FRC in Tunnel Lining

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Precast tunnel segments

- The lining is made by rings. Each ring is made by precast segment

- The tunnel is excavated by means of the TBM (Tunnel Boring Machine)
Precast tunnel segments

De-moulding

Storage of segments

wood blocks
Transportation and positioning of the segment
(the segments need to be transported around the segment plant, to the project site, down to the tunnel)

Positioning of the segment by means of erector system
(pin shear erector or vacuuming system)
Precast tunnel segments

Test of in-plane action
(thrust phase, global behaviour)

Splitting Test
(thrust phase, local behaviour)

Critical stage
Precast tunnel segments

Final stage:

- Favorable loading condition: lining under compression and bending: limited flexural demand
- Shear forces due to bending are small (minimum shear reinforcement generally sufficient): stirrups can be substituted by fibers;
- Possible improvement of crack control of fibers
Main advantages of using FRC

- Enhanced toughness

- Smaller crack opening (durability) and fiber corrosion resistant (durability)

- Higher resistance to impact loading
Main advantages of using FRC

- No detachment of cracked concrete blocks in tunnels
- Improved industrial process
- Reduction of storage areas for reinforcement
- Reinforcement spread everywhere in the segment (corners)
Development of FRC tunnel linings

Growing use of FRC for precast tunnel segments:
from ’80s → 78 tunnels

FRC & RC/FRC (Hybrid) precast tunnel segments: case studies over the years

- 2011-2017
- 2006-2010
- 2000-2005
- ’90s
- ’80s

Number of tunnels: 0 5 10 15 20 25 30 35 40

Legend:
- Hybrid RC/FRC
- FRC
Fiber Reinforced Concrete, FRC


Main loading conditions investigated in order to optimize the reinforcement.

There is NOT a unique solution but it is fundamental to know and to be able to quantify in a comprehensive design procedure the benefits due FRC.

Thrust phase:
- Experimental tests on local splitting behavior on small specimens;
- 3D Non linear finite analyses (unfavorable conditions);
- Small scale/full scale tests

Final stage:
- Plane strain model-2D½ bedded ring model (parametric study);
- Analytical procedure for the evaluation of lining behavior at SLS;
- Analytical procedure for the evaluation of lining behavior at ULS

Grouting process:
- Experimental tests on local splitting behavior on small specimens;
- 3D Non linear finite analyses (unfavorable conditions);
- Small scale/full scale tests
TBM thrust phase

Possible approaches for taking into account FRCs properties during this stage:

• Full scale experimental tests

• Small scale experimental tests

• Non linear numerical simulations

Conforti, Tiberti, Plizzari, Caratelli, Meda, TUST, 2017

Conforti, Tiberti, Plizzari, TUST, 2015
TBM thrust phase: local splitting phenomena

Thrust phase:
high compressive stresses on a small area

Proper specimens dimensions and configurations were adopted in order to study this local behavior.
TBM thrust phase: local splitting phenomena

Experimental campaign on SFRC prismatic specimens

**Hooked-end-steel fibers**
The 60/65 steel fibers are characterized by a length of 60 mm, a diameter of 0.90 mm (aspect ratio of 65) and tensile strength of 2300 MPa.

<table>
<thead>
<tr>
<th>60/65 BATCHES</th>
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</tr>
</thead>
<tbody>
<tr>
<td>60/65-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60/65-40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60/65-40H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RC BATCHES</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RC-0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC-1.0</td>
<td></td>
<td></td>
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</table>

Traditional reinforcement
φ8

<table>
<thead>
<tr>
<th>Concrete</th>
<th>60/65-25</th>
<th>60/65-40/40H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0-4 [kg/m³]</td>
<td>889.6</td>
<td>889.6</td>
</tr>
<tr>
<td>Coarse aggregate 0-10 [kg/m³]</td>
<td>332.2</td>
<td>332.2</td>
</tr>
<tr>
<td>Coarse aggregate 10-20 [kg/m³]</td>
<td>583.6</td>
<td>583.6</td>
</tr>
<tr>
<td>Cement content [kg/m³]*</td>
<td>390</td>
<td>390</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>Super-plasticizer [L]</td>
<td>1.56</td>
<td>2.16</td>
</tr>
<tr>
<td>60/65 fibers [kg/m³]</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>60/65 fibers volume fraction [%]</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td>Concrete slump [mm]</td>
<td>170</td>
<td>140</td>
</tr>
</tbody>
</table>

