and transient load cases:**
  Stripping (demolding), storage, transportation and handling

• **Construction load cases:**
  TBM thrust jack forces, tail skin grouting, secondary (localized) grouting

• **Final service load cases:**
  Ground, groundwater and surcharge loads, longitudinal joint bursting, additional distortion, other specific loads
Load and Resistance Factor Design (LRFD)

- **Load factors:** 1.25 - 1.5 depends on nature of applied loads
- **Strength reduction factors:** 0.7 except bearing (0.65)
- **Load combinations:**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Required Strength (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load case 1: stripping</td>
<td>$U = 1.4w$</td>
</tr>
<tr>
<td>Load case 2: storage</td>
<td>$U = 1.4(w + F)$</td>
</tr>
<tr>
<td>Load case 3: transportation</td>
<td>$U = 1.4(w + F)$</td>
</tr>
<tr>
<td>Load case 4: handling</td>
<td>$U = 1.4w$</td>
</tr>
<tr>
<td>Load case 5: thrust jack forces</td>
<td>$U = 1.2J$</td>
</tr>
<tr>
<td>Load case 6: tail skin grouting</td>
<td>$U = 1.25(w + G)$</td>
</tr>
<tr>
<td>Load case 7: secondary grouting</td>
<td>$U = 1.25(w + G)$</td>
</tr>
<tr>
<td>Load case 8: earth pressure and groundwater load</td>
<td>$U = 1.25(w + WA_p) + 1.35(EH + EV) + 1.5 ES$</td>
</tr>
<tr>
<td>Load case 9: longitudinal joint bursting</td>
<td>$U = 1.25(w + WA_p) + 1.35(EH + EV) + 1.5 ES$</td>
</tr>
<tr>
<td>Load case 10: additional distortion</td>
<td>$U = 1.4M_{distortion}$</td>
</tr>
</tbody>
</table>

Note: $w =$ self-weight; $F =$ self-weight of segments positioned above; $J =$ TBM jacking force; $G =$ grout pressure; $WA_p =$ groundwater pressure; $EV =$ vertical ground pressure; $EH =$ horizontal ground pressure; $ES =$ surcharge load; and $M_{distortion} =$ Additional distortion effect.
Segment Stripping & Segment Handling

- Simulated by two cantilevers loaded under its self weight (e.g. at 5-6 h)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Dynamic Shock Factor</th>
<th>Maximum Developed Bending Moment</th>
<th>Key Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demolding</td>
<td>N.A</td>
<td>$wa^2/2$</td>
<td>$f'<em>c$ and $\sigma^*</em>{p}$ at 5-6 h</td>
</tr>
<tr>
<td>Handling</td>
<td>2.0</td>
<td>$w(L^2/8-S^2/2)+w(L/2+S)f$ (slings) (others)</td>
<td>$f'<em>c$ and $\sigma^*</em>{p}$ at 28 d</td>
</tr>
</tbody>
</table>

$\sigma^*_{p}$ is the back calculated residual tensile strength for fiber reinforced concrete
Segment Storage & Transportation

- Simulated by simply supported beams loaded under its self-weight and eccentricity (e.g. 5-6 h)
- Segments comprising a ring piled up within one stock

<table>
<thead>
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<th>Key Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>N.A</td>
<td>$w(L^2/8-S^2/2)+F_2e$</td>
<td>$f'_c$ and $\sigma_p^*$ at 5-6 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$w(S^2/2)+F_1e$</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>2.0</td>
<td>$w(L^2/8-S^2/2)+F_2e$</td>
<td>$f'_c$ and $\sigma_p^*$ at 28 d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$w(S^2/2)+F_1e$</td>
<td></td>
</tr>
</tbody>
</table>

*$\sigma_p$ is the back calculated residual tensile strength for fiber reinforced concrete
TBM Thrust Jack Forces

Design checks:
• Bursting tensile stresses
• Spalling tensile stresses
• Compressive stresses

Analysis and design methods:
• Simplified equations
• Analytical methods
• Finite Element Analyses (2D/3D)
• Non-linear Fracture Mechanics
Analysis & Design Methods for Jack Forces

Simplified Equations

\[ T_{burst} = 0.25P_{pu}\left(1 - \frac{h_{anc}}{h - 2e_{anc}}\right) \]
\[ d_{burst} = 0.4(h - 2e_{anc}) \]

