Structural use of fibre reinforced concrete in precast segments

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Lessons from Twenty Years of Application

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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

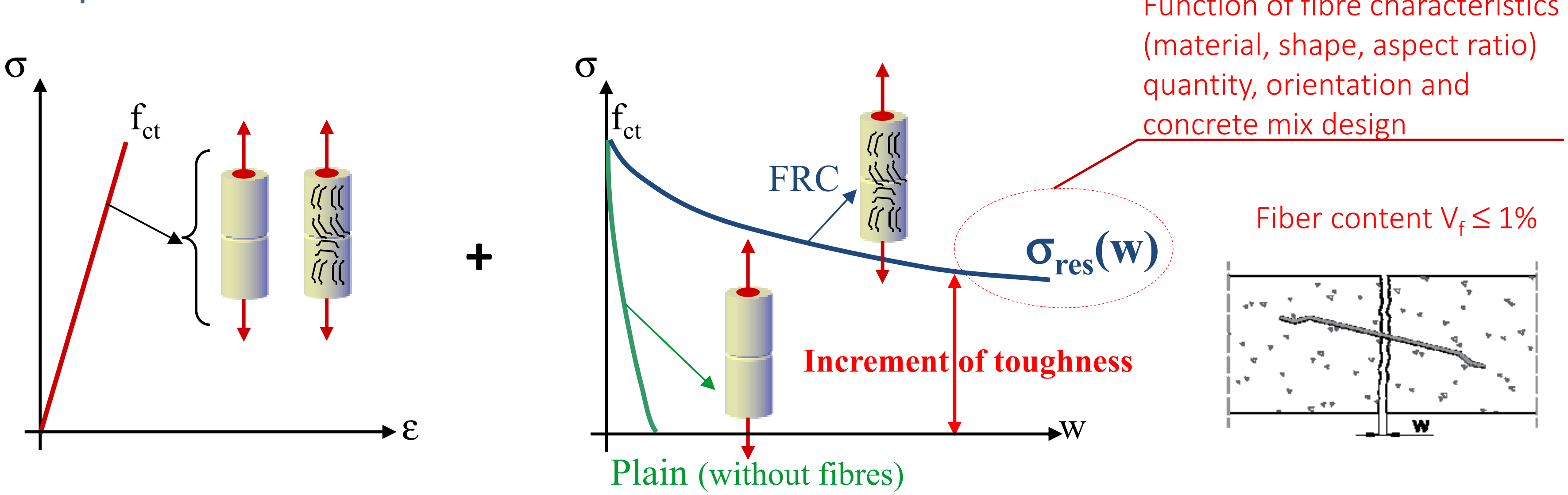
- Take advantage of more than 20 years of FRC practice in precast tunnel lining → **feedback from real cases**
- Support a **performance–based design** of FRC structural elements → all kind of fibers respecting long-term requirements
- Provide **additional design principles** to complete the existing 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

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:

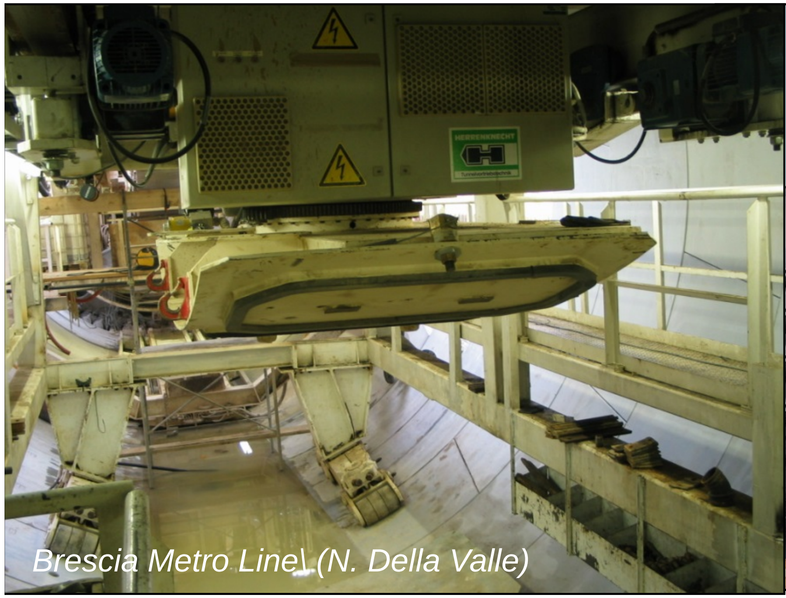
- **enhanced resistance to crack development** (post-cracking strength)
- considerable **increase of toughness** (i.e., ability to resist internal crack propagation) of **FRC considered as a composite**
- **optimized reinforcement for diffused stresses**



Precast tunnel lining

Temporary load conditions: flexural demand on tunnel segments

- Storage load condition
- Placing process / de-moulding

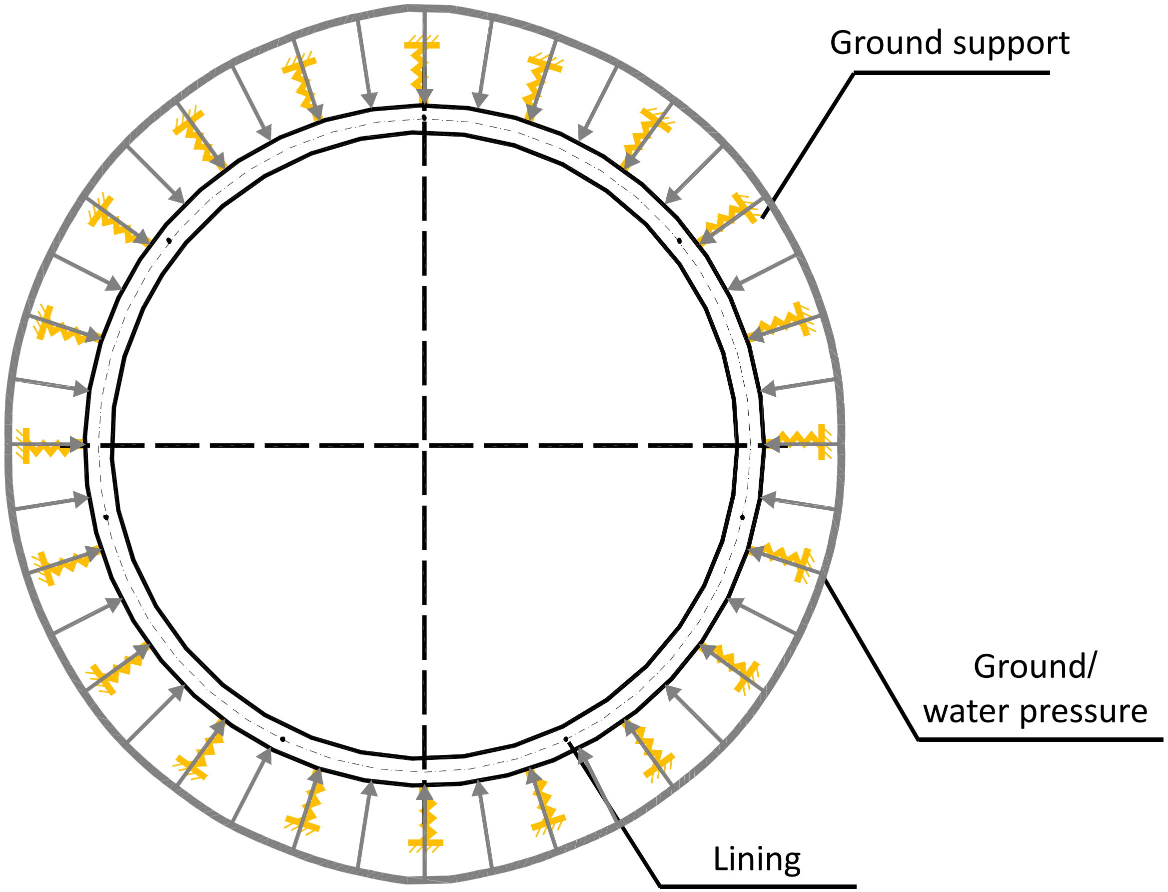


Brescia Metro Line\ (N. Della Valle)

