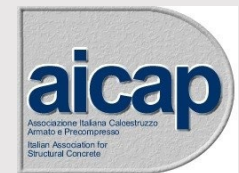


RIVESTIMENTI IN ANELLI DI CONCI PREFABBRICATI DI GALLERIE REALIZZATE CON TBM INDUSTRIALIZZAZIONE E SOSTENIBILITÀ

Brescia, 16 novembre 2023

Aula Magna Ingegneria - Università di Brescia (UniBs)

Organizzato da:



Associazione italiana
cemento armato e
precompresso



Collegio dei
Tecnici della
industrializzazione
Edilizia



**Società
Italiana
Gallerie**
Italian Tunnelling Society

Giovanni Plizzari, Giuseppe Tiberti, Ivan Trabucchi
DICATAM, Università degli Studi di Brescia
giovanni.plizzari@unibs.it

Con il patrocinio di:



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OUTLINES

- 1. INTRODUCTION**
- 2. LOCAL BEHAVIOR UNDER TBM THRUST SHOES**
- 3. EXPERIMENTAL TESTS ON TUNNEL SEGMENTS**
- 4. SEGMENTS OPTIMIZATION**

INTRODUCTION

Limit states

Ultimate limit states (**ULS**) are those associated with collapse or **failure**, and generally govern the strength of the structure or structural members because they correspond to the maximum load carrying resistance of such member

Climate limit states (**CLS**) are those associated with collapse of the **environment**, and generally govern the **temperature** of the **planet** because they correspond to the maximum **carbon dioxide** resistance of such **planet**

How to achieve the Climate Limit States

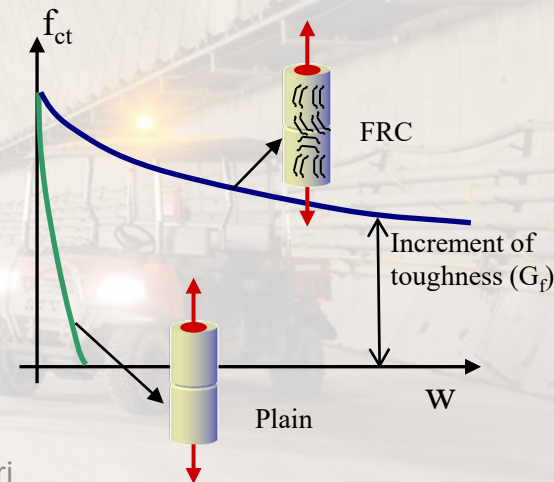
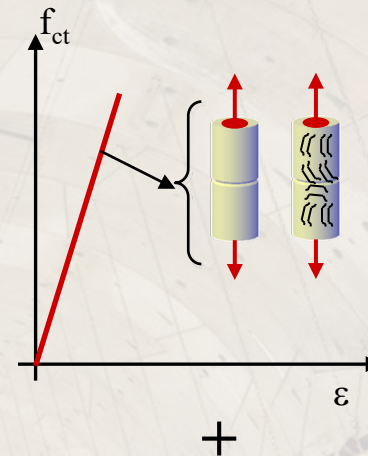
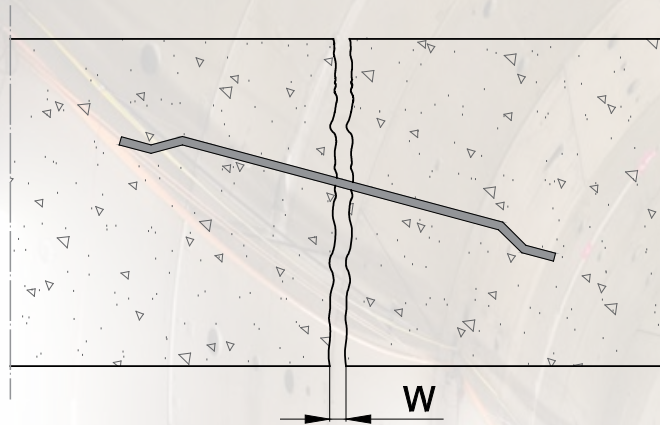
- Use low-carbon material
- Reduce the not-renewable energy for the production
- Reduce the transportation
- Enhance the durability (for the reduction of maintenance costs)
- Reduce the material use → *optimized design MATERIAL + STRUCTURE*
- *etc..*

Fibre Reinforced Concrete (FRC)



Fibre Reinforced Concrete (FRC)

Short fibres, having a straight or deformed shape, uniformly dispersed in the concrete matrix



Main advantages of FRC:

- obtain **post-cracking residual** properties
- **Smaller crack opening**
- Higher **impact loading** resistance
- Better **fatigue** resistance

Fibres for concrete

They differ according to the type of shape and material they are made of:

• Steel fibers



• Aluminum fibers



• Glass fibers



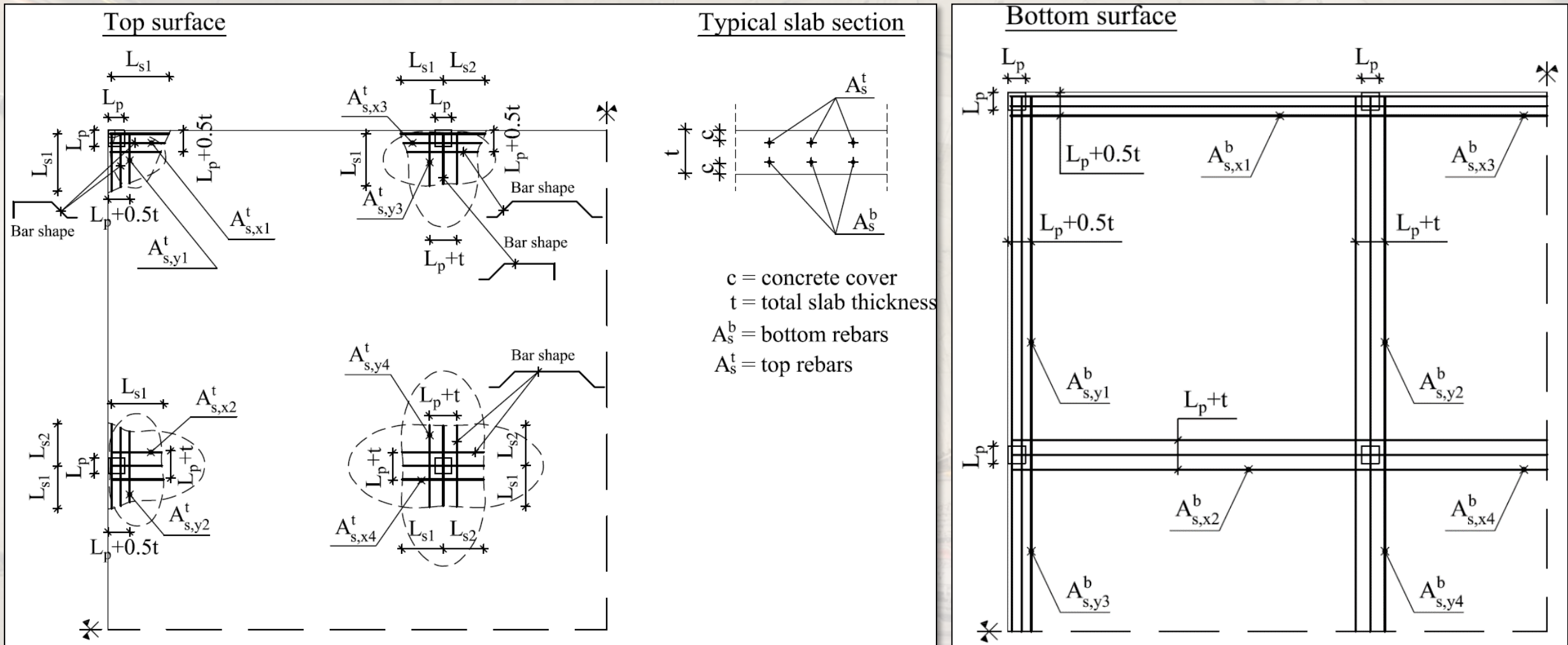
• Carbon fibers



• Plastic fibers

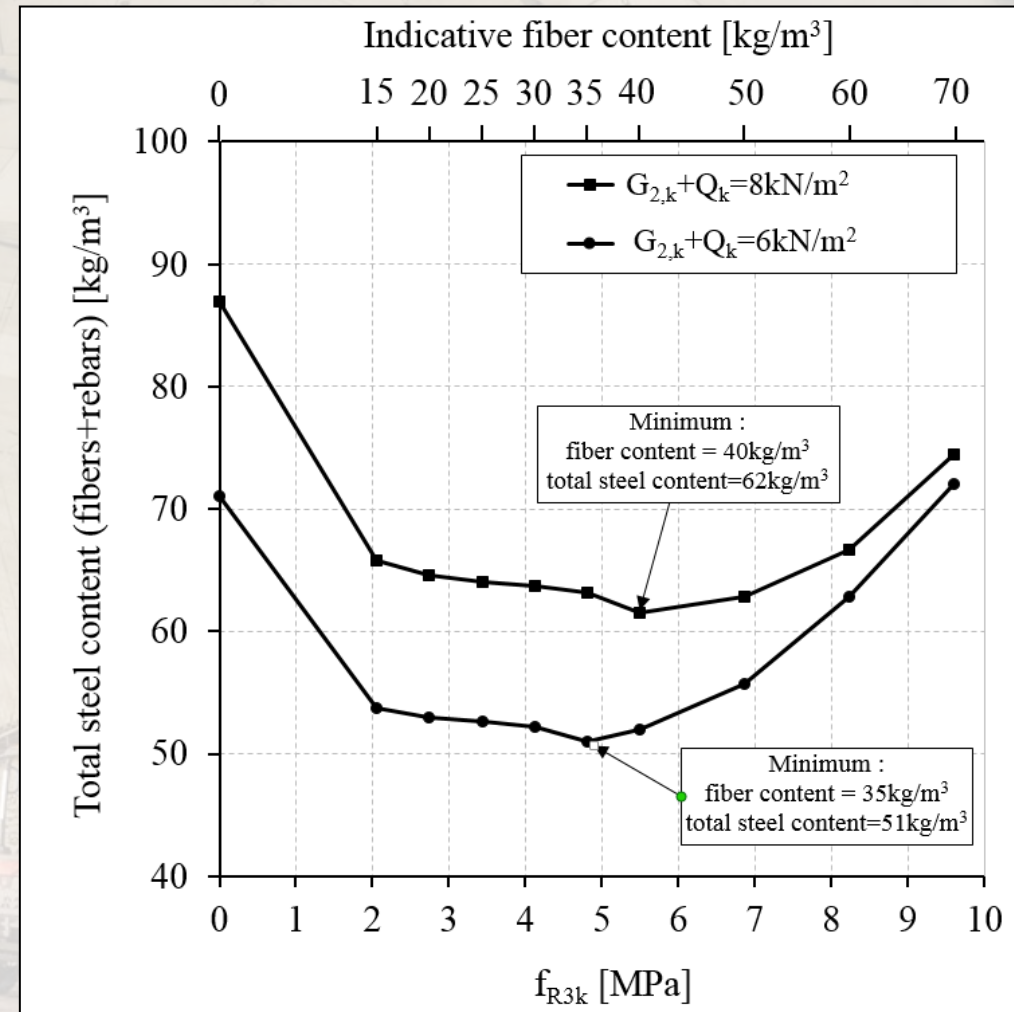


Optimized Reinforcement for elevated slabs



Optimized Reinforcement for elevated slabs

The **optimized reinforcement** depends on the **FRC performance** as well as on the properties of the applied loads (i.e., load value, load distribution, etc.)



Italian Guidelines for FRC

20-2-2018 Supplemento ordinario n. 8 alla GAZZETTA UFFICIALE Serie generale - n. 42


Per valori intermedi è ammessa una interpolazione lineare.
Nel caso in cui sia richiesta una valutazione in tempi diversi da $t \rightarrow \infty$ del coefficiente di viscosità questo potrà essere valutato secondo modelli tratti da documenti di comprovata validità di cui al Capitolo 12.

11.2.11. DURABILITÀ
Per garantire la durabilità delle strutture in calcestruzzo armato ordinario o precompresso, esposte all'azione dell'ambiente, si devono adottare i provvedimenti atti a limitare gli effetti di degrado indotti dall'attacco chimico, fisico e quelli derivanti dalla corrosione delle armature e dai cicli di gelo e disgelo.
A tal fine, valutare opportunamente le condizioni ambientali del sito ove sorgerà la costruzione o quelle di impiego, conformemente alle indicazioni della tabella 4.1.311 delle presenti norme, in fase di progetto dovranno essere indicate le caratteristiche del calcestruzzo da impiegare in accordo alle *Linee Guida sul calcestruzzo strutturale* edite dal Servizio Tecnico Centrale del Consiglio Superiore dei Lavori Pubblici facendo anche, in assenza di analisi specifiche, utile riferimento alle norme UNI EN 206 ed UNI 11104. Inoltre devono essere rispettati i valori del copriferro nominale di cui al punto 4.1.6.1.3, nonché le modalità e la durata della maturazione umida in accordo alla UNI EN 13697:2010, alle *Linee Guida per la messa in opera del calcestruzzo strutturale* ed alle *Linee Guida per la valutazione delle caratteristiche del calcestruzzo in opera* pubblicate dal Servizio Tecnico Centrale del Consiglio Superiore dei Lavori Pubblici.
Ai fini della valutazione della durabilità, nella formulazione delle prescrizioni sul calcestruzzo, si potranno prescrivere anche prove per la verifica della resistenza alla penetrazione degli agenti aggressivi, quali ad esempio anidride carbonica e cloruri. Si può ricorrere a prove di tipo non distruttivo.

11.2.12. CALCESTRUZZO FIBRORINFORZATO (FRC)
Il calcestruzzo fibrorinforzato (FRC) è caratterizzato dalla presenza di fibre discontinue nella matrice cementizia; tali fibre possono essere realizzate in acciaio o materiale polimerico, e devono essere marcate CE in accordo alle norme europee armonizzate, quali la UNI EN 14889-1 ed UNI EN 14889-2 per le fibre realizzate in acciaio o materiale polimerico.
La miscela del calcestruzzo fibrorinforzato deve essere sottoposta a valutazione preliminare secondo le indicazioni riportate nel precedente § 11.2.3 con determinazione dei valori di resistenza a trazione residua f_{Rk} per lo Stato limite di esercizio e f_{Rk} per lo Stato limite Ultimo determinati secondo UNI EN 14651:2007.
Per la qualificazione del calcestruzzo fibrorinforzato e la progettazione delle strutture in FRC si dovrà fare esclusivo riferimento a specifiche disposizioni emanate dal Consiglio Superiore dei Lavori Pubblici.


11.3. CONTROLLI
11.3.1. CONTROLLI
Le presenti norme prevedono tre forme di controllo obbligatorie:
- in stabilimento di produzione, da eseguirsi sui lotti di produzione;
- nei centri di trasformazione;
- di accettazione in cantiere.
A tale riguardo il *Lotto di produzione* si riferisce a produzione continua, ordinata cronologicamente mediante apposizione di contrassegni al prodotto finito (rotolo finito, bobina di trefolo, fascio di barre, ecc.). Un lotto di produzione deve avere valori delle grandezze nominali omogenee (dimensionali, meccaniche, di formazione) e può essere compreso tra 30 e 120 tonnellate.
11.3.1.2. CONTROLLI DI PRODUZIONE IN STABILIMENTO E PROCEDURE DI QUALIFICAZIONE
Tutti gli acciai oggetto delle presenti norme, siano essi destinati ad utilizzo come armature per calcestruzzo armato normale o precompresso o ad utilizzo diretto come carpenterie in strutture metalliche, devono essere prodotti con un sistema permanente di controllo interno della produzione in stabilimento che deve assicurare il mantenimento dello stesso livello di affidabilità nella conformità del prodotto finito, indipendentemente dal processo di produzione.
Fatto salvo quanto disposto dalle norme europee armonizzate, ove applicabili, il sistema di gestione della qualità del prodotto che sovrintende al processo di fabbricazione deve essere predisposto in coerenza con la norma UNI EN ISO 9001 e certificato da parte di un organismo terzo indipendente, di adeguata competenza ed organizzazione, che opera in coerenza con le norme UNI CEI EN ISO/IEC 17021-1.
Quando non sia applicabile la marcatura CE, ai sensi del Regolamento UE 305/2011, la valutazione della conformità del controllo di produzione in stabilimento e del prodotto finito è effettuata attraverso la procedura di qualificazione di seguito indicata.

— 315 —




*Consiglio Superiore dei Lavori Pubblici
Servizio Tecnico Centrale*

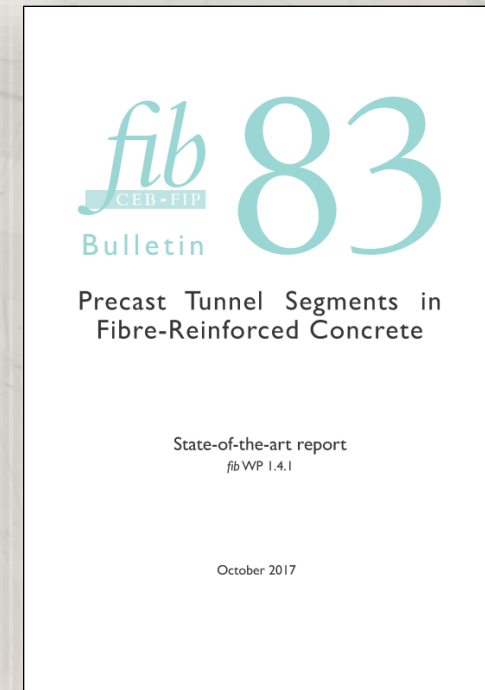
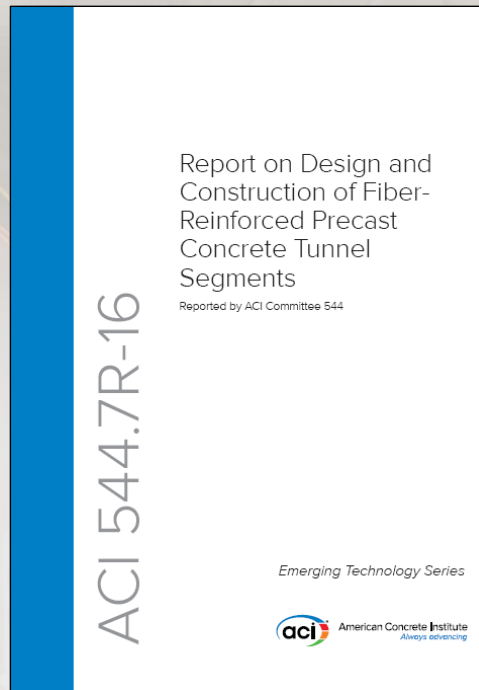
Linea guida per l'identificazione, la qualificazione, la certificazione di valutazione tecnica ed il controllo di accettazione dei calcestruzzi fibrorinforzati FRC (Fiber Reinforced Concrete)



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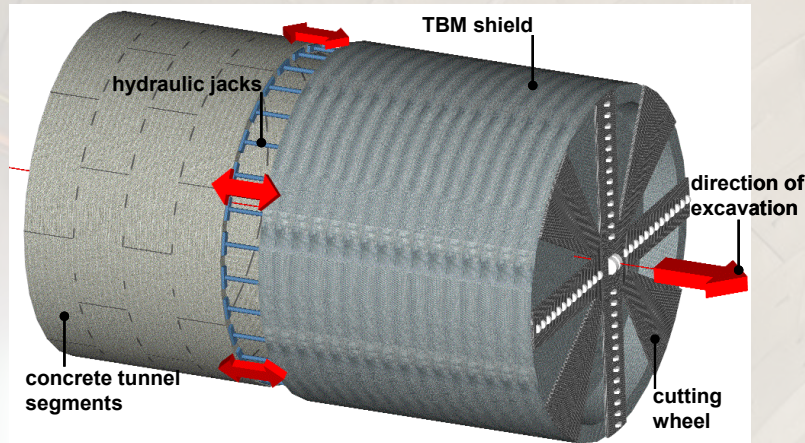
Linee guida per la progettazione, messa in opera, controllo e collaudo di elementi strutturali in calcestruzzo fibrorinforzato con fibre di acciaio o polimeriche.

International Guidelines for FRC application in segmental lining

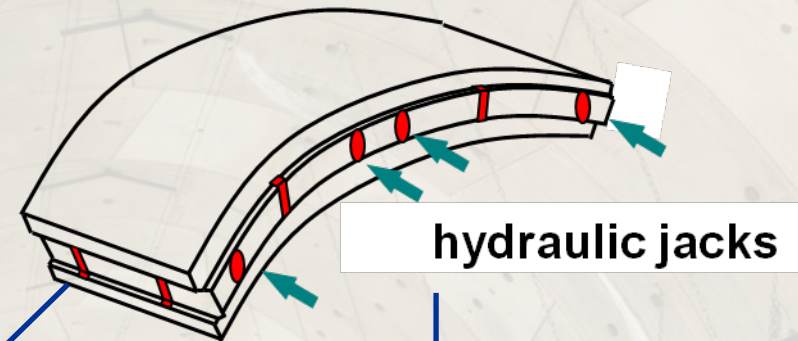


- **ACI Committee 544 (2016).** “Report on Design and Construction of Fiber Reinforced Precast Concrete Tunnel Segments”, ACI 544.7R-16, American Concrete Institute, Farmington Hills, MI, 36 p.
- **ITA report n. 16 (2016),** “Twenty years of FRC tunnel segments practice: lessons learnt and proposed design principles”, April 2016, ISBN 978-2-970-1013-5-2, 71 p.
- **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, 168 p.