ACI 318

\[ T_{burst} = 0.25P_{pu}\left(1 - \frac{h_{anc}}{h}\right) \]
\[ d_{burst} = 0.5(h - 2e_{anc}) \]

Analytical Methods (Iyengar, 1962)

FEM

DAUB
Tail Skin and Secondary Grouting Pressure

**Tail Skin Grouting**
- Simulated in 2D by a solid ring
- Grout pressure at crown is slightly higher than groundwater pressure
- Invert grout pressure calculated from equilibrium b/w grout pressure, self-weight and shear stresses of grout
- Radial pressure applied w/ linear distribution

**Secondary Grouting**
- To fill a local gap b/w lining & excavation profile after primary grouting
- Simulated in 2D
- Interaction with ground is modeled by radial springs
- Grout pressure applied w/ triangular distribution

\[ \sigma_g = 225 \text{ kPa} \]
\[ \sigma_g = 245 \text{ kPa} \]
\[ \sigma_g = 264.5 \text{ kPa} \]

Axial Forces
1573 kN
114 kN.m

Bending Moments

Max \( \sigma_g \) = 225 kPa distributed triangularly over a 36°

Axial Forces
1734 kN

Bending Moments
Ground and Groundwater Loads

**Elastic Equation Method**

<table>
<thead>
<tr>
<th>Load</th>
<th>Bending Moment</th>
<th>Axial Force</th>
<th>Shear Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Load</td>
<td>(1-2G2)^P R₁/4</td>
<td>S₂ R₂/4</td>
<td>-S₂ R₂/4</td>
</tr>
<tr>
<td>Horizontal Load</td>
<td>(1-2G2)^Q R₂/4</td>
<td>C₂ R₂/4</td>
<td>-C₂ R₂/4</td>
</tr>
<tr>
<td>Horizontal Triangular Load</td>
<td>(6-3G2-12C2+4C3) R₁/16</td>
<td>(C+8G2-4C3)* R₂/16</td>
<td>(C+8G2-4C3)* R₂/16</td>
</tr>
</tbody>
</table>

**Beam-Spring Method**

- Longitudinal Joint (Rotational Spring)
- Circumferential Joint (Shear Spring)
- Ground Reaction (Radial Spring)

**Discrete Element Method (DEM)**

**Finite Element Method (FEM)**
Longitudinal Joint Bursting Forces

**Design checks:**
- Bursting tensile stresses
- Compressive stresses

**Analysis and design methods:**
- Simplified equations
- Analytical methods
- Finite Element Analyses (2D/3D)

Tensile Stress

Compressive Stresses

DAUB (2013)
Fibers as an Alternative to Reinforcing Bars

**Advantages**
- Cost saving (10-40%)
- Improved precast production efficiency
- Reduce *spalling* or *bursting* of concrete cover at vulnerable edges and corners
- **Ductility & robustness**
- Crack width reduction
- High strength against unintentional *impact loads*
FRC (Only) Segments: Axial Force-Bending Moment Interaction Diagram

Zones 1&2

Zone 3
How to Implement FRC Residual Strength

**ASTM C1609**

$P/2 \rightarrow P/2$

$150 \times 150 \times 150$

**Parametric Study**

Required Reduction Factor

$f_1 = \frac{P_1 L}{bd^2}$

$f_{600}^D = \frac{P_{600}^D L}{bd^2}$

$f_{150}^D = \frac{P_{150}^D L}{bd^2}$

$\mu \sigma_{eff}$, psi

$\phi P_n, \text{kN}$

$\phi M_n, \text{kN.m}$

The Concrete Convention and Exposition
FRC Segments: Choice of Constitutive Law
Strength Design Example—FRC Segment

Geometry and Strength Parameters

- $D_i = 5.5$ m (18 ft)
- $b = 1.5$ m (5 ft)
- $h = 0.3$ m (12 in)
- $L_{\text{curved}} = 3.4$ m (11.2 ft)
- $f'_c @ 4h$: 15 MPa (2,200 psi)
- $f'_c @ 28d$: 45 MPa (6,500 psi)
- $f_1 = 3.8$ MPa (540 psi)
- $f^D_{150} @ 4h$: 2.5 MPa (360 psi)
- $f^D_{150} @ 28d$: 4 MPa (580 psi)
- $T_{\text{TH TBM}} = 20,000$ kN on 16 jack pairs
- Jack Shoes Contact Area: 0.2 x 0.87 m

