Tunnel linings in Fiber Reinforced Concrete

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19th May 2017, FRC Tunnel Lining Workshop, Rome, Italy
fib Model Code 2010

fib Model Code for Concrete Structures 2010

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Main goal of the fib Model Code

To provide guidance to engineers to properly (and safely) design FRC structural elements both at serviceability and ultimate limit states, based on the state-of-the-art knowledge
Engineers can design structures with new materials only if they are performance based!
Structural design of concrete in tension

\[ f_{cd} = \frac{f_{ck}}{\text{Safety factor}} \]

Concrete class

C40/50
A **performance approach** is chosen: the material has to be tested as composite, because the mechanical response cannot be properly identified by knowing the mix design and the mechanical characteristics of each component.

**UNIAXIAL TENSION TEST**

**BENDING TEST**
### EN 14651

- $h_{sp} = 125$ mm
- $b = 150$ mm

Linear stress distribution

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2}$$
Place the best performing reinforcement (fibers and/or rebars) where required by tensile stresses in the structural elements.
Reinforcement use in structural elements

• In structural elements both distributed and localized stresses are generally present
• Conventional rebars represent the best reinforcement for localized stresses
• Fibers represent the best reinforcement for diffused stresses
• Structural optimization generally requires the use of a combination of rebars and fibers
• Structural ductility is generally enhanced
Documents regarding FRC tunnel segments


Fiber Reinforced Concrete, FRC

The use of FRC for precast tunnel segments:

from ’80s → 78 tunnels

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

- 2006-2010: 15 FRC, 15 Hybrid RC/FRC
- 2000-2005: 10 FRC, 5 Hybrid RC/FRC
- ’90s: 5 FRC
- ’80s: 1 FRC

Legend:
- Hybrid RC/FRC
- FRC
Precast tunnel segment loading conditions

De-moulding

Storage of segments

arms of picking system

K-dead weight

adhesion forces

wood blocks
Precast tunnel segment loading conditions

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 segment loading conditions

- Thrust jack phase

**Diagram:***
- Hydraulic jacks
- Plane actions (placing situation)
- Splitting

*Images:*
- Barcelona Metro Line (N. Della Valle)
A number of **irregularities** can occur in practice during the **thrust jack phase**

1) thrust jacks may be not exactly on place
2) ring joint may not be plane

1) thrust jacks may be not exactly on place:

- Eccentricity of the hydraulic jacks
2) ring joint may not be in plane → non-smooth support in the ring joint: uneven supports
Segmental tunnel lining: load conditions

- Grouting process:
  - Grouting process: complete/incomplete grouting

**Complete grouting**
- Local increase of GROUT pressure as fictitious bedding
- Plastic shear yield stress GROUT
- Lining-GROUT Contact pressure act as uniform bedding
- Dead weight of the lining
- Water pressure

**Incomplete grouting**
- If grout is injected incompletely along the tunnel’s circumference
- Only the local increase of GROUT pressure occurs on the lining
Precast tunnel segment loading conditions

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 FRC in precast tunnel segments

- Enhanced toughness
- Smaller crack opening (durability)
- Higher resistance to impact loading
Main advantages of FRC in precast tunnel segments

- No detachment of cracked concrete blocks in tunnels
- Improved industrial process
- No more storage areas for reinforcement
- Reinforcement spread everywhere in the segment
Ongoing research & developed

- 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:
- 3D Non linear finite analyses (unfavorable conditions);
- Experimental tests on local splitting behavior on small specimens;
- 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:

Ground support
Lining
Thrust phase: numerical modelling
Damaged segments during TBM operations
Barcelona Metro Line 9

- During the construction of the Barcelona Metro Line 9, spalling localized cracks appear: probably due to eccentric load (relative position between jacks and tunnel segment).