Loading conditions

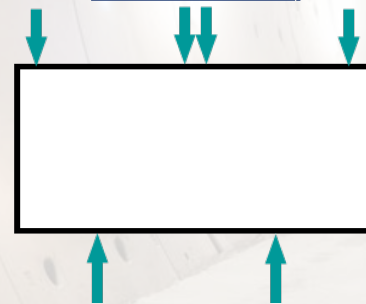


TUNNEL SEGMENT



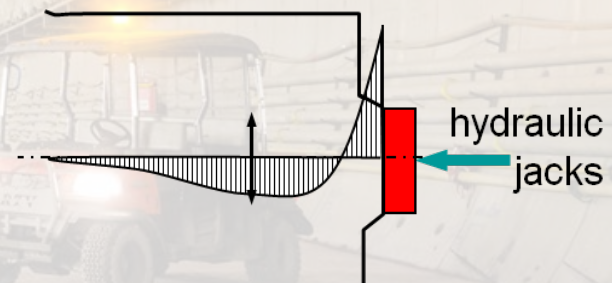
Test of in-plane action

(thrust phase, global
behaviour)



Splitting Test

(thrust phase, local
behaviour)



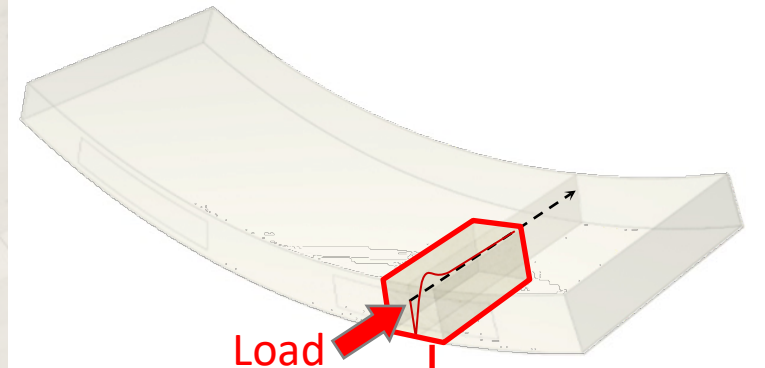
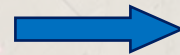
Critical phase

LOCAL BEHAVIOR UNDER TBM THRUST SHOES

TBM thrust phase: local splitting phenomena

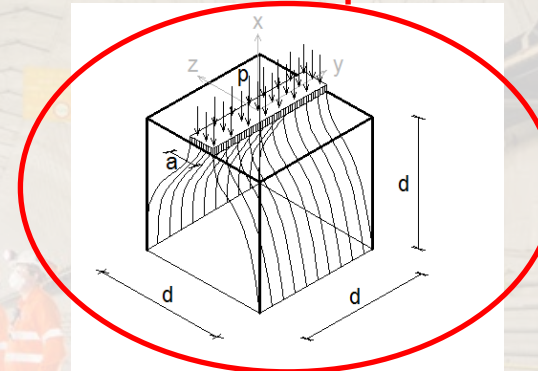
Thrust phase:

high compressive
stresses on a small area



Proper specimens dimensions
and configurations

to study this local behavior



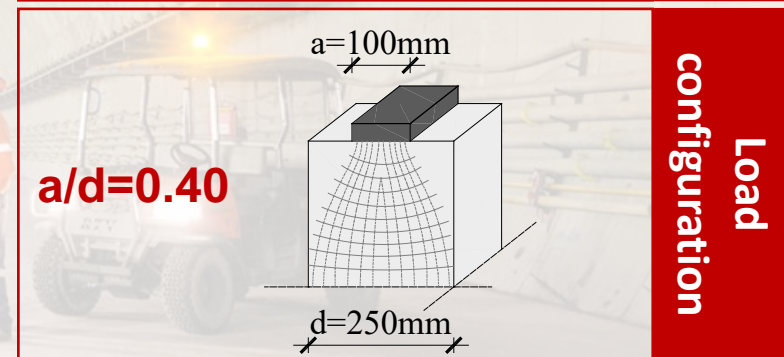
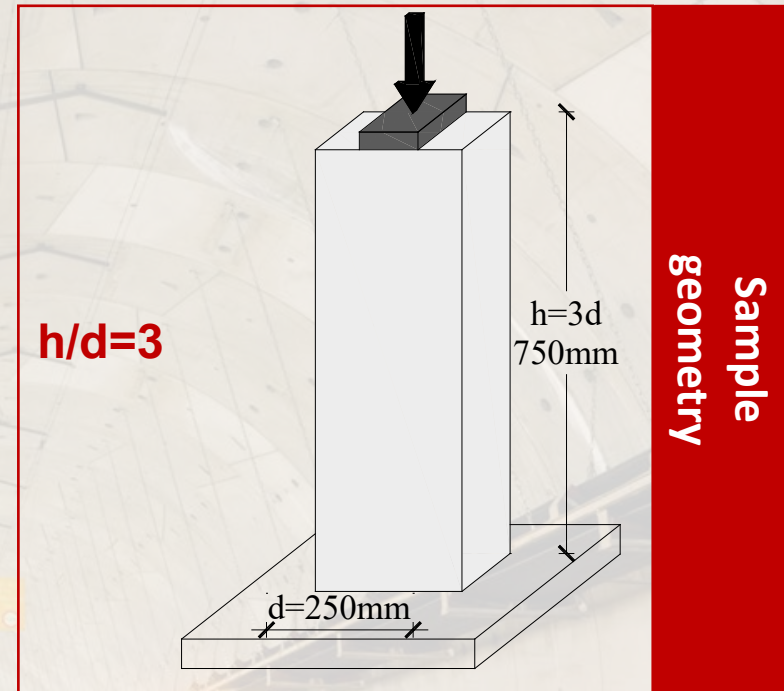
Local splitting phenomena: experimental campaign

Experimental campaign:

- prismatic samples
- line load configuration
- reinforcement solutions:
 - fibres only
 - rebars only
- two casting directions

Fibre type:

	60/65
Material	steel
Shape	double hooked end
Diameter [mm]	0.90
Length [mm]	60
Aspect ratio [-]	65
Dosage [kg/m ³]	25-40-60

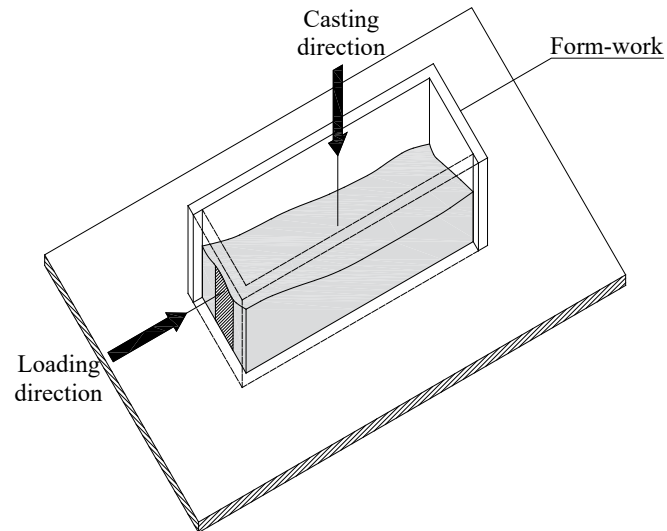


Local splitting phenomena: experimental campaign

Horizontal casting

**Casting direction
perpendicular to
loading direction**

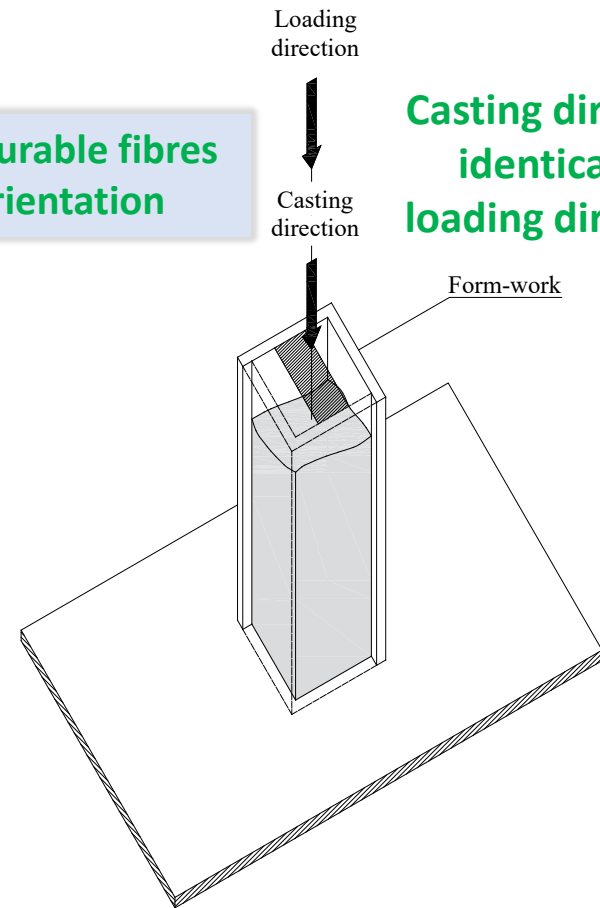
**Unfavourable fibres
orientation**



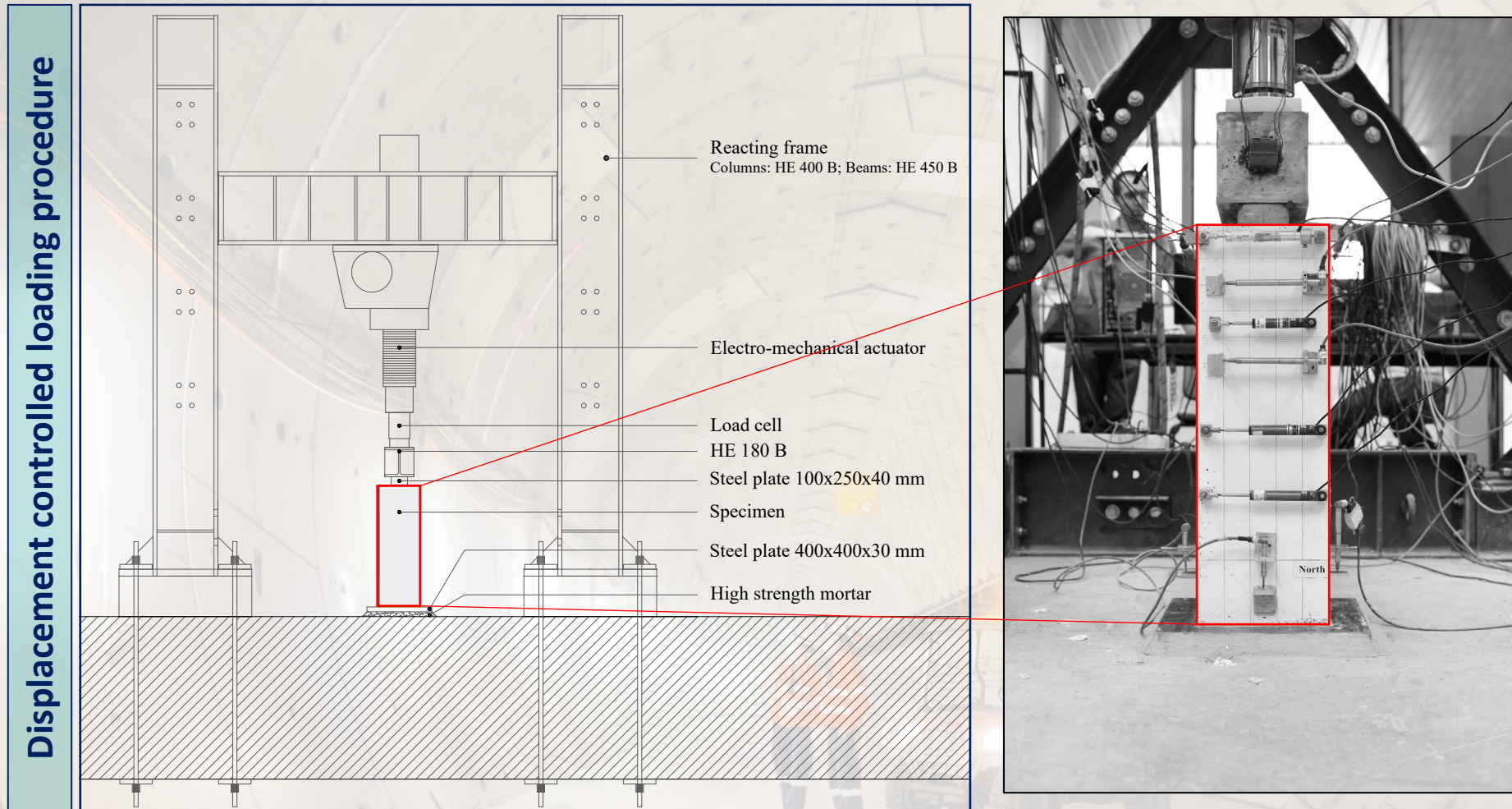
Vertical casting

**Favourable fibres
orientation**

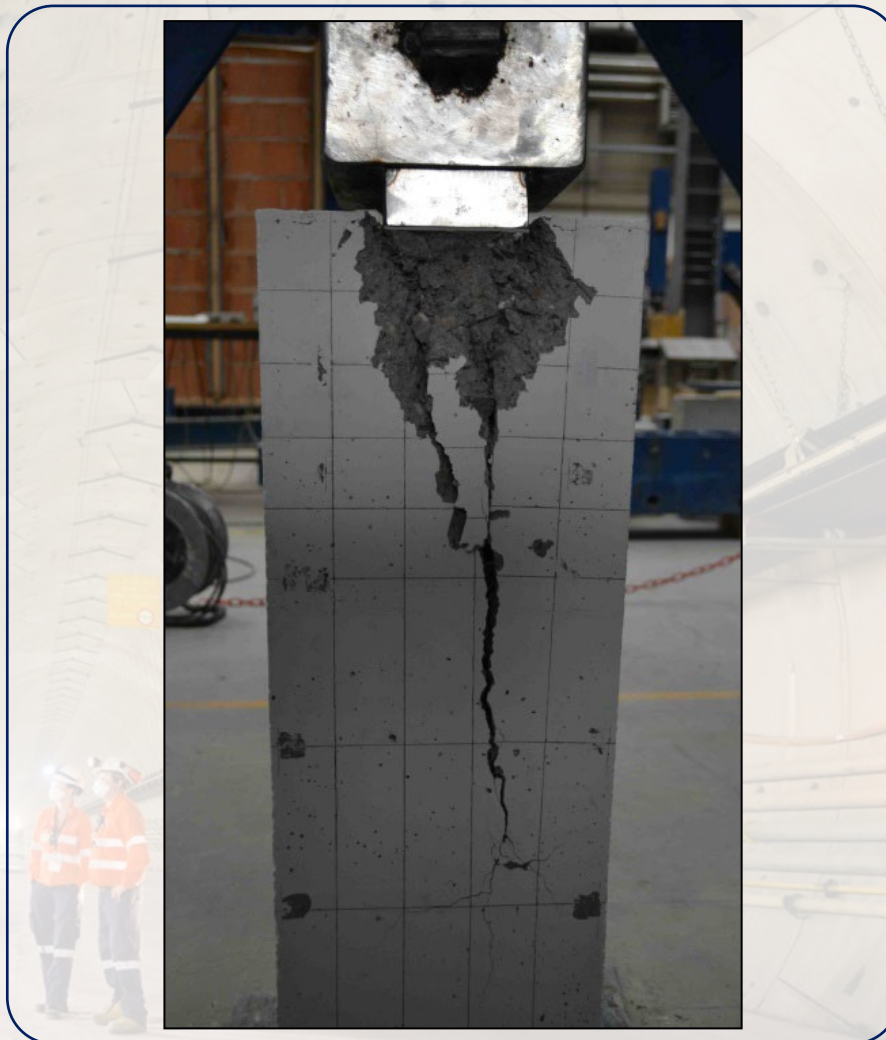
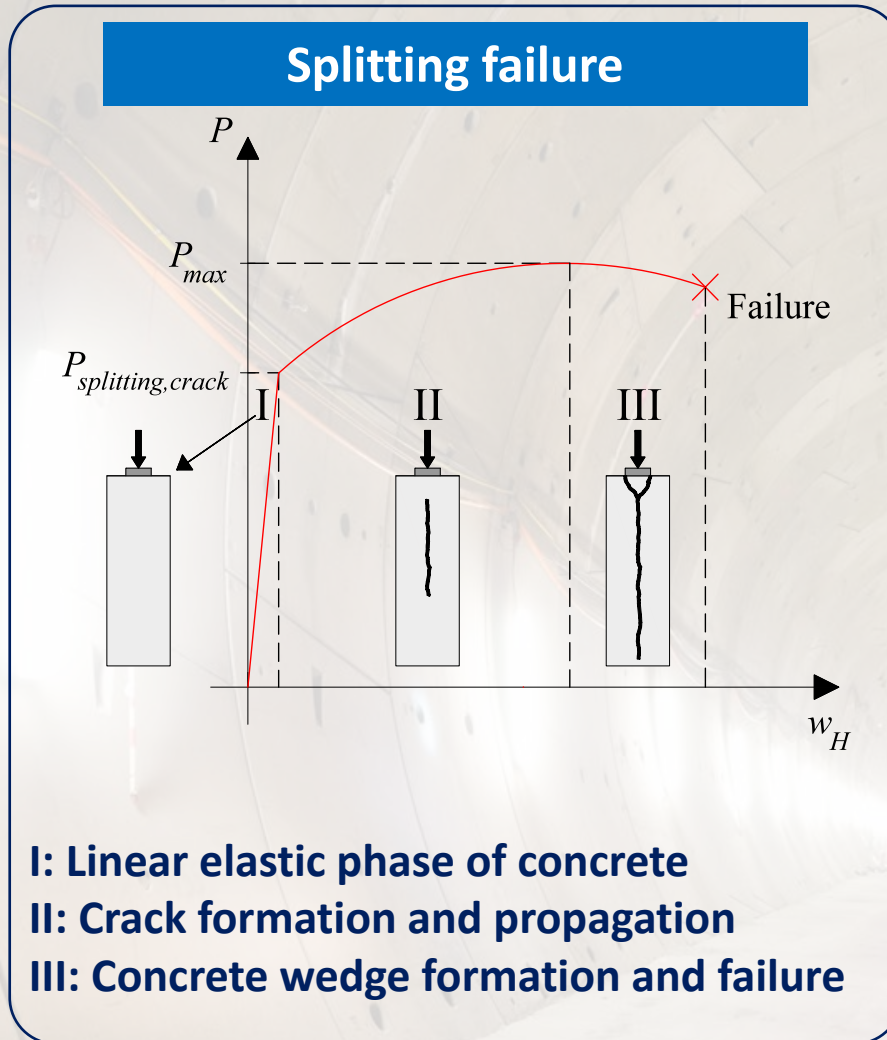
**Casting direction
identical to
loading direction**



Local splitting phenomena: experimental campaign

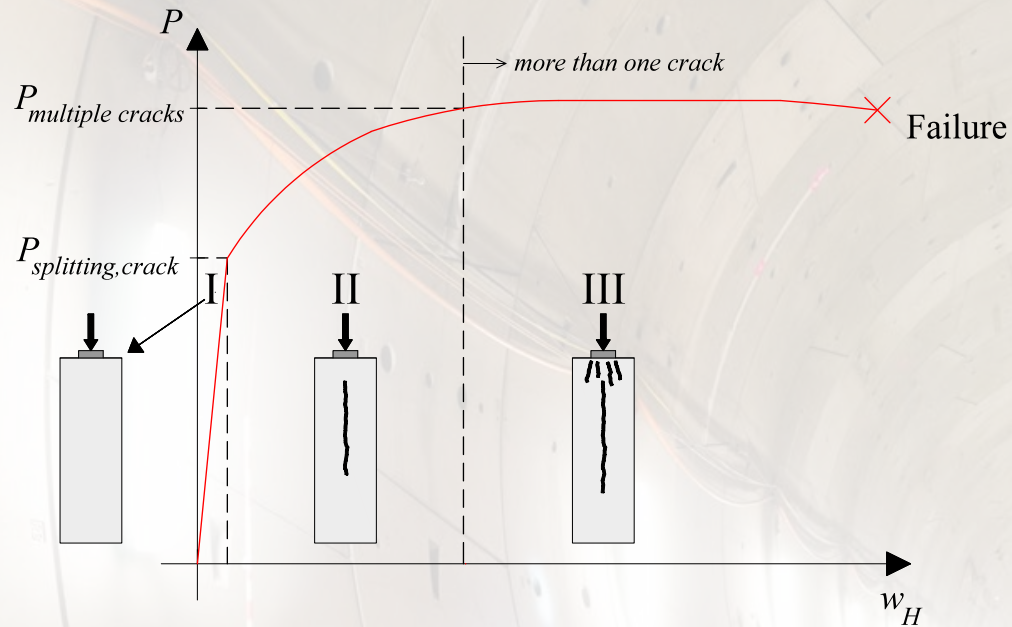


Local splitting phenomena: experimental campaign



Local splitting phenomena: experimental campaign

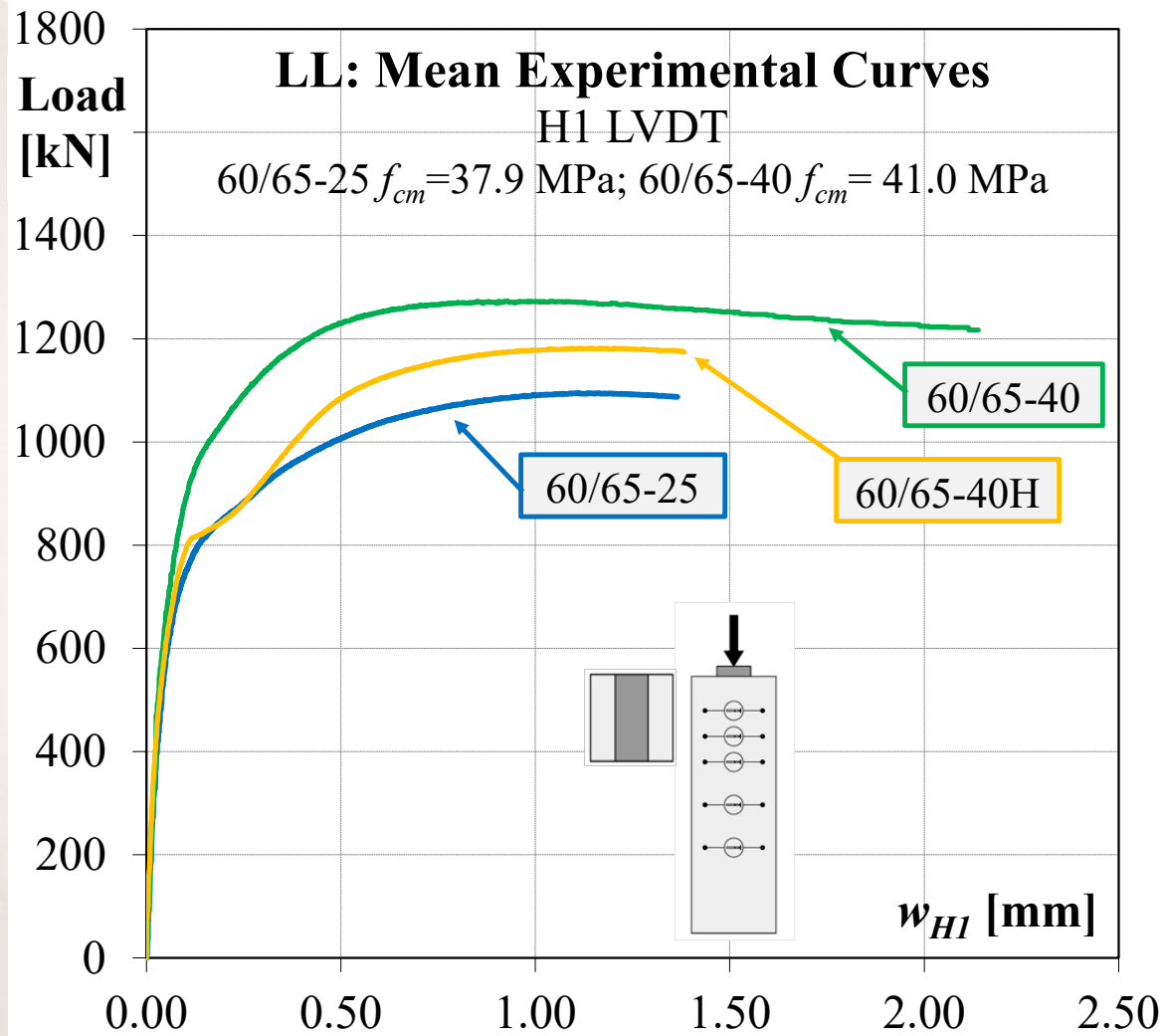
Crushing failure



- I: Linear elastic phase of concrete**
- II: Crack formation and propagation**
- III: Multi-cracking in compressed zone and failure**



Local splitting phenomena: experimental campaign



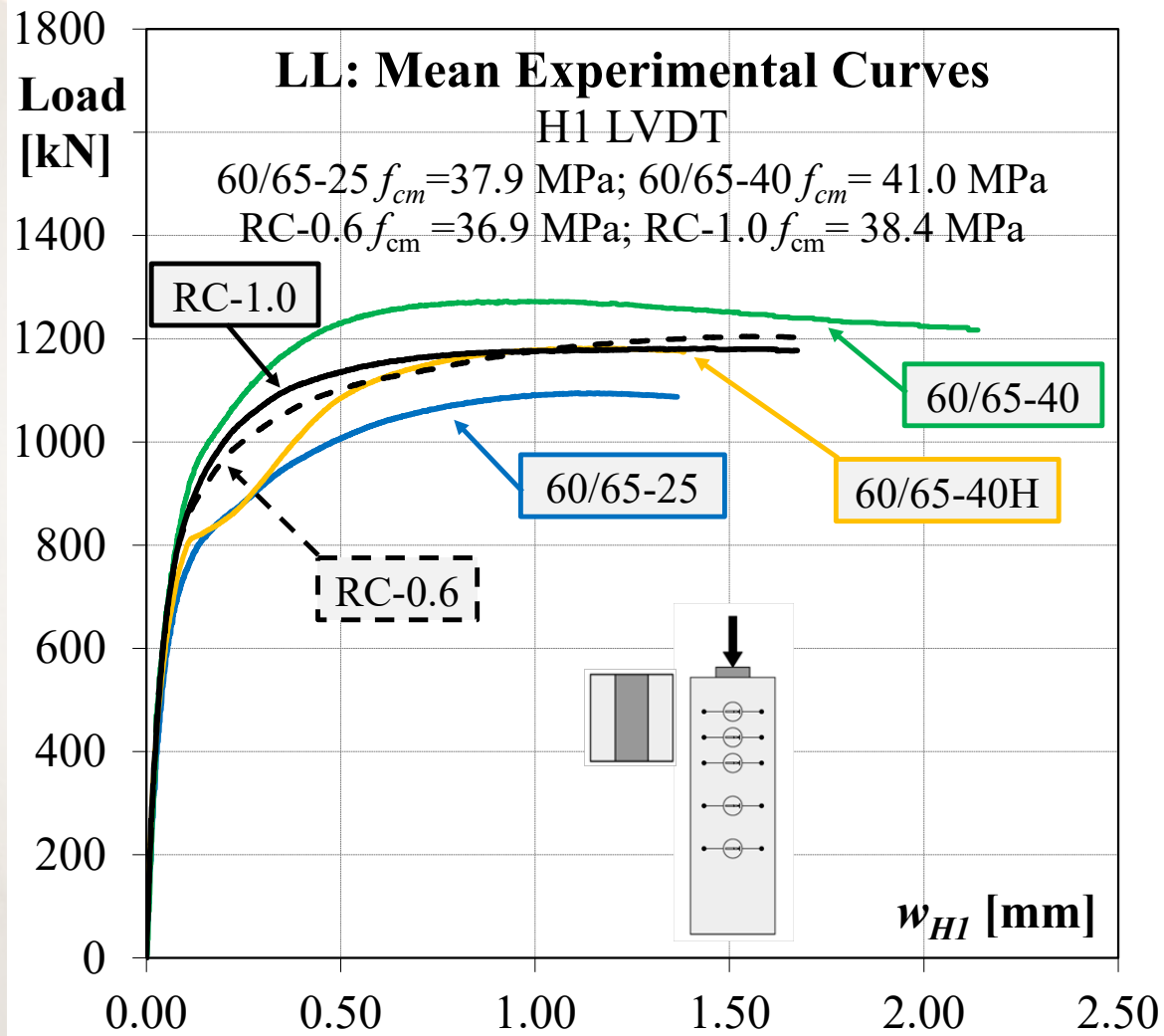
25 kg/m³ of steel fibers significantly enhance the splitting behavior and the bearing capacity of a concrete prism (up to +54%), as well as the specimen ductility