Barcelona Metro Line

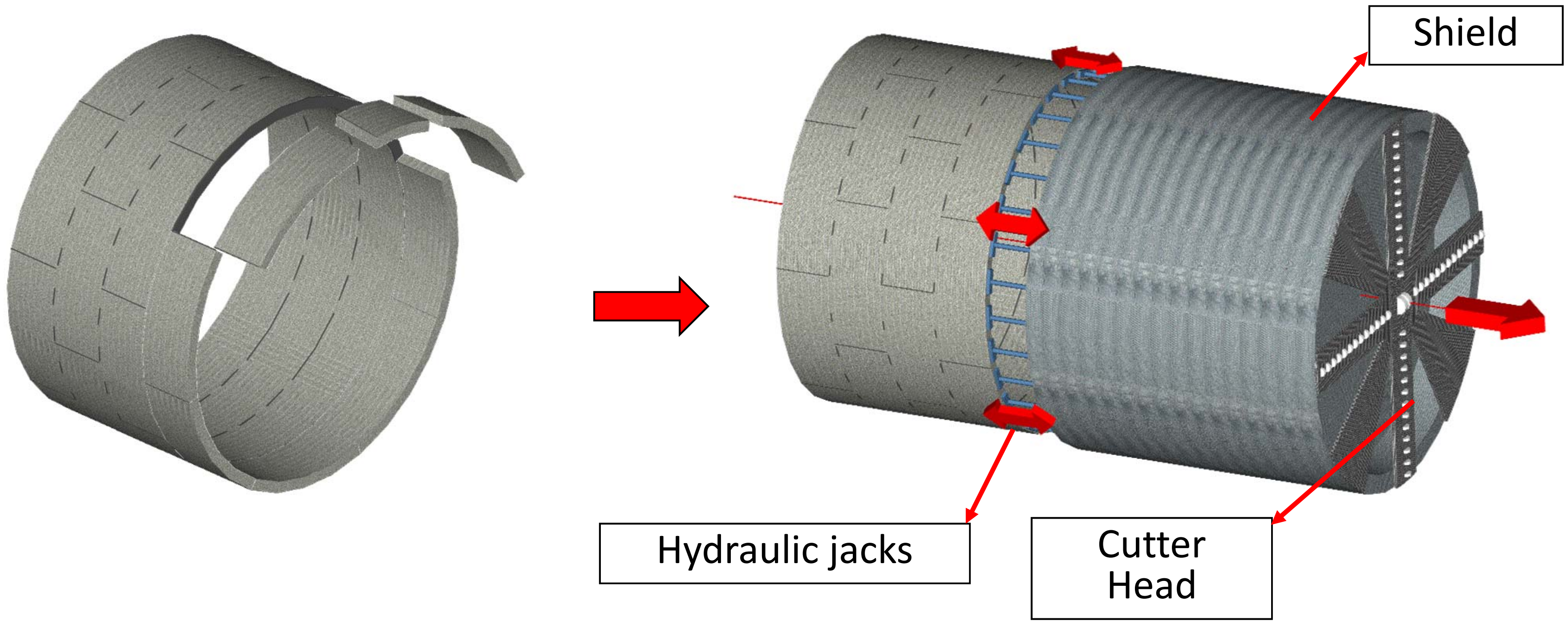
Precast tunnel lining

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

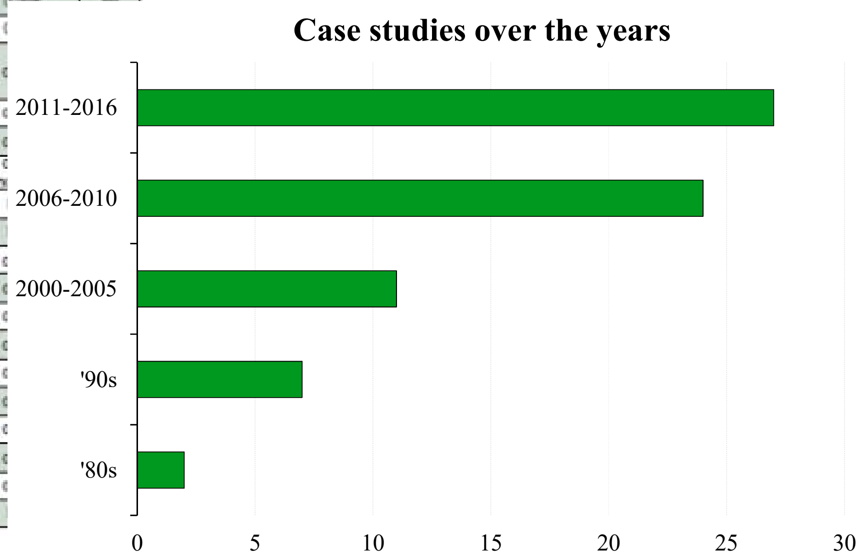
- Enhancement of structural behaviour
  - high resistance against impact loads during transportation and handling
  - stable development of splitting cracks
  - reduction of stirrups and replacement of shear reinforcement
  - reduced spalling / damages to corners
  - combines with reinforcing bars to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

TUNNEL NAME	YEAR	COUNTRY	FUNCTION	DI (M)	H (M)	DI/H (-)	TYPE OF FRC	FIBRE CONTENT (KG/m³)	FIBRE VOLUME FRACTION (%)	REBARS USED
Metrosud	1982	Italy	Subway	5.8	0.30	19.3	SFRC	N.A.*	N.A.*	No
Fanaco	1989	Italy	Water Supply	3.0	0.20	15.0	SFRC	N.A.*	N.A.*	No
Heathrow Baggage Handling	1993	England	Service	4.5	0.15	30.0	SFRC	30	0.38%	No
Heathrow Express	1994	England	Railway	5.7	0.22	25.9	SFRC	30	0.38%	No
Napoli metro	1995	Italy	Subway	5.8	0.30	19.3	SFRC	40	0.51%	No
Lesotho Highlands	1995	South Africa	Water Supply	4.5	0.30	15.0	SFRC	50	0.64%	No
Hachinger	1998	Germany	Water Supply	2.2	0.18	12.2	SFRC	N.A.*	N.A.*	No
2nd Heinenoord	1999	Netherlands	Road	7.6	0.35	21.7	SFRC	N.A.*	N.A.*	No
Jubilee Line	1999	England	Subway	4.5	0.20	22.3	SFRC	30	0.38%	No
Trasvases Manabi (La Esperanza)	2001	Ecuador	Water Supply	3.5	0.20	17.5	SFRC	30	0.38%	No
Essen	2001	Germany	Subway	7.3	0.35	20.9	SFRC	N.A.*	N.A.*	No
Sorenberg	2002	Switzerland	Gas Pipeline	3.8	0.25	15.2	SFRC	40	0.51%	No
Canal de Navarra	2003	Spain	Water Supply	5.4	0.25	21.6	N.A.*	N.A.*	N.A.*	No
Oenzberg tunnel	2003	Switzerland	Railway	10.8	0.30	36.0	N.A.*	N.A.*	N.A.*	No
Oenzberg-TBM	2003	Switzerland	Railway	11.4	0.40	28.5	SFRC	30	0.38%	Yes
Oenzberg-Shield	2003	Switzerland	Railway	11.4	0.40	28.5	SFRC	60	0.76%	No
Barcelona Metro Lin 9 - Can Zam Stretch	2003	Spain	Subway	10.9	0.35	31.1	SFRC	60	0.76%	No
Channel Tunnel Rail Link (CTRL)	2004	England	Railway	7.2	0.35	20.4	SFRC	30		
Heathrow Express Extension (HexEx)	2005	England	Railway	5.7	0.22	25.9	SFRC	30		
Metropolitan Expressway Central Circular Shinjuku Route tunnel	2005	Japan	Road	10.9	0.45	24.2	SFRC	53		
San Vicente	2006	USA	Water Supply	3.2	0.18	17.8	SFRC	30		
Heathrow – SWOT	2006	England	Water Supply	2.9	0.20	14.5	SFRC	30		
Barcelona Metro Line 9 - Stretch I	2006	Spain	Subway	8.4	0.32	26.3	SFRC	30 and 25		
Lötschberg	2007	Switzerland	Temporary pilot	4.5	0.22	20.5	SFRC	N.A.*		
Beacon Hill Tunnels	2007	USA	Road	6.7	0.30	22.3	N.A.*	N.A.*		
Hofoldinger Stollen	2007	Germany	Water Supply	2.9	0.18	16.1	SFRC	40		
Madrid Metro	2007	Spain	Subway	8.4	0.30	28.0	SFRC	25		
Gold Coast Desalination Plant	2008	Australia	Water Supply	3.4	0.20	17.0	SFRC	35		
Big Walnut Sewer	2008	USA	Waste Water	3.7	0.23	16.1	SFRC	35		
Heathrow – PiccEx	2008	England	Subway	4.5	0.15	30.0	SFRC	30		
Heathrow Express Ext. Tunnel to T5	2008	England	Railway	5.7	0.22	25.9	SFRC	30		
Hobson Bay	2009	New Zealand	Waste Water	3.7	0.25	14.8	SFRC	40		
Sao Paulo Metro Line 4	2009	Brazil	Subway	8.4	0.35	24.0	SFRC	35		
Copenhagen District Heating Tunnel	2009	Denmark	Water Supply	4.2	0.30	14.0	SFRC	35		
Docklands Light Railway (DLR) Extension	2009	England	Railway	5.3	0.25	21.2	SFRC	N.A.*		

