Structural use of fibre reinforced concrete in precast segments

24 May 2018 – Zürich

Lessons from Twenty Years of Application

Giuseppe Tiberti (1), Giovanni Plizzari (1), Elena Chiriotti (2)
Authors

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Associate Professor of Structural Engineering in Department of Civil Engineering, Architecture, Land, Environment and of Mathematics of the University of Brescia. He got a Ph.D. in Materials for Engineering in 2009, from the University of Brescia. His domains of specialization include tunnel linings made by precast segments in Fiber Reinforced Concrete, concrete pavements and nonlinear analyses of reinforced concrete structures.

Giovanni Plizzari (Italy)

Professor of Structural Engineering in Department of Civil Engineering, Architecture, Land, Environment and of Mathematics of the University of Brescia. His research domains include material properties and structural applications of high-performance concrete, fiber-reinforced concrete, concrete pavements, fatigue and fracture of concrete, and steel-to-concrete interaction in reinforced concrete structures. He is member of fib Task Group 8.3 “Fiber Reinforced Concrete” and he was involved in Chapters devoted to FRC of fib Model Code 2010.

Elena Chiriotti (France)

Graduated in Civil Engineering from the Politecnico of Turin, Italy, she obtained a PhD in rock mechanics in 1997. After spending 11 years at Geodata, Italy, she joined SYSTRA, from 2007 to 2015, as director of Tunnels and Underground Structures Department. Since 2015 she is the co-founder and CEO of INCAS Partners, consulting company in the domain of technical, strategical and contractual issues related to underground works. Elena is an active member of AFTES and ITA, she participates in several national and international working groups. Since 2016, she is the animator of ITA Working Group 2 – Research.
Content of the presentation

- ITA WG02 Report n.16/2016 – FRC in precast segments
- Why Fiber Reinforced Concrete?
- 20 years of case histories – lessons learned
- Standards and recommendations on FRC: what is missing?
- Contribution of ITA WG02 Report n.16/2016
- Concluding remarks & future developments
Scope of ITA WG02 Report n. 16/2016

- Take advantage of more than 20 years of FRC practice in precast tunnel lining → feedback from real cases
- Support a performance-based design of FRC structural elements → all kind of fibers respecting long-term requirements
- Provide additional design principles to complete the existing standards and recommendations for the specific case of segmental lining for tunnels
  - loading conditions
  - recent research advances
  - analytical and numerical design procedures to consider the post-cracking residual strength provided by fibers
Content of ITA WG02 Report n. 16/2016

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Why Fibre Reinforced Concrete (FRC)

FRC is a composite material with a cementitious matrix and a discontinuous reinforcement, the fibers (e.g., metal, glass, synthetic or natural materials) offering:

- enhanced resistance to crack development (post-cracking strength)
- considerable increase of toughness (i.e., ability to resist internal crack propagation) of FRC considered as a composite
- optimized reinforcement for diffused stresses
Precast tunnel lining

Temporary load conditions: flexural demand on tunnel segments
- Storage load condition
- Placing process / de-moulding

Barcelona Metro Line

Brescia Metro Line (N. Della Valle)

Barcelona Metro Line
Precast tunnel lining

Final load condition: the lining is loaded by the ground/water pressure: so called lining embedded soil load condition. Favorable condition, the lining is mainly under compression.
Precast tunnel lining

Temporary load conditions: Tunnel Boring Machine thrust phase. The TBM is pushed forward by thrust jacks in order to guarantee the excavation process (thrust phase). These hydraulic jacks push off on the last placed ring.
Use of FRC in precast tunnel lining – key factors

- **Enhancement of structural behaviour**
  - high resistance against impact loads during transportation and handling
  - stable development of splitting cracks
  - reduction of stirrups and replacement of shear reinforcement
  - reduced spalling / damages to corners
  - combines with reinforcing bars to cope with high localized stresses

- **Improvement of precasting process**
  - time reduction in shaping, handling and placing rebars
  - reduction/elimination of storage areas for traditional reinforcement
20 years of FRC applications – case histories

- 73 case histories
  - 37 in America, Asia, Australia
  - 36 in Europe

From the ‘90s to 2016 (with two cases in the 80’s, in Italy)

