RIVESTIMENTI IN ANELLI DI CONCI PREFABBRICATI DI GALLERIE REALIZZATE CON TBM

Brescia, 23 Giugno 2022

Aula Magna Ingegneria - Università di Brescia (UniBs)

ORGANIZZATORI

Collegio dei tecnici della Industrializzazione Edilizia

Società Italiana Gallerie
Italian Tunnelling Society

CON IL PATROCINIO DI

Ordine Ingegneri della provincia di Brescia

Università degli Studi di Brescia

fib CEB-FIP Fédération Internationale du Béton

MEDIA PARTNER

ingenio

SAIE Bologna, 19/22 ottobre 2022

PRESENTAZIONE

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

Università degli Studi di Brescia

SPERIMENTAZIONE E SOSTENIBILITÀ

1. Introduzione

2. Comportamento locale del concio al di sotto delle scarpe di spinta

3. Ottimizzazione dell'armatura dei conci

4. Verifica del comportamento dei conci

Introduzione

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.

Hoe to achieve the Climate Limit States

Use low-carbon material

Reduce the not-renewable energy for the production

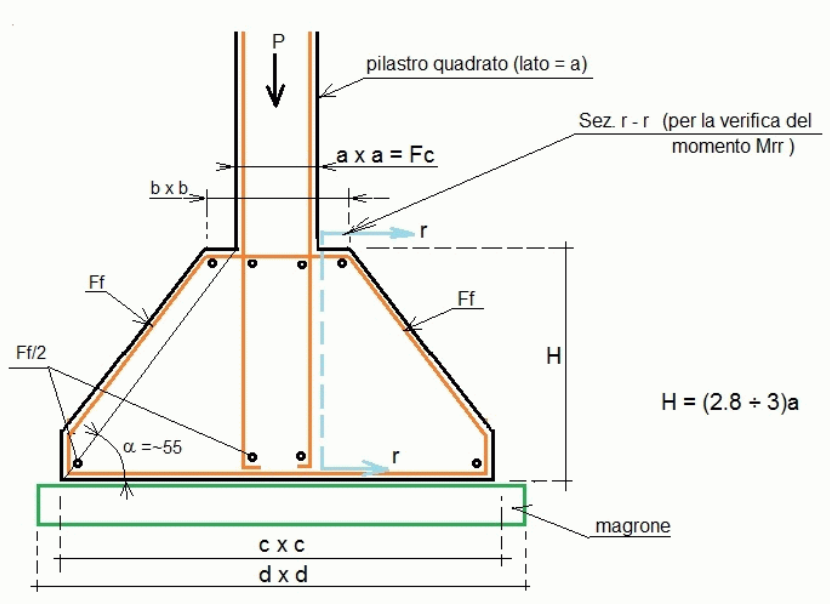
Reduce the transportation

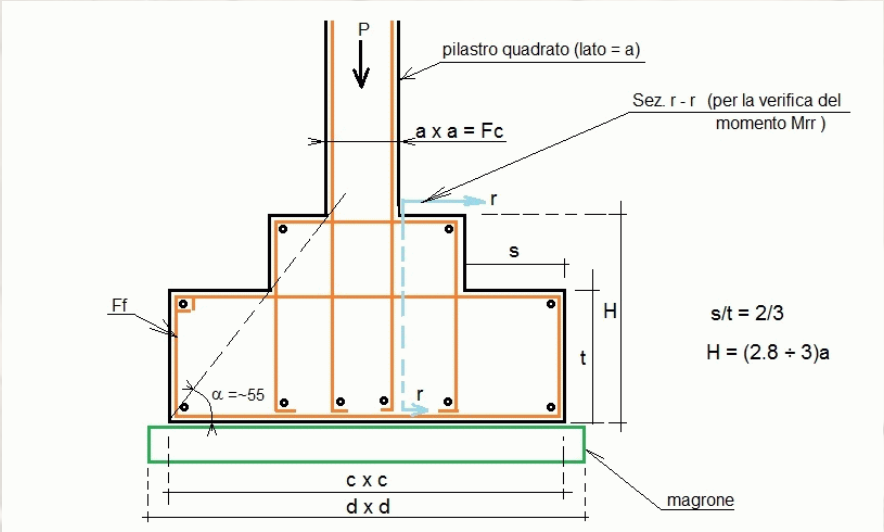
Enhance the durability (for the reduction of the maintenance cost)

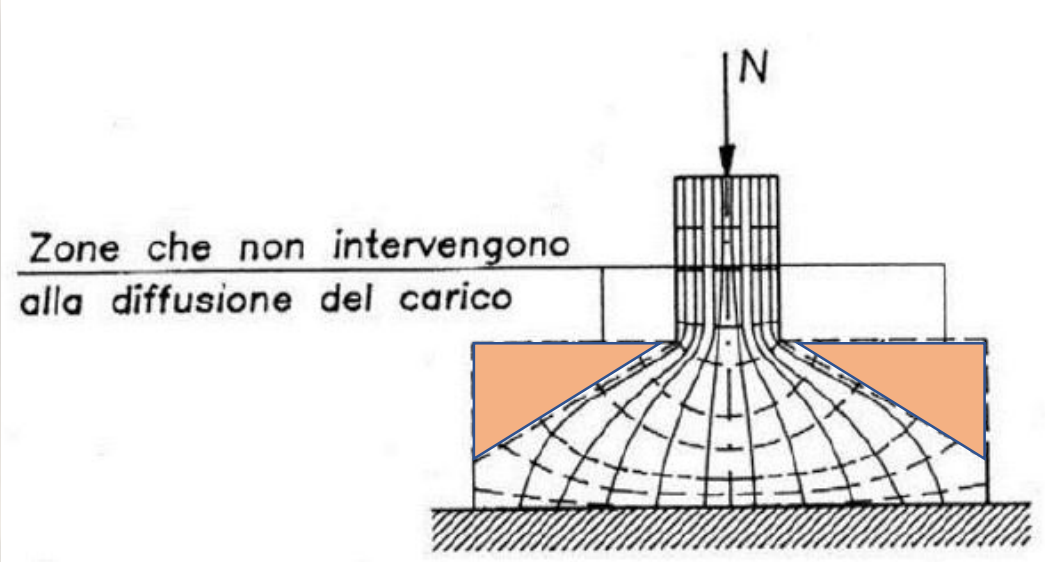
Reduce the material use

etc.

Ottimizzazone del materiale







Fiber Reinforced Concrete (FRC)