- Ring composed of 5+1 segments
- Tunnel excavated in fractured rock
Design Checks for Strength (ULS)

### ACI 318

<table>
<thead>
<tr>
<th>Phase</th>
<th>Specified Residual Strength, MPa (psi)</th>
<th>Maximum Bending Moment, kNm/m (kipf-ft/ft)</th>
<th>Bending Moment Strength, kNm/m (kipf-ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demolding</td>
<td>2.5 (360)</td>
<td>5.04 (1.13)</td>
<td>26.25 (5.91)</td>
</tr>
<tr>
<td>Storage</td>
<td>2.5 (360)</td>
<td>18.01 (4.05)</td>
<td>26.25 (5.91)</td>
</tr>
<tr>
<td>Transportation</td>
<td>4.0 (580)</td>
<td>20.80 (4.68)</td>
<td>42.00 (9.44)</td>
</tr>
<tr>
<td>Handling</td>
<td>4.0 (580)</td>
<td>10.08 (2.26)</td>
<td>42.00 (9.44)</td>
</tr>
</tbody>
</table>

**Tangential direction**

\[
\sigma_p = \frac{1.2T_{burst}}{\phi_h \cdot d_{burst}} = \frac{1.2 \times 17.32 \times 1000}{0.7 \times 8 \times 1.77 \times 12} = 174 \text{ psi (1.2 MPa)}
\]

**Radial direction**

\[
\sigma_p = \frac{1.2T_{burst}}{\phi_d \cdot d_{burst}} = \frac{1.2 \times 17.55 \times 1000}{0.7 \times 34 \times 5} = 177 \text{ psi (1.22 MPa)}
\]
Future Materials: Design for Service-Crack Width

Steps for FRC segments:

1- Determination of neutral axis

2- Determination of compressive/tensile strains at extreme fibers

3- Calculation of crack width using gauge length concept

Fiber properties:

\[ f_{f}^O = 4 \text{ MPa (0.58 ksi)} \]

\[ \sigma_p = 0.34 \times 4 \text{ MPa} = 1.36 \text{ MPa (0.197 ksi)} \]

Stresses:

\[ f_{f} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \sigma_p = 1.36 \text{ MPa (0.197 ksi)} \]

\[ \sigma_{p,t} = 0.34 \times 4 \text{ MPa} = 1.36 \text{ MPa (0.197 ksi)} \]

\[ \sigma_{p,s} = 0.34 \times 4 \text{ MPa} = 1.36 \text{ MPa (0.197 ksi)} \]

Strains:

\[ \varepsilon_{top} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{PC,T} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{PC,S} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{sb} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{st} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{st} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{st} = 17.1 \text{ MPa (2.48 ksi)} \]

\[ \varepsilon_{st} = 17.1 \text{ MPa (2.48 ksi)} \]
Future Materials: Crack Width Reduction Under Excessive Service Loads

Service Loads:
M = 239 kN.m (177 kips-ft)
N = 2,068 kN (465 kips)

Alternatives:
1- RC
2- FRC

FRC results in ~45% crack width reduction in average

<table>
<thead>
<tr>
<th>Maximum Crack Width in RC Segments</th>
<th>Maximum Crack Width in FRC Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI 224.1R (2007) - Gergely &amp; Lutz</td>
<td>0.10 mm (0.0039 in)</td>
</tr>
<tr>
<td>ACI 224.1R (2007) - Frosch</td>
<td>0.14 mm (0.0056 in)</td>
</tr>
<tr>
<td>JSCE (2007)</td>
<td>0.14 mm (0.0053 in)</td>
</tr>
<tr>
<td>EN 1992-1-1 (2004)</td>
<td>0.07 mm (0.0028 in)</td>
</tr>
<tr>
<td>fib Model Code (2010)</td>
<td>0.10 mm (0.0040 in)</td>
</tr>
<tr>
<td>CNR-DT 204 (2006)</td>
<td></td>
</tr>
<tr>
<td>RILEMTC 162-TDF (2003)</td>
<td>0.04 mm (0.0017 in)</td>
</tr>
<tr>
<td>DAfStb (2012)</td>
<td>0.047 mm (0.0018 in)</td>
</tr>
</tbody>
</table>
Future Materials: Allowable SLS Crack Width