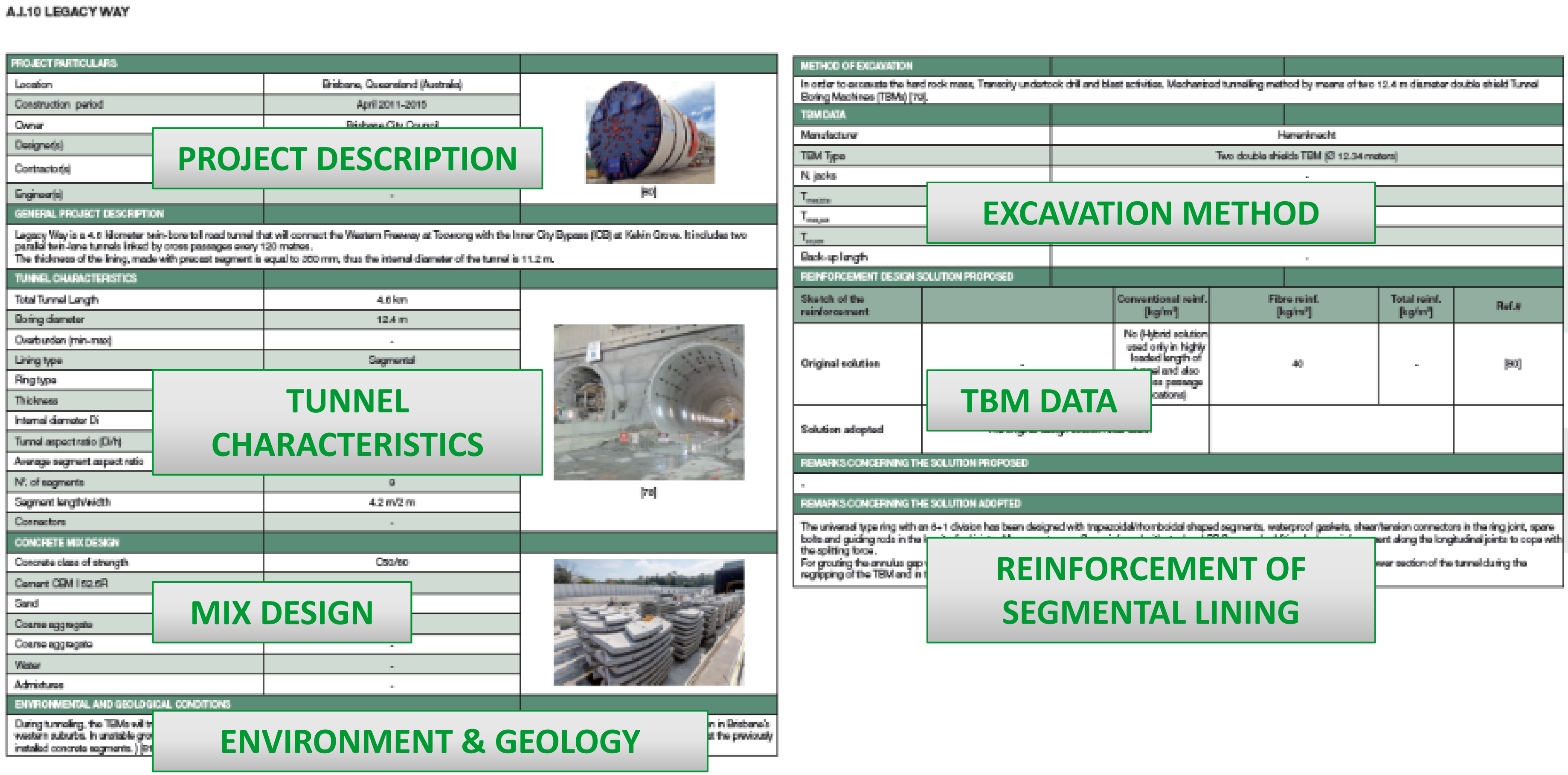
- 73 case histories
  - 37 in America, Asia, Australia
  - 36 in Europe
- From the '90s to 2016 (with two cases in the 80's, in Italy)



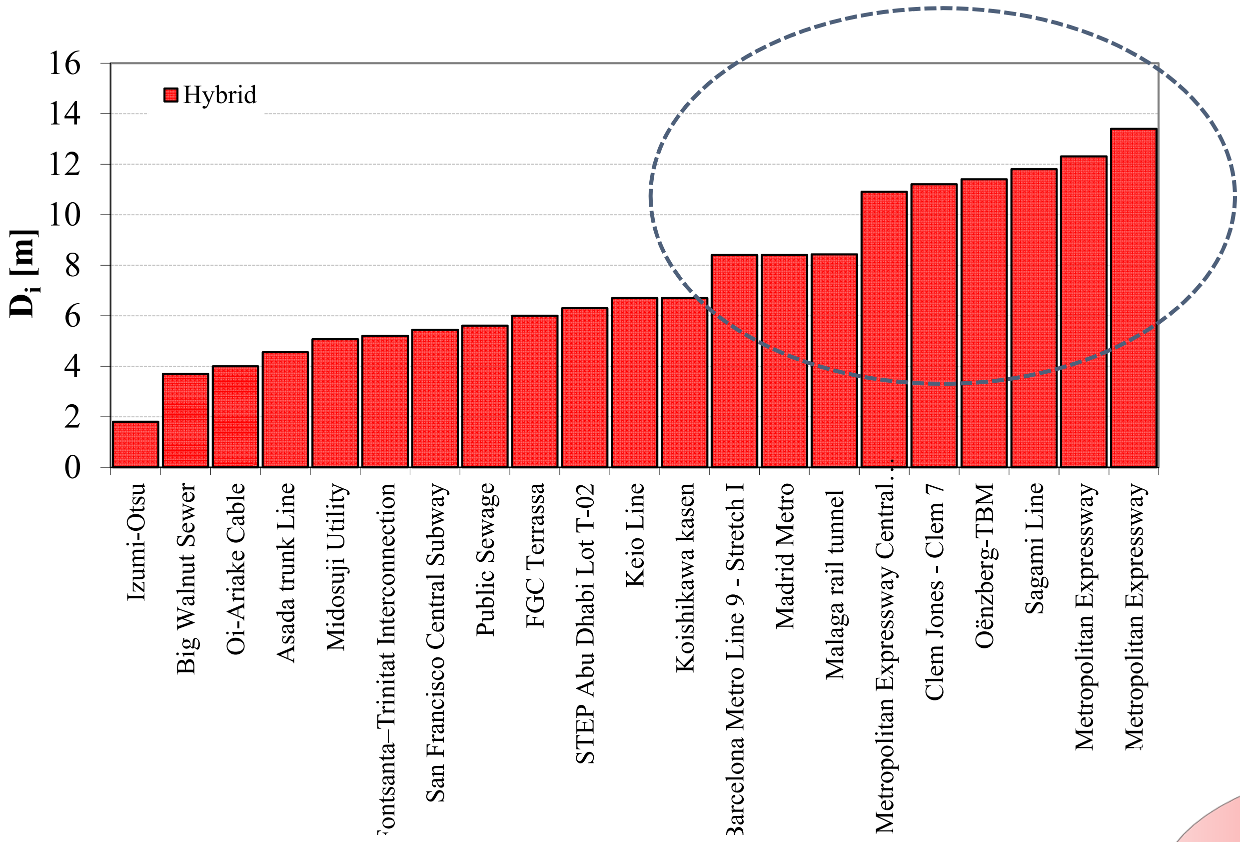
Lessons from Twenty Years of Application
ITA WG02 – Tiberti, Plizzari, Chiriotti