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

Local splitting phenomena: experimental campaign



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})

Local splitting phenomena: new analytical proposal

Tunnelling and Underground Space Technology 50 (2015) 438–450

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Precast segments under TBM hydraulic jacks: Experimental investigation on the local splitting behavior

Giuseppe Tiberti, Antonio Conforti*, Giovanni A. Plizzari

Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy

Composites Part B 105 (2016) 82–92

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Splitting and crushing failure in FRC elements subjected to a high concentrated load

Antonio Conforti*, Giuseppe Tiberti, Giovanni A. Plizzari

Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy

Construction and Building Materials 307 (2021) 124334

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on Steel Fiber Reinforced Concrete and Reinforced Concrete elements under concentrated loads

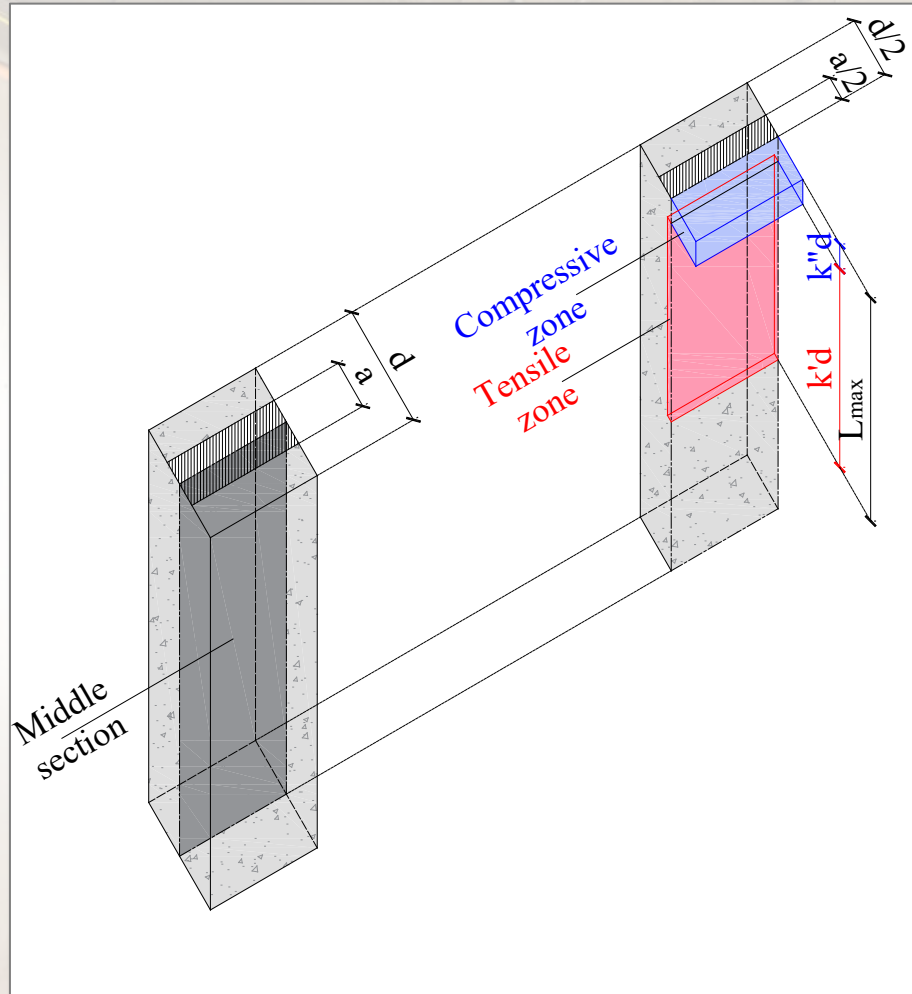
Ivan Trabucchi^{a,*,1}, Giuseppe Tiberti^a, Antonio Conforti^a, Filippo Medeghini^b, Giovanni A. Plizzari^a

^aDepartment of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Italy
^bInstitute of Concrete Structures, Ruhr University Bochum, Germany

18 samples

ID	P _{crack,splitting} [kN]	P _{max,splitting} [kN]	L _{max} [mm]
LL-PC-1	1152	1152	750
LL-PC-2	1011	1011	750
LL-PC-3	970	970	750
LL-PFRC-1	1020	1439	560
LL-PFRC-2	840	1271	510
LL-PFRC-3	885	1160	590
SFRC33/55-1	795	1001	600
SFRC33/55-2	750	955	460
SFRC33/55-3	840	1072	560
SFRC60/75-1	800	1042	620
SFRC60/75-2	760	1006	650
SFRC60/75-3	795	1064	670
60/65-25-1	765	1072	460
60/65-25-2	670	1121	600
60/65-25-3	710	1093	400
30/80-25-1	767	1163	425
30/80-25-2	810	1207	410
30/80-25-3	770	1174	375

Local splitting phenomena: new analytical proposal



Hypotheses when $P_{\max, \text{splitting}}$ is reached:

1. Rigid plastic constitutive law in compression
2. Rigid plastic constitutive law in tension
3. $k' = f(f_{R1m})$ (variable)
4. $k'' = 0.20$ (constant)
5. Residual strength = $k * f_{R1m}$

Transition from nominal flexural tensile strength (EN14651 beams) to uniaxial tensile strength on the specimen

Approximation of the length/depth of splitting crack as a function of FRC nominal flexural strength

Local splitting phenomena: new analytical proposal

Stress distribution along the middle section

+

Predefined and uniform max strength for FRC in tension along splitting crack



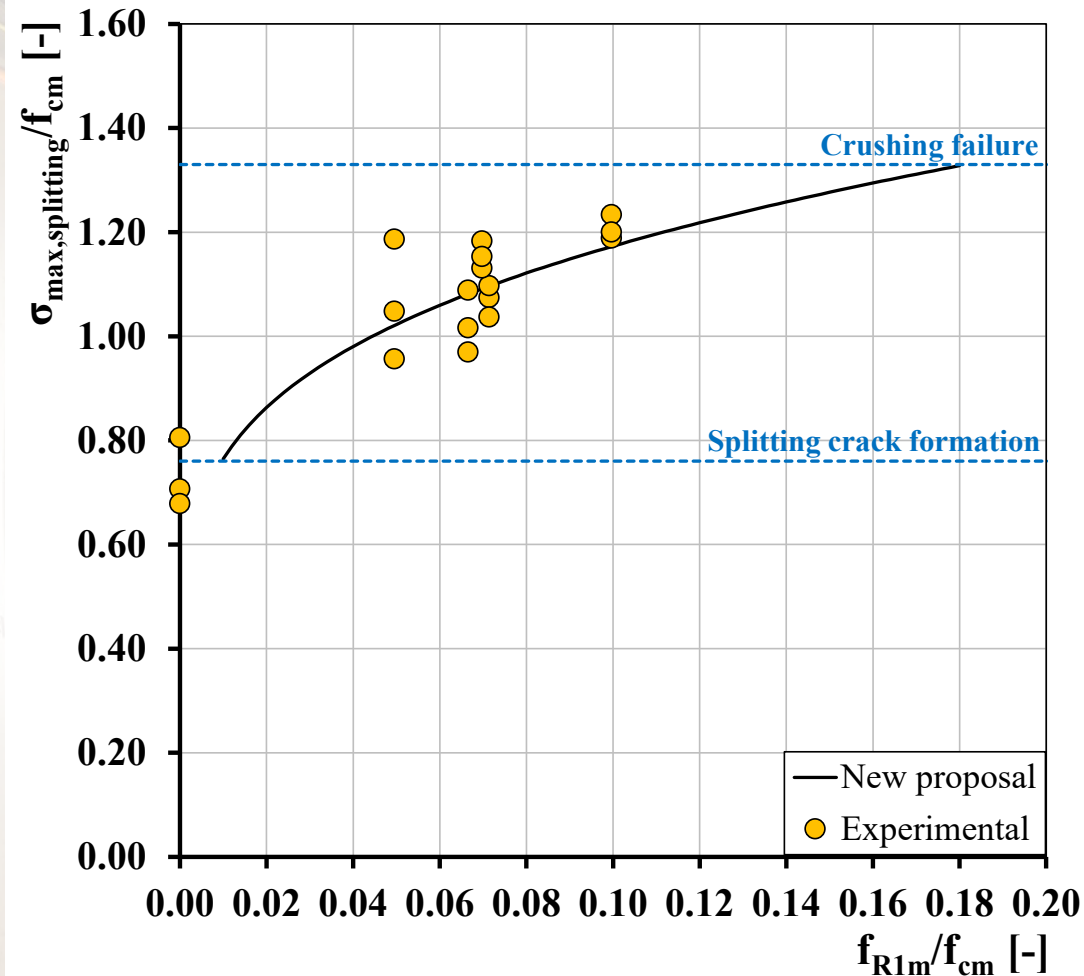
Splitting crack length estimation

$$k' = 0.32 \left(\frac{k f_{R1m}}{f_{cm}} \right)^{-0.425} \quad \text{Eq.1}$$

Formulation for evaluating $P_{\max, \text{splitting}}$

$$P_{\text{crack, splitting}} \leq P_{\max, \text{splitting}} = 4 (0.33 f_{R1m}) \frac{d b}{1 - \frac{a}{d}} (k'^2 + 0.20 k') \leq P_{\text{crushing}} \quad \text{Eq.2}$$

Local splitting phenomena: new analytical proposal



Comparison between

Experimental

($\sigma_{max,splitting,exp}$)
and

analytical

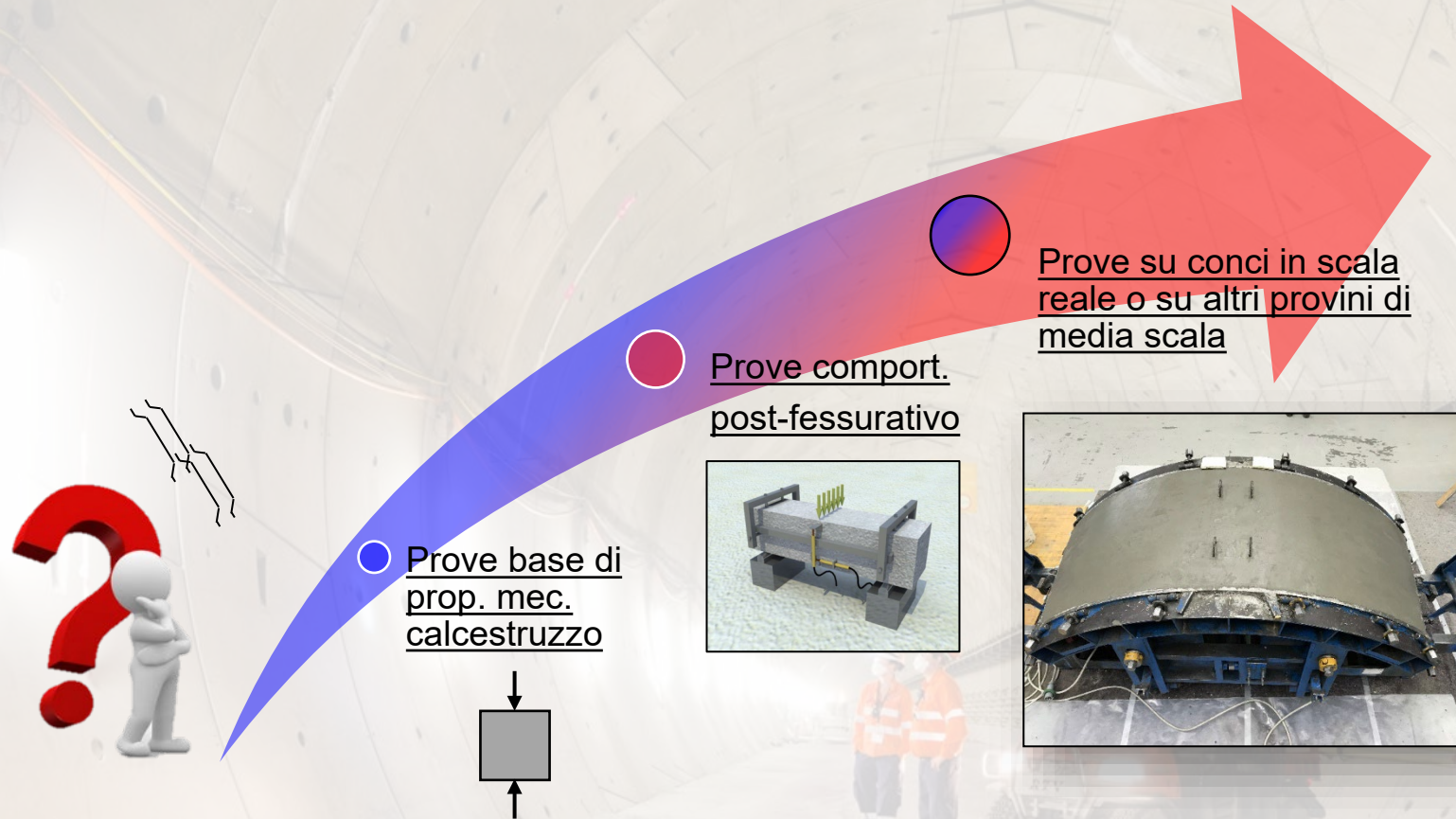
($\sigma_{max,splitting,proposal}$)
results

**Mean Absolute
Percentage Error
MAPE = 4.9%**

EXPERIMENTAL TESTS ON TUNNEL SEGMENTS

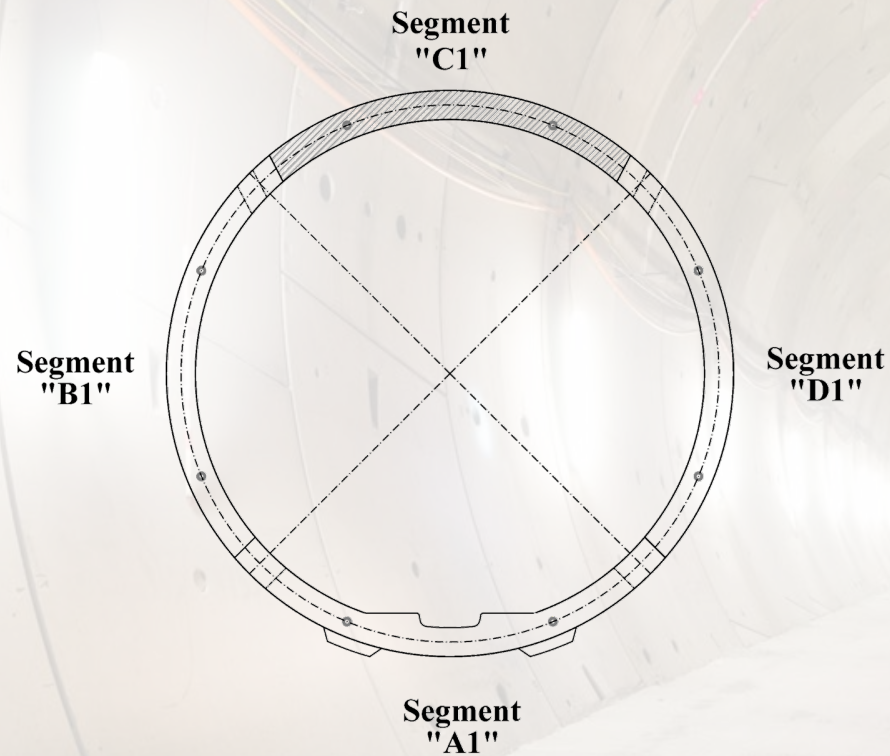
Experimental testing

Typical research path based on experimental tests for Fiber Reinforced Concretes



CASE STUDY: Scilla tunnel

- internal diameter: 3.50 m
- thickness: 0.20 m
- width: 1.10 m
- N° of segments (per ring): 4

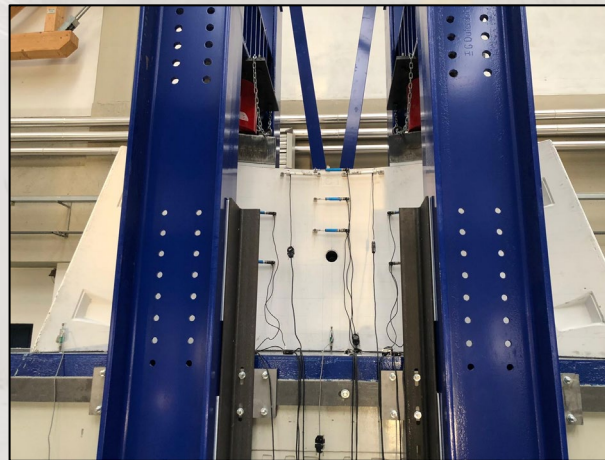


CASE STUDY: Scilla tunnel

- **prove a flessione** atte a simulare la **fase di stoccaggio, trasporto etc.**

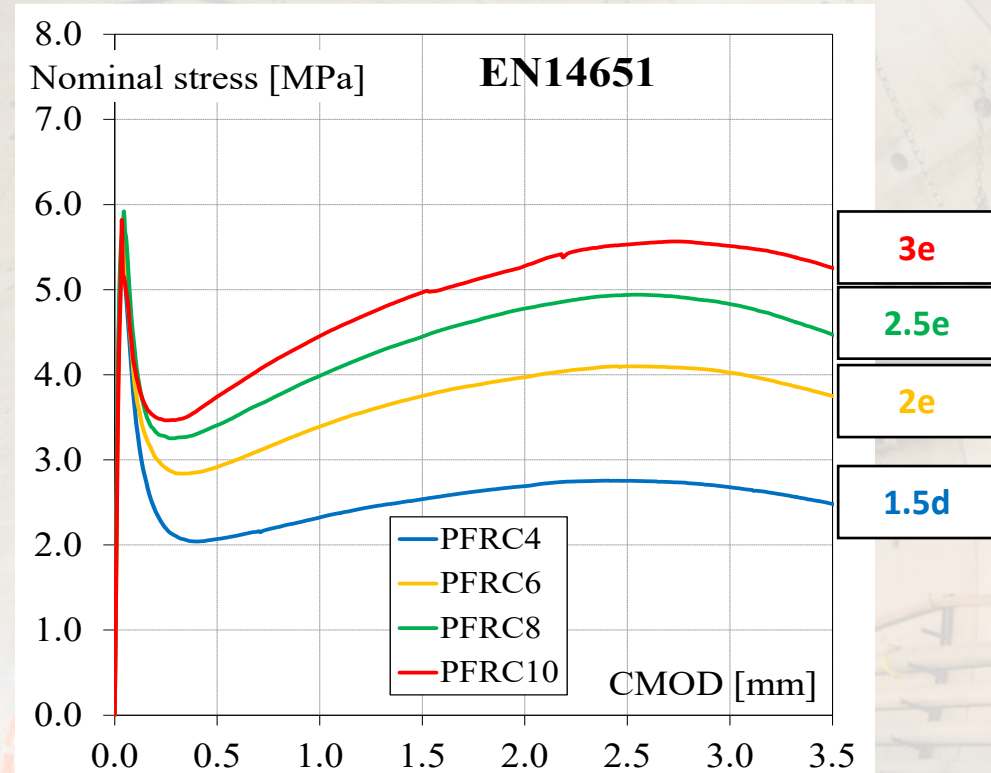
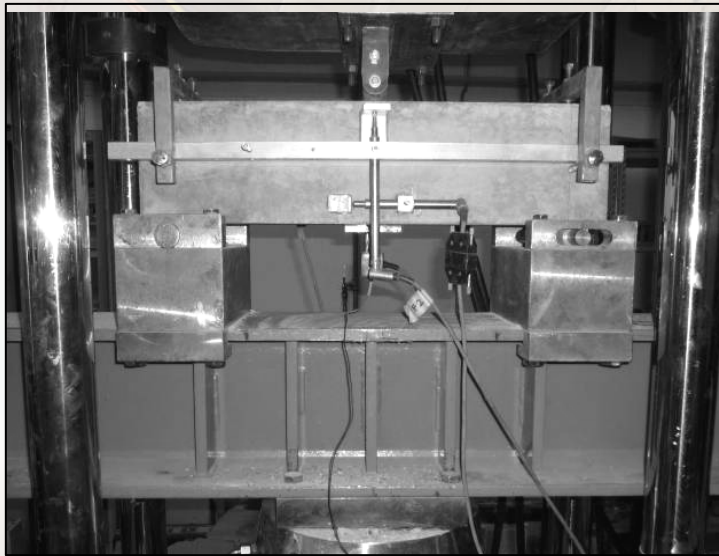


- **prove con carichi concentrati di notevole entità** atti a simulare **l'azione della TBM**



CASE STUDY: Scilla tunnel

Fase preliminare di studio di calcestruzzi rinforzati con fibre macro-sintetiche in polipropilene, fibre PP



Il dosaggio di 8 kg/m^3 è stato scelto per la realizzazione dei conci

CASE STUDY: Scilla tunnel

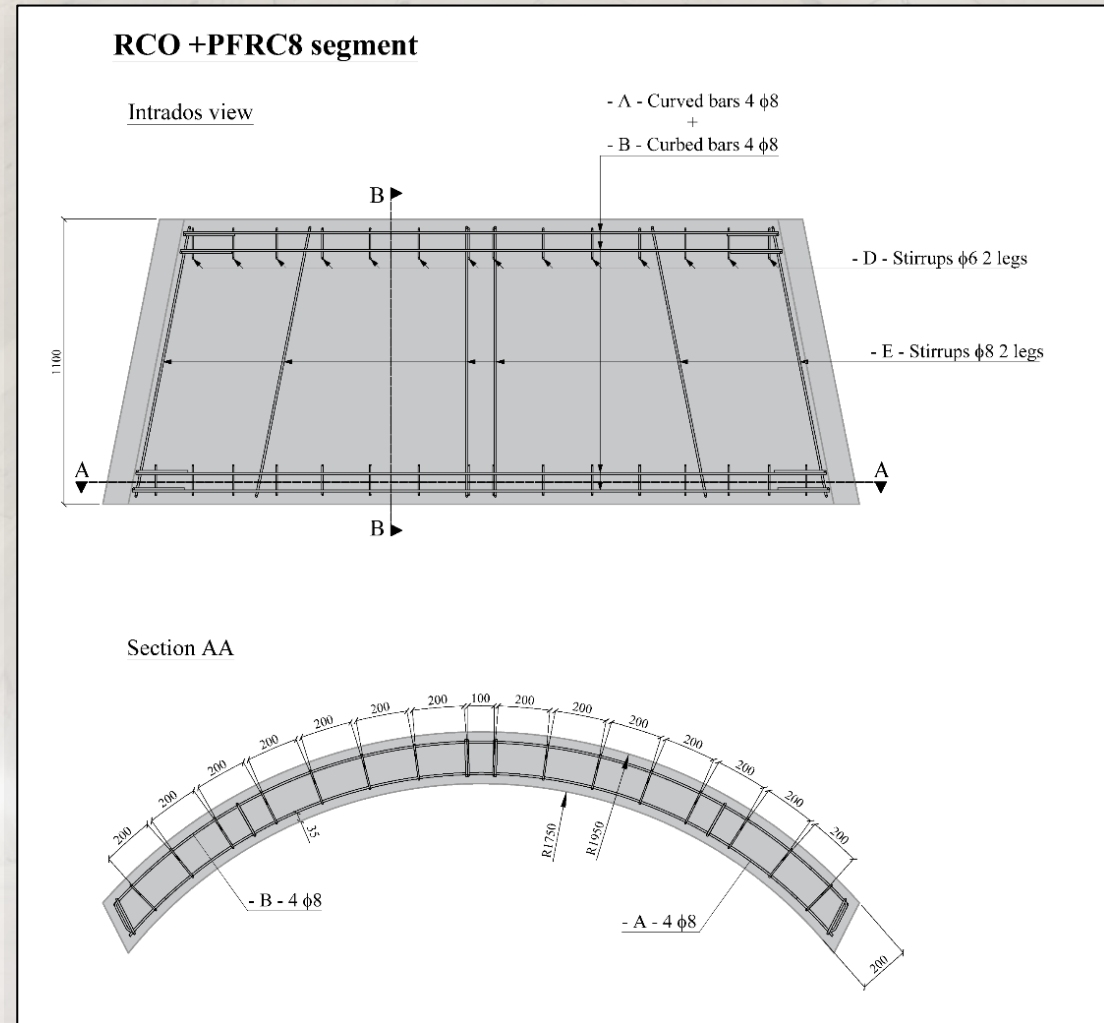
- Le seguenti soluzioni di rinforzo **per i conci** sono state oggetto di indagine:
 - **RC**: soluzione tradizionale di riferimento (**solo barre di armatura di acciaio**)
 - **RCO+PFRC8**: **soluzione ibrida ottimizzata (quantitativo limitato di barre di armatura)** e **8 kg/m³** di fibre macro-sintetiche in polipropilene, PP fibers
 - **PFRC8**: soluzione basata sull'impiego di **solo rinforzo fibroso**
- Le soluzioni di rinforzo sono state scelte sulla base di una progettazione preliminare secondo i seguenti principi:
 - **Fibre PP** impiegate per il controllo di **fenomeni locali di splitting** (fase di spinta della TBM)
 - Fibre PP in combinazione con armatura tradizionale (**configurazione ibrida**) per controllare **fenomenologie di spalling** (fase di spinta della TBM)
 - Fibre PP in combinazione con armatura tradizionale (**configurazione ibrida**) per sfruttare la mutua collaborazione tra fibre e barre in termini di **controllo fessurativo** e di **capacità portante a flessione** (comportamento flessionale: la percentuale longitudinale di armatura adottata per la soluzione RCO+PFRC8 è stata ridotta allo 0.11%)