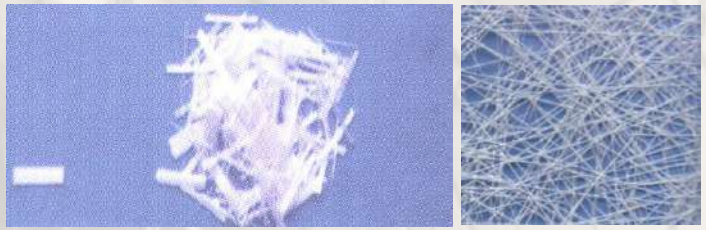
Fibers for concrete

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

- **Steel fibers**

- **Aluminum fibers**

- **Glass fibers**



- **Carbon fibers**

- **Plastic fibers**

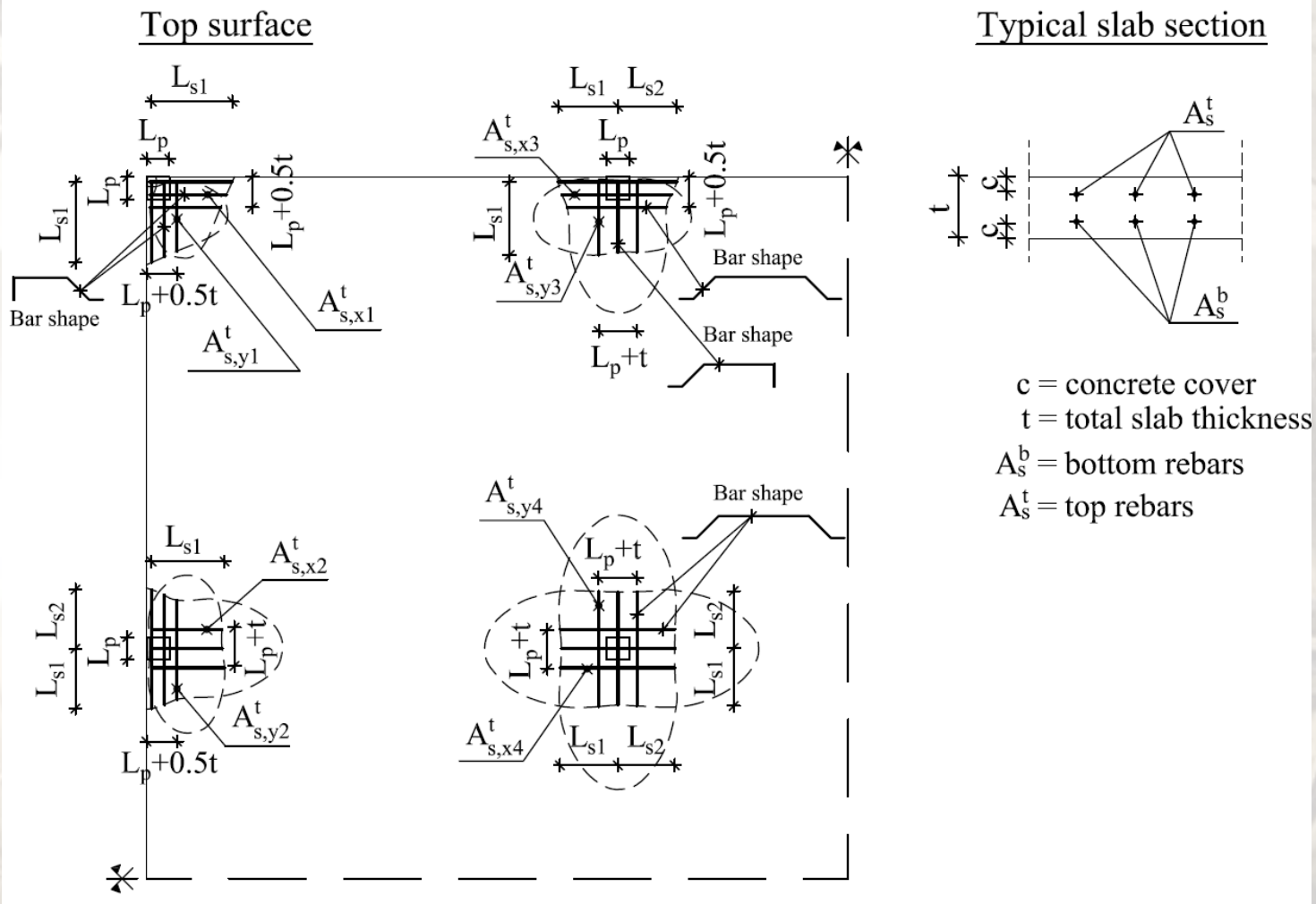
Macro fibre aventi diverse forse forme/ancoraggi e disperse nella matrice cementizia al momento del getto.

Le fibre si attivano dopo la **fessurazione del calcestruzzo.** Il calcestruzzo è in grado di trasmettere sforzi in fase post-fessurativa

PRINCIPALI VANTAGGI DEL FRC

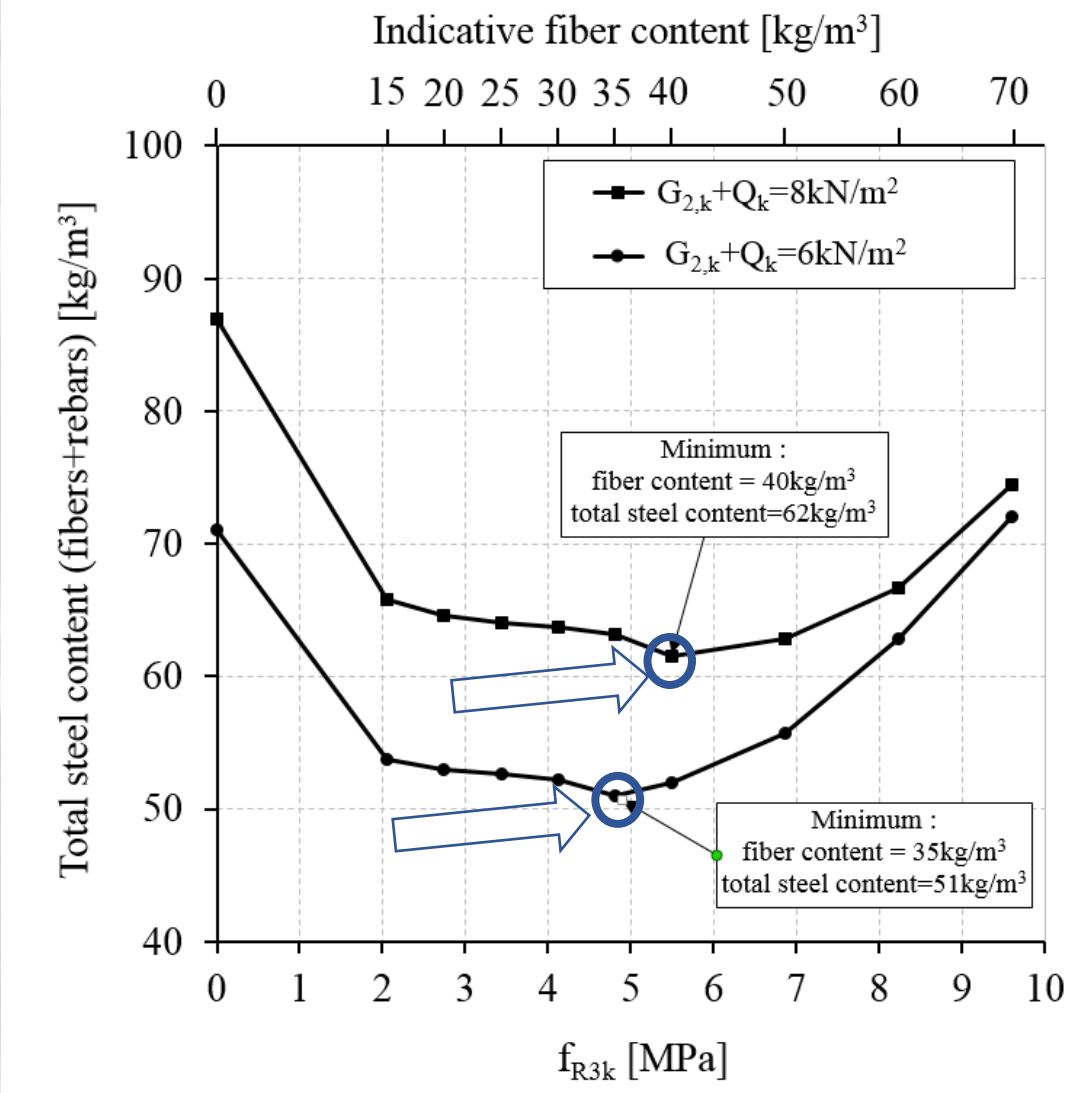
- Incremento delle proprietà residuali post-fessurative → **tenacità**
- Aperture di fessura più piccole→ **panorama fessurativo più distribuito** (durabilità)
- Maggiore resistenza agli **urti** e miglioramento **del comportamento a fatica**

Optimized Reinforcement for elevated slabs



Optimized Reinforcement for elevated slabs

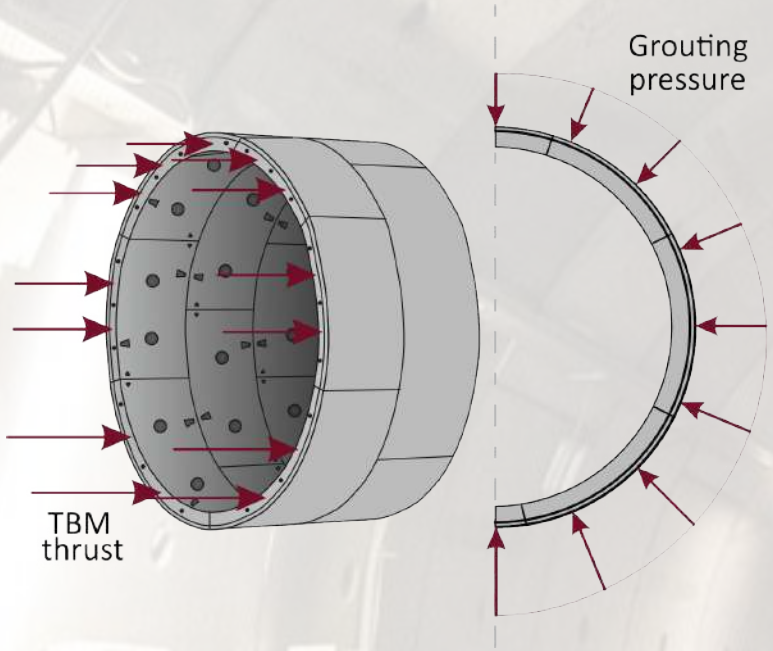
The optimized reinforcement depends on the FRC performance as well as on the properties of the applied loads (i.e., load value, load distribution, etc.)