* CEM II/A-LL 42.5R
TBM thrust phase: local splitting phenomena

Experimental campaign on SFRC prismatic specimens

Two different casting directions:

Vertical Casting
Casting Direction = Loading Direction

Horizontal Casting
Casting Direction ⊥ Loading Direction

Line load configuration:

LINE LOAD
Top view

North Side
West Side
South Side
Perspectival representation

<table>
<thead>
<tr>
<th>75</th>
<th>100</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 East Side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100mm</td>
<td>250mm</td>
<td></td>
</tr>
<tr>
<td>b=3d=750mm</td>
<td></td>
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</tbody>
</table>
TBM thrust phase: local splitting phenomena

Two failure mechanisms were observed:

I: Linear elastic phase of concrete
II: Crack formation and propagation
III: Concrete wedge formation and failure
Two failure mechanisms were observed:

CRUSHING FAILURE

I: Linear elastic phase of concrete
II: Crack formation and propagation
III: Multi-cracking in compressed zone and failure
TBM thrust phase: local splitting phenomena

Comparison between different fiber contents:

25 kg/m³ of steel fibers significantly enhance the splitting behavior and the bearing capacity of a concrete prism (up to +54%), as well as the specimen ductility.

40 kg/m³ of steel fibers are able to change the failure mode from splitting to crushing in elements under LL configuration.

A higher fiber content determines a greater stiffness in the post-cracking phase.

Casting direction influences fiber orientation, thus the resistance and post-cracking behaviour of specimens.
TBM thrust phase: local splitting phenomena

Comparison between different SFRC and RC solutions:

All RC samples showed a crushing failure at a load level of about 1200 kN

As expected, an increment of splitting reinforcement led to a better control of the splitting crack

RC samples showed similar performance to 40kg/m³ of fibers, coherently with the failure mechanism (the different crushing load is in accordance to the difference compressive strength $f_{cm}$).
TBM thrust phase: FRC tunnel segments

(I) Force on thrust shoe
- ground conditions
- tunnel overburden
- number of shoes

(II) Ratio governing local splitting behavior

(TBM THRUST PHASE)

(III) Segment configuration

(IV) Irregularities
- eccentric placement of thrust shoes
- un-even support

(V) FRC performance
**Tunnel segment geometry**

**MAIN CHARACTERISTICS:**
- Tunnel overburden 30 ÷ 70 m;
- Internal diameter 10.90 m;
- External diameter 11.60 m.

**SEGMENT GEOMETRY:**
- Length (Li) 4.70 m;
- Depth (b) 1.80 m;
- Thickness (t) 0.35 m.
(I) Force on thrust shoes

- 30 hydraulic jacks: 4 jacks/segment;
- **service load applied by each jack**: 3 MN;
- **service load applied on each segment**: 12 MN;
- **nominal maximum load by each jack**: 4.7 MN;
- **nominal maximum load on each segment**: 18.8 MN.
(II) Ratio governing local splitting behavior

**Radial direction**

- \( a_{\text{rad}} = 225 \) mm
- \( d_{\text{rad}} = 350 \) mm
- \( a_{\text{rad}} / d_{\text{rad}} = 0.64 \)

**Tangential direction**

- \( a_{\text{tan}} = 1235 \) mm
- \( d_{\text{tan}} = 2350 \) mm
- \( a_{\text{tan}} / d_{\text{tan}} = 0.53 \)
(III) Segment configuration

**Configuration A**
- Two pairs of thrust jack;
- four bearing pads.

**Configuration B**
- Two pairs of thrust jack;
- two bearing pads.
(IV) Irregularities

Perfect placement of thrust shoes → NORMAL LOADING CONDITION

Eccentric placement of thrust shoes → OUTWARD ECCENTRICITY
(V) FRC performance

FRC Post-cracking properties determined according to: EN-14651

<table>
<thead>
<tr>
<th>Series ID</th>
<th>Fiber ID</th>
<th>$E_c$ [GPa]</th>
<th>$f_{cm,cube}$ [MPa]</th>
<th>$f_{ctm}$ [MPa]</th>
<th>$f_{Lk}$ [MPa]</th>
<th>$f_{R1k}$ [MPa]</th>
<th>$f_{R2k}$ [MPa]</th>
<th>$f_{R3k}$ [MPa]</th>
<th>$f_{R4k}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC 2b</td>
<td>33/0.75</td>
<td>40.2</td>
<td>75.7</td>
<td>4.53</td>
<td>5.11</td>
<td>2.30</td>
<td>1.94</td>
<td>1.73</td>
<td>1.59</td>
</tr>
<tr>
<td>SFRC 6c</td>
<td>50/0.75</td>
<td>40.1</td>
<td>74.1</td>
<td>4.50</td>
<td>5.21</td>
<td>6.49</td>
<td>7.14</td>
<td>6.77</td>
<td>6.10</td>
</tr>
</tbody>
</table>
(V) FRC performance