CASE STUDY: Scilla tunnel

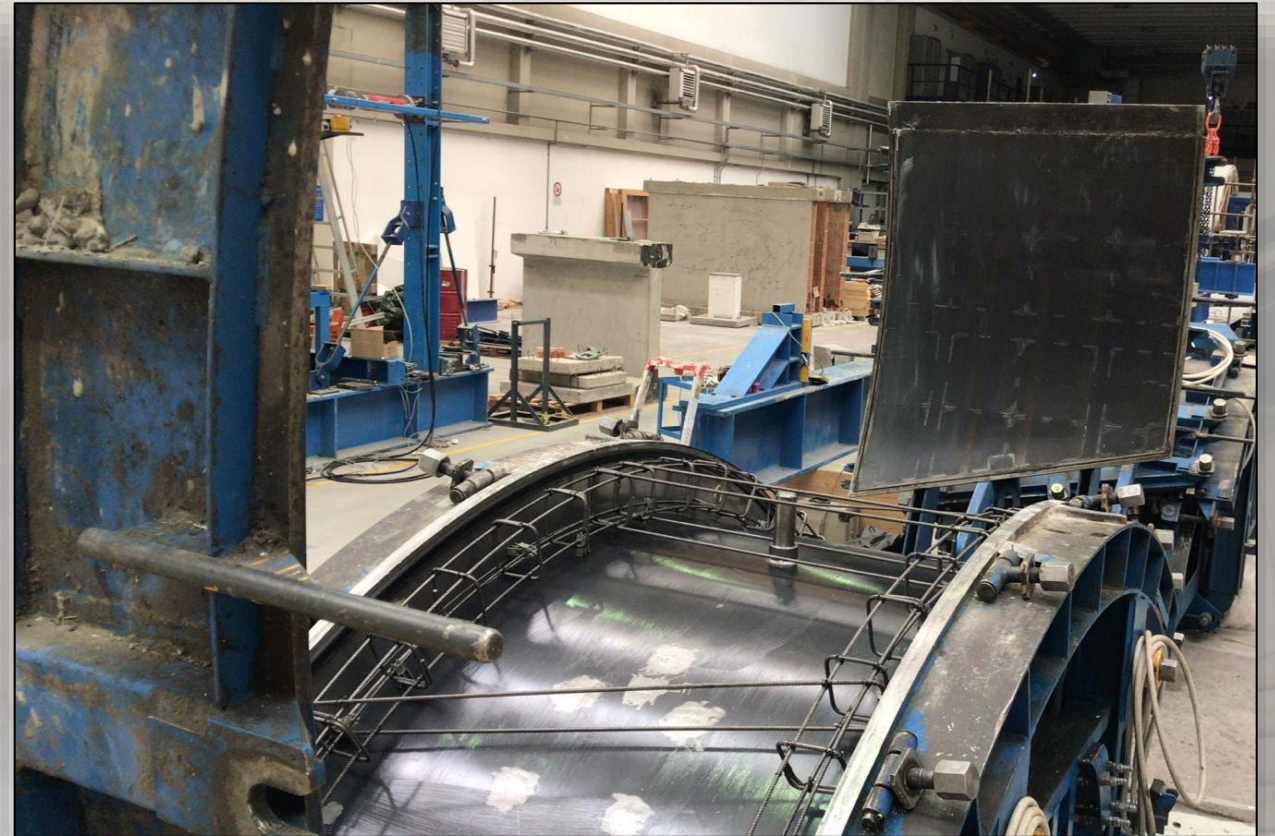
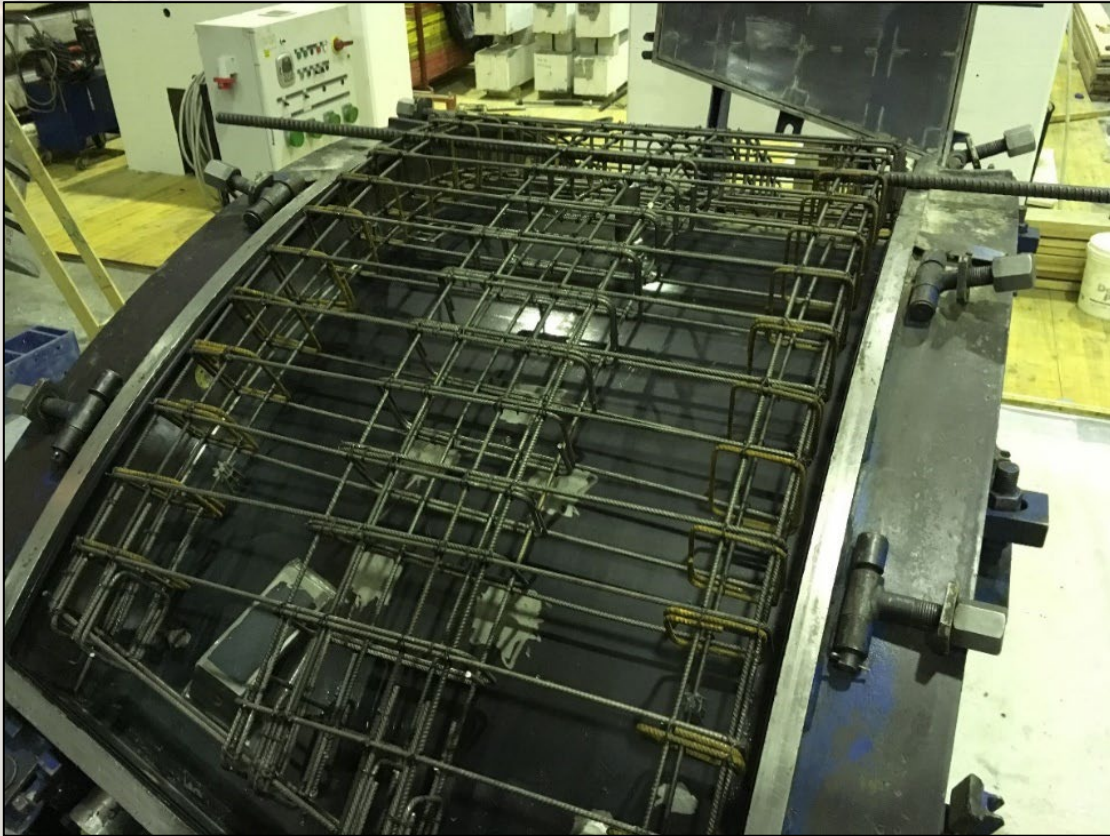
- Classe di calcestruzzo: C50/60
- Barre di armatura longitudinali:
 - barre curve di acciaio, 4+4 $\phi 8$
 - percentuale di armatura, $\rho_s = 0.11\%$
- Fibre macro-sintetiche, Fibre PP, 8 kg/m³

- Armatura a taglio: fibre PP, 8 kg/m³
- Armatura per comportamento locale di splitting: fibre PP, 8 kg/m³

- **Armatura totale:**
 8 kg/m³ fibre PP
 + contenuto di barre di 35 kg/m³



CASE STUDY: Scilla tunnel



Contenuto equivalente di barre di armatura = 110 kg/m^3 (RC) vs. 35 kg/m^3 (RCO+PFRC8): **riduzione del 68%**

CASE STUDY: Scilla tunnel



CASE STUDY: Scilla tunnel

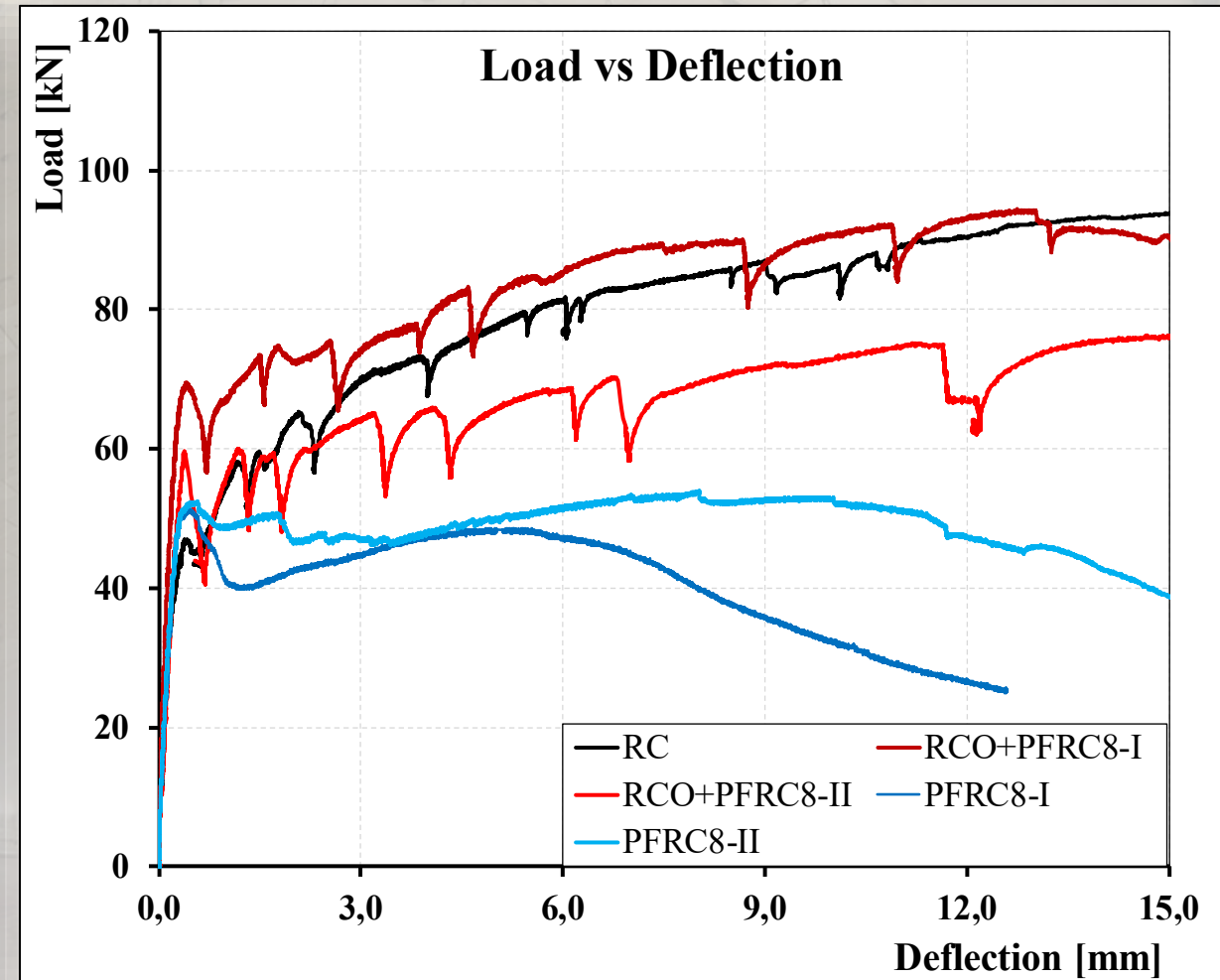
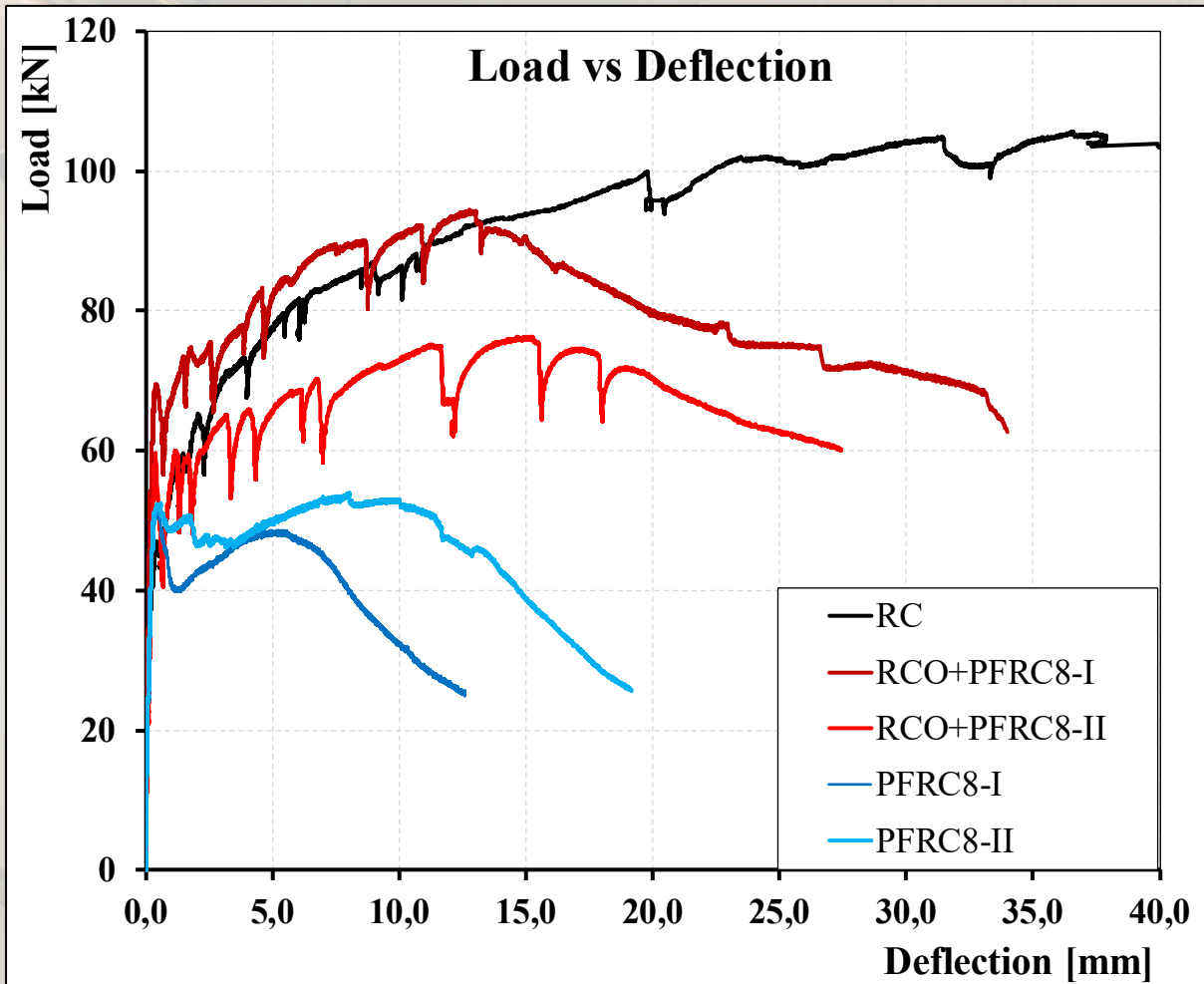
- **In totale 10 conci sono stati gettati:**
 - con riferimento **alle prove a flessione su conci in scala reale**, cinque conci sono stati gettati e provati:
 - un concio di riferimento RC
 - due conci RCO+PFRC8 (configurazione ibrida)
 - due conci PFRC8
 - con riferimento **alle prove con carichi concentrati atti a simulare l'azione della TBM** su conci in scala reale, cinque conci sono stati gettati e provati:
 - un concio di riferimento RC
 - due conci RCO+PFRC8 (configurazione ibrida)
 - due conci PFRC8

CASE STUDY: Scilla tunnel – bending tests

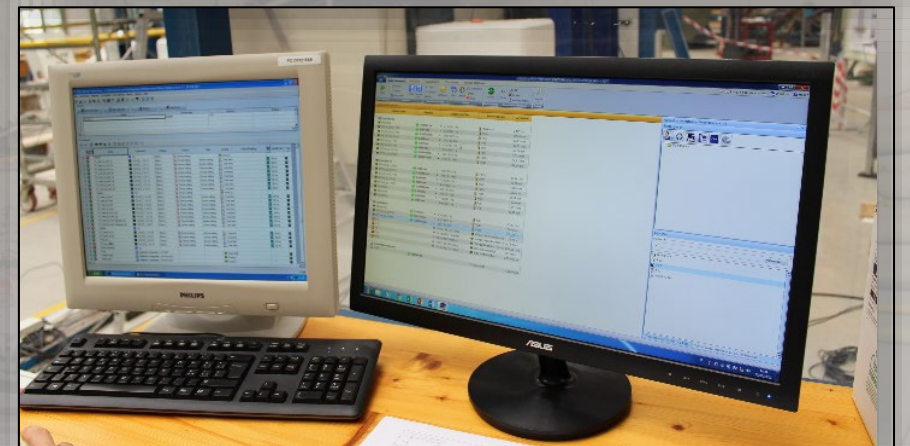
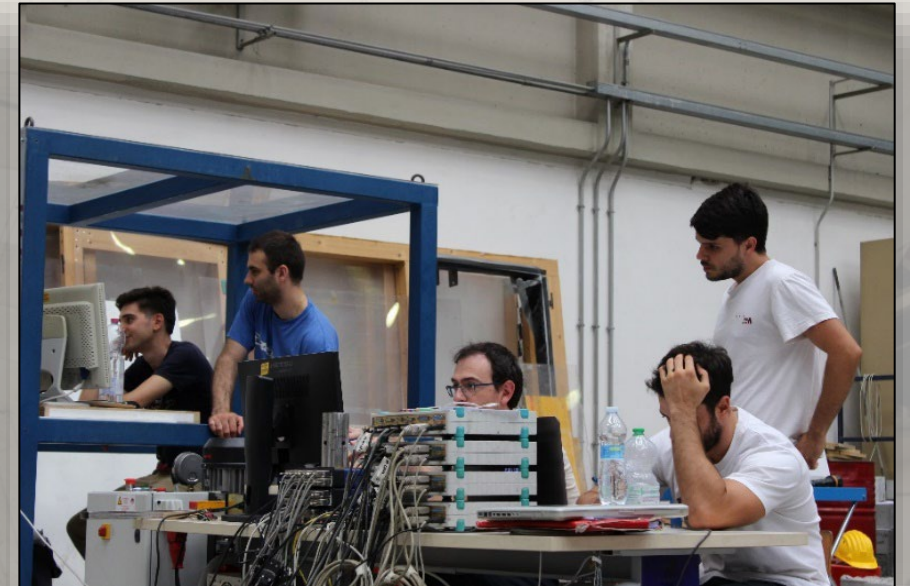
I due appoggi sono continui sull'intera lunghezza del concio, mentre il carico all'estradosso è stato applicato con due piastre (150x200 mm) posizionate su uno strato di malta ad alte prestazioni



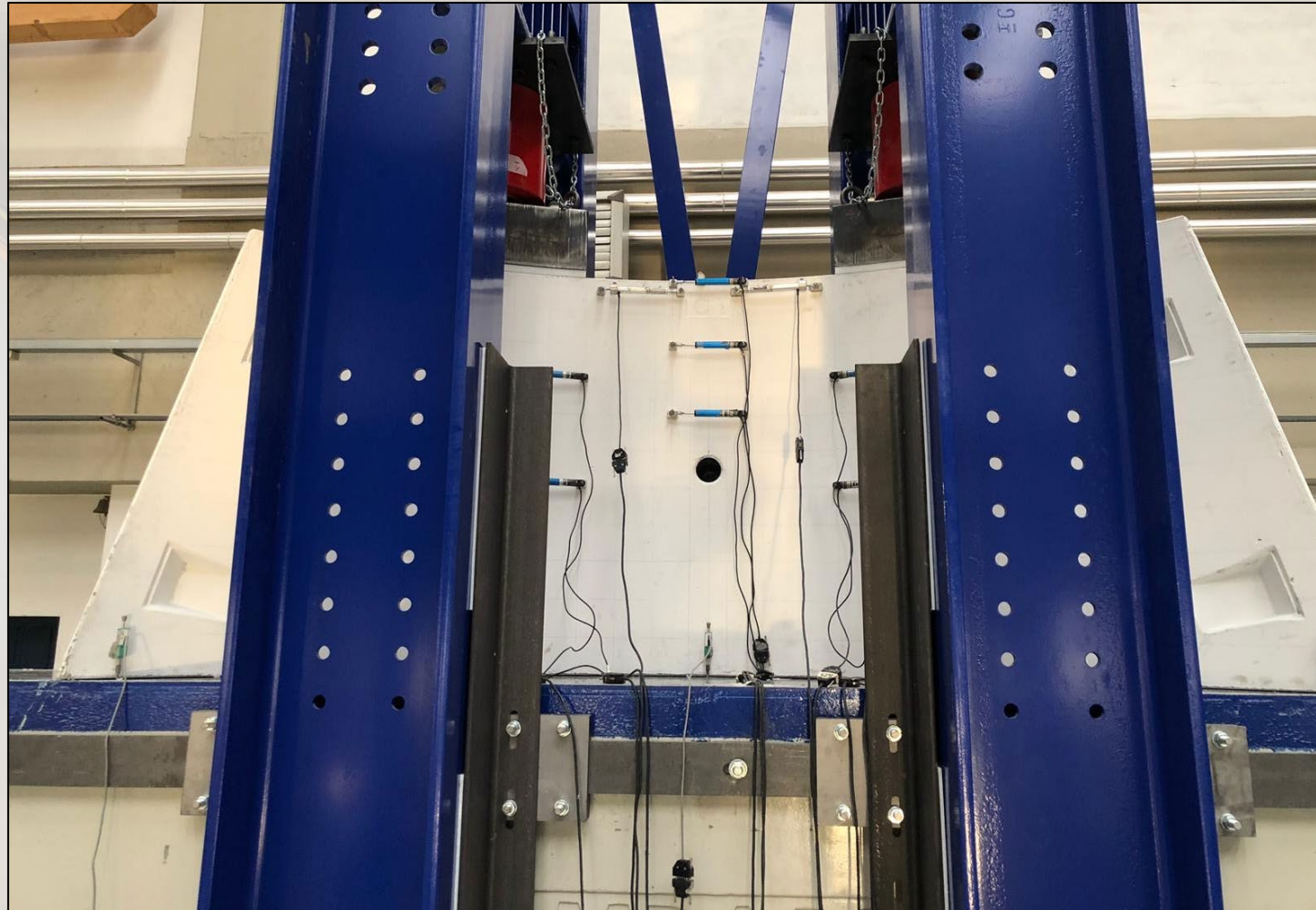
CASE STUDY: Scilla tunnel – bending tests