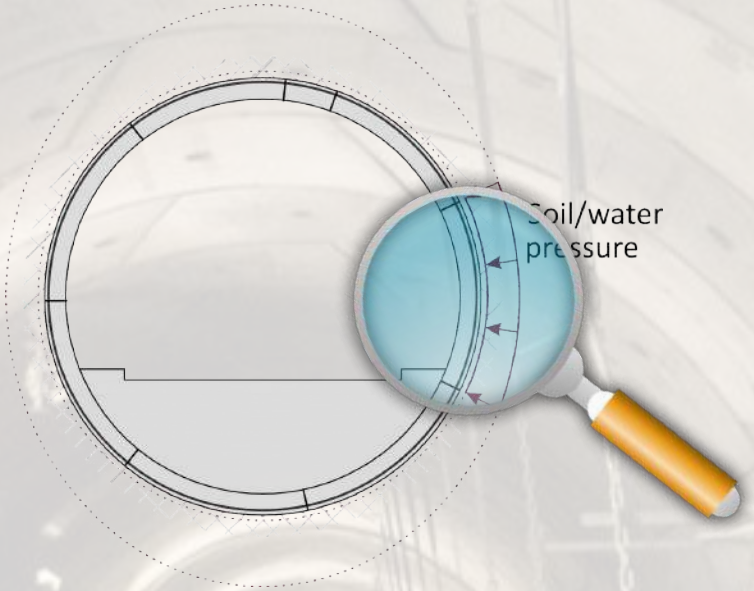


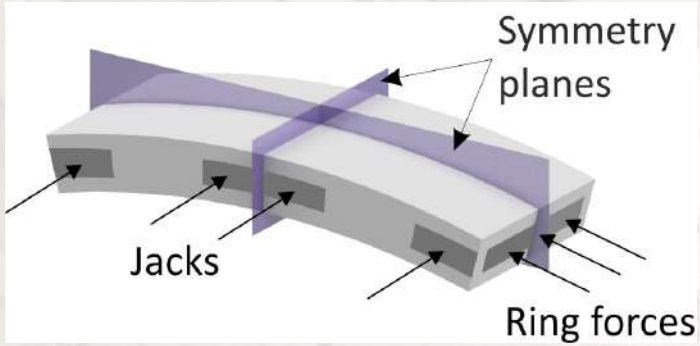
Optimized hybrid topology of segmental tunnel linings

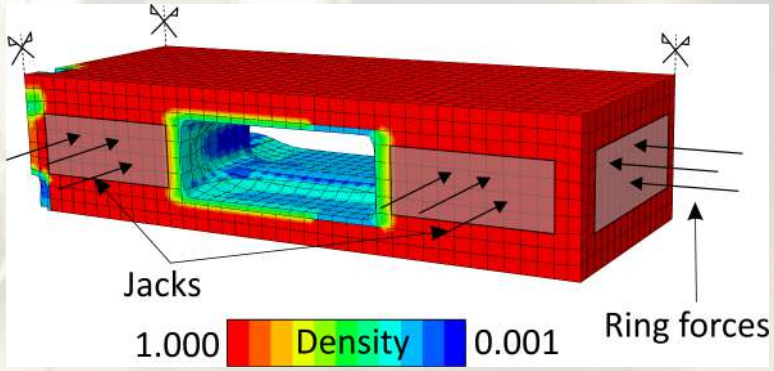
- Diego N. Petraroia, Filippo Medeghini, Peter Mark & Giovanni A. Plizzari
- Institute of Concrete Structures, Ruhr University Bochum, Germany
- DICATAM, University of Brescia, Italy

Topology optimization of segments







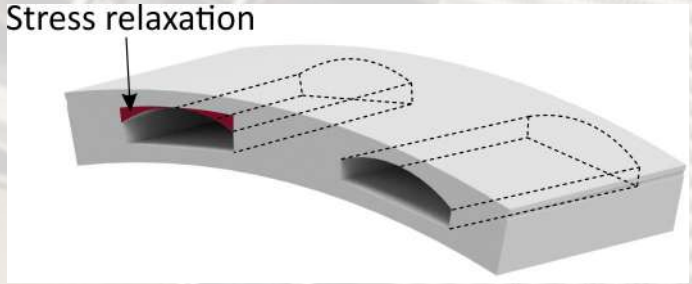


$$\min_{\boldsymbol{x}}: \quad c(\boldsymbol{x}) = \sum_{i=1}^{3} \mathbf{U}_i^T \mathbf{K} \mathbf{U}_i$$