- Bending cracks appear: probably due to no-smooth support in the ring joint.
Case-study: Barcelona Line 9

THRUST PHASE

- 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
Numerical model adopted

- Normal loading condition: ideal positioning of hydraulic jacks and bearing pads:
  - Spring elements, SP1TR, no-tension, positioned on the 4 bearing pad surfaces.
  - Support of the ring joint uniform
  - Spring elements, no-tension, acting in tangential direction in order to simulate the presence of adjacent segments
  - Two pairs of actuators acting on steel plates: total service load approximately 12 MN
Linea 9 – Barcelona – Thrust jack phase

- The following reinforcement combinations were adopted:

50/1,0-\( V_f = 0.57\% \rightarrow 45 \text{ kg/m}^3 \) (FRC 3c)
50/0.75-\( V_f = 0.32\% \rightarrow 25 \text{ kg/m}^3 \) (FRC 3b)

RC \rightarrow 97 \text{ kg/m}^3
RC+50/0.75-\( V_f = 0.32\% \rightarrow 122 \text{ kg/m}^3 \)

RCO+50/0.75-\( V_f = 0.32\% \rightarrow 71 \text{ kg/m}^3 \)
Linea 9 – Barcelona – Thrust jack phase

- Normal loading condition (ideal placement of supports and jacks):

![Graph showing Normal loading condition with various load conditions and cracking types marked.]

Splitting cracks

Spalling cracks
**Eccentric placement of thrust jack**

- **Eccentricity applied outward:**

  - Because of the eccentricity, the segment tilts outward providing a no-smooth support.

  - A bending moment occurs.

Splitting and spalling stresses initiate at an earlier load level.
Eccentric placement of thrust jack

- Eccentricity applied outward:

- Reduction of the s.f. with respect to the normal load condition;
- Noticeable increment of the crack pattern Between the loading areas (thrust jacks);

- Fiber reinforcement considered cannot locally compete with traditional rebar concentrated in the chords (proposed solution)
Eccentric placement of thrust jack

- Eccentricity applied outward:

  The cracks between the loads develop over the total depth of the segment due to the increased bending moment for the outward tilting.

  Similar deeply penetrating cracks have been observed in the Line 9 of the Barcelona Metro, when 9.3 MN were applied by the jacks.

  These numerical crack patterns refer to a load of 12.6 MN.

  Eccentricity could explain the presence of these cracks.
Case-study: United Arab Emirates

- Similar irregularities (eccentricities) occurred in other case studies:
Case-study: Brasil

- Metro line in Brasil (internal diameter, 6m, lining thickness 0.30m):
- Preliminary 2D analyses:
Case-study: Brasil

- Metro line in Brasil:
  - 3D analyses

- FRC 3c
- FRC 4c
- FRC 3c +RC Optimized
- RC
Case-study: Riyadh

- Metro line in Riyadh:

Preliminary 2D analyses

3D analyses:
- FRC + RC
Thrust phase: numerical modelling

- **Valencia Metro Line 1**

![Diagram of Valencia Metro Line 1 with joint angles and dimensions](image)

**Transverse Section**

Stirrups $\phi 8 @ 200$

- $50$
- $100$
- $100$
- $400$

Chord $8 \phi 12$

350

- $350$

400

- $54.000°$
- $12.000°$
- $350$
- $100$
- $100$
- $400$
- $350$
- $400$
- $1528$
- $1472$
- $1500$
- $1490$
- $4221$
- $4221$
- $8442$
- $9242$
- $180°$
- $270°$
- $90°$
- $0°/360°$

Stirrups $\phi 8 @ 200$
Thrust phase: numerical modelling

- Malpensa Saronno Railway
Thrust phase: numerical modelling

- **Malpensa Saronno Railway**

![Diagram of a tunnel lining with dimensions and deflections marked.](image)

- Deflection: 2.7 m, 1.7 m, 0.3 m, 7.25 m, 0.3 m

- Total Amount: 85 kg/m³

- Total Amount: 82 kg/m³

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Thrust phase: experimental tests

Thrust phase:
high compressive stresses on a small area

Proper specimens dimensions and configurations were adopted in order to study this local behavior.