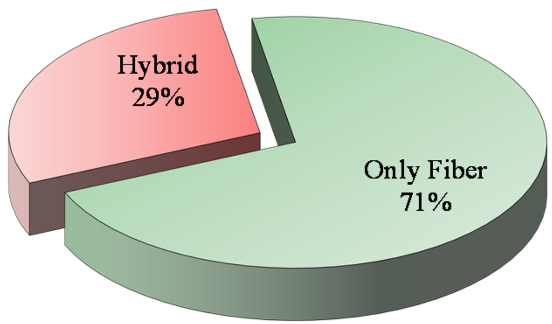
Collected case histories

16 case histories documented in detail

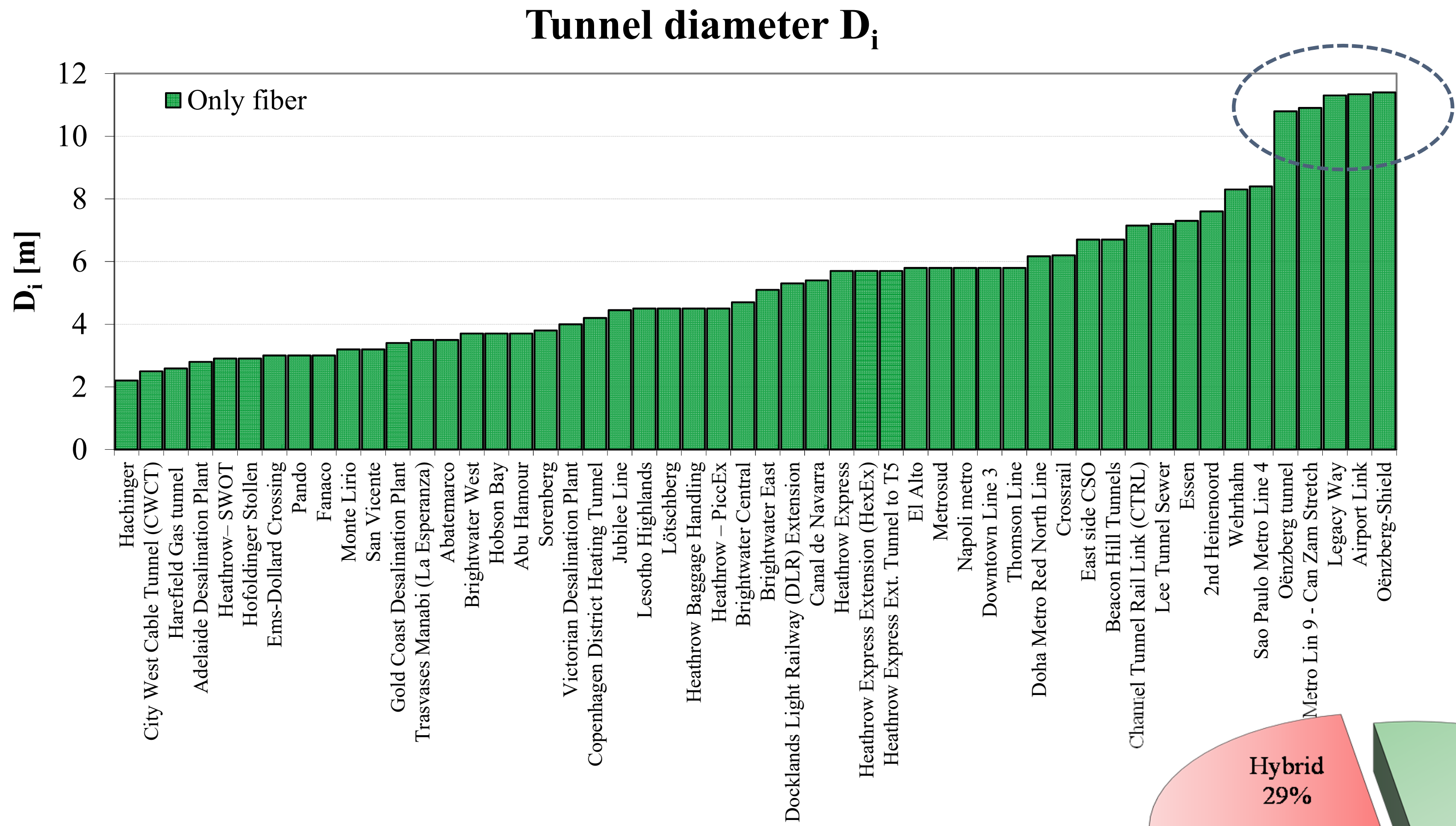


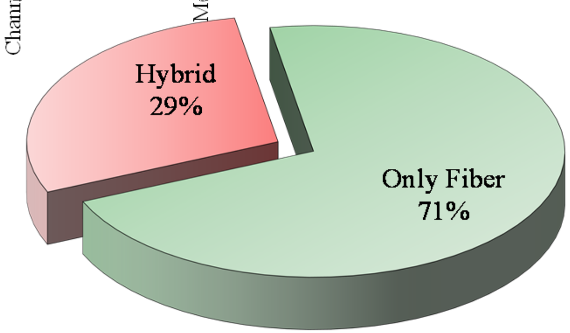
Collected case histories





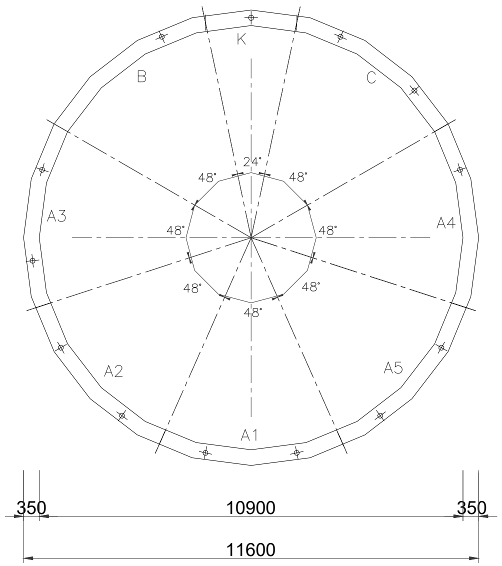
Collected case histories





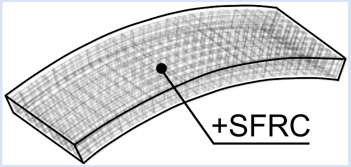
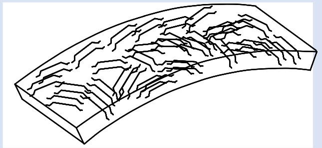
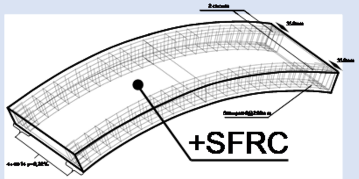
Barcelona Metro Line 9 (2004-2005)

TUNNEL CHARACTEERISTICS	
Total Tunnel Length	41.4 km
Boring diameter /TBM	12.1 m / EPB
Overburden (min-max)	30-70 m
Lining type	Segmental
Ring type	Universal ring
Thickness	0.35 m
Internal diameter D_i	10.9 m
Tunnel aspect ratio (D_i/h)	31.14
Average segment aspect ratio	13.88
No. of segments	7 segments+1 key segment
Segment length/width	4.7 m/1.8 m



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

Barcelona Metro Line 9 (2004-2005)

Reinforcement design solution studied	Rebars [kg/m³]	Fibres [kg/m³]	Total [kg/m³]	Reference
Original solution  (structural contribution of fibres not considered)	97	25 SFRC 50/1.0 L_f/ϕ_f=50 $f_{t,fibre}$=1100 MPa	122	Gettu et al. 2004
Experimental solution 01 	---	60 SFRC 50/1.0 L_f/ϕ_f=50 $f_{t,fibre}$=1100 MPa	60	Gettu et al. 2004
Experimental solution 02  	46 (in 2 chords along the longer segment sides)	25 SFRC 50/0.75, L_f/ϕ_f = 66.67, $f_{t,fibre}$=1100 MPa	71	Plizzari et al. 2005

Main lessons learned

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)

Legacy Way Tunnel, Australia (2011-2015)

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

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)

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

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. liningl final stage)

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

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

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

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

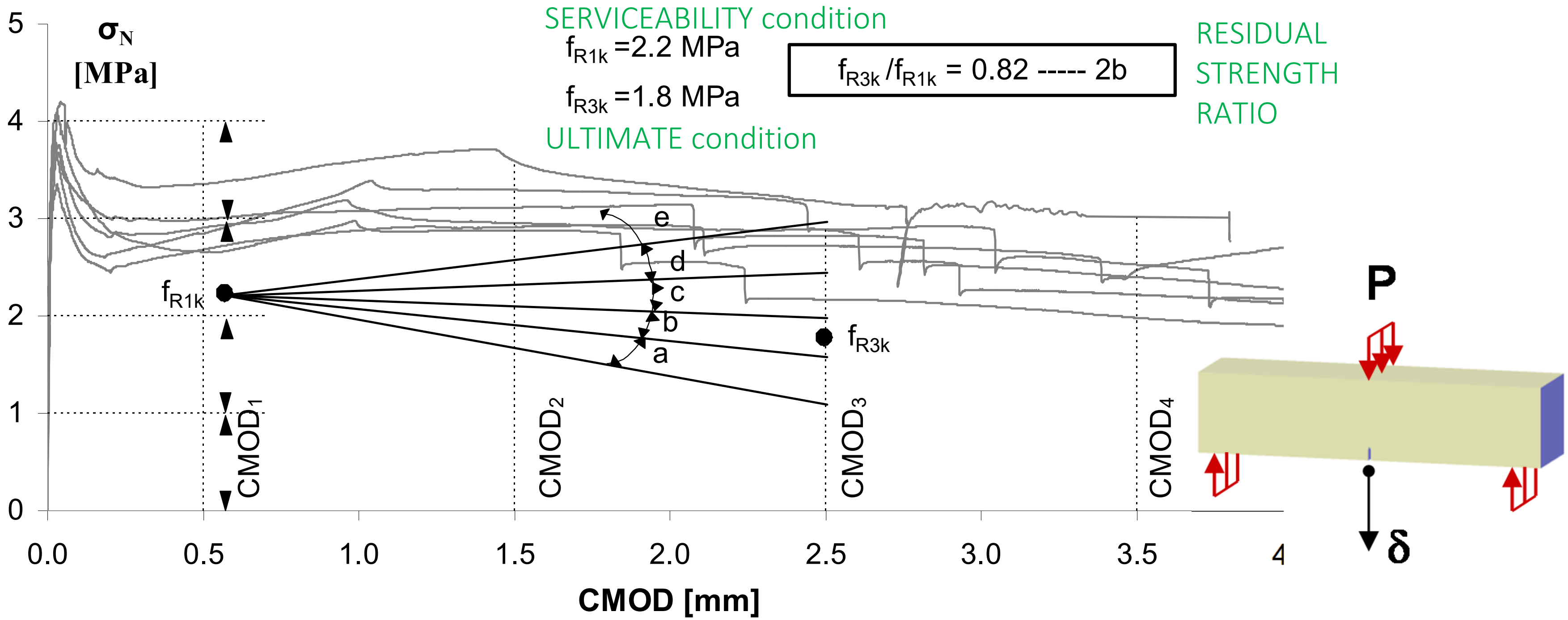
- The **flexural demand** in tunnel segments is a key-point for evaluating the possibility to completely substitute traditional rebars with FRC
- Localized bending stresses can be due to acting **ground loads** or can be generated by **contact irregularities** occuring during the **TBM thrust phase**

Recom.