CASE STUDY: Scilla tunnel – point load tests

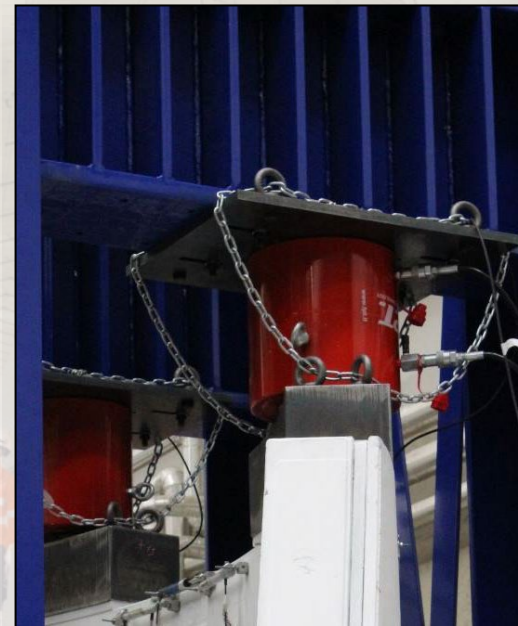


CASE STUDY: Scilla tunnel – point load tests



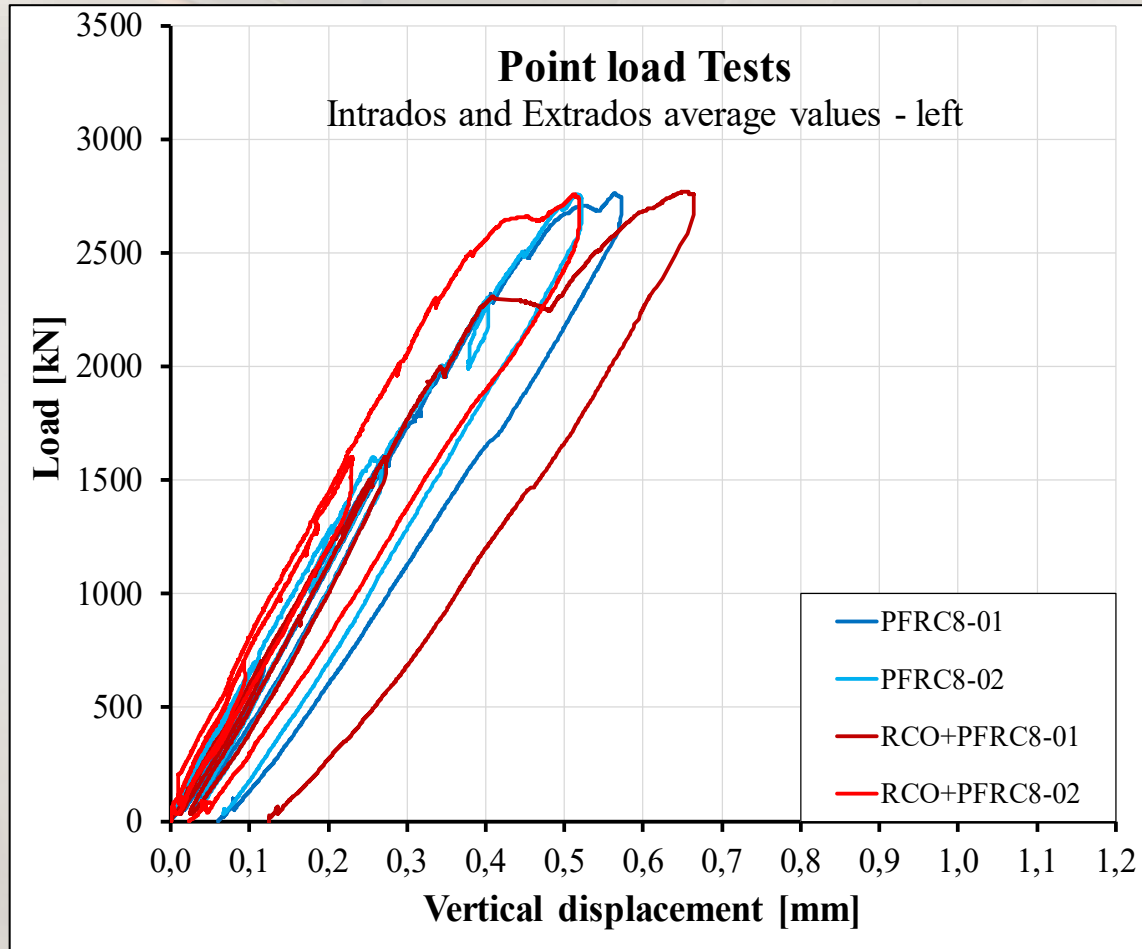
CASE STUDY: Scilla tunnel – point load tests

- carico nominale in esercizio per ogni scarpa: **700 kN**
- carico eccezionale per ogni scarpa: **1000 kN** (1.43 volte il carico di esercizio)
- carico massimo in caso di emergenza per ogni scarpa di spinta: **1600 kN** (2.29 volte il carico di esercizio)

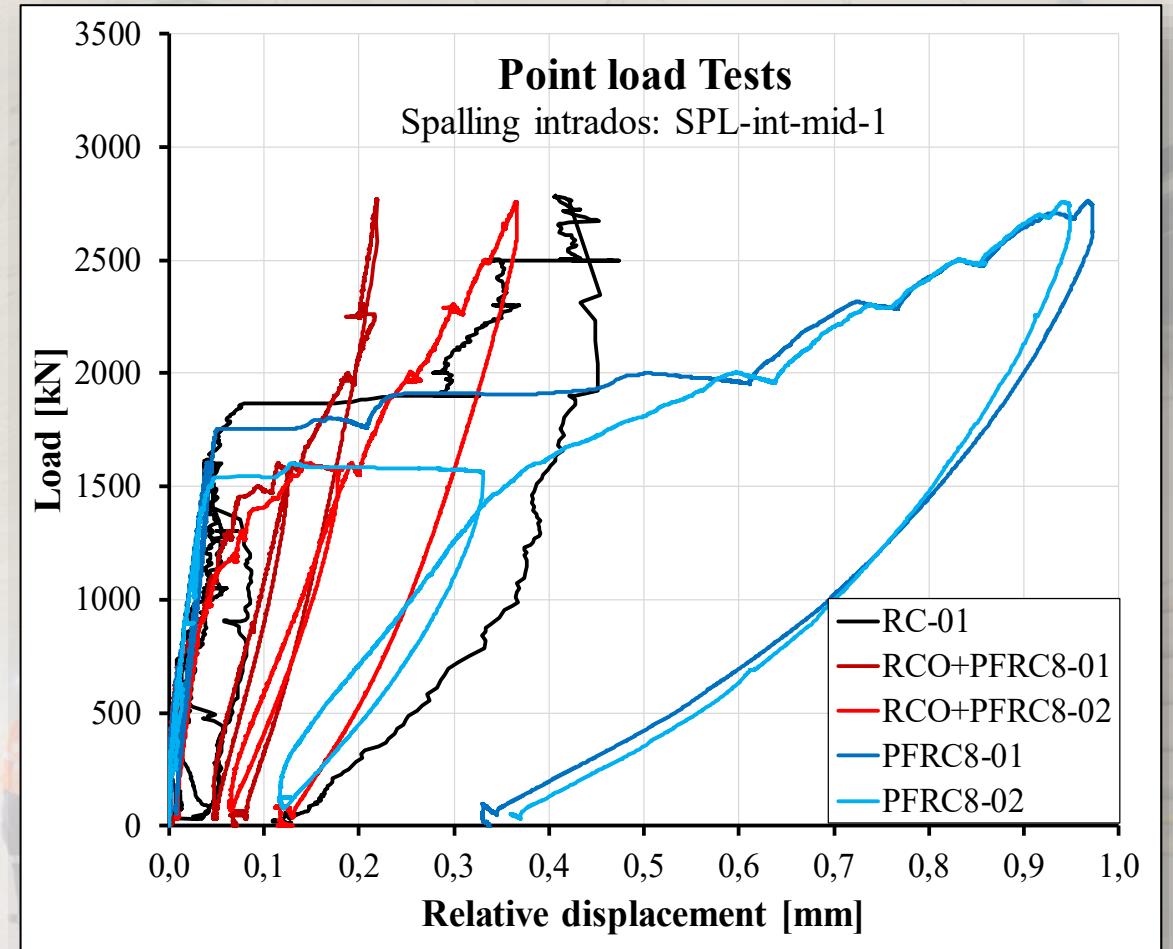


CASE STUDY: Scilla tunnel – point load tests

Carico-spostamento verticale

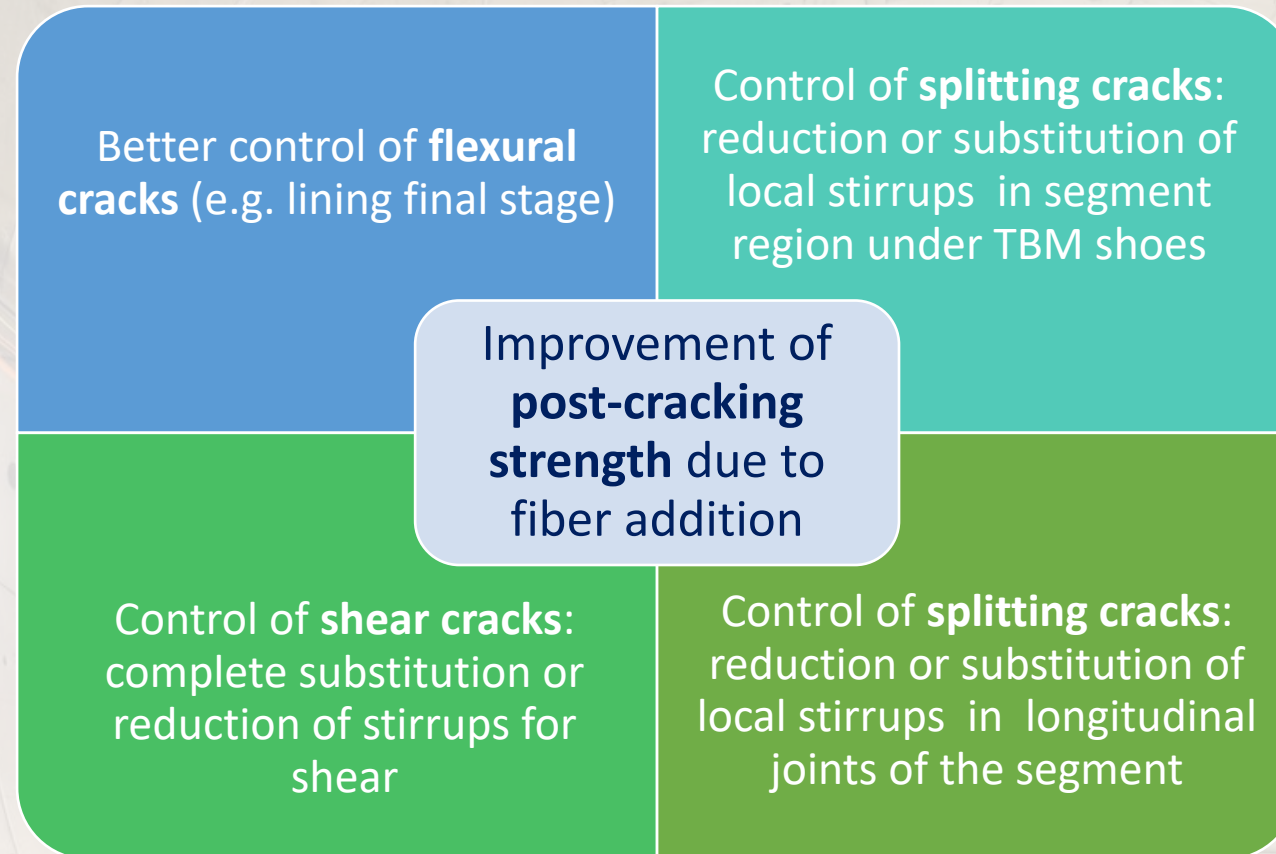


Carico-apertura di fessura



FRC OPTIMIZATION

Enhancement of structural behavior



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 - lesson

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
- The **flexural demand** in tunnel segments is a key-point for evaluating the possibility to completely substitute traditional rebars with FRC

Keys

- 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.

Recom.

- 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)

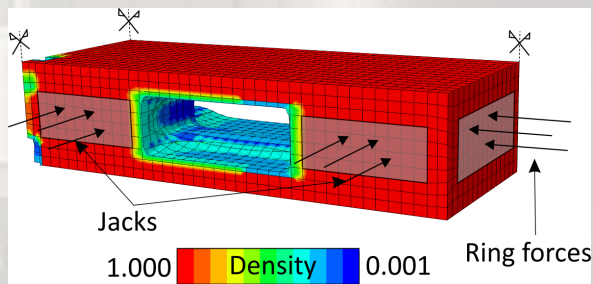
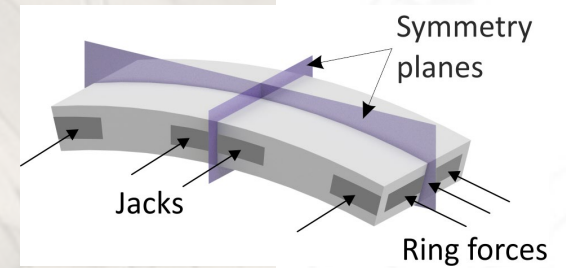
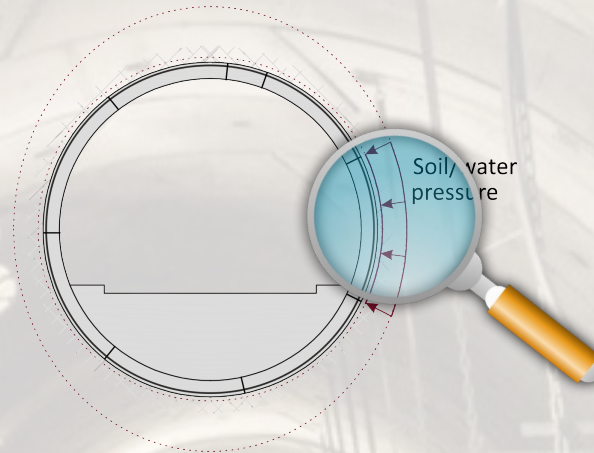
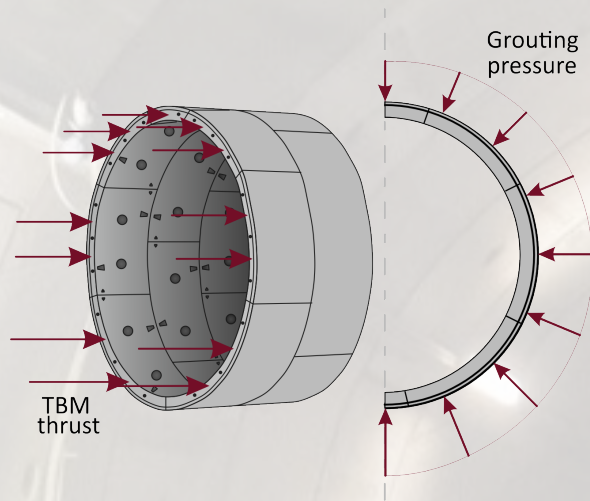
Optimized Reinforcement for elevated slabs

Optimized hybrid topology of segmental tunnel linings

- Diego N. Petraroia, Filippo Medeghini, Peter Mark & Giovanni A. Plizzari
- Institute of Concrete Structures, Ruhr University Bochum, Germany
- DICATAM, University of Brescia, Italy



Topology optimization of segments.

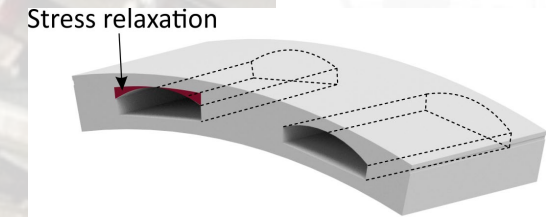


$$\min_{\mathbf{x}}: c(\mathbf{x}) = \sum_{i=1}^3 \mathbf{U}_i^T \mathbf{K} \mathbf{U}_i$$

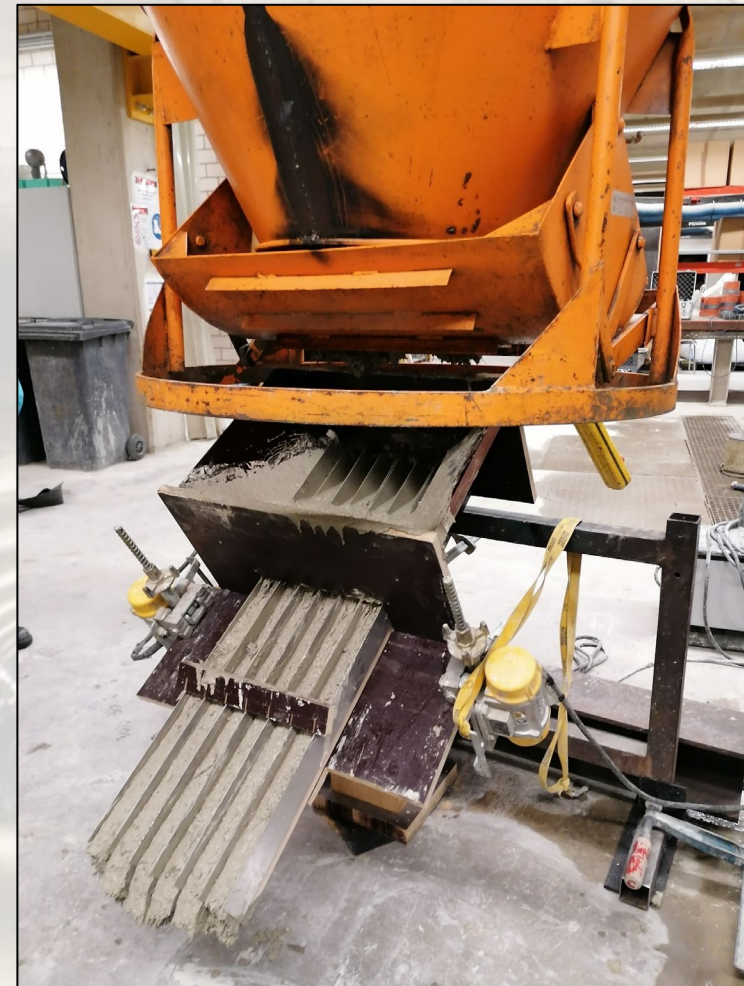
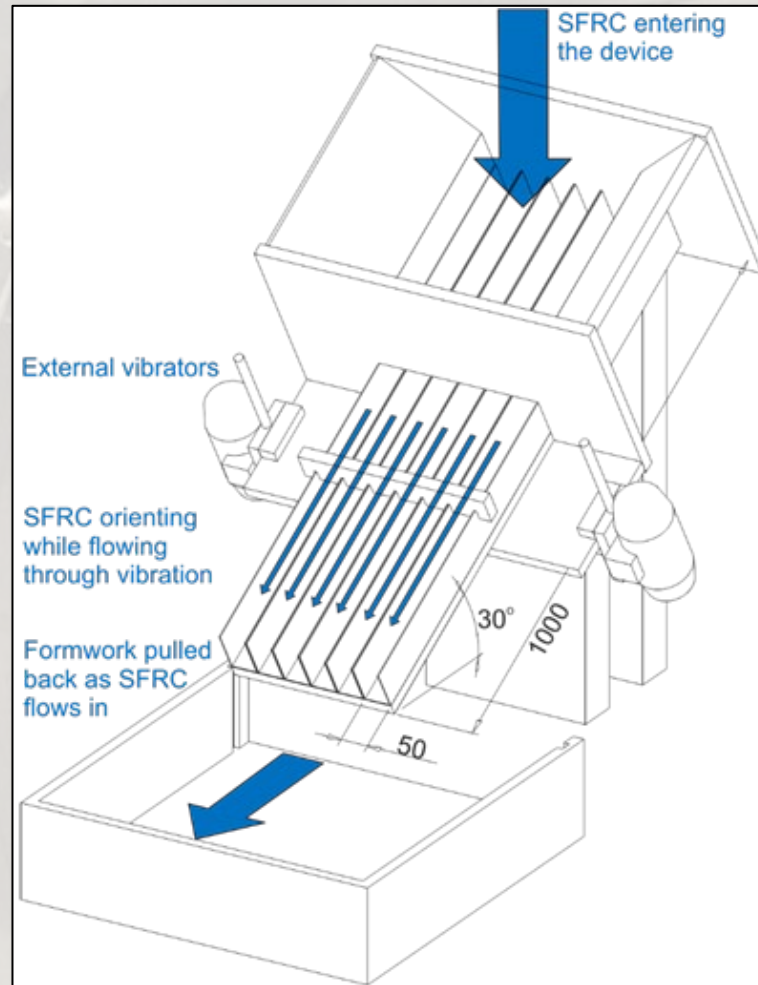
$$\text{subject to: } V(\mathbf{x})/V_0 = 0.75$$

$$\mathbf{K} \mathbf{U} = \mathbf{F}$$

$$0 < \mathbf{x} \leq 1$$



Local splitting phenomena: new perspective on fiber orientation



In collaboration with:
RUHR
UNIVERSITÄT
BOCHUM
RUB

Filippo Medeghini
Giuseppe Tiberti
Peter Mark
Giovanni Plizzari

Local splitting phenomena: new perspective on fiber orientation

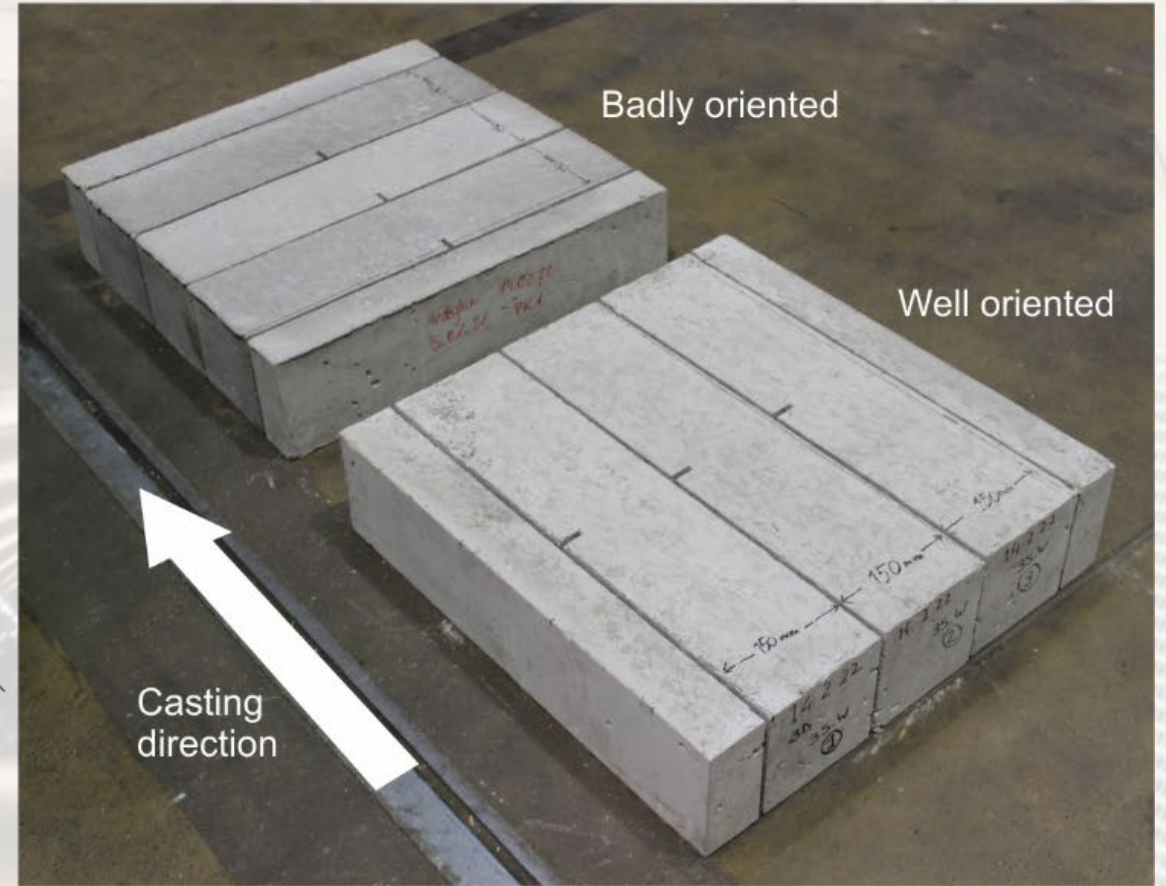
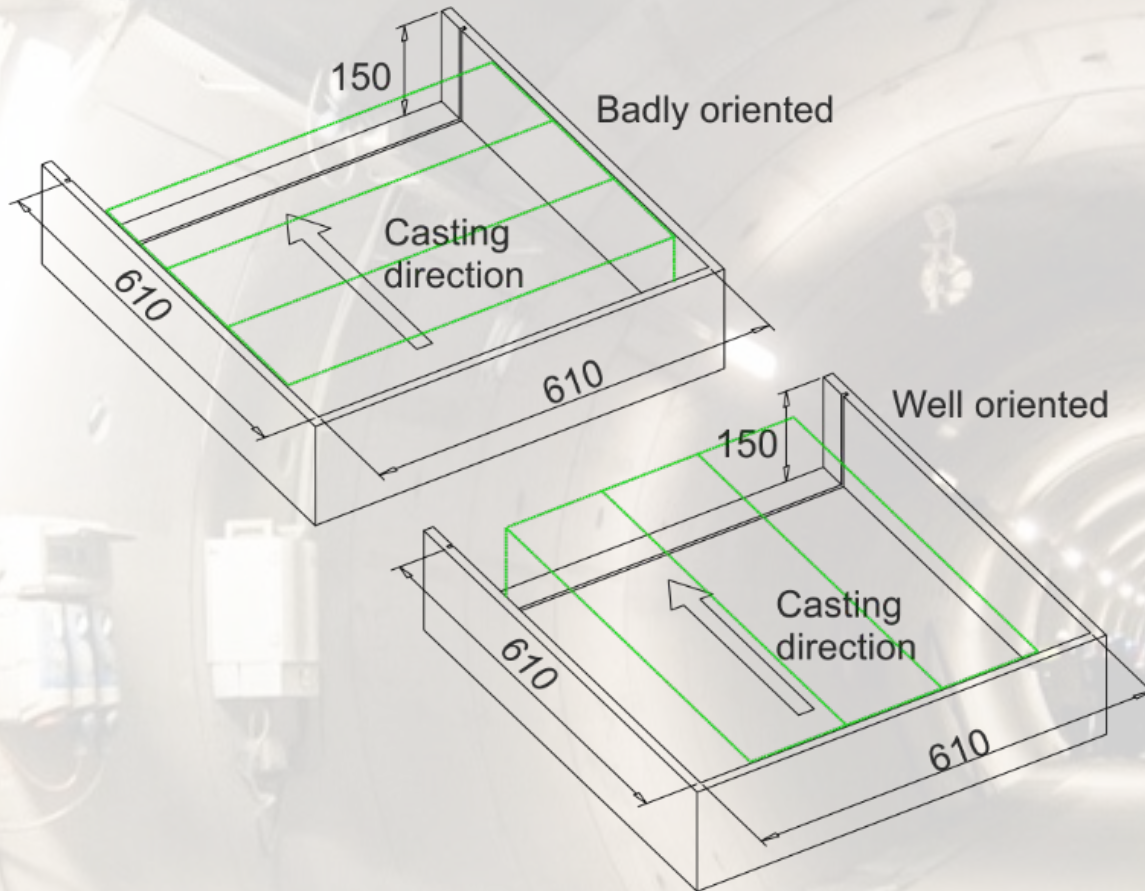
In collaboration with:

RUHR
UNIVERSITÄT
BOCHUM

RUB



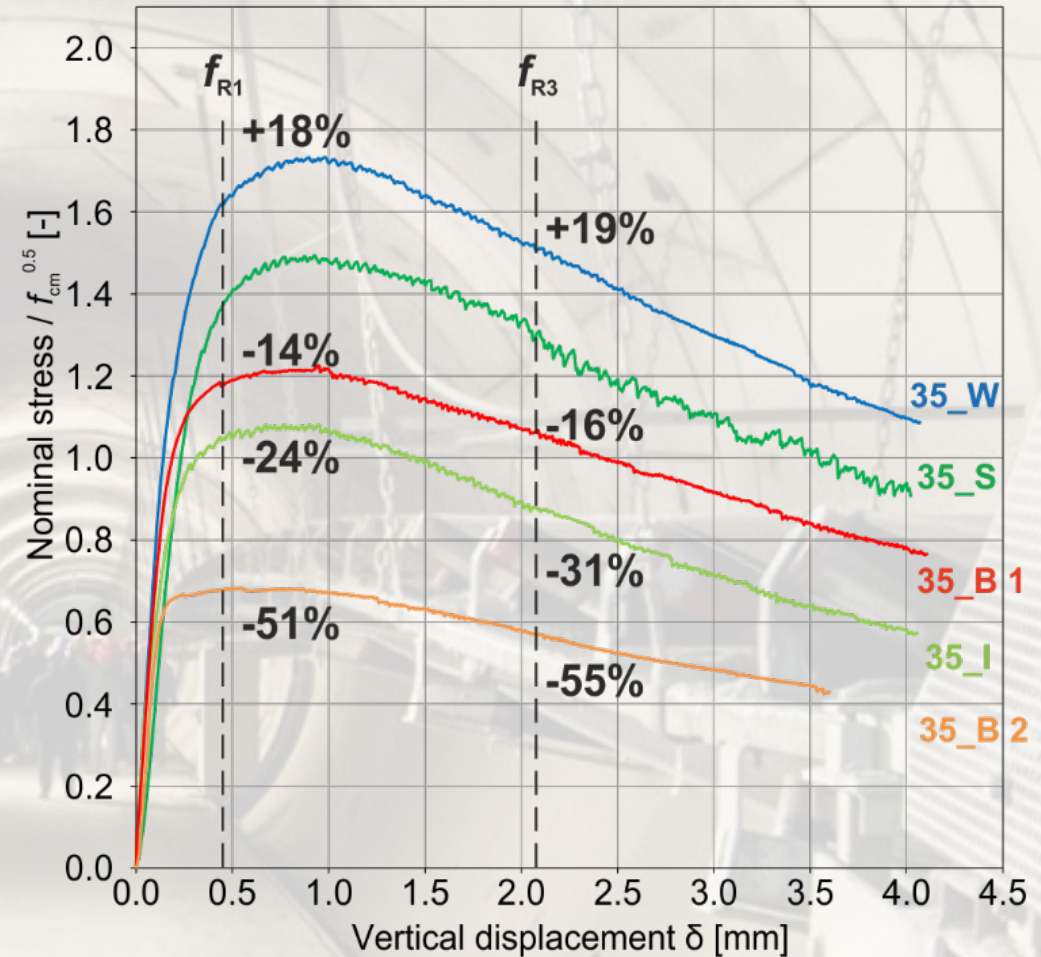
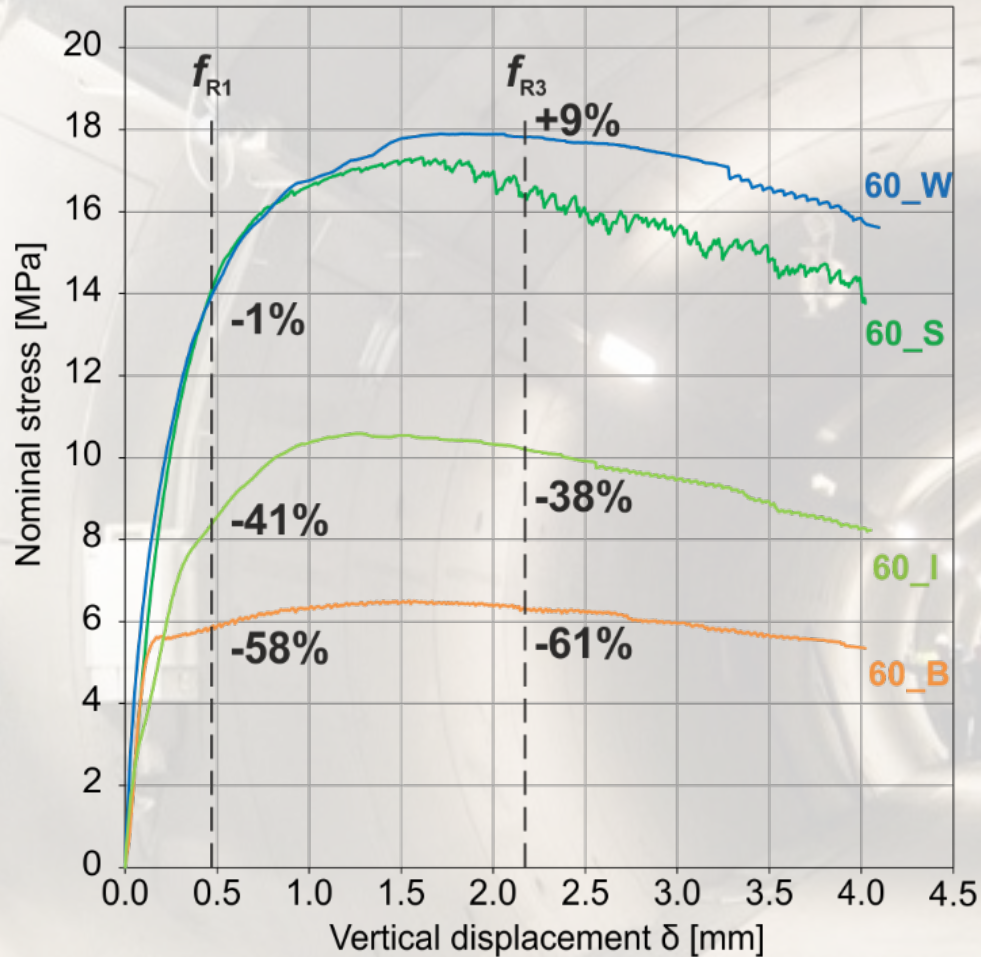
Specimen preparation



Material properties

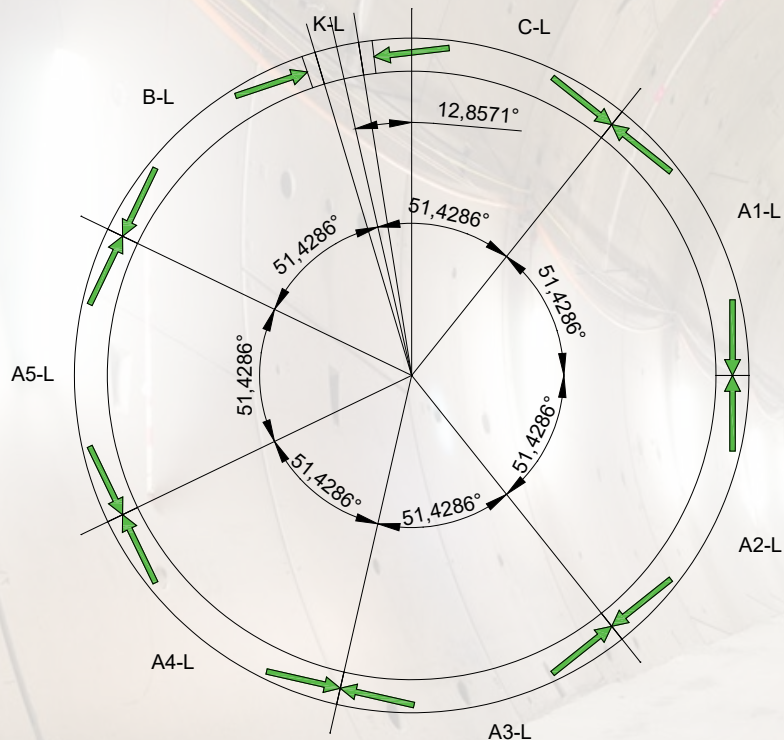
	60 Series				35 Series						
Series designation	60_W	60_S	60_I	60_B	35_W 1	35_W 2	35_S	35_I 1	35_I 2	35_B 1	35_B 2
Batch number	1	2	3	4	5	7	8	5	6	6	7
Flow table test (cm) [34]	46	53	46	40	44	41	50	44	58	58	41
$f_{cm,cube}$ (MPa)	79,3	79,0	79,3	76,9	79,8	68,1	62,3	79,8	68,1	68,1	68,1

Experimental results



Numerical modelling

High axial load
+
Concrete partially loaded area
along longitudinal joints



High thickness requirements

Received: 7 March 2019 | Revised: 13 July 2019 | Accepted: 31 July 2019
DOI: 10.1002/suco.201900081

TECHNICAL PAPER

fib WILEY

Hybrid reinforcement design of longitudinal joints for segmental concrete linings

Mario Smarslik | Peter Mark

Starting point to develop a new concept of
hybrid solution for precast tunnel
segments

Reduced thickness compared to the
traditional solution

Numerical modelling

CASE STUDY: Wehrhahn-Linie Düsseldorf (Metro tunnel)

Width: 1.50 m
Thickness: **0.45 m**
Average length: 3.93 m

Tunnel lining aspect ratio:

$$\frac{\text{Internal diameter}}{\text{Thickness}} = \frac{D_i}{H} = \frac{8.30}{0.45} = 18.4$$

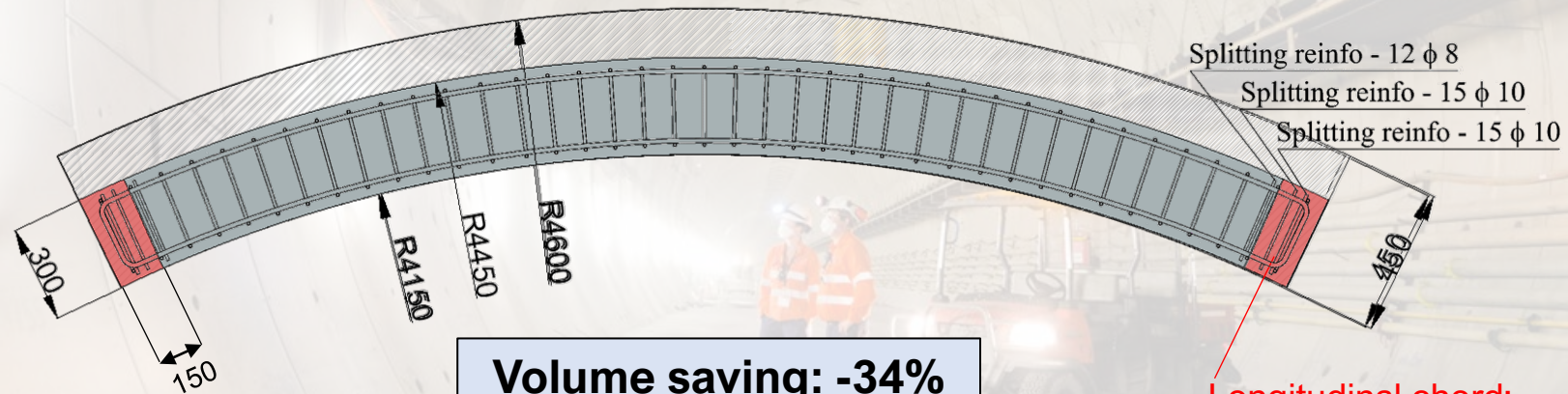
Original segment

Width: 1.50 m
Thickness: **0.30 m**
Average length: 3.86 m

Tunnel lining aspect ratio:

$$\frac{\text{Internal diameter}}{\text{Thickness}} = \frac{D_i}{H} = \frac{8.30}{0.30} = 27.7$$

Hybrid segment



Volume saving: -34%
[$V_{450} = 2.65 \text{ m}^3$ $V_{300} = 1.74 \text{ m}^3$]

Longitudinal chord:
C70/85
FRC 8c

Numerical modelling

Materials mechanical properties

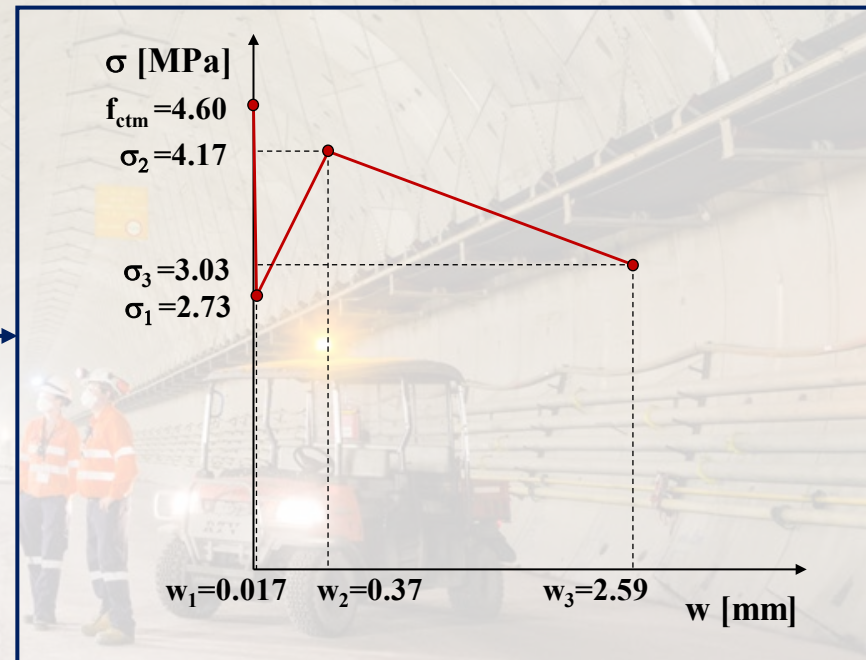
ID	E_{cm} [MPa]	f_{cm} [MPa]	f_{ctm} [MPa]	f_{R1m} [MPa]	f_{R3m} [MPa]
HPFRC70-8C	41000	78	4.60	10.6	10.6

ID	E_{cm} [MPa]	f_{cm} [MPa]	f_{ck} [MPa]	f_{ctm} [MPa]	f_{ctk} [MPa]
C40/50	35000	48	40	3.50	2.50
C70/85	41000	78	70	4.60	3.20

Post-cracking residual flexural strength

Semi-analytical
model
proposed by
eng. Mudadu
[PhD. Thesis]

Uni-axial post-cracking law



Numerical modelling

Materials mechanical properties

ID	E_{cm} [MPa]	f_{cm} [MPa]	f_{ctm} [MPa]	f_{R1m} [MPa]	f_{R3m} [MPa]
HPFRC70-8C	41000	78	4.60	10.6	10.6

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Post-cracking residual flexural strength

Semi-analytical
model
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eng. Mudadu
[PhD. Thesis]

Uni-axial post-cracking law

Materials modelling

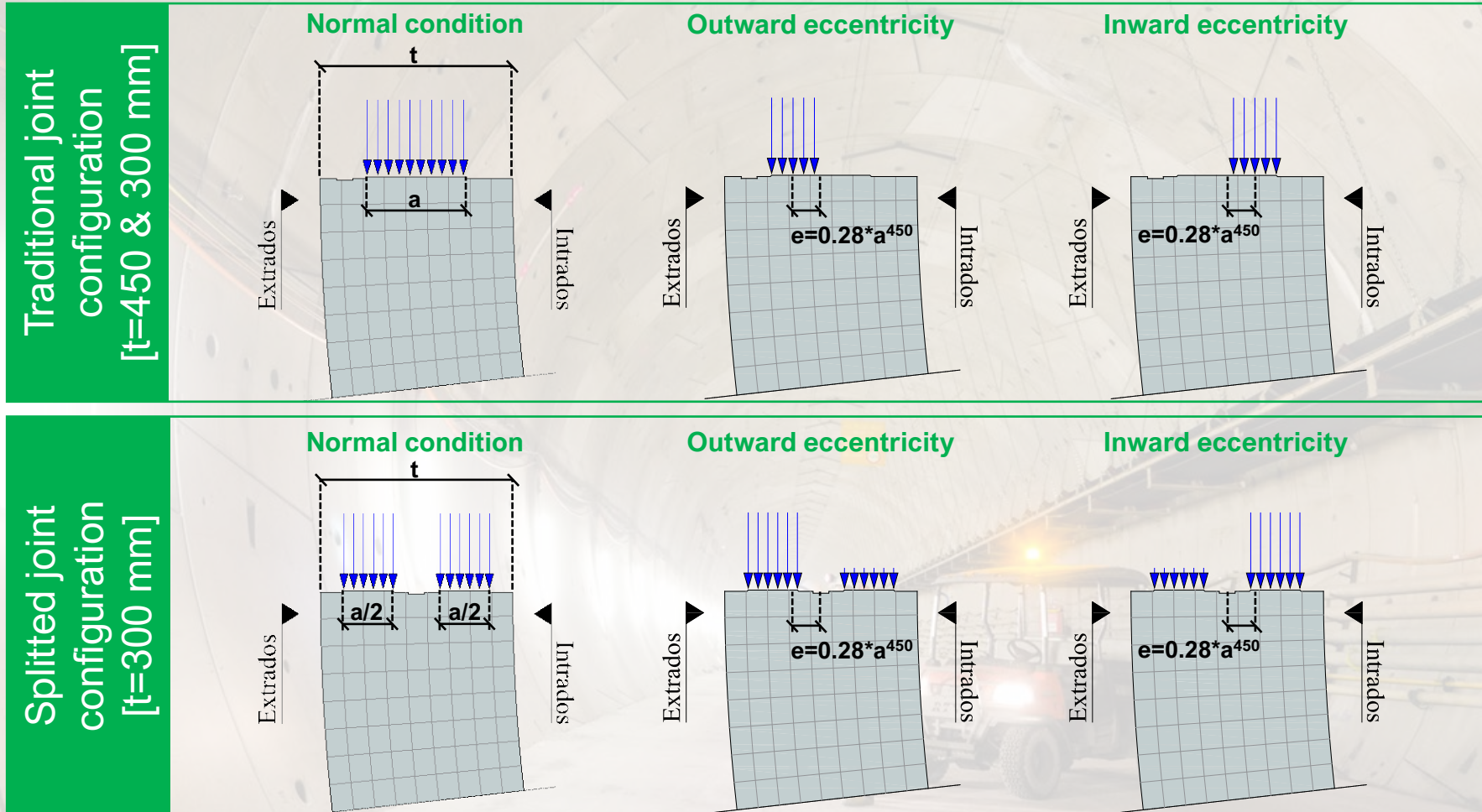
**SMEARED CRACKING
APPROACH**



**Total-strain rotating
crack model**

Numerical modelling

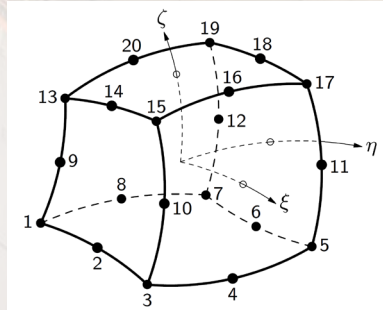
Joint configurations and loading conditions along the longitudinal joint:



Numerical modelling

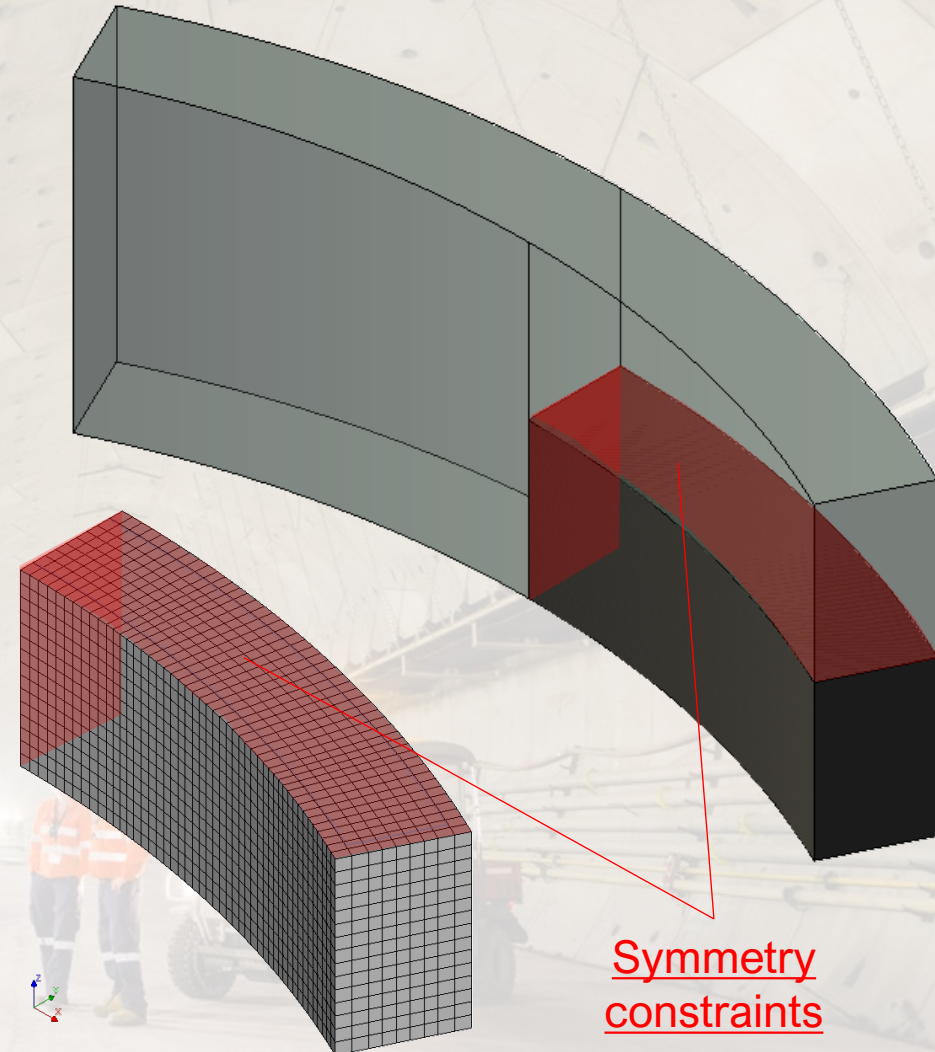
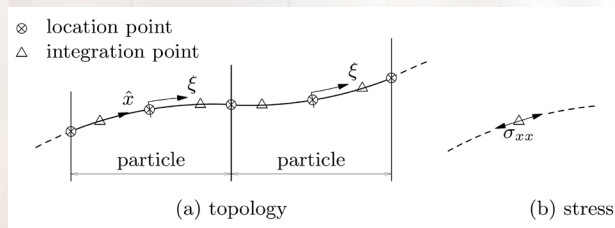
Segment