Force exerted by jack
Experimental tests: local splitting behavior

FRC
Post-cracking properties
determined according to EN-14651

<table>
<thead>
<tr>
<th>$f_{R,1m}$ [MPa]</th>
<th>$f_{R,3m}$ [MPa]</th>
<th>$f_{R,1k}$ [MPa]</th>
<th>$f_{R,3k}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.40</td>
<td>3.60</td>
<td>1.73</td>
<td>2.65</td>
</tr>
</tbody>
</table>

FRC (C40/50)
can be classified according to MC2010 as “2e”
**Experimental tests: local splitting behavior**

**LINE LOAD TESTS (LL)**
- 3 in PC
- 3 in FRC-V  \textit{Well oriented}
  (casting direction=loading direction)
- 3 in FRC-H  \textit{Not-well oriented}
  (casting direction orthogonal to loading direction)

**POINT LOAD TESTS (PL)**
- 3 in PC
- 3 in FRC-V  \textit{Well oriented}
- 3 in FRC-H  \textit{Not-well oriented}
Experimental tests: small-scale tunnel segments without curvature

\( a = 150 \text{ mm}; \ a/d^* = 0.3 \)

2 in PC
2 in FRC
2 in RC+FRC with different casting direction

\( a = 100 \text{ mm}; \ a/d^* = 0.2 \)

2 in PC
2 in FRC
2 in RC+FRC with different casting direction
Fibers significantly enhance the splitting bearing capacity (+40%), as well as the ductility.

The casting direction influences the splitting bearing capacity. However even in case of loading direction orthogonal to casting direction, fibers enhance the splitting bearing capacity (+20%)
Experimental tests: small-scale tunnel segments without curvature

First crack was the spalling crack (between point loads) → then splitting failure

Spalling crack → better controlled in case of FRC and RC+FRC
Experimental tests: full-scale tunnel segments (in collaboration Univ. Tor Vergata)

- Full-scale tests which simulate the TBM thrust forces and bending tests
Experimental tests: full-scale tunnel segments (in collaboration Univ. Tor Vergata)

- Optimized reinforcement made by a combination of traditional rebars and FRC:

  - FRC (mean values): $f_{R1m} \approx 3$ MPa   $f_{R3m} \approx 4.6$ MPa
Experimental tests: full-scale tunnel segments (in collaboration Univ. Tor Vergata)

- Flexural tests and point load tests:

**Flexural Test**
- RC: $f_{cm} = 48.2$ MPa; $\rho_s = 0.22\%$
- FRC: $f_{cm} = 49.9$ MPa
- RC+FRC: $f_{cm} = 49.8$ MPa; $\rho_s = 0.18\%$

**Point Load Test**
- RC: $f_{cm} = 48.2$ MPa; FRC: $f_{cm} = 49.9$ MPa; RC+FRC: $f_{cm} = 49.8$ MPa
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:
Embedded in ground/grout process, FEA & Analytical approach: parametric study

- The following basic hypotheses were assumed in the parametric study:

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

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

- Two different ground conditions were adopted:
  - $E_{\text{oed}}=50 \, \text{MPa}$; $E_{\text{oed}}=100 \, \text{MPa}$
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:

\[ K_{spring,\, ground} = \frac{0.5 \cdot E_{oed}}{R_{ext}} \]
Finite element model

- Contact behaviour in the longitudinal joints and ring joints were considered by means of local springs

- Ring joints were simulated by local springs, working in radial direction → exchange of forces through the ring joint occurs in the bearing pads
Finite element model

- The $2\frac{1}{2}$ D enables to take into account the interaction between adjacent rings: the maximum bending moment and shear force arising in the the lining can be evaluate

  - Single ring FE model (the interaction through longitudinal and ring joints is neglected)
  - $2\frac{1}{2}$ 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%
Numerical results

- Embedded in soil load condition:

By referring to:
- the same tunnel depth (normalized) → $D_{ext}$;
- the same ground stiffness → $E_{oed}$;

*The lining flexural demand is the same: the local non-linear behaviour introduced in the longitudinal joints does not change significantly the global lining behaviour.*
Reinforcement optimization

- The most severe internal forces in the lining were compared to the sectional response at ULS
- The domain $M_{Rd}-N_{Ed}$ at ULS of the reinforcement combinations adopted was calculated by means of the following hypotheses:
- Minimum longitudinal steel ratio: $\rho=0.20\%$

\[ \varepsilon_{u} = 1\% \]
\[ -\varepsilon_{u} = -1\% \]
\[ f_{yd} \]
\[ f_{ctd} \]
\[ \chi=0.25 \]
\[ \chi=0.50 \]
\[ \chi=0.75 \]
Reinforcement optimization