### Concrete Codes:
- ACI 224.1R (2007): 0.3 mm (0.012 in)
- EN 1992-1-1 (2004): 0.3 mm (0.012 in)
- Model Code (2010): 0.2 mm (0.008 in)

### Tunnel Codes:
- LTA (2007): 0.3 mm (0.012 in)
- DAUB (2013): 0.2 mm (0.008 in)
- JSCE (2007): 0.004 d<sub>c</sub>
- ÖVBB (2011):

<table>
<thead>
<tr>
<th>Requirement Class</th>
<th>Designation</th>
<th>Application</th>
<th>Requirement</th>
<th>Allowable Crack Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT1</td>
<td>Largely dry</td>
<td>- One-pass lining with very tight waterproofing requirements - Portal areas</td>
<td>Impermeable</td>
<td>0.20 mm (0.008 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT2</td>
<td>Slightly moist</td>
<td>- One-pass lining for road and railway tunnels with normal waterproofing requirements (excluding portals)</td>
<td>Moist, no running water in tunnel</td>
<td>0.25 mm (0.010 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT3</td>
<td>Moist</td>
<td>- One-pass lining without waterproofing requirements - two-pass lining systems</td>
<td>Water dripping from individual spots</td>
<td>0.30 mm (0.012 in)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT4</td>
<td>Wet</td>
<td>- One-pass lining without waterproofing requirements - two-pass lining as drained system</td>
<td>Water running in some places</td>
<td>0.30 mm (0.012 in)</td>
</tr>
</tbody>
</table>
Ongoing Studies: Crack Width vs. Infiltration

Flow through parallel plates

\[ Q = \frac{w \cdot b \cdot \Delta P}{12 \mu \cdot d} \]

Flow through Concrete

\[ Q = \xi \frac{\Delta P l w^3}{12 \mu l} = \xi \frac{g l w^3}{12 \nu} \]

Flow Rates for FRC

- water pressure
- segment thickness
- Assumptions

<table>
<thead>
<tr>
<th>Crack Width (mm)</th>
<th>Initial Flow Rate (liter/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
</tr>
<tr>
<td>0.2</td>
<td>150</td>
</tr>
<tr>
<td>0.3</td>
<td>350</td>
</tr>
</tbody>
</table>

Flow Rates for FRC

- reinforcement type
- Assumptions

<table>
<thead>
<tr>
<th>Crack Width (mm)</th>
<th>Initial Flow Rate (liter/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>0.1</td>
<td>500</td>
</tr>
<tr>
<td>0.2</td>
<td>800</td>
</tr>
<tr>
<td>0.3</td>
<td>1200</td>
</tr>
</tbody>
</table>

Flow Rates RC vs. FRC

- reinforcement type
- Assumptions

<table>
<thead>
<tr>
<th>Crack Width (mm)</th>
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<tbody>
<tr>
<td>0</td>
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</table>

The Concrete Convention and Exposition
Future Materials: Hybrid Reinforcement

Interaction diagrams for design of hybrid fiber-reinforced tunnel segments

Yiming Yao · Mehdi Bakhshi · Varya Nasri · Barzin Mobasher

1.1 All compression, bottom fiber yielded in compression
1.2 All compression, bottom fiber not yielded in compression
2.1 Compression controlled, no tension crack
2.2 Compression controlled, tension crack
3 Tension controlled

Material Models

All Modes of Failure

Closed-Form Solution
Conclusion

• **ACI 544.7R** successfully addressed the demand in industry for a guide on FRC segments

• In mid-size tunnels use of fiber reinforcement can lead to elimination of steel bars required for strength, resulting in construction cost saving of up to 40%.

• Use of fiber in tunnel segments results in reduction of crack width by ~45% under the service load for Serviceability Limit State (SLS) design.

• Service design and hybrid reinforcement strength design will be added in the future to ACI 544.7R.
Thank you for your attention

Mehdi Bakhshi, PhD, PE
Senior Tunnel Engineer at AECOM
Member of ACI committees 305, 350, 506, 544, and 533
mehdi.bakhshi@aecom.com
D 212.896.0257  C 480.370.1685
125 Broad St, 16th floor, New York, NY 10004