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

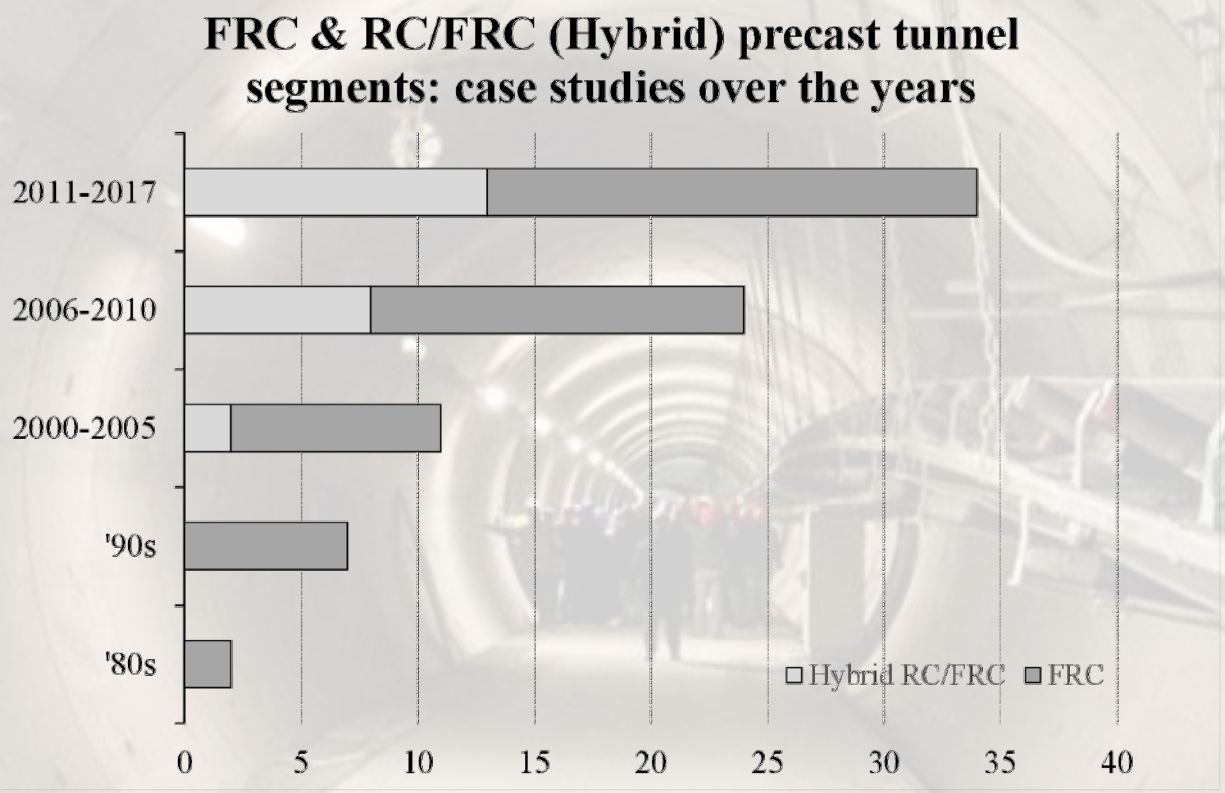
$$\mathbf{KU} = \mathbf{F}$$

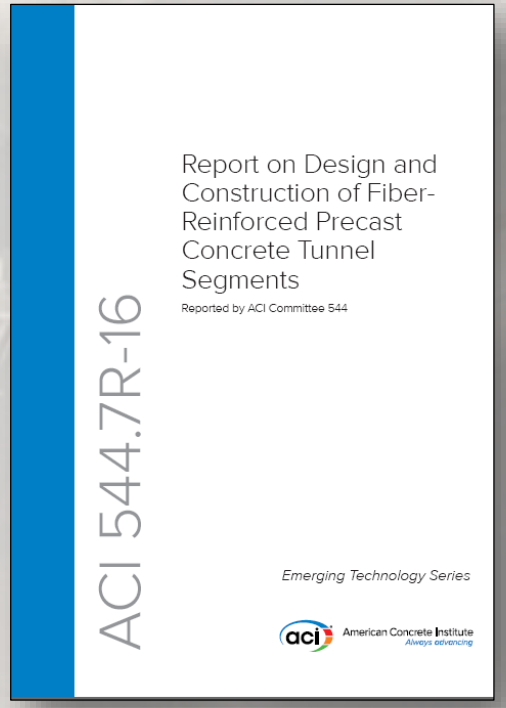
$$0 < \boldsymbol{x} \leq 1$$

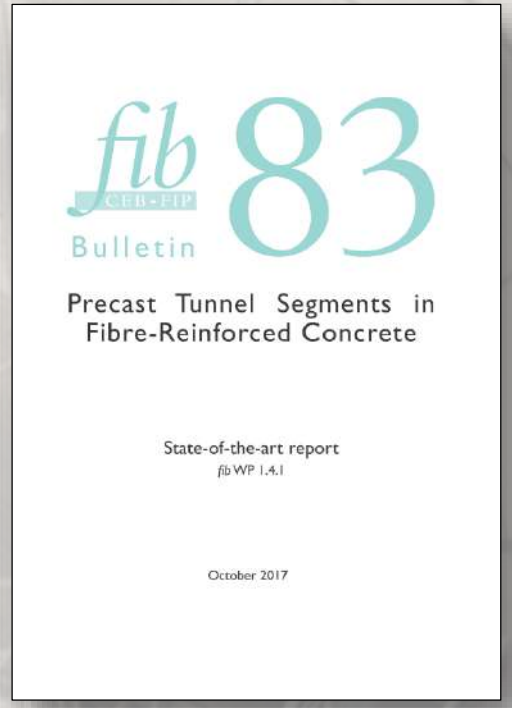


Impiego del FRC nei conci prefabbricati

anni 80 ad oggi → 78 casi di rivestimenti di galleria



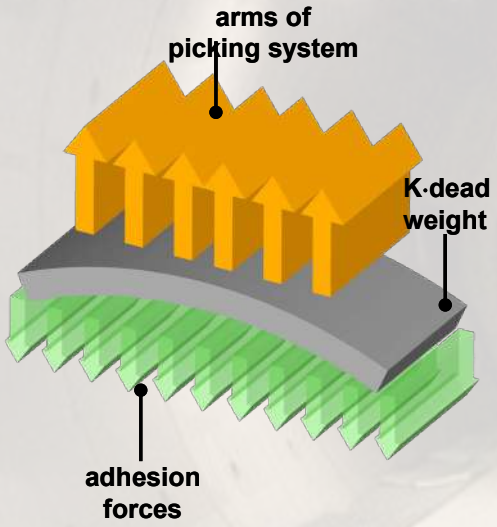




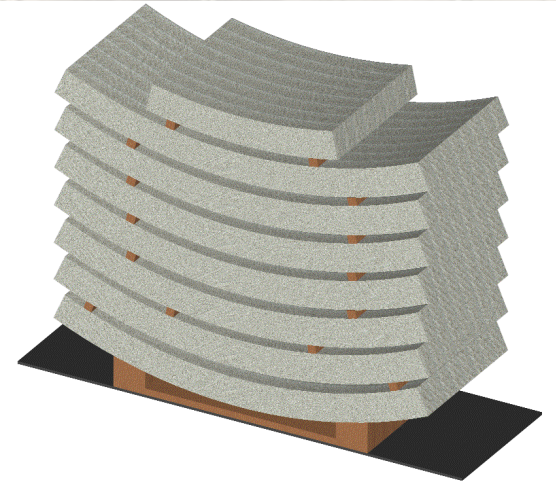
- **ACI Committee 544 (2016).** *"Report on Design and Construction of Fiber Reinforced Precast Concrete Tunnel Segments"*, ACI 544.7R-16, American Concrete Institute, Farmington Hills, MI, 36 p.
- **ITA report n. 16 (2016)**, *"Twenty years of FRC tunnel segments practice: lessons learnt and proposed 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

De-moulding



Storage of segments

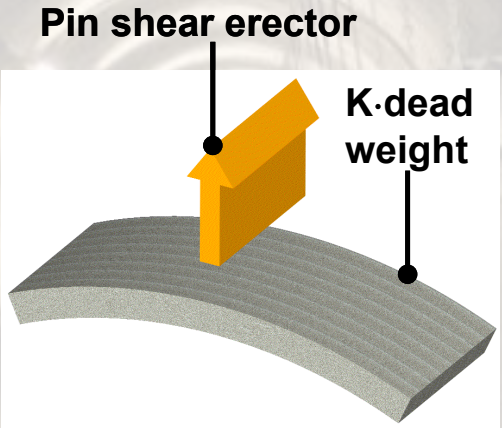


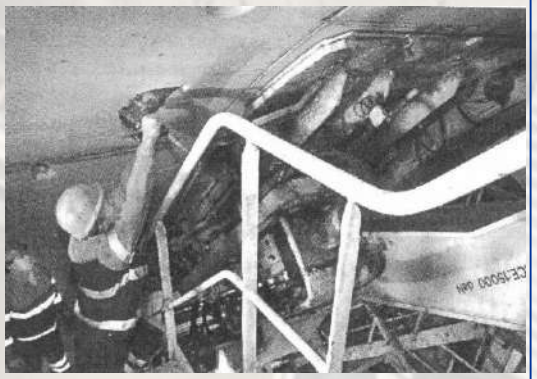
Loading conditions

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

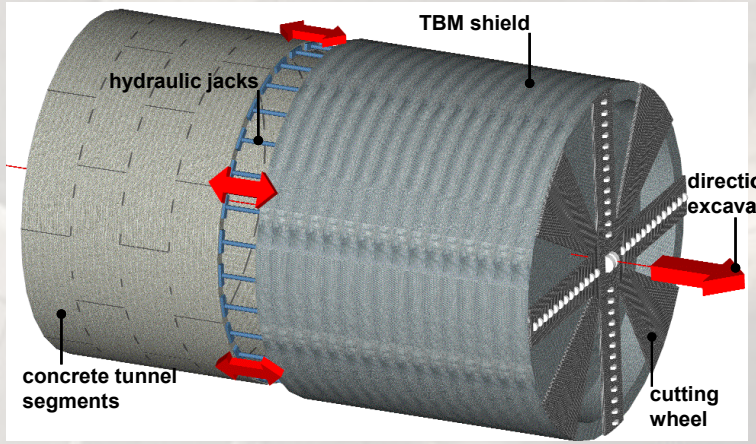
Positioning of the segment by means of erector system

(pin shear erector or vacuuming system)

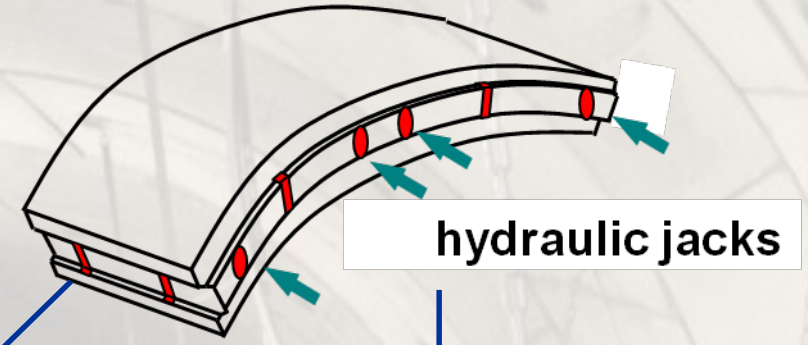




Loading conditions

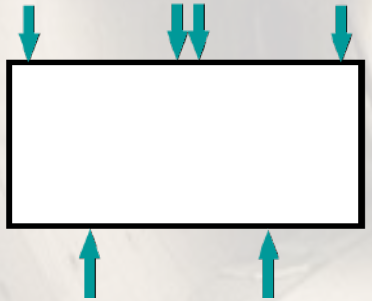


TUNNEL SEGMENT



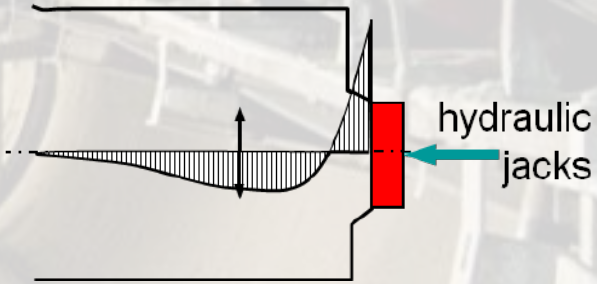
Test of in-plane action

(thrust phase, global behaviour)