Case studies over the years
Collected case histories

16 case histories documented in detail

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Collect case histories

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Collected case histories

Tunnel diameter $D_i$

- **Only fiber**

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<table>
<thead>
<tr>
<th>TUNNEL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Tunnel Length</td>
</tr>
<tr>
<td>Boring diameter /TBM</td>
</tr>
<tr>
<td>Overburden (min-max)</td>
</tr>
<tr>
<td>Lining type</td>
</tr>
<tr>
<td>Ring type</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Internal diameter $D_i$</td>
</tr>
<tr>
<td>Tunnel aspect ratio ($D_i/h$)</td>
</tr>
<tr>
<td>Average segment aspect ratio</td>
</tr>
<tr>
<td>No. of segments</td>
</tr>
<tr>
<td>Segment length/width</td>
</tr>
</tbody>
</table>

One of the first pilot project for the application of SFRC in precast segments

<table>
<thead>
<tr>
<th>Reinforcement design solution studied</th>
<th>Rebars [kg/m³]</th>
<th>Fibres [kg/m³]</th>
<th>Total [kg/m³]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original solution</td>
<td>97</td>
<td>25 SFRC 50/1.0</td>
<td>122</td>
<td>Gettu et al. 2004</td>
</tr>
<tr>
<td>(structural contribution of fibres not considered)</td>
<td></td>
<td>Lₚ/ᵦₚ=50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>fₜ, fibre = 1100 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental solution 01</td>
<td>---</td>
<td>60 SFRC 50/1.0</td>
<td>60</td>
<td>Gettu et al. 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lₚ/ᵦₚ=50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>fₜ, fibre = 1100 MPa</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental solution 02

<table>
<thead>
<tr>
<th>Reinforcement design solution studied</th>
<th>Rebars [kg/m³]</th>
<th>Fibres [kg/m³]</th>
<th>Total [kg/m³]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>46</td>
<td>25 SFRC 50/0.75</td>
<td>71</td>
<td>Plizzari et al. 2005</td>
</tr>
<tr>
<td>(in 2 chords along the longer segment sides)</td>
<td></td>
<td>Lₚ/ᵦₚ = 66.67, fₜ, fibre = 1100 MPa</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

30 rings of Solution 01 constructed, installed and instrumented in the Bon-Pastor to Cam-Zam section. Occurrence of splitting cracks and local failures (contact irregularities). Solution not generalized to the whole tunnel (original solution adopted, conventional rebars not optimized by fully exploiting the fibres contribution).

Main lessons learned

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Legacy Way Tunnel, Australia (2011-2015)

<table>
<thead>
<tr>
<th>TUNNEL CHARACTERISTICS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Tunnel Length</td>
<td>4.6 km</td>
</tr>
<tr>
<td>Boring diameter / TBM</td>
<td>12.4 m / double-shield</td>
</tr>
<tr>
<td>Overburden (min-max)</td>
<td>---</td>
</tr>
<tr>
<td>Lining type</td>
<td>Segmental</td>
</tr>
<tr>
<td>Ring type</td>
<td>Universal ring</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Internal diameter $D_i$</td>
<td>11.30 m</td>
</tr>
<tr>
<td>Tunnel aspect ratio ($D_i/h$)</td>
<td>32.3</td>
</tr>
<tr>
<td>Average segment aspect ratio</td>
<td>12.10</td>
</tr>
<tr>
<td>No. of segments</td>
<td>9</td>
</tr>
<tr>
<td>Segment length/width</td>
<td>4.2 m/2 m</td>
</tr>
</tbody>
</table>

Large diameter tunnels where a solution with fibres only was adopted. Hybrid reinforcement used only in highly loaded sections of the tunnel and at the cross-passage locations.
Monte Lirio Tunnel, Panama (2005-2010)