- 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 (*)**



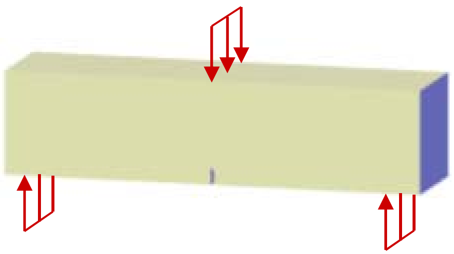
CMOD = Crack Mouth Opening Displacement, from a 3-point bending test on a notched beam

f_{Rjk} = characteristic residual flexural tensile strength corresponding to CMODj

(*) Then published in 2012

Existing standards and recommendations

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



Material behavior on small samples)

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

FRC precast tunnel segments

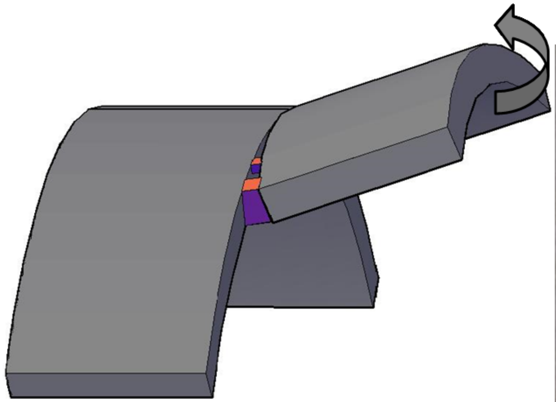
(*) refers only to the design Steel Fibre Reinforced Concrete (SFRC)

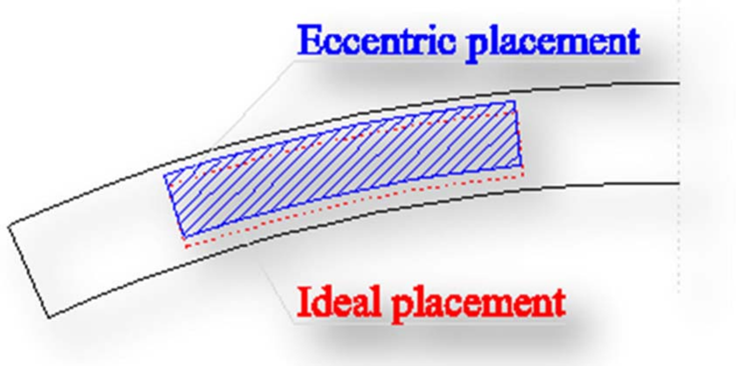
NOTE: fib bulletin n.83, WP 1.4.1, *Precast tunnel segments in fibre-reinforced concrete* (2017), appears one year after ITA WG02 publication n.16

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.).



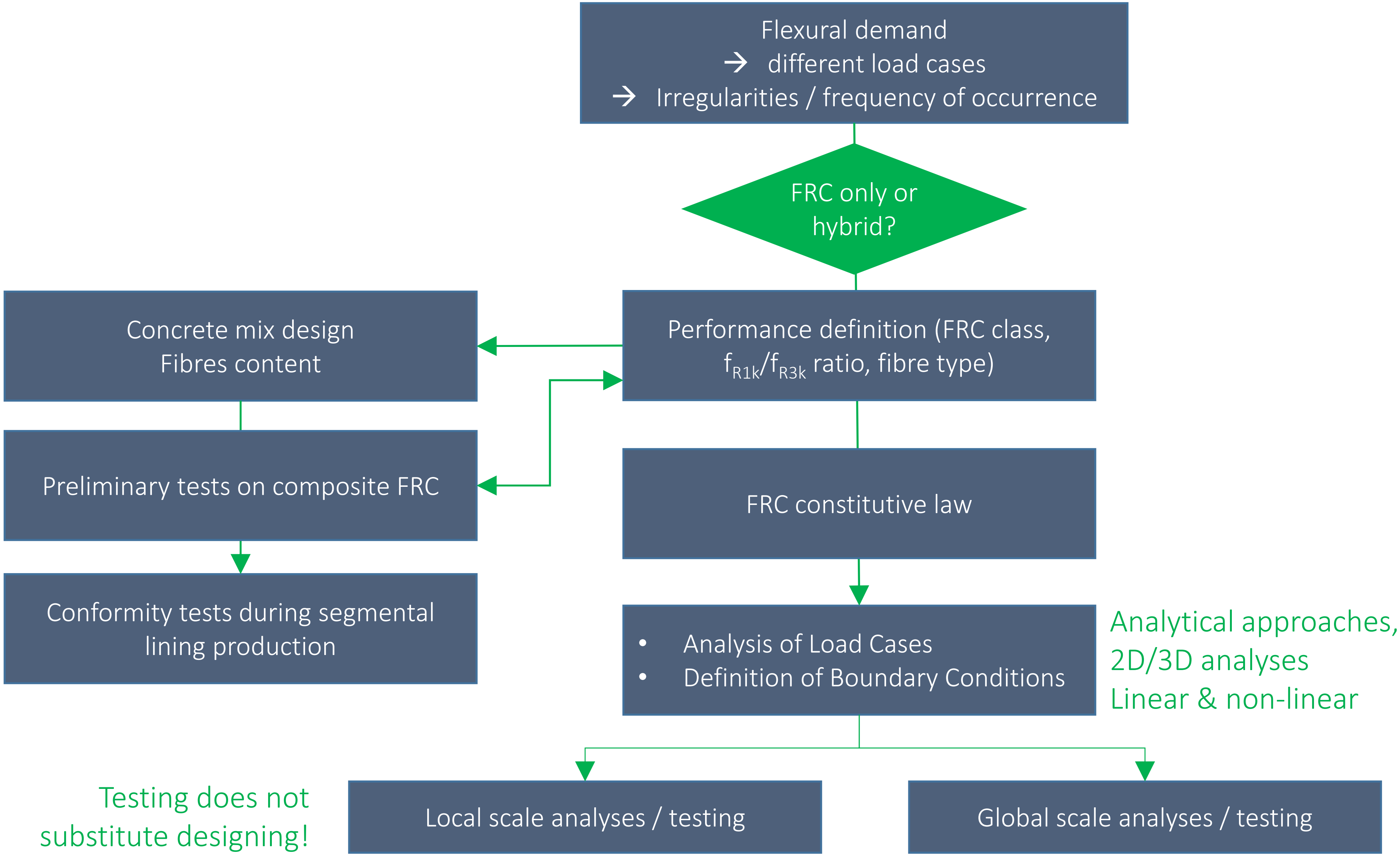


Post-cracking residual strengths **can be exploited during these stages** even if no specific recommendations are given by Model Code 2010

→ 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

Our recommendations – General approach



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

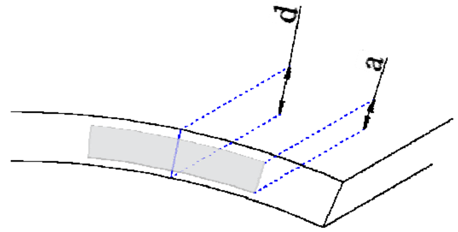
Our recommendations – Ex. TBM thrust phase

Identification of issues

(I) Thrust Force

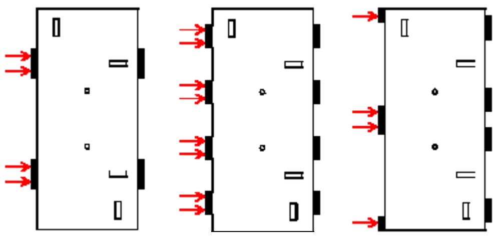
- ground conditions
- tunnel overburden
- number of shoes

(II) Ratio governing local splitting behavior



TBM THRUST PHASE

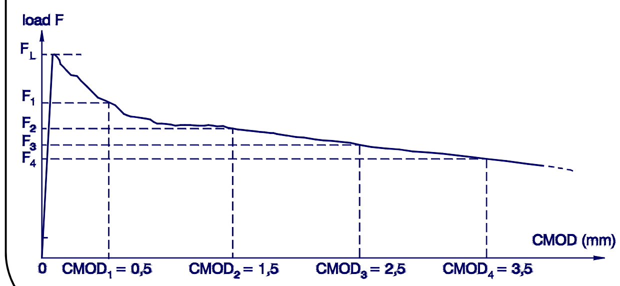
(III) Segment configuration



(IV) Irregularities

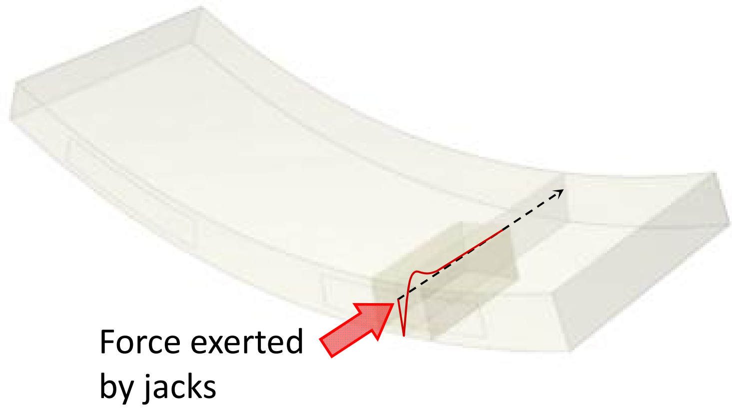
- eccentric placement of thrust shoes
- un-even support

(V) FRC performance



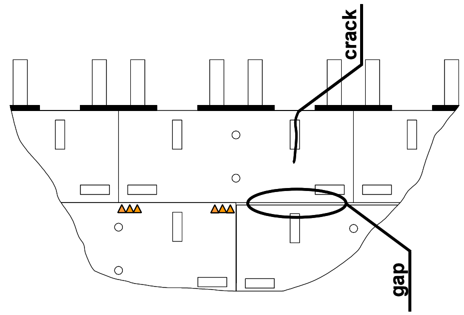
Our recommendations – Ex. TBM thrust phase

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**

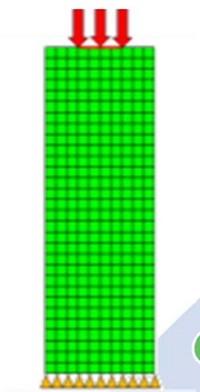
ANALYSIS OF GLOBAL BEHAVIOUR : consider possible irregularities of contact (e.g., eccentricity of thrust shoes, uneven support, etc.)