Splitting Test

(thrust phase, local behaviour)



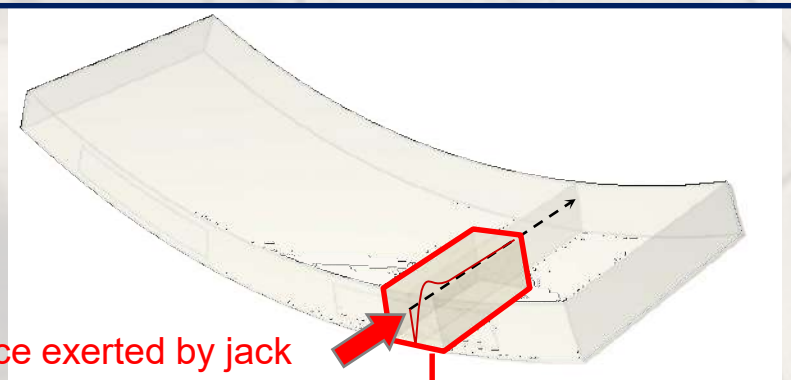
Critical stage

Comportamento locale del concio al di sotto delle scarpe di spinta

TBM thrust phase: local splitting phenomena

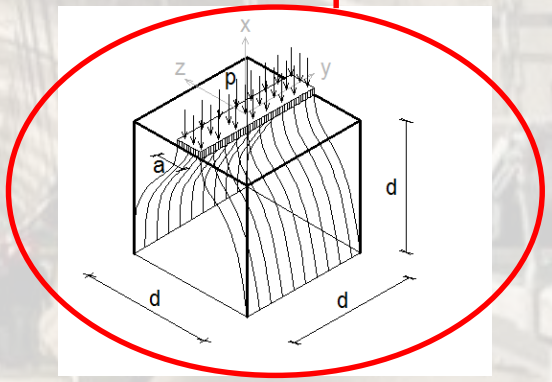
Thrust phase:

high compressive stresses on a small area



Proper specimens dimensions and configurations

were adopted in order to study this local behavior



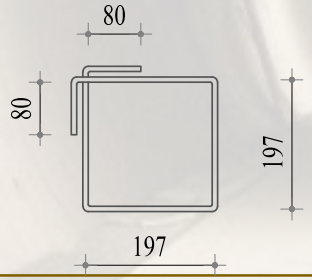
TBM thrust phase local splitting phenomena

Experimental campaign on SFRC prismatic specimens

60/65 BATCHES
60/65-25
60/65-40
60/65-40H

RC BATCHES
RC-0.6
RC-1.0

Traditional reinforcement ϕ8



Hooked-end-steel fibers

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

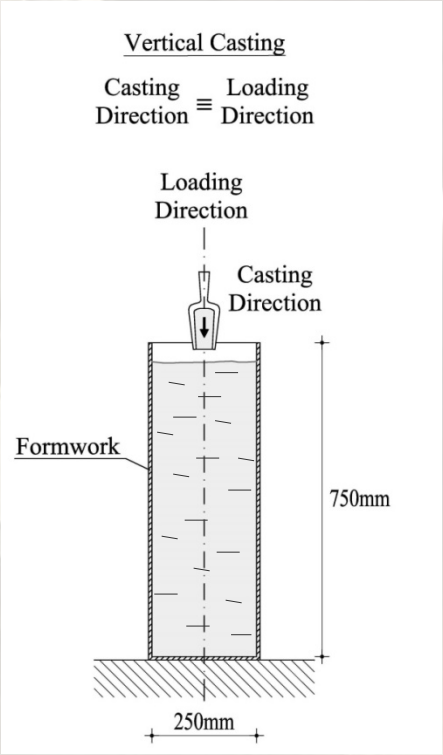
Concrete	60/65-25	60/65-40/40H
Sand 0-4 [kg/m^3]	889.6	889.6
Coarse aggregate 0-10 [kg/m^3]	332.2	332.2
Coarse aggregate 10-20 [kg/m^3]	583.6	583.6
Cement content [kg/m^3]*	390	390
Water-cement ratio	0.48	0.48
Super-plasticizer [L]	1.56	2.16
60/65 fibers [kg/m^3]	25	40
60/65 fibers volume fraction [%]	0.32	0.51
Concrete slump [mm]	170	140

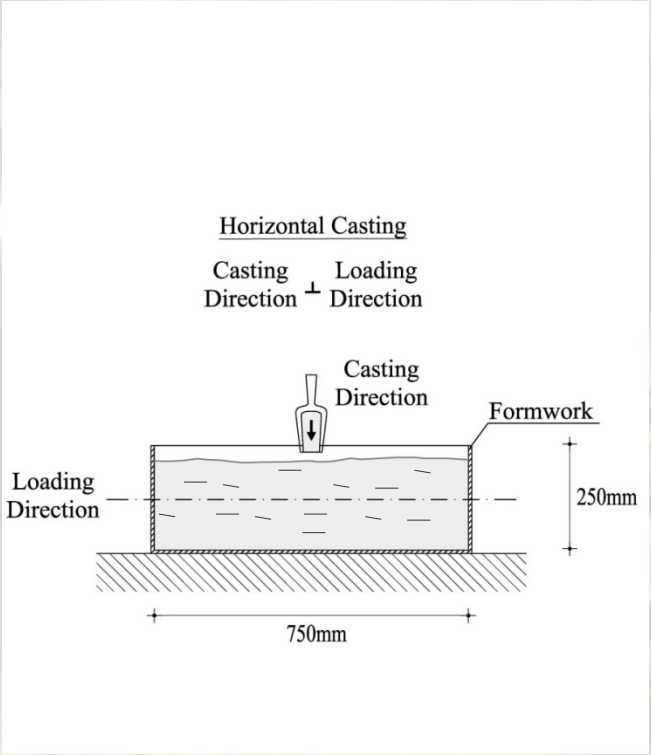
* CEM II/A-LL 42.5R

TBM thrust phase: local splitting phenomena

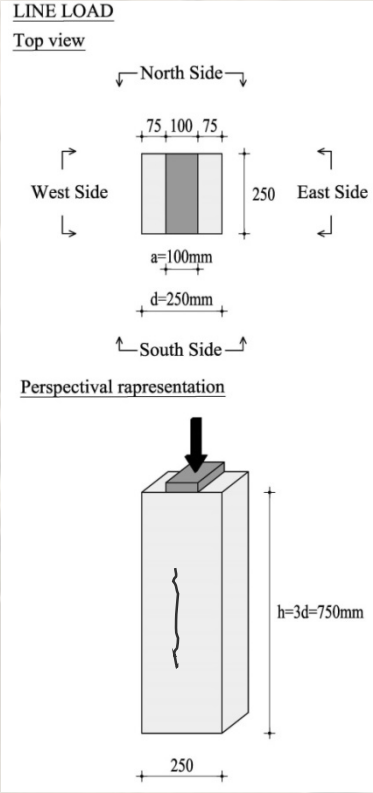
Experimental campaign on SFRC prismatic specimens

Two different casting directions:



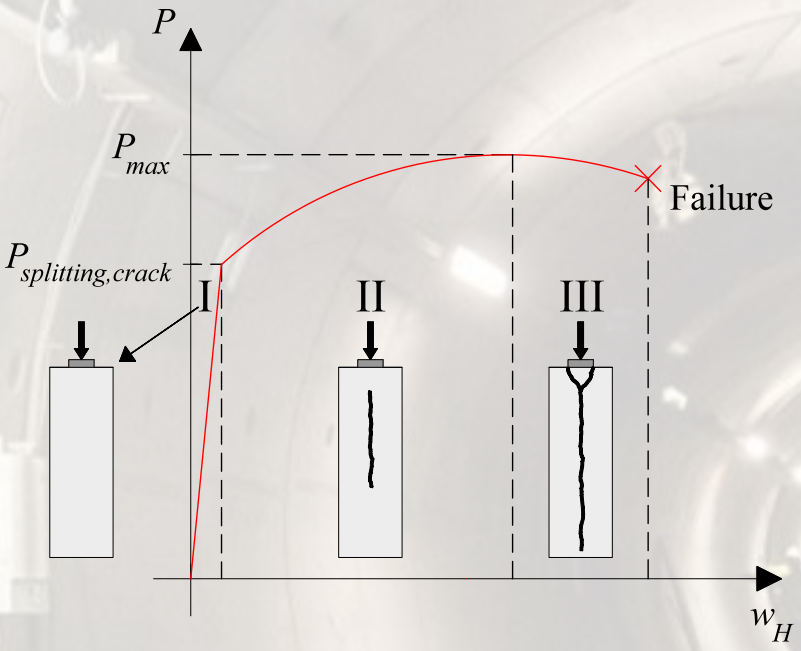


Line load configuration:



TBM thrust phase: Failure mechanism

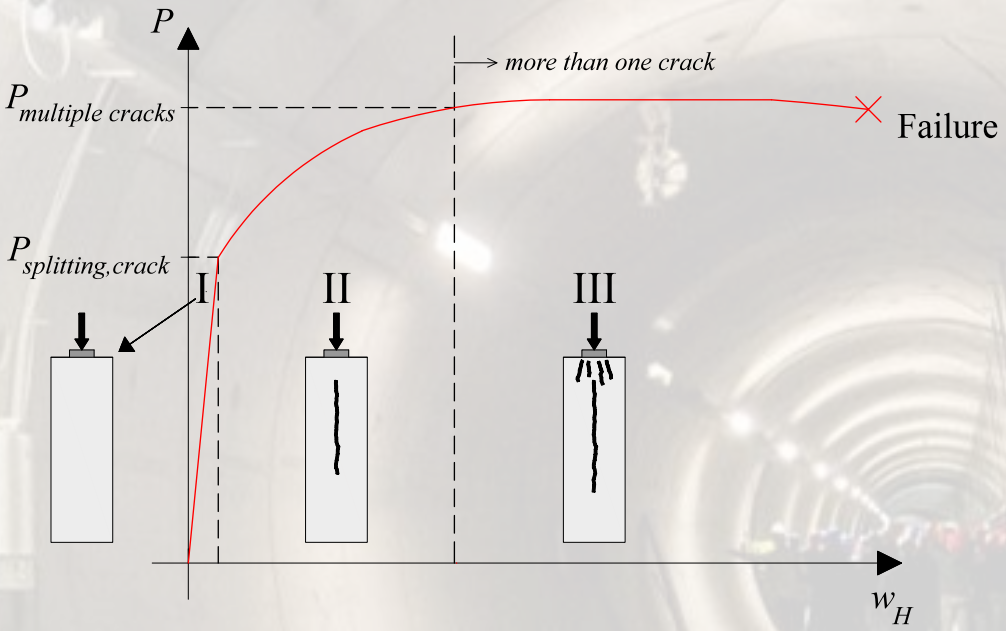
SPLITTING FAILURE



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

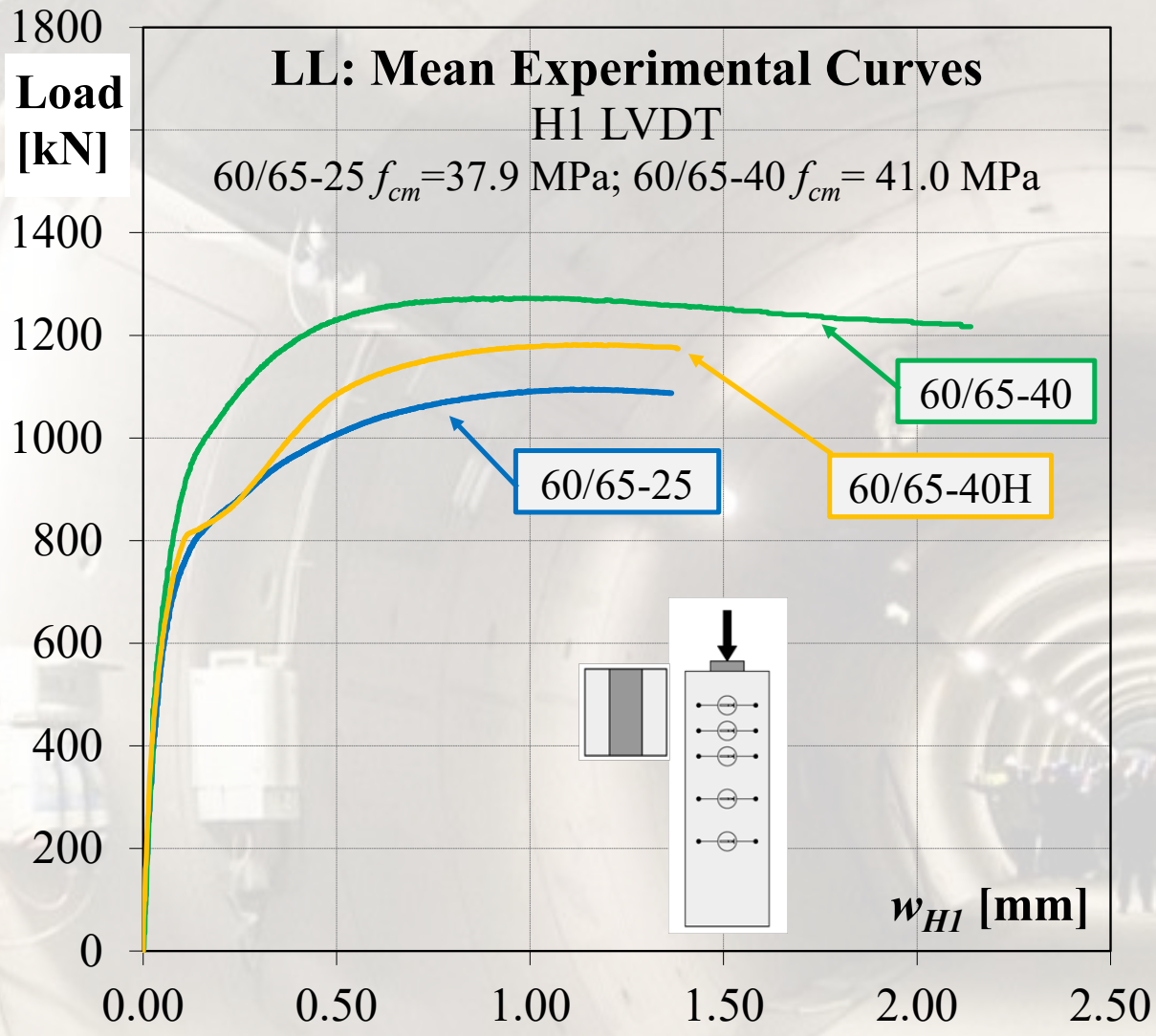
TBM thrust phase: local splitting phenomena