<table>
<thead>
<tr>
<th>TUNNEL CHARACTERISTICS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Tunnel Length</td>
<td>7.9 km</td>
</tr>
<tr>
<td>Boring diameter / TBM</td>
<td>3.9 m /</td>
</tr>
<tr>
<td>Overburden (min-max)</td>
<td>-</td>
</tr>
<tr>
<td>Lining type</td>
<td>Segmental</td>
</tr>
<tr>
<td>Ring type</td>
<td>Universal ring</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Internal diameter $D_i$</td>
<td>3.20 m</td>
</tr>
<tr>
<td>Tunnel aspect ratio ($D_i/h$)</td>
<td>12.8</td>
</tr>
<tr>
<td>Average segment aspect ratio</td>
<td>7.75</td>
</tr>
<tr>
<td>No. of segments</td>
<td>6 segments</td>
</tr>
<tr>
<td>Segment length/width</td>
<td>1.84 m/1.2 m</td>
</tr>
</tbody>
</table>

Design according to the fib Model Code 2010, assisted by full scale bending and thrust tests (the latter to reproduce the TBM action on the segment during excavation). The full-scale tests were developed on FRC segments, without conventional reinforcement.
20 years of FRC applications – lessons

Enhancement of structural behaviour

Better control of **flexural cracks** (e.g. lining final stage)

Control of **splitting cracks**:
- reduction or substitution of local stirrups in segment region under TBM shoes

Control of **shear cracks**:
- complete substitution or reduction of stirrups for shear

Improvement of **post-cracking strength** due to fiber addition

Control of **splitting cracks**:
- reduction or substitution of local stirrups in longitudinal joints of the segment

Towards a **performance-based FRC design** based on the ability of the composite material to resist internal crack propagation (i.e., toughness)
20 years of FRC applications – lessons

Lessons learnt

• Localized stresses are better resisted by conventional rebars
• Diffused stresses (e.g., splitting stresses) are better resisted by fibres
• Fibre content is not a complete information → residual post-cracking strength

Keys

• The flexural demand in tunnel segments is a key-point for evaluating the possibility to completely substitute traditional rebars with FRC
• Localized bending stresses can be due to acting ground loads or can be generated by contact irregularities occurring during the TBM thrust phase

• Nature/frequency of load conditions (both ground & excavation) → High localized stresses in the specific project? Where/when? Possible to reduce/avoid contact irregularities during TBM thrust? Etc.

• If not → high-performance FRC or hybrid solution (rebars and FRC); in alternative, use FRC only and foresee hybrid in critical alignment sections (intersections, bad ground conditions, etc.)

• Design considering post-cracking strength and prescribe FRC performances the necessary boundary conditions

• Composite material → specific mix-design (workability, durability, etc.) and fibres selection vs. concrete strength (pull-out rather than rupture)
Existing standards and recommendations

- **Model Code 2010** and some other relevant codes [RILEM TC 162-TDF, CNR-DT 204, DafStb Guideline] provide the **performance-based design approach** and classes based on FRC post-cracking residual strength.

- The ITA-Report n.16 of WG02 refers directly to Model Code 2010 (*)

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**CMOD** = Crack Mouth Opening Displacement, from a 3-point bending test on a notched beam

\[ f_{Rjk} = \text{characteristic residual flexural tensile strength corresponding to CMOD}_j \]

(*) Then published in 2012
# Existing standards and recommendations

<table>
<thead>
<tr>
<th>Evaluation of post-cracking FRC residual strengths</th>
<th>Design of FRC</th>
<th>Design of FRC for tunnel linings</th>
</tr>
</thead>
<tbody>
<tr>
<td>- EN-14651</td>
<td>- fib Model Code 2010</td>
<td>- AFTES recommendations (*)</td>
</tr>
<tr>
<td>- ASTM C1609/C1609M</td>
<td>- RILEM TC 162-TDF</td>
<td>- DBV recommendations (*)</td>
</tr>
<tr>
<td>- ASTM C1399/C1399M</td>
<td>- CNR-DT-204</td>
<td>- DAUB recommendations (*)</td>
</tr>
<tr>
<td>- ASTM C1550/1550M</td>
<td>- DafStb Guideline</td>
<td>- ACI report 544.7R-16</td>
</tr>
<tr>
<td>- JCI-SF4</td>
<td></td>
<td></td>
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<tr>
<td>- DIN 1045-2</td>
<td></td>
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</tr>
</tbody>
</table>