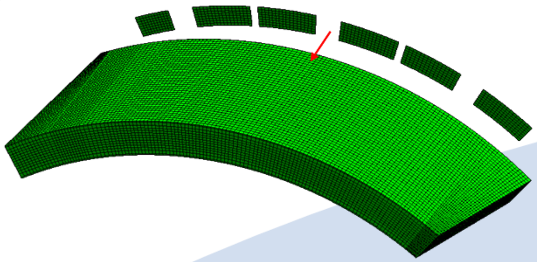


- **FRC tunnels segments** (fibres only) more **vulnerable to irregular load conditions** → **increased localized stresses** → **attention** to the **type** and **frequency of occurrence** of such **irregularities** → **analysis with different boundary conditions**

Our recommendations – Step-by-step analyses

Proposed procedure

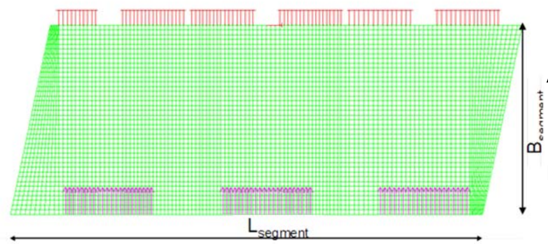


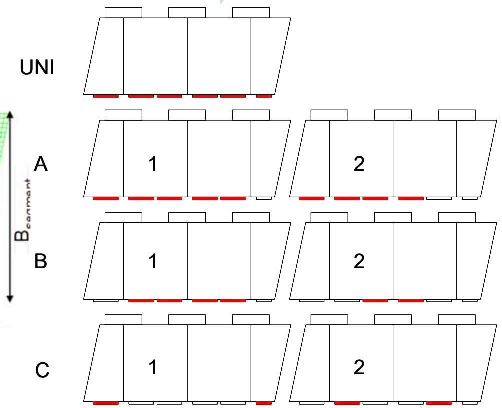


Advanced segment 3D model – non-linear

Simplified segment 2D model – non-linear

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





Evaluation of local splitting stresses

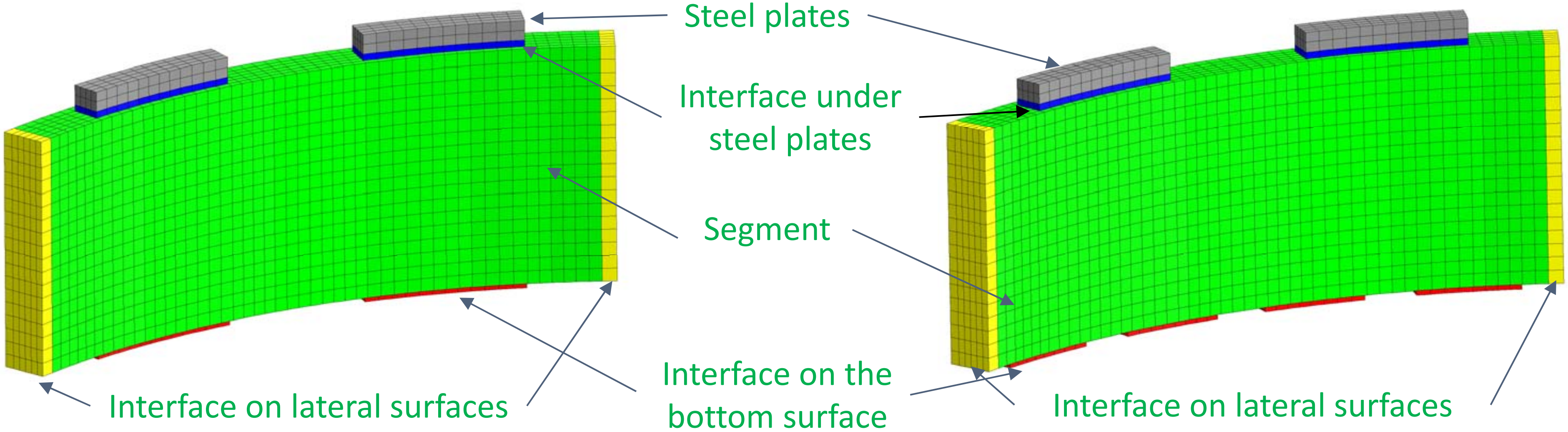
Evaluation of local and global mechanism with respect to possible use of FRC.
Capture the post-cracking FRC contribution.
Asses the maximum crack width (if any) at service condition (with crack control due to fibers)

Our recommendations – Modelling

3D advanced numerical model

Configuration A

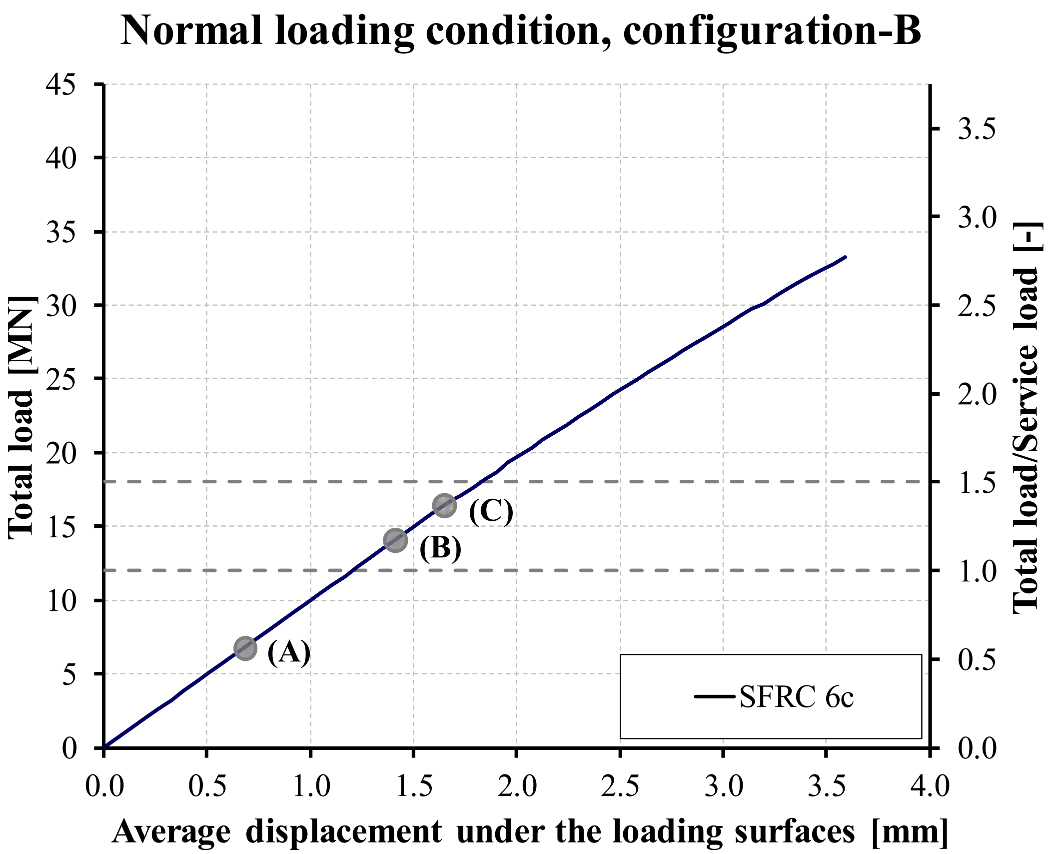
Configuration B

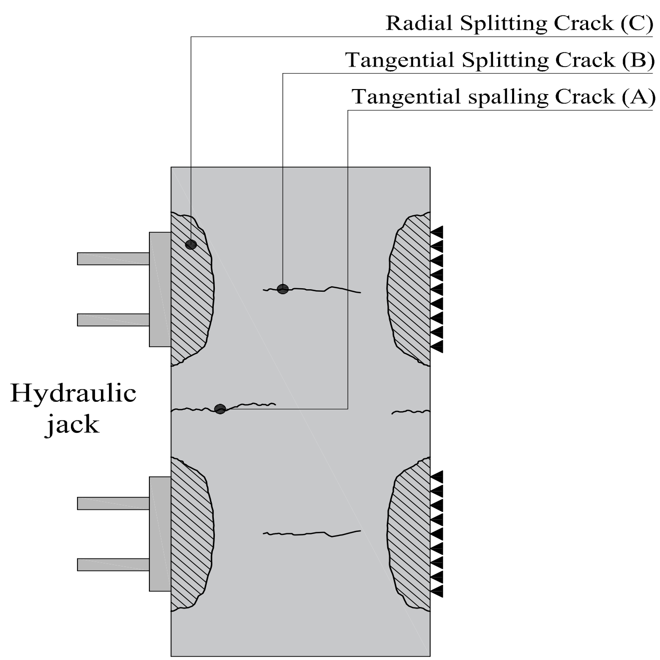


Not only a complex 3D geometry, but
a **post cracking constitutive law**
reproducing the FRC behaviour