CRUSHING FAILURE



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

Experimental results



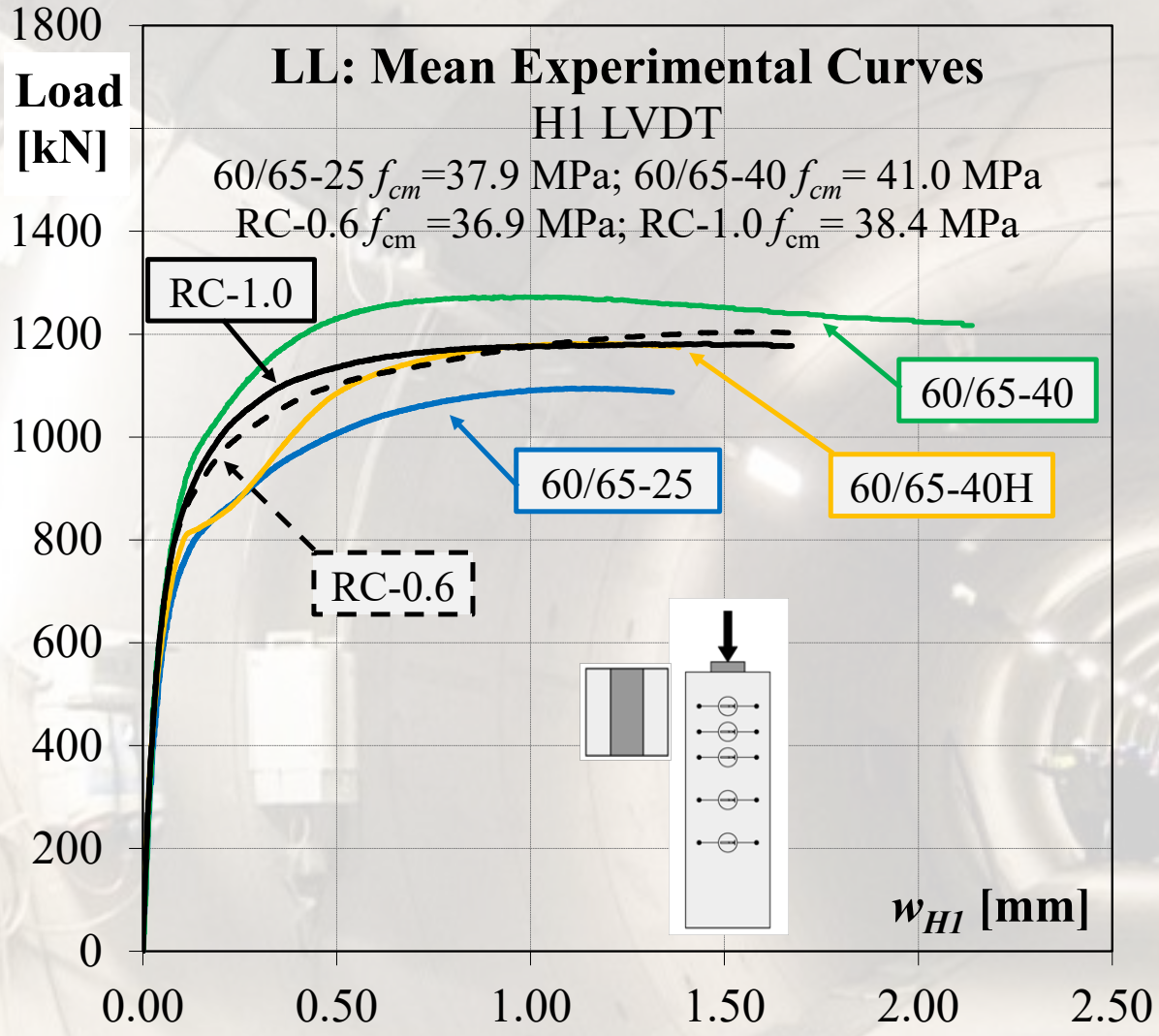
25 kg/m^3 of steel fibers significantly enhance the splitting behavior and the bearing capacity of a concrete prism (up to +54%), as well as the specimen ductility.

40 kg/m^3 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

Comparison between different SFRC and RC solutions



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

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

RC samples showed similar performance to 40kg/m^3 of fibers, coherently with the failure mechanism (the different crushing load is in accordance to the difference compressive strength f_{cm}).

Ottimizzazione dell’armatura dei conci

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

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.

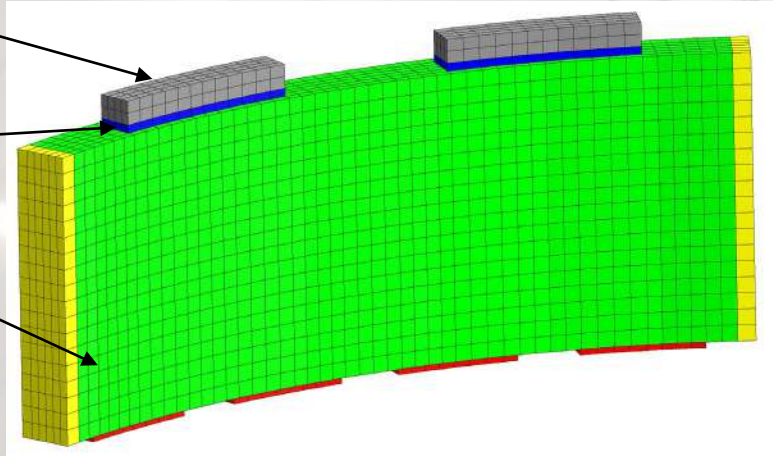
- Nature/frequency of **load conditions** (both ground & excavation) → High localized stresses in the specific project ? Where/when? Possible to reduce / avoid contact irregularities during TBM thrust? etc.
- If not → **high-performance FRC** or **hybrid solution (rebars and FRC);** in alternative, use 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)