### Material behavior on small samples

### Behaviour of Structural Elements (e.g., slab or beam)

### FRC precast tunnel segments

(*) refers only to the design Steel Fibre Reinforced Concrete (SFRC)

NOTE: fib bulletin n.83, WP 1.4.1, Precast tunnel segments in fibre-reinforced concrete (2017), appears one year after ITA WG02 publication n.16
What is missing in standards/recommendations?

fib Model Code 2010
• Describes the performance approach for FRC design
• easily applied for beams or slabs,
• needs to be contextualized to precast tunnel segments (e.g., temporary loading condition during excavation → eccentricity, TBM thrust, injections, etc.).

Post-cracking residual strengths can be exploited during these stages even if no specific recommendations are given by Model Code 2010

DEVELOP SPECIFIC BASES FOR DESIGN

NOTE: fib bulletin n.83, WP 1.4.1, Precast tunnel segments in fibre-reinforced concrete (2017), appears one year after ITA WG02 publication n.16

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Our recommendations – General approach

Flexural demand
→ different load cases
→ Irregularities / frequency of occurrence

FRC only or hybrid?

Concrete mix design
- Fibres content

Preliminary tests on composite FRC

Performance definition (FRC class, \( f_{R_{1k}}/f_{R_{3k}} \) ratio, fibre type)

FRC constitutive law
- Analysis of Load Cases
- Definition of Boundary Conditions

Local scale analyses / testing

Global scale analyses / testing

• Analysis of Load Cases
• Definition of Boundary Conditions

Analytical approaches, 2D/3D analyses
Linear & non-linear

Conformity tests during segmental lining production

Testing does not substitute designing!

Concrete mix design

Flexural demand

Performance definition (FRC class, \( f_{R_{1k}}/f_{R_{3k}} \) ratio, fibre type)

Local scale analyses / testing

Global scale analyses / testing

Testing does not substitute designing!

Concrete mix design

FRC only or hybrid?

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Global scale analyses / testing

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Global scale analyses / testing

Testing does not substitute designing!

Concrete mix design

FRC only or hybrid?

Performance definition (FRC class, \( f_{R_{1k}}/f_{R_{3k}} \) ratio, fibre type)

Local scale analyses / testing

Global scale analyses / testing

Testing does not substitute designing!
Our recommendations - Tools

Introduction of the post-cracking strength of FRC in the segmental lining design approach

ANALYTICAL APPROACHES: proposed by standards (e.g., Model Code 2010) for typical flexural behavior (beam theory: the segment is assimilated to a beam during demoulding, handling, transportation, and final stage)

NUMERICAL NON-LINEAR METHODS: recognized by standards (e.g., Model Code 2010). In case of tunnel segments, such models are necessary for capturing FRC contribution under TBM jacks and in longitudinal joints

EXPERIMENTAL TESTS on small scale samples or full-scale tunnel segments

CONFORMITY TESTS: during the production of precast FRC segments, the residual post-cracking strength shall be systematically verified
Our recommendations – Ex. TBM thrust phase

Identification of issues

(I) Thrust Force
- ground conditions
- tunnel overburden
- number of shoes

(II) Ratio governing local splitting behavior

(III) Segment configuration

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

(V) FRC performance

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Our recommendations – Ex. TBM thrust phase

ANALYSIS OF LOCAL BEHAVIOUR: analyse the tensile transverse stresses (splitting or bursting stresses perpendicular to the loading direction)

- Specific experimental tests prove that FRC enables a stable propagation of cracks compared to plain concrete → appropriate design tools → non-linear numerical analyses and experimental tests

ANALYSIS OF GLOBAL BEHAVIOUR: consider possible irregularities of contact (e.g., eccentricity of thrust shoes, uneven support, etc.)