- solid brick isoparametric elements
- 20 nodes
- quadratic interpolation
- Gauss integration scheme 3x3x3

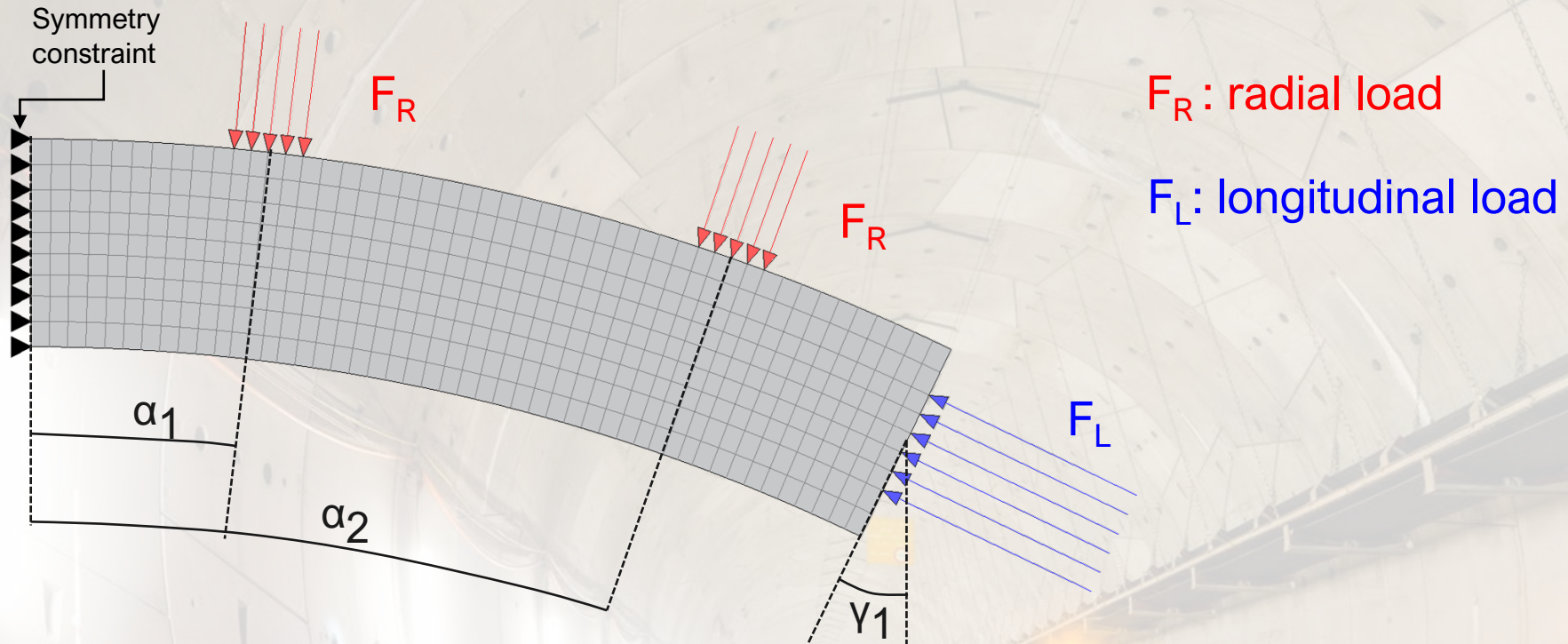


Bars reinforcement

- embedded reinforcement



Numerical modelling

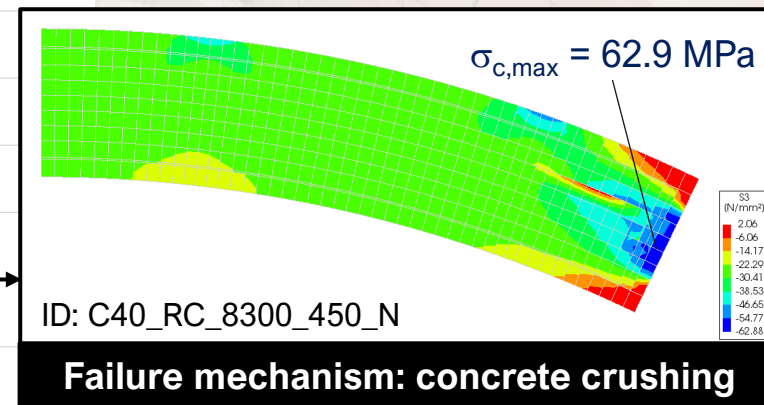
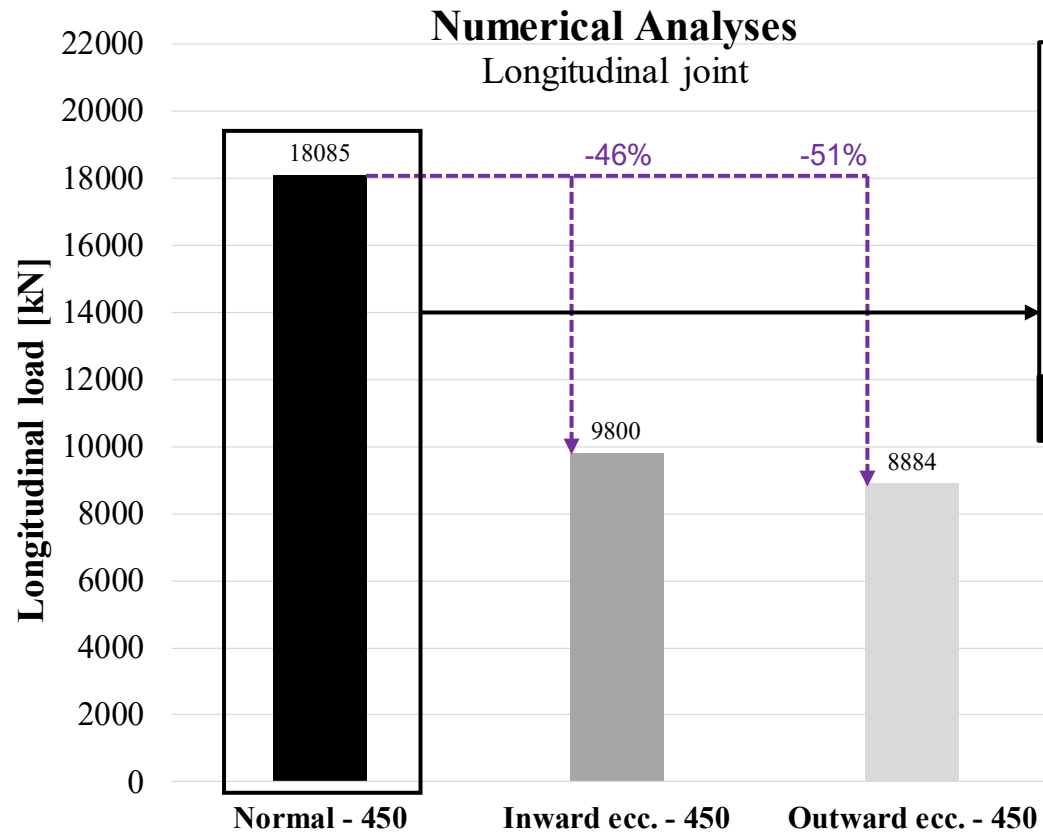


In the analyses the loads were applied to guarantee the vertical equilibrium.
The following relationship has to be fulfilled:

$$\sum \text{Vertical forces} = F_R \cdot \cos\alpha_1 + F_R \cdot \cos\alpha_2 - F_L \cdot \text{sen}\gamma_1 = 0 \quad \frac{F_L}{F_R} = \frac{\cos\alpha_1 + \cos\alpha_2}{\text{sen}\gamma_1}$$

Numerical modelling

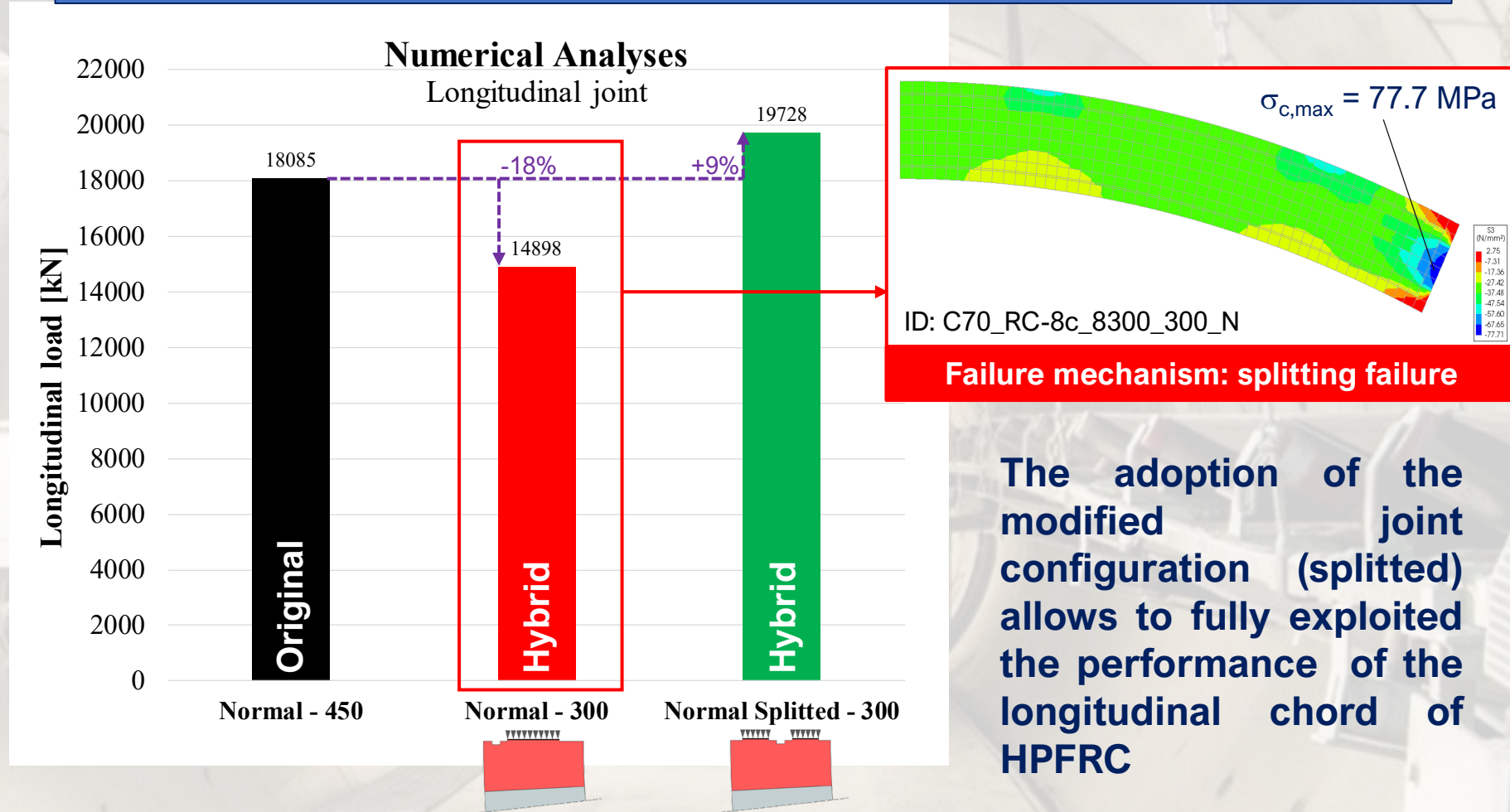
Original segment: normal vs. eccentric loading condition



The eccentricity greatly influences the bearing capacity of the longitudinal joint

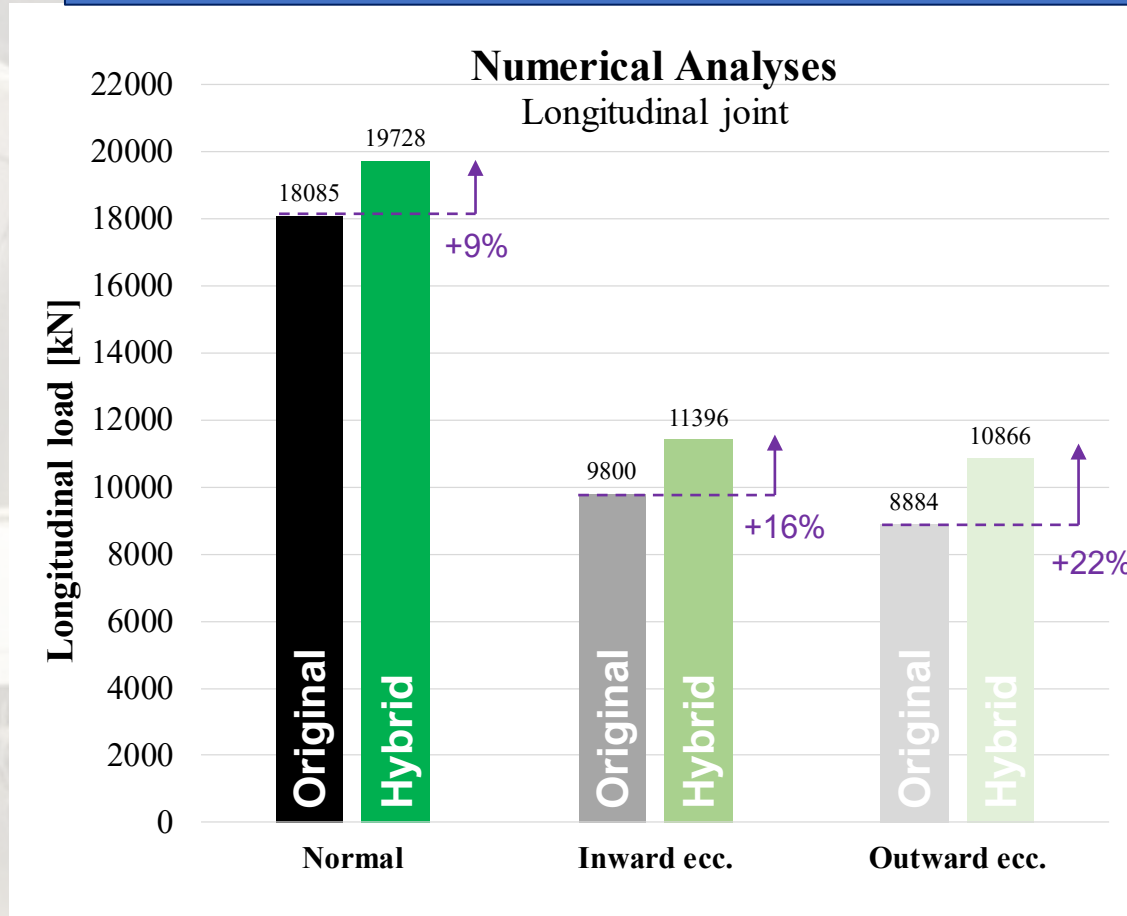
Numerical modelling

Normal condition: original vs. hybrid segments

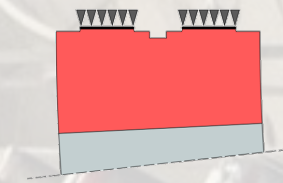


Numerical modelling

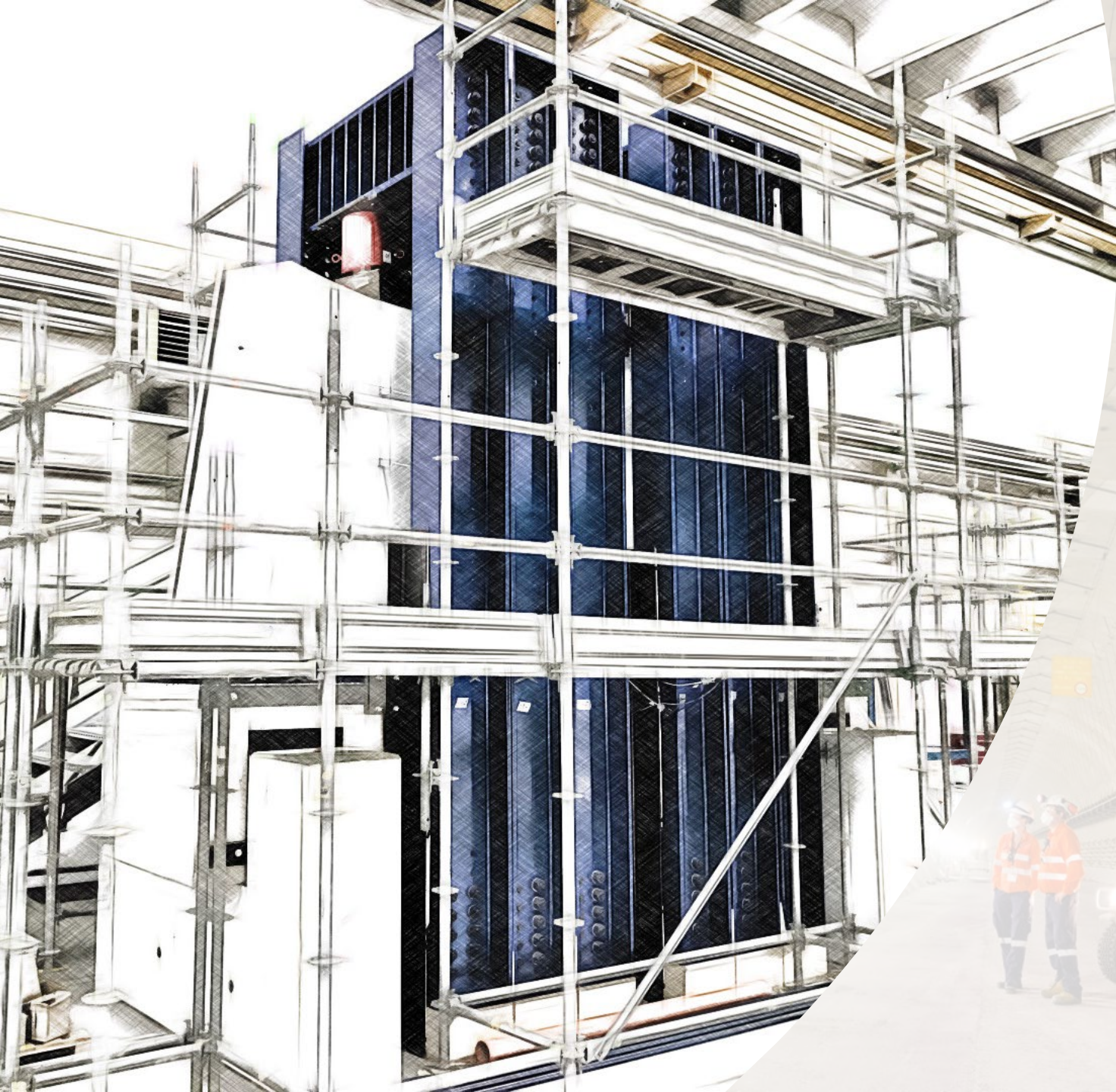
Normal and eccentric conditions: original vs. hybrid segments



Hybrid reinforcement
+
Splitted condition



Higher bearing capacity compared to the original solution



**Grazie per
l'attenzione
!!**



EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

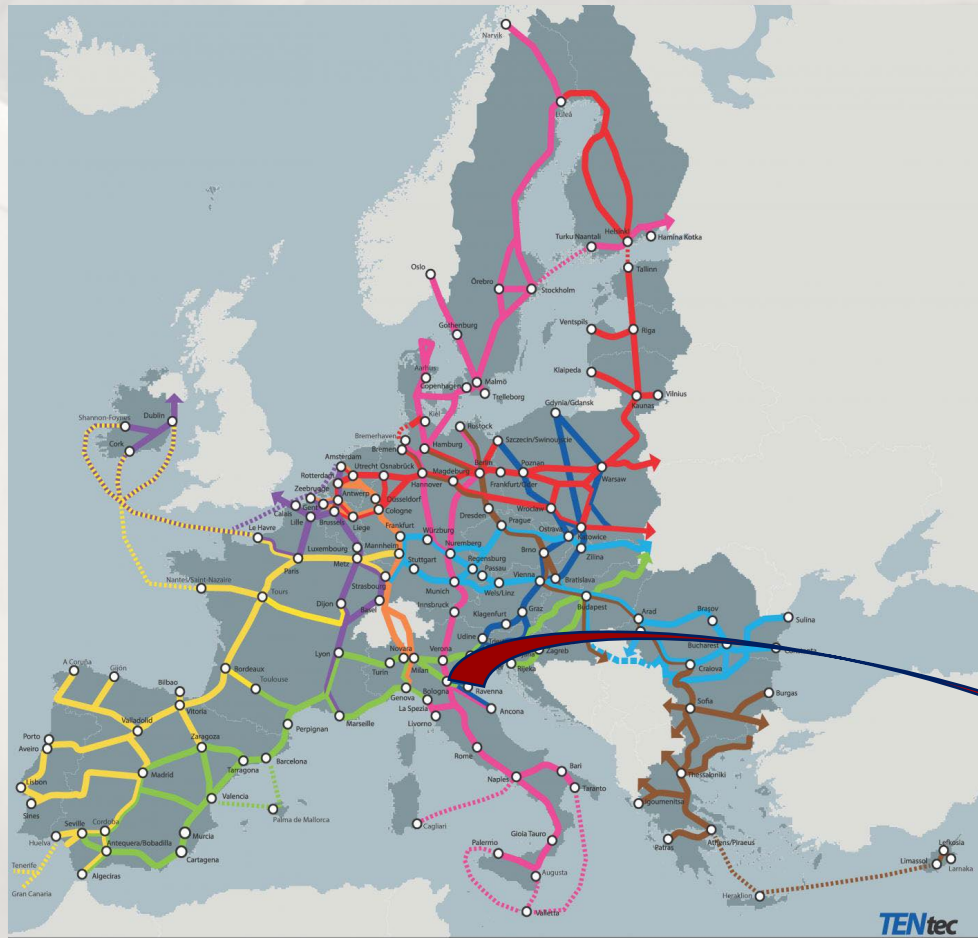


Image source: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

Trans-European Transport Network (TEN-T)

The Trans-European Transport Network (TEN-T) policy addresses the **implementation** and **development** of a **Europe-wide network of railway lines...**

...The ultimate objective is to close gaps, remove bottlenecks and technical barriers, as well as to strengthen social, economic and territorial cohesion in the EU.