Our recommendations – Modelling

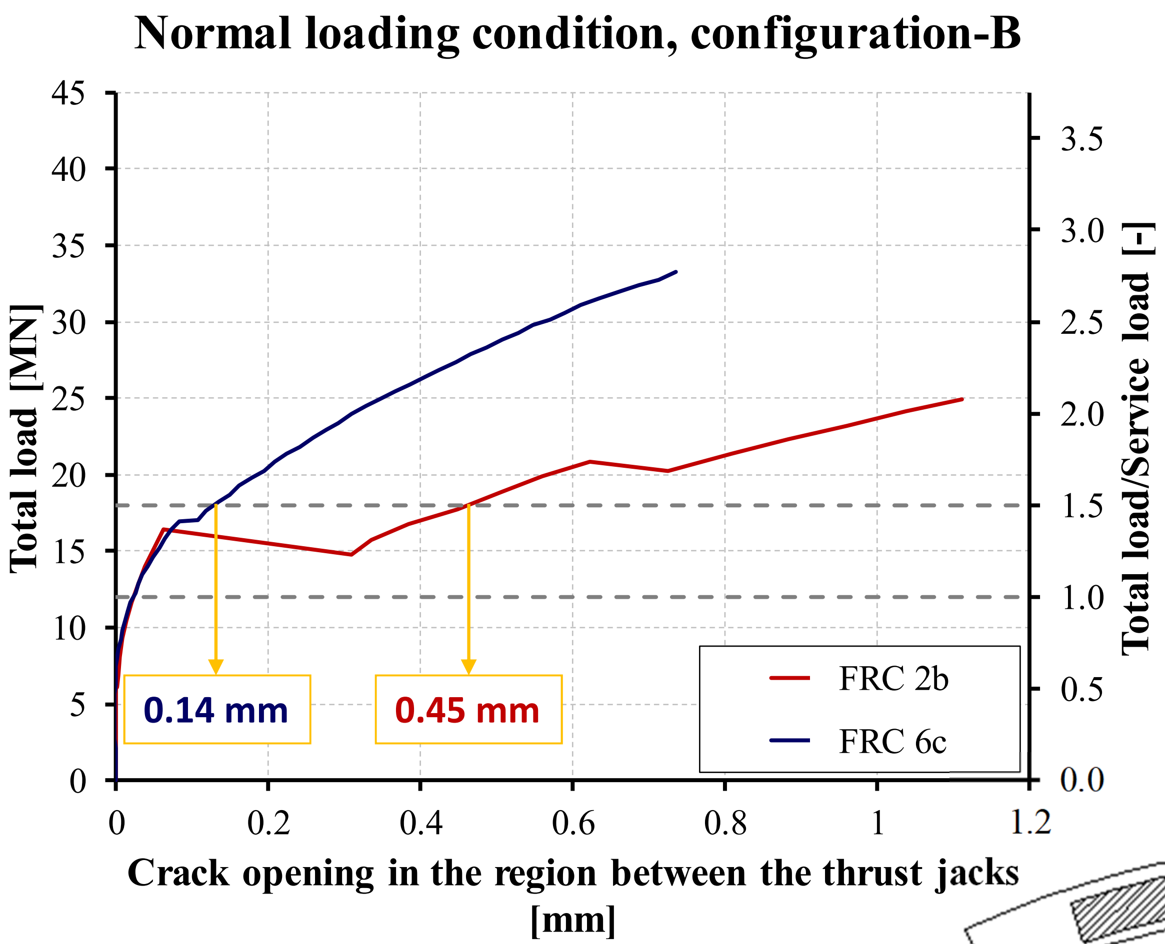
Global behavior: bearing capacity & development of cracks



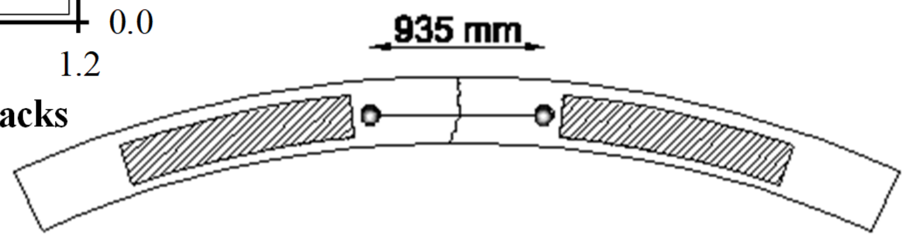


Our recommendations – Modelling

<u>Local behavior</u>: influence of FRC performance on spalling crack



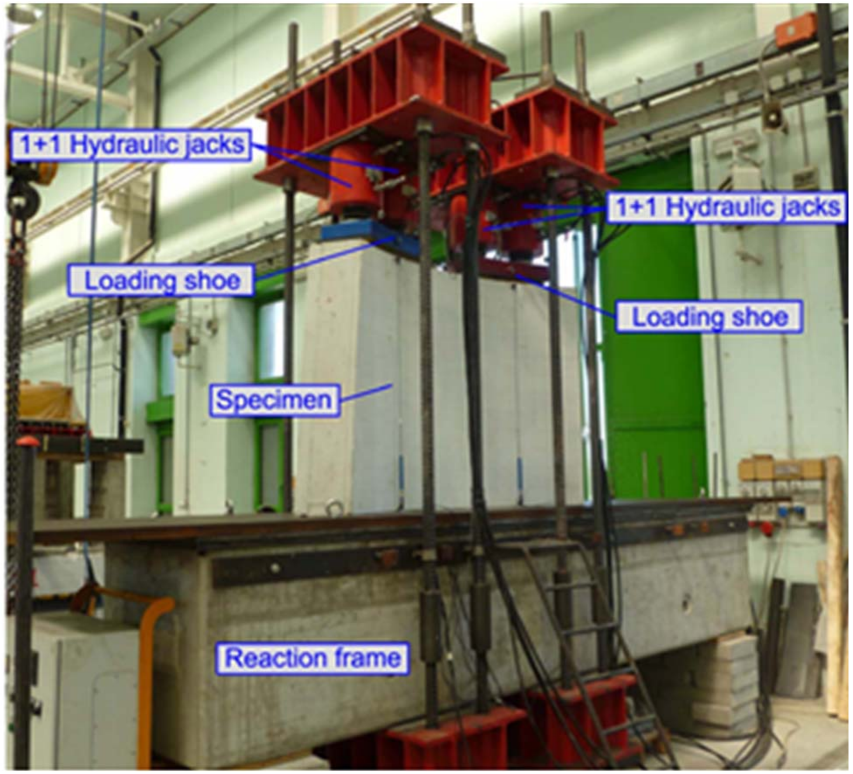
FRC 2b exhibits a crack opening of about **three times** of that shown by FRC 6c at 1.5 times the service load



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**



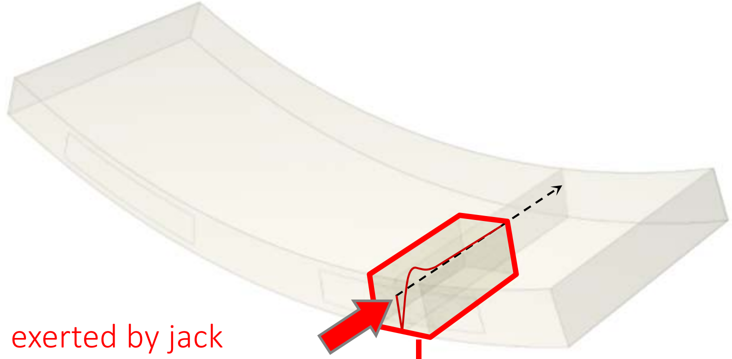
FULL SCALE TEST: **local behavior** and **boundary conditions** of the segment are considered

Our recommendations – Testing

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

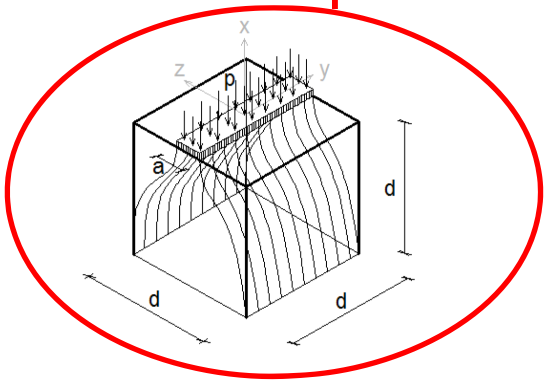
Thrust phase:

high compressive stresses on a small area



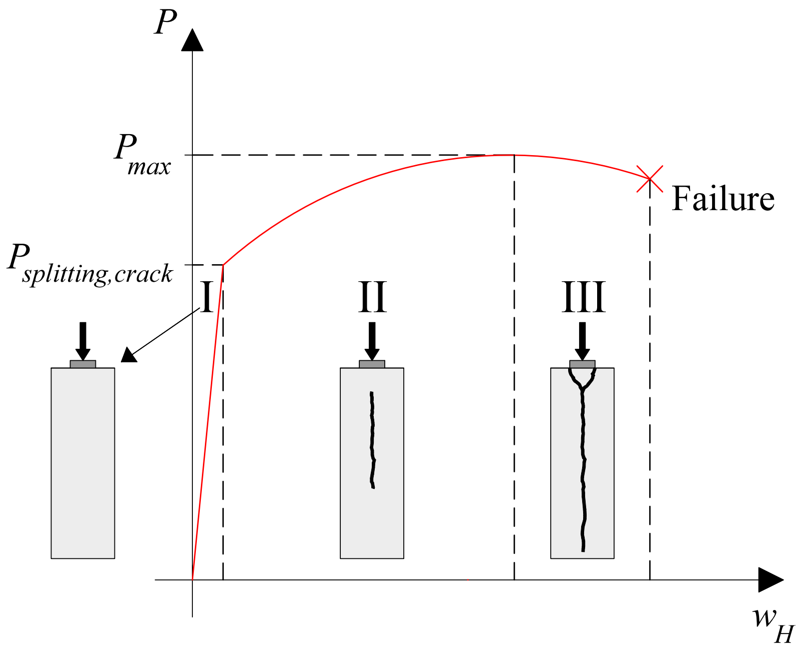
Proper specimens dimensions and configurations

were adopted in order to study this local behavior



Our recommendations – Testing

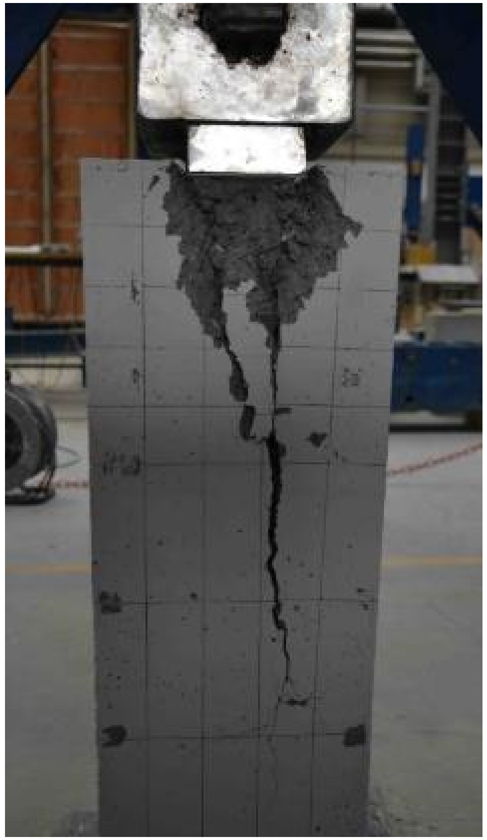
SMALL SCALE TEST - typical behavior of **FRC samples** having **adequate** post-cracking **strengths (FRC class 2e or higher)**