- FRC tunnels segments (fibres only) more vulnerable to irregular load conditions → increased localized stresses → attention to the type and frequency of occurrence of such irregularities → analysis with different boundary conditions
Our recommendations – Step-by-step analyses

Proposed procedure

- Simplified local, 2D, linear or non-linear numerical model or analytical formulations

- Evaluation of local splitting stresses

- Simplified segment 2D model – non-linear

- Evaluation of local and global mechanism with respect to possible use of FRC. Capture the post-cracking FRC contribution. Assess the maximum crack width (if any) at service condition (with crack control due to fibers)

- Advanced segment 3D model – non-linear

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Our recommendations – Modelling

3D advanced numerical model

Configuration A

Steel plates
Interface under steel plates
Segment
Interface on lateral surfaces

Configuration B

Interface on the bottom surface
Interface on lateral surfaces

Not only a complex 3D geometry, but a post cracking constitutive law reproducing the FRC behaviour

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Our recommendations – Modelling

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

Normal loading condition, configuration-B

FRC 2b exhibits a crack opening of about three times of that shown by FRC 6c at 1.5 times the service load.
Our recommendations – Testing

Experimental tests on small samples (local behaviour) or full-scale tunnel elements (local and global behaviour) as useful tools for proving the design approach.

SMALL SCALE TEST reproducing the local behavior under TBM thrust jacks

FULL SCALE TEST: local behavior and boundary conditions of the segment are considered
Our recommendations – Testing

SMALL SCALE TEST - typical behavior of FRC samples for evaluating local splitting behavior

Thrust phase:
high compressive stresses on a small area

Proper specimens dimensions and configurations were adopted in order to study this local behavior
Our recommendations – Testing

SMALL SCALE TEST - typical behavior of FRC samples having adequate post-cracking strengths (FRC class 2e or higher)

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

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Our recommendations – Modelling joints

Long term condition – Consider the interaction between 2 adjacent rings for FRC segments

JOINTS (between perfect continuity and perfect hinge)  
→ rotational spring in a bedded beam model

Acting load → transfer zone (contact area) → deformations → rotation by integrating the curvature over the depth of the contact area → stiffness of the rotational spring by calculating the bending moment vs. rotation relationship of the equivalent concrete beam

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## Our recommendations – Other load cases

<table>
<thead>
<tr>
<th>LOAD CASE</th>
<th>Approach</th>
<th>SLS</th>
<th>ULS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demoulding</td>
<td>Analytical</td>
<td>Avoid cracks as much as possible during these stages.</td>
<td>$\sigma_{1,2} \leq f_{ctk,0.05} (\text{demoulding})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The SLS verification is independent by fibre resistant contribution</td>
<td>Minimum required bearing capacity that segments must provide for not collapsing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(since fibres act after cracking)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segment internal forces (N, V, M) are calculated</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control of $\sigma_{1,2}$ (principal tensile stress) in the most</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>critical tunnel segment section, calculated by means of Mohr’s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>circle according to the combination of N, V, M</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>Analytical</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attention to misalignment of the supports of piled tunnel segments</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{1,2} \leq f_{ctk,storage}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaluation (or estimation) of FRC fracture parameters (fRi), at the time of storage (an experimental campaign on testing samples is recommended)</td>
<td></td>
</tr>
<tr>
<td>Segments erection</td>
<td>Analytical</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Concrete mechanical and fracture properties at 28 days</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{1,2} \leq f_{ctk}$</td>
<td></td>
</tr>
</tbody>
</table>
Concluding remarks & future developments

- We follow the fib Model Code 2010, adding recommendations for a complete segmental lining design procedure
- We support a performance-based FRC design
- We help clarifying for which loading conditions or stress conditions fiber contribution can be exploited
- In doing that, we promote the use of non-linear modelling
- We consider testing fundamental for proving the design approach (not to substitute it)

- Expected future developments: analytical simplified approach (adequate for practitioners) for taking into account:
  - the fiber contribution (at least bearing capacity) against local splitting behaviour
  - the local FRC contribution in longitudinal joints

...also missing in fib bulletin 83 (2017)
Thanks you for your kind attention!

For detailed questions: giuseppe.tiberti@unibs.it; giovanni.plizzari@unibs.it

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Useful papers/books on this topic

1. ACI Committee 544 (2016), *Report on Design and Construction of Fibre Reinforced Precast Concrete Tunnel Segments*, ACI 544.7R-16, American Concrete Institute, Farmington Hills, MI, pp. 36.