FRC classification according to Model Code 2010

The strength interval is defined by two subsequent numbers in the series:
1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, … [MPa]
while the letters a, b, c, d, e correspond to the residual strength ratios:

- a if $0.5 \leq \frac{f_{R3k}}{f_{R1k}} < 0.7$
- b if $0.7 \leq \frac{f_{R3k}}{f_{R1k}} < 0.9$
- c if $0.9 \leq \frac{f_{R3k}}{f_{R1k}} < 1.1$
- d if $1.1 \leq \frac{f_{R3k}}{f_{R1k}} < 1.3$
- e if $1.3 \leq \frac{f_{R3k}}{f_{R1k}}$

(5.6-1)

<table>
<thead>
<tr>
<th>Series ID</th>
<th>Fiber ID</th>
<th>$f_{R1k}$ [MPa]</th>
<th>$\frac{f_{R3k}}{f_{R1k}}$ [-]</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC 2b</td>
<td>33/0.75</td>
<td>2.30</td>
<td>0.75</td>
<td>2b</td>
</tr>
<tr>
<td>SFRC 6c</td>
<td>50/0.75</td>
<td>6.49</td>
<td>1.04</td>
<td>6c</td>
</tr>
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</table>
Numerical Model: mesh discretization

Number of elements:
- Steel Plates: 192
- Interface under steel plates: 96
- Segment: 5184
- Interface on the bottom surface: 96
- Interface on lateral surfaces: 216

Number of elements:
- Steel Plates: 192
- Interface under steel plates: 96
- Segment: 5184
- Interface on the bottom surface: 128
- Interface on lateral surfaces: 216
Numerical Model: modeling of material

Inverse analysis method: discrete crack approach
Numerical Model: modeling of material

- SFRCs uni-axial post cracking laws: characteristic values (applied in the model by means of a smeared crack approach):

<table>
<thead>
<tr>
<th>Series ID</th>
<th>Bi-linear tensile post-cracking law</th>
<th>$f_{ck}$ [MPa]</th>
<th>$f_{ctk}$ [MPa]</th>
<th>$w_1$ [mm]</th>
<th>$\sigma_1$ [MPa]</th>
<th>$w_c$ [mm]</th>
<th>$G_{f,tot}$ [N/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC 2b</td>
<td><img src="image.png" alt="Diagram" /></td>
<td>54.17</td>
<td>3.16</td>
<td>0.075</td>
<td>0.67</td>
<td>6.0</td>
<td>2.13</td>
</tr>
<tr>
<td>SFRC 6c</td>
<td><img src="image.png" alt="Diagram" /></td>
<td>54.17</td>
<td>3.16</td>
<td>0.020</td>
<td>2.25</td>
<td>15.0</td>
<td>16.91</td>
</tr>
</tbody>
</table>

- SFRCs uni-axial compressive law: Thorenfeldt

- Steel conventional rebars: embedded reinforcement, $f_{yk}=500$ MPa, $f_{sk}=575$ MPa
**Global behavior**: bearing capacity & development of cracks

**Numerical Results**

**Global behavior**: bearing capacity & development of cracks
**Local behavior**: influence of FRC performance on spalling crack

SFRC 2b exhibits a crack opening of about **three times** of that shown by SFRC 6c at 1.5 times the service load.
**Numerical Results**

**Local behavior:** influence of the adopted segment configuration

**Normal loading condition**

- **Configuration-B**
- **Configuration-A**

Configuration-A leads to **higher spalling crack opening** with respect Configuration-B:

SFRC 6c: from 0.14 mm to 0.35 mm at 1.5 times the service load
**Local behavior:** influence of the eccentricity

Outward eccentricity leads to **higher spalling crack opening:**

SFRC 6c: from 0.12 mm (normal loading condition) to 0.89 mm at service load

SFRC 6c behaves like RC (reference solution)
Optimized reinforcement

Traditional Reinforcement

Steel content: 97 kg/m$^3$

Optimized Reinforcement

Steel content: $48$ kg/m$^3$ + SFRC 2b
Optimized reinforcement

These rebars (\(\rho_s \sim 0.2-0.3\%\)) guarantee an adequate bearing capacity at ULS and \(M_{\text{yielding}} > M_{\text{cracking}}\).