AV/AC Torino-Venezia

EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

The Project:

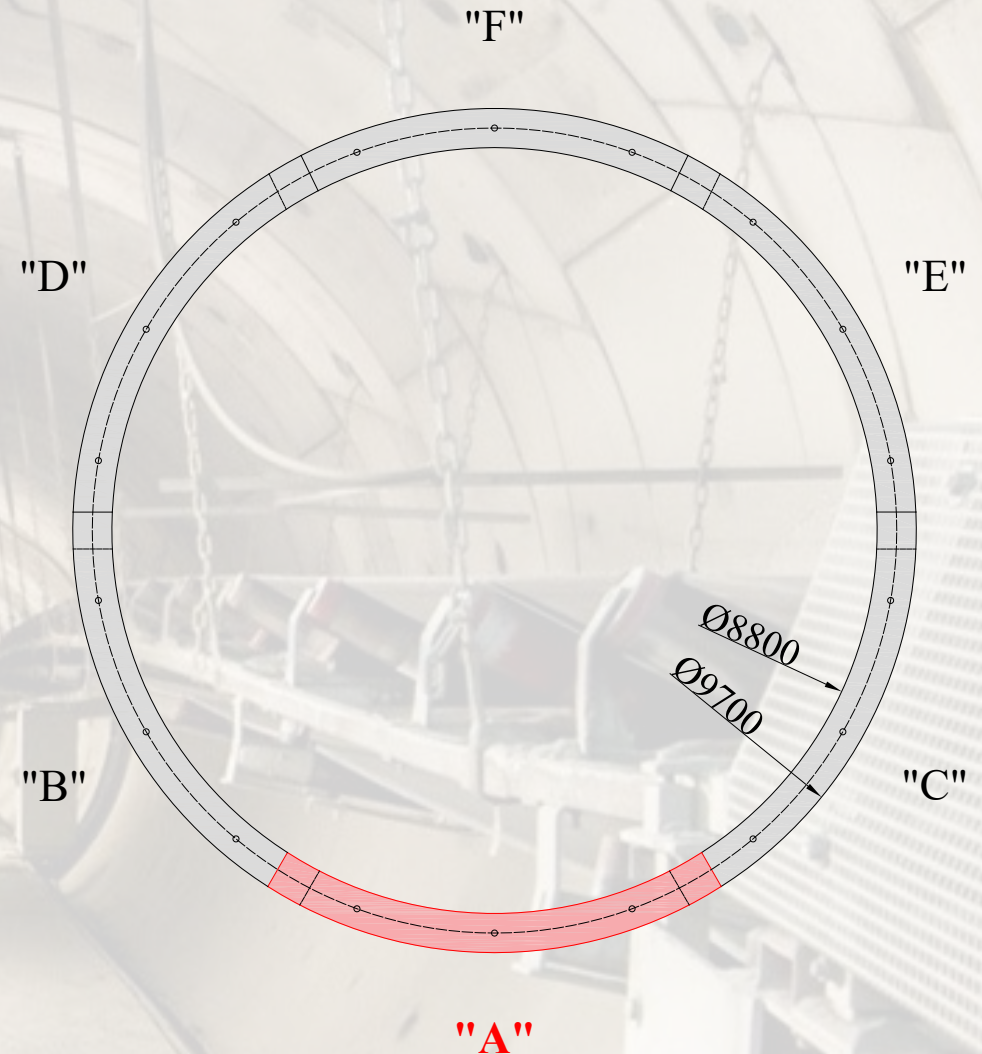
The case study is part of the new **high-speed and high-capacity** Brescia-Verona railway line. It is a **twin-tunnel** lining, each 4800 m long

Lining's geometric features:

Internal diameter: 8.80 m
External diameter: 9.70 m
Thickness: 0.45 m
Width: 2.00 m

Experimental program

Trapezoidal **segment "A"** was chosen



EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel



TWO SEGMENT TYPE "A" WAS TESTED

The force exerted by the TBM thrust system on tunnel segments during the excavation process were applied through a steel-concrete reacting frame



POINT LOAD TEST

FEATURES OF THE REACTING FRAME

- Self-equilibrated system
- concrete beam 1x1x5 m + 6 steel frames
- maximum thrust capacity: 16 MN
- different loading configurations
- maximum sample height: 2 m

EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel



TWO SEGMENT TYPE "A" WAS TESTED

Two loading point for each segment

The size of thrust shoes were the same of the original design

According to the original design the following **loads for each loading point** were considered:

- 1875 kN
- 3750 kN
- 4800 kN
- 5833 kN
- 6650 kN

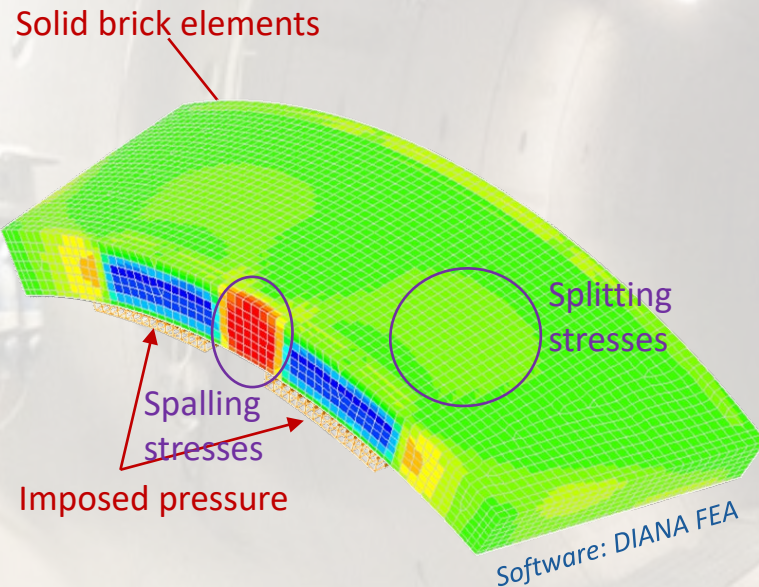
- 7500 kN TBM max. load

EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

How to define instrumentation?



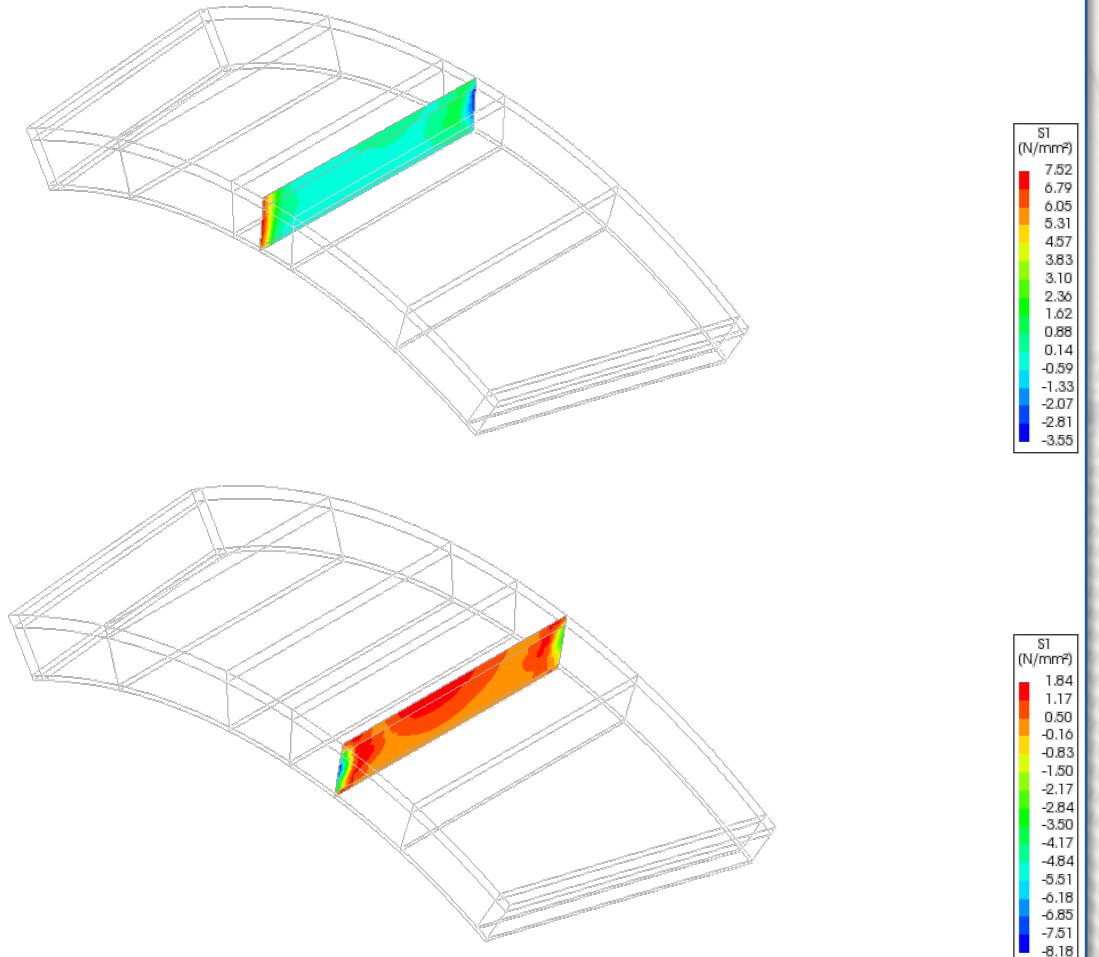
Simplified numerical models can help to identify the position in which to place it



Analysis1
Geometry load case 1
Cauchy Total Stresses S1
min: -3.55N/mm² max: 7.52N/mm²



Analysis1
Geometry load case 1
Cauchy Total Stresses S1
min: -8.18N/mm² max: 1.84N/mm²

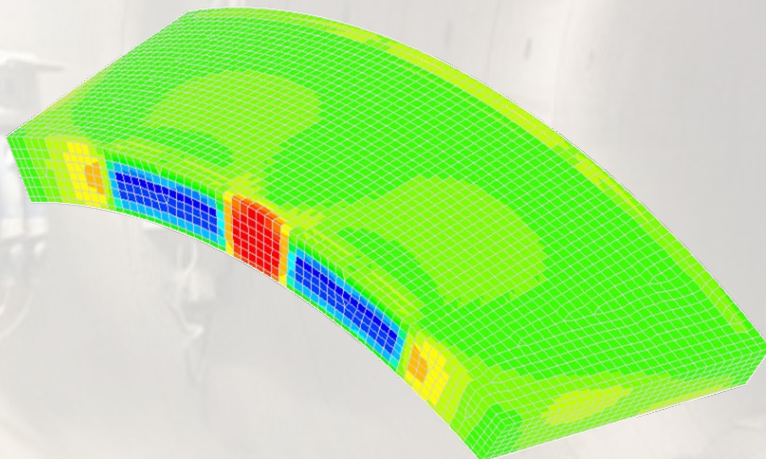


EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

How to define instrumentation?

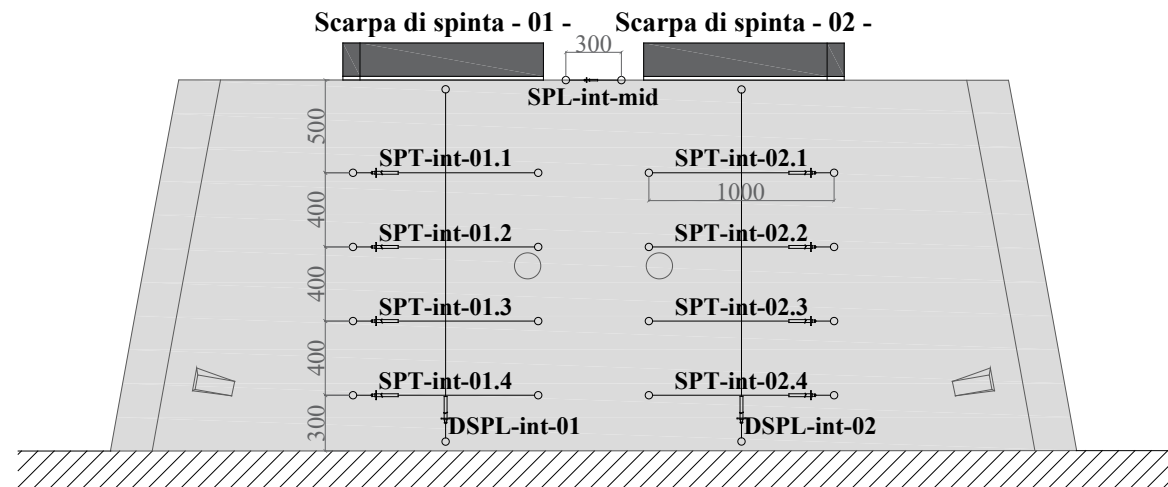


Simplified numerical models can help to identify the position in which to place it



Several displacement transducers were used for monitoring **crack developments** and **displacements** of tunnel segments:

- 4 LVDTs for vertical displacement
- 2 LVDTs for spalling cracks
- 16 LVDTs for splitting cracks



EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

GLOBAL BEHAVIOUR

Segments presented **similar structural response** under TBM load:

C.01 – max vertical displacement: **0.79 mm**

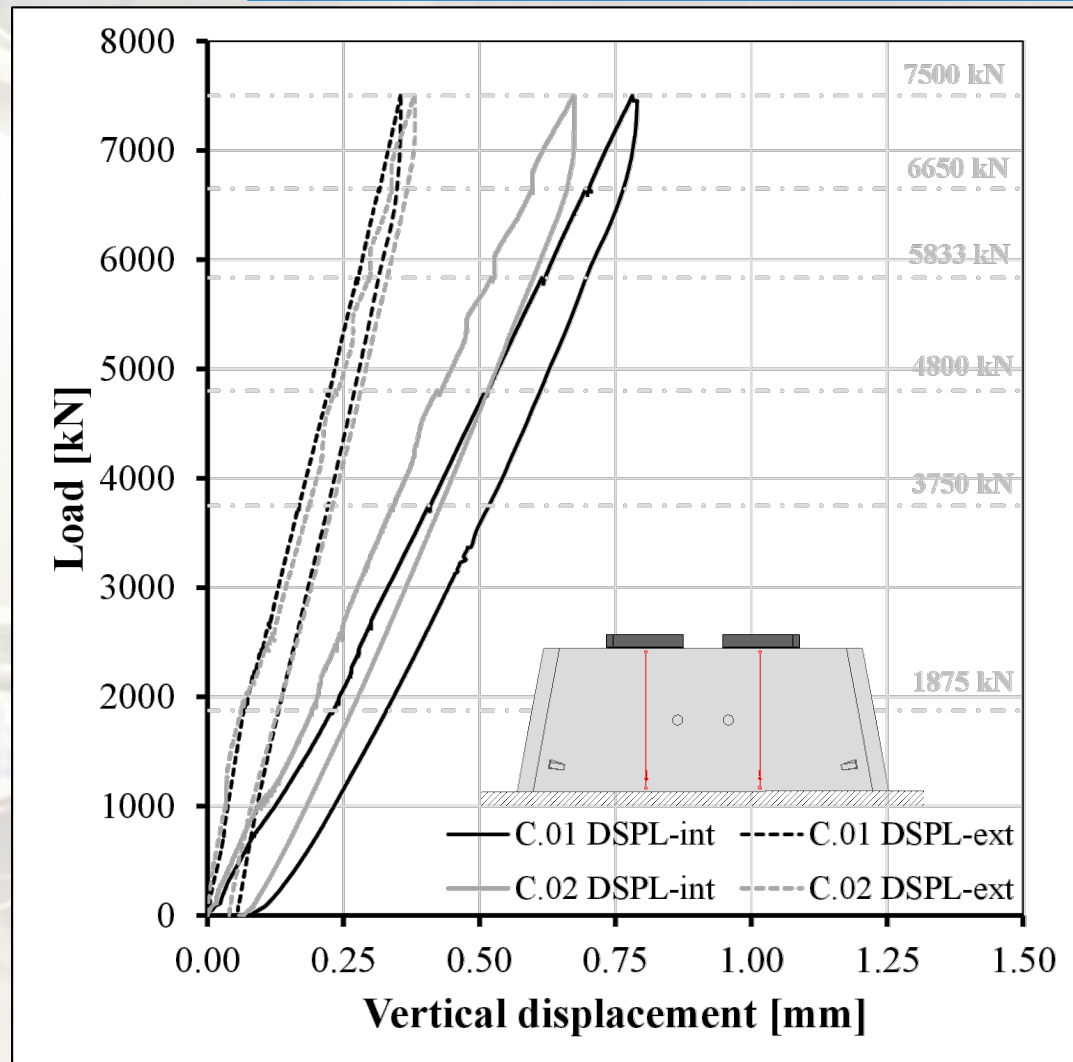
C.02 – max vertical displacement: **0.67 mm**

Vertical displacement was **more pronounced on intrados** side than on extrados side

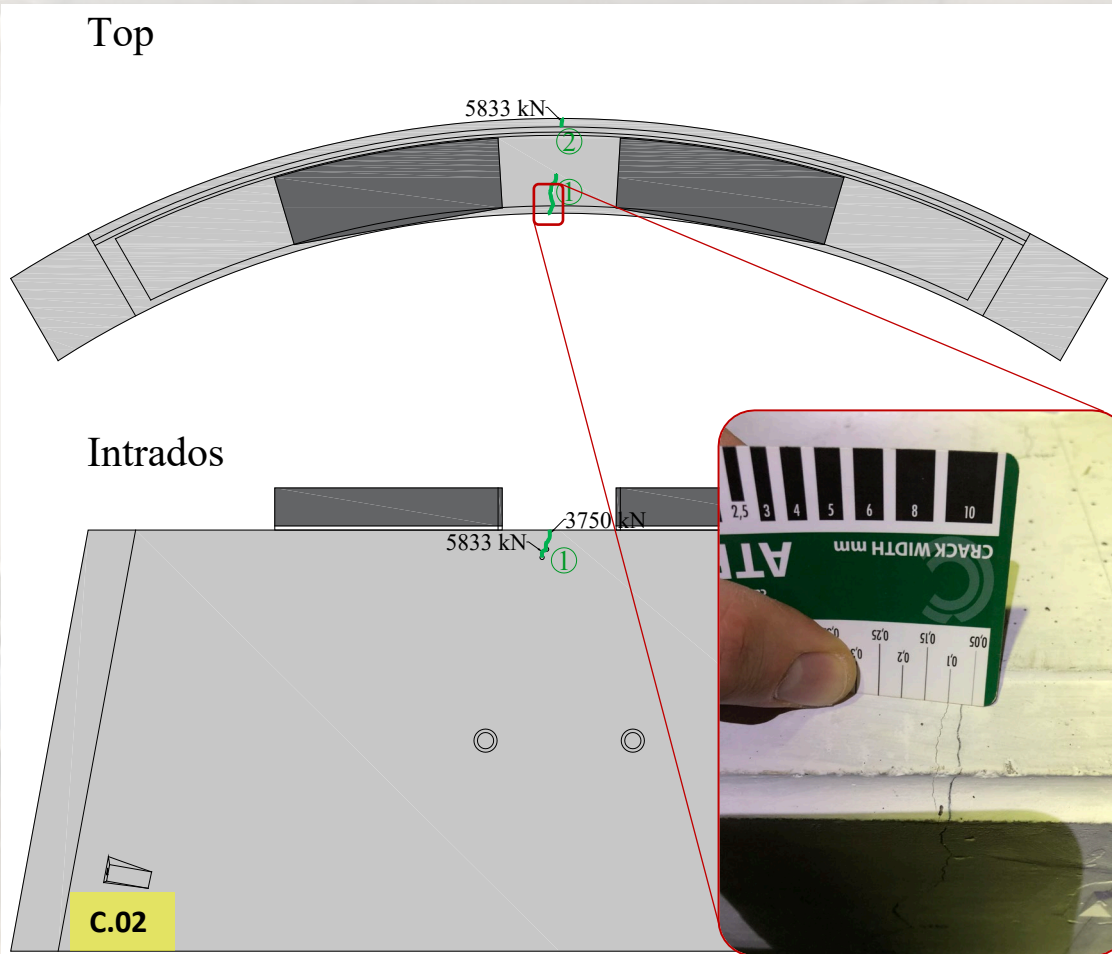


Thrust shoes are shifted on intrados side due to the gaskets

Ratio between intrados and extrados side around 2



EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel



CRACK WIDTHS «C.01»					
N. [-]	3750 kN [mm]	4800 kN [mm]	5833 kN [mm]	6650 kN [mm]	7500 kN [mm]
1	-	<0.05	0.05	0.05	0.10
2	-	-	<0.05	<0.05	0.05
3	-	-	-	<0.05	<0.05

CRACK WIDTHS «C.02»					
N. [-]	3750 kN [mm]	4800 kN [mm]	5833 kN [mm]	6650 kN [mm]	7500 kN [mm]
1	0.05	0.05	0.05	0.10	0.10
2	-	-	<0.05	0.05	0.05

Only **spalling cracks** were detected

Crack opening at maximum load: 0.10 mm

Crack opening after unloading: close or <<0.05 mm

EXPERIMENTAL CHECK FOR AN ONGOING PROJECT: Lonato tunnel

LOCAL BEHAVIOUR

Spalling cracks appeared on intrados side and progressively develop to extrados side

C.01 – Crack onset: **4800 kN**

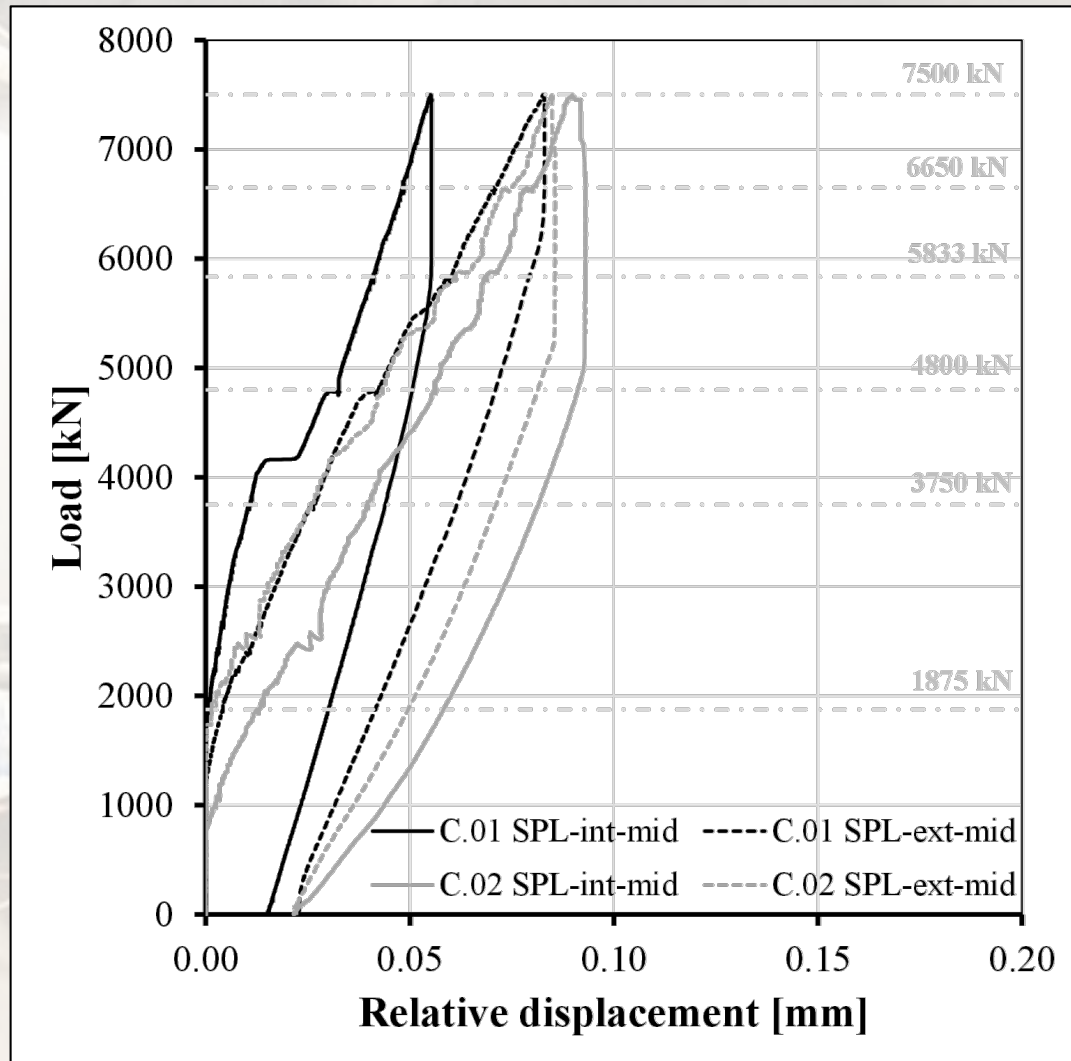
C.02 – Crack onset: **3750 kN**

Displacement transducers were properly located to measure the crack opening

No sudden increases are monitored by displacement transducers



The design reinforcement is adequate to control splitting cracking phenomena



Loading conditions

Load cases

Production & transient
stages

Construction
stages

Service
stages

Segment stripping

Segment storage

Segment transportation

Segment handling

TBM thrust jack forces

Tail skin back-grouting

Earth pressure,
groundwater

Longitudinal joint bursting
load

TBM thrust jack forces
It is a **critical phase**, and it tends to govern the amount of reinforcement (fiber or traditional reinforcement) as the service states

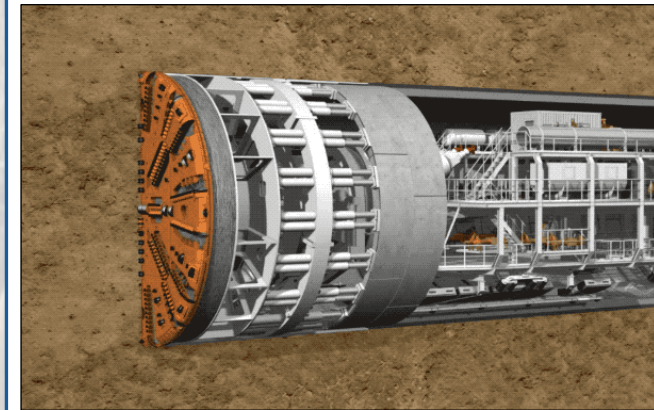


Image source: <https://www.herrenknecht.com/en/>

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)