<table>
<thead>
<tr>
<th>Reinforcement configuration</th>
<th>Fiber</th>
<th>Rebars</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC $\rho=0.20%$</td>
<td>$\chi$</td>
<td>$\rho$ [%]</td>
</tr>
<tr>
<td>RC $\rho=0.20% +$ SFRC $\chi=0.25$</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>RC $\rho=0.20% +$ SFRC $\chi=0.50$</td>
<td>0.50</td>
<td>0.20</td>
</tr>
<tr>
<td>RC $\rho=0.20% +$ SFRC $\chi=0.75$</td>
<td>0.75</td>
<td>0.20</td>
</tr>
</tbody>
</table>

$A_s = \rho = 0.20\%$
$h = 325 \rightarrow 675$ mm (t.lining configurations)
$b = 1000$ mm
$d' = 41$ mm

Domain - Brescia Lining Configuration

- $N_{Ed}$ [kN/m]
- $M_{Rd}$ [kNm/m]
Safety factor at ULS

- Comparison between the lining bending moment and the resistant one: safety factor at ULS

All the reinforcement combinations investigated are able to guarantee an adequate safety factor at ULS for all the depth projections considered.

The lining shear capacity was estimated by means of the MC2010: the combination of the minimum longitudinal reinforcement proposed ($\rho=0.20\%$) can completely replace the shear reinforcement based on stirrups.
Safety factor at ULS

- Comparison between the safety factor at ULS resulting for the Brescia lining configuration and the Highway l.config.

By referring to the same concrete strength-class: the safety factor at ULS is **higher in the lining with smaller diameter**
Safety factor at ULS

- Comparison between the safety factor at ULS resulting for the Brescia lining configuration and the Highway l.config.
FRC performance in combination with rebars (SLS)

Four point bending tests on a beam

Beam Cross-Section

Sample

Constant/low gradient of bending moment: reinforcement and surrounding concrete can be assumed as a tension tie
FRC performance in combination with rebars (SLS)

1\textsuperscript{st} phase (NSC and HSC): tie 950/1000 mm long tested in by means of a hydraulic servo-controlled (closed-loop) testing machine with MTS control

2\textsuperscript{nd} phase (only NSC): tie 1000 mm and 1500 long tested in by means of a available steel reacting frame conveniently modified.

Typical instrumented specimen (2\textsuperscript{nd} phase):
FRC performance in combination with rebars (SLS)

The typical response terms of axial load vs. average tensile strain of RC and FRC for NSC and HSC series
FRC performance in combination with rebars (SLS)

Plain Concrete (NSC)  FRC (NSC)

Fibre addition determines a reduction of the mean crack spacing
FRC performance in combination with rebars (SLS)

Mean crack spacing $s_{rm}$ (NSC)

Crack spacing reduction with respect to plain samples [%]
Average reduction fiber $V_f=0.5\%$ - 27.1%
Average reduction fiber $V_f=1.0\%$ - 38.7%
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”*
Study of the sectional lining response at SLS

- The following FRC were considered in combination with RC, $\rho=0.21\%$
- The design tunnel depth projection (1.2D) was considered

$$M_{SLS}\text{-crack open.}, \text{comparison: tunnel depth} = 27.4 \text{ m}$$

- 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

$M_{\text{SLS}}$-crack open., comparison: tunnel depth = 27.4 m

- 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


Published papers


Published papers


Thank you for your kind attention!!
Tunnel linings in fiber reinforced concrete

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Outlines

- Part 1: Presentation of the research group on high performance fiber reinforced concrete
- Part 2: Introduction: precast segmental tunnel lining
- Part 3: Fiber effects in precast tunnel segments
- Part 4: Ongoing research & research developed
- Part 5: Published papers
The research group under the leadership of prof. Plizzari is active on the study of high performance fiber reinforced concrete and their structural applications.

The research group working on FRC tunnel linings:
- Giovanni Plizzari (Professor);
- Giuseppe Tiberti (Assistant professor);
- Antonio Conforti (Post-PhD fellowship);
- Ivan Trabucchi (PhD student);
- Antonio Mudadu (PhD student).