The combination of these rebars with SFRC 2b:

- enhances the flexural bearing capacity (demoulding, storage, handling)
- noticeable improves crack control
Optimized reinforcement

These rebars (intrados and extrados) in combinations with SFRC 2b guarantee a noticeable better crack control for:

spalling crack between the thrust jacks during the TBM thrust phase
Optimized reinforcement

Minimum amount of stirrups in order to avoid:

- **buckling phenomena** of longitudinal rebars
- spalling off of the cover due to **radial stresses** caused by **curved shape** of longitudinal rebars

**practical issues:**
for placing the reinforcement cage
Optimized reinforcement

Local stirrups:
These stirrups are mainly placed for **practical reasons** (handling and lifting the reinforcement cage)

+ SFRC 2b

enhance the control of **local effect** in the **longitudinal joints** such as local splitting stress due to hooping force (normal force)
NOTE THAT:

- Local radial splitting cracking phenomena:

- Local tangential splitting cracking phenomena:

are mainly controlled by Fiber Reinforcement only
**Numerical Results**

**Local behavior**: influence of the eccentricity

**Outward eccentricity, configuration-A**

Outward eccentricity leads to **higher spalling crack opening**: SFRC 6c, RCO+SFRC 2b and RC (reference solution) exhibit a **similar behavior**.
Embedded in ground/grout process: FEA & Analytical approach

- A broad parametric study was carried by referring to:
  - Embedded in soil load condition
  - Grouting phase

- The results concerning two different lining geometries are presented herein:

Brescia metro line

Tunnel having large diameter
The following basic hypotheses were assumed in the parametric study:

- Reference concrete strength class C40/50
- Lining thickness equal to $1/22 \, D_{int}$
- German configuration of the bearing pads in the ring joints
- Ground water table is located at the level of the ground surface
- Ring made by 9 equal segments. Ring depth equal to 1 m

Different tunnel overburdens were considered ranging from $1D_{ext}$ to $4D_{ext}$:

- Two different ground conditions were adopted:
  - $E_{oed}=50 \, MPa$; $E_{oed}=100 \, MPa$
A segmented double ring beam model was used: so called 2½ D model.

This simplified numerical model enables to take into account:

- interaction between two adjacent rings through the ring joints
- interaction between adjacent segments through the longitudinal joints

The stiffness of the ground radial springs were estimated according to the following equation:

\[ K_{spring, ground} = \frac{0.5 \cdot E_{oed}}{R_{ext}} \]
• Contact behaviour in the longitudinal joints and ring joints were considered by means of local springs.

Local springs adopted in the longitudinal joint.

• Ring joints were simulated by local springs, working in radial direction → exchange of forces through the ring joint occurs in the bearing pads.
The 2½ D enables to take into account the interaction between adjacent rings: the maximum bending moment and shear force arising in the lining can be evaluated.

- Single ring FE model (the interaction through longitudinal and ring joints is neglected)
- 2½ D FE model, “coupled rings”

“Coupled rings” configuration: increment of the maximum bending moment equal to 23-26%
“Coupled rings” configuration: increment of the maximum shear force equal to 44-53%
Study of the tunnel lining at SLS: Analytical approach

- The combination of traditional and fiber reinforcement, RC+FRC involves the goal to find an **opportune crack opening criterion**

Study of tension-stiffening mechanism for a RC+FRC concrete lining section

**proposed analytical simple model**

It was modified in order to describe a RC+FRC tensile member

Leonhardt’s approach has been used to treat a concrete beam as a tensile member:

**introduction of the “effective tensile area”**
The following FRC were considered in combination with RC, $\rho=0.21\%$

The design tunnel depth projection (1.2D) was considered

It turns out that fibers are effective in terms of crack control within an average crack opening of about 0.3mm
Study of the sectional lining response at SLS

- Evaluation of the FRC (defined by $\chi$) to combine with rebars

A combination of $\rho=0.12\%$ and FRC (corresponding $\chi=0.50$) represents the most convenient solution.
Published papers


Published papers


Published papers


Published papers


Thank you for your kind attention!