I: Linear elastic phase of concrete

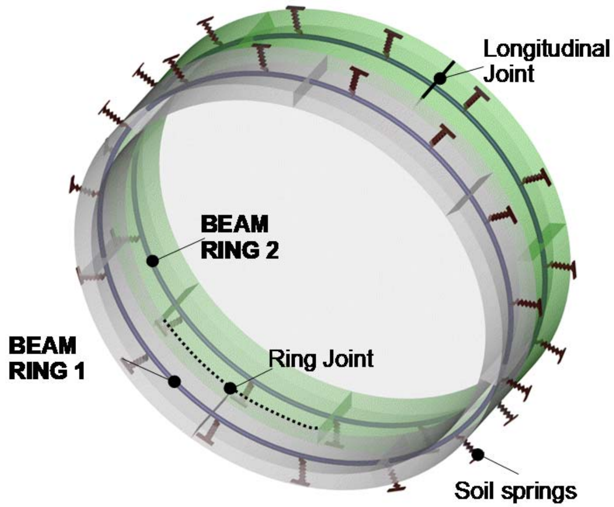
II: Crack formation and propagation

III: Concrete wedge formation and failure



Our recommendations – Modelling joints

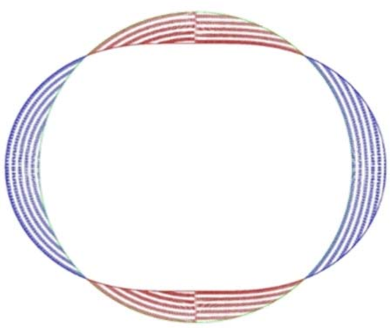
Long term condition – Consider the interaction between 2 adjacent rings for FRC segments



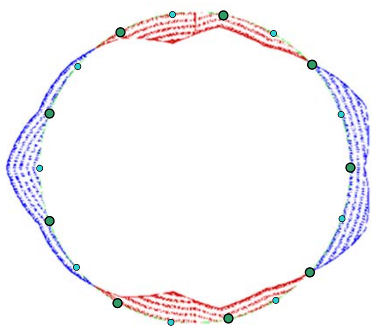
JOINTS (between perfect continuity and perfect hinge) → rotational spring in a bedded -beam model

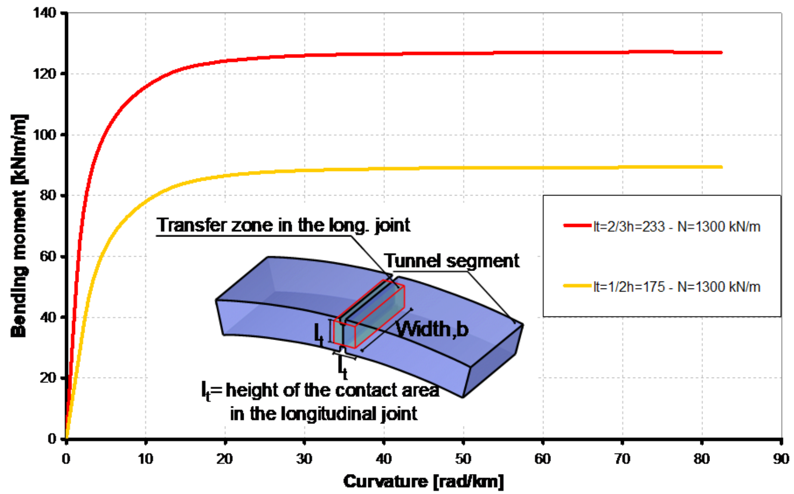
Acting load → transfer zone (contact area) → deformations → rotation by integrating the curvature over the depth of the contact area → stiffness of the rotational spring by calculating the bending moment vs. rotation relationship of the equivalent concrete beam

Without joints

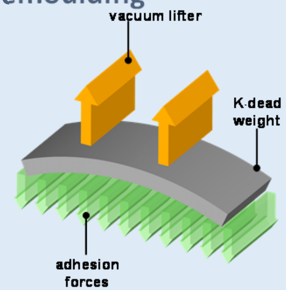
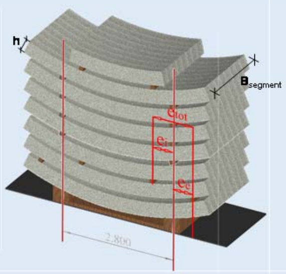
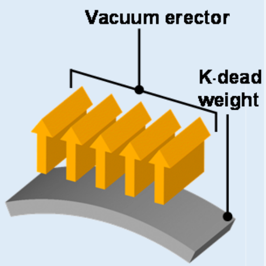


With joints





Our recommendations – Other load cases

LOAD CASE	Approach	SLS		ULS
Demoulding 	Analytical	Avoid cracks as much as possible during these stages. The SLS verification is independent by fibre resistant contribution (since fibres act after cracking) Segment internal forces (N, V, M) are calculated Control of σ1,2 (principal tensile stress) in the most critical tunnel segment section, calculated by means of Mohr's circle according to the combination of N, V, M	$\sigma_{1,2} \leq f_{ctk,0.05}(demoulding)$	Minimum required bearing capacity that segments must provide for not collapsing
Storage 	Analytical		Attention to misalignment of the supports of piled tunnel segments $\sigma_{1,2} \leq f_{ctk,storage}$ Evaluation (or estimation) of FRC fracture parameters (fRi), at the time of storage (an experimental campaign on testing samples is recommended)	
Segments erection 	Analytical		Concrete mechanical and fracture properties at 28 days $\sigma_{1,2} \leq f_{ctk}$	

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

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.
2. Caratelli A., Meda A., Rinaldi Z. (2012), *Design according to MC2010 of a fibre-reinforced concrete tunnel in Monte Lirio*, Panama, Structural Concrete, V.13, No. 3, 2012, pp. 166–173.
3. Di Prisco M., Plizzari G.A., Vandewalle L. (2009), *Fibre reinforced concrete: new design perspectives, Materials and Structures*, ISSN: 1359-5997, DOI 10.1617/s11527-008-9385-7, Vol. 42, No. 9, pp. 1261-1281,.
4. EN-14651 (2005), *Test method for metallic fibre concrete - Measuring the flexural tensile strength (limit of proportionally (LOP), residual),* European Committee for Standardization, 18pp.
5. FIB (2012), *fib Model Code Final Complete Draft*, fib bulletins 65 and 66, March 2012-ISBN 978-2-88394-105-2 and April 2012-ISBN 978-2-88394-106-9.
6. fib Working Party 1.4.1 (2017), *Tunnels in fiber reinforced concrete*, fib Bulletin 83, “ Precast tunnel segments in fibre-reinforced concrete”, ISSN 1562-3610, ISBN 978-2-88394-123-6, October 2017
7. Kasper T., Edvardsen C., Wittneben G., Neumann D. (2008), *Lining design for the district heating tunnel in Copenhagen with steel fibre reinforced concrete segments*, Tunnelling and Underground Space Technology 23, pp. 574-587.
8. AFTS Recommendation n.GT38R1A1 (2013), *Design, dimensioning and execution of precast steel fibre reinforced concrete arch segments*, Tunnels et espace souterrain, n. 238, July-August, 2013, pp. 312-324
9. Tiberti G., Conforti A., Plizzari G.A. (2015), *Precast segments under TBM hydraulic jacks: experimental investigation on the local splitting behaviour*. Tunnelling and Underground Space Technology, Vol. 50, pp. 438-450, doi: 10.1016/j.tust.2015.08.013.
10. Conforti, A., Tiberti, G., Plizzari, G.A., Caratelli, A., Meda, A. (2017). “Precast tunnel segments reinforced by macro-synthetic fibers”, Tunnelling and Underground Space Technology, Vol. 63, March 2017, ISSN 0886-7798, pp. 1-11, doi: http://dx.doi.org/10.1016/j.tust.2016.12.005.
11. Conforti, A., Tiberti, G., Plizzari, G.A. (2016). “Combined effect of high concentrated loads exerted by TBM hydraulic jacks”, Magazine of Concrete Research, Vol. 68, Issue 21, November 2016, ISSN: 0024-9831, pp. 1122-1132, doi: http:// dx.doi.org/10.1680/jmacr.15.00430.