Numerical modelling

Steel plates

Interface under steel plates

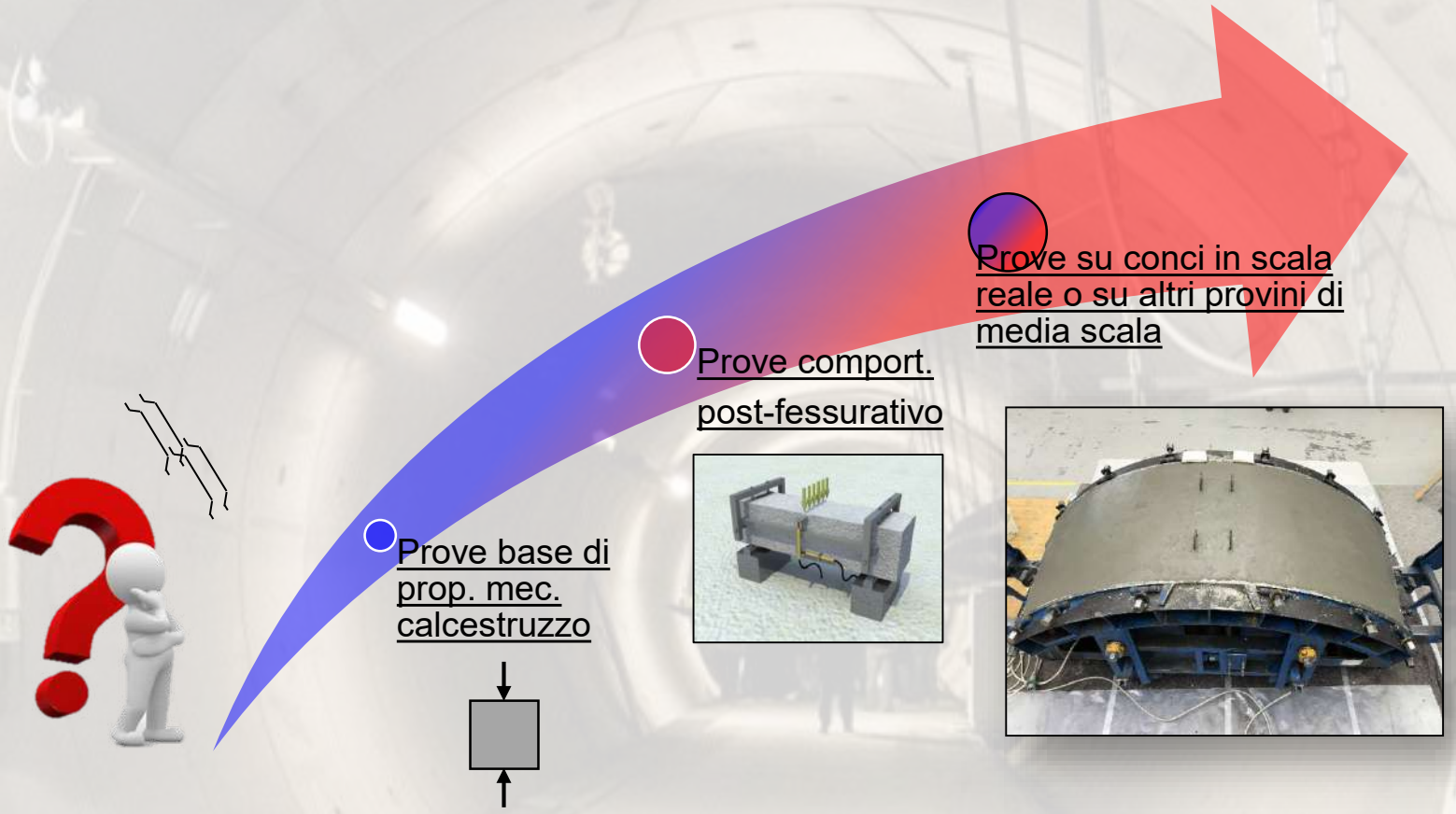
Segment



Interface on lateral surfaces

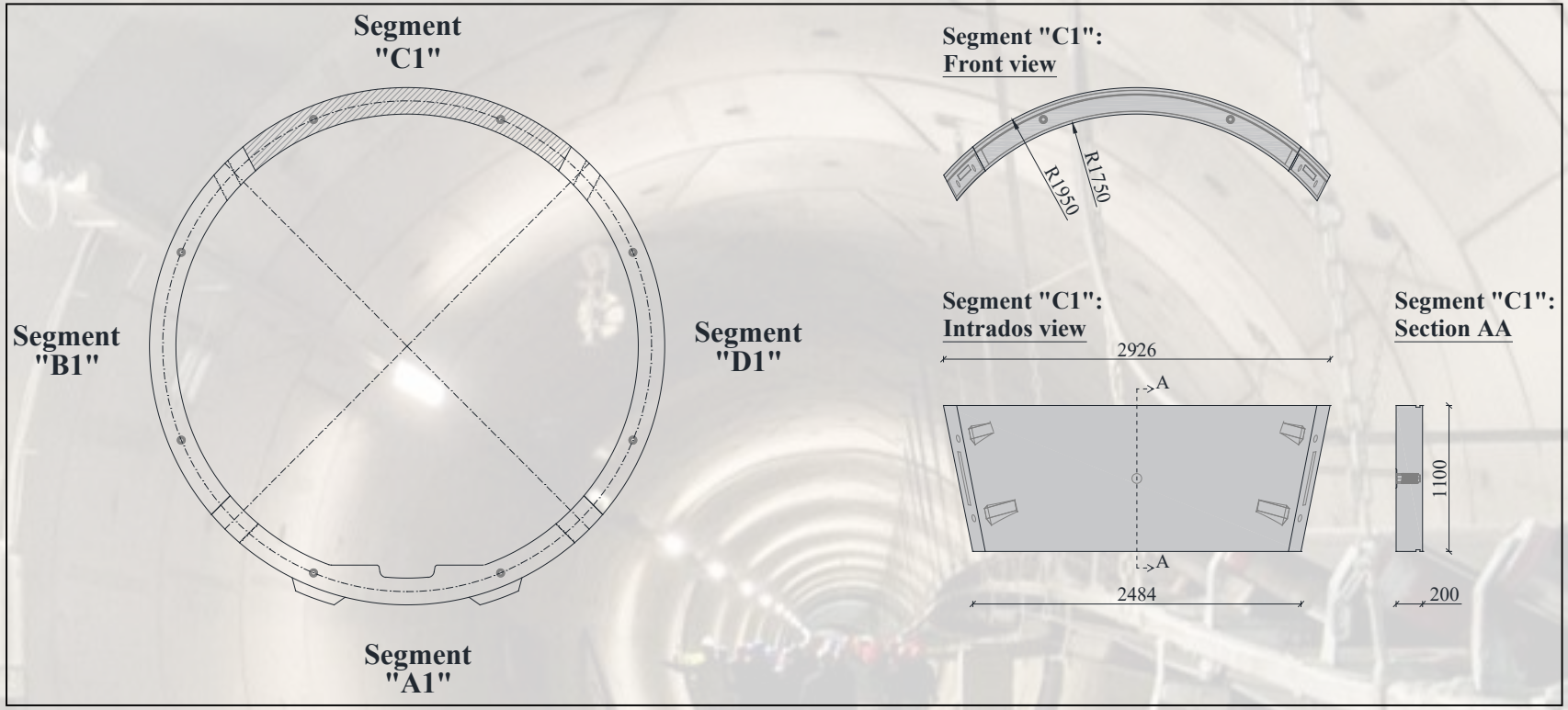
La sperimentazione sui conci prefabbricati

- Tipico percorso di ricerca sulla base di prove sperimentali per calcestruzzi fibrorinforzati:



La galleria di “Scilla”

- Una tra le principali infrastrutture della inter-connessione elettrica tra Sicilia e Calabria:

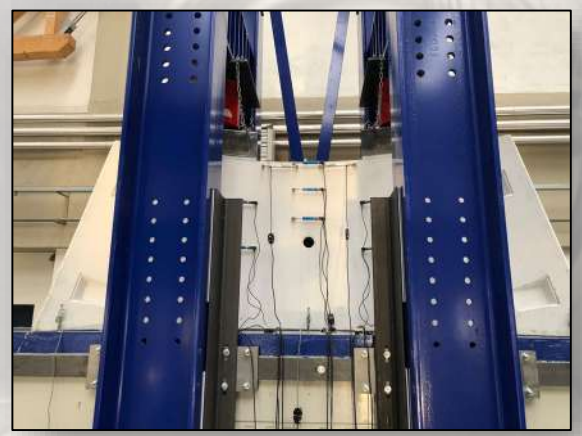


- Il rivestimento presenta un diametro interno (Di) of 3500 mm, uno spessore (t) di 200 mm ed una profondità di 1100 mm: il concio C1 è stato oggetto di indagine

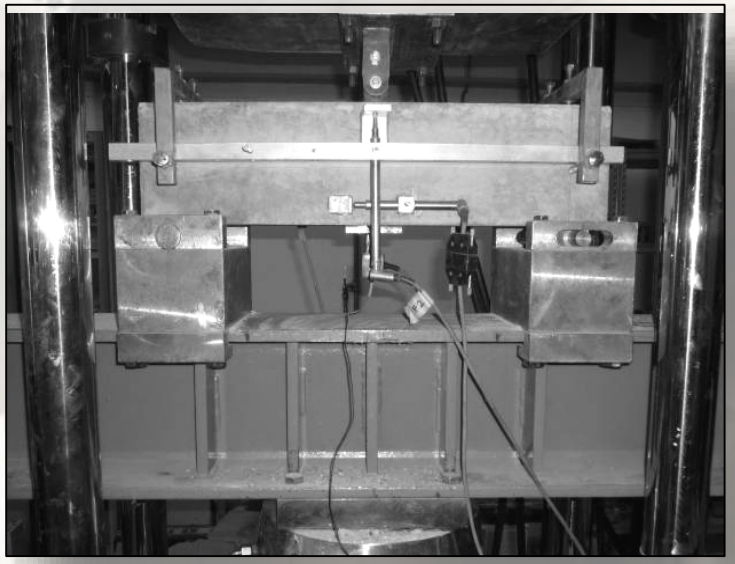
Prove sperimentali su conci in scala reale

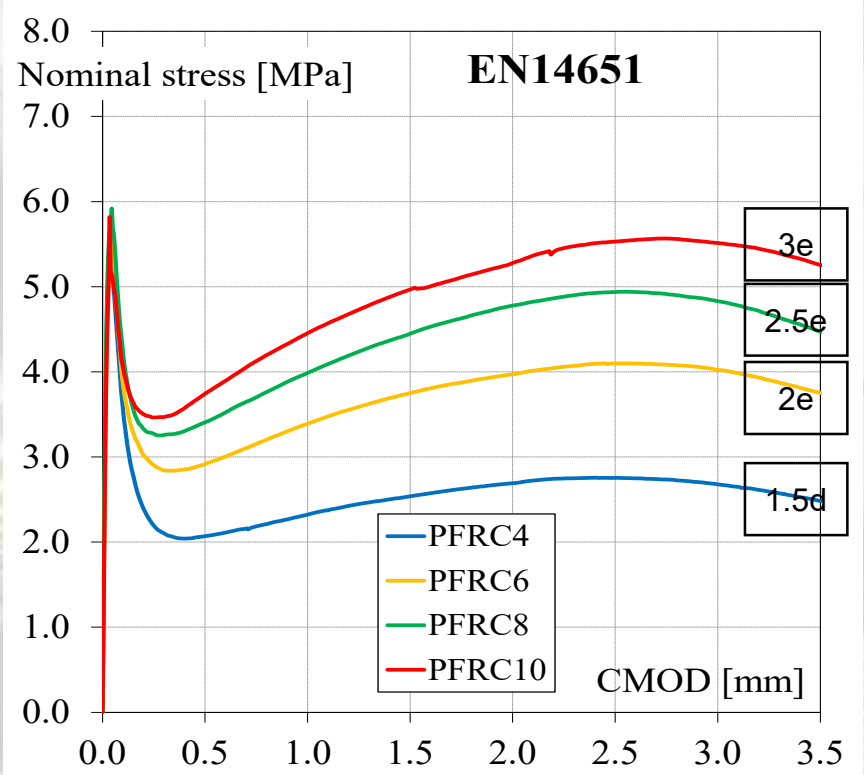
- **prove a flessione** atte a simulare la **fase di stoccaggio, trasporto etc**.

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



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





- Il dosaggio di **8 kg/m³ è stato scelto** per la realizzazione dei conci

- 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/m^3** 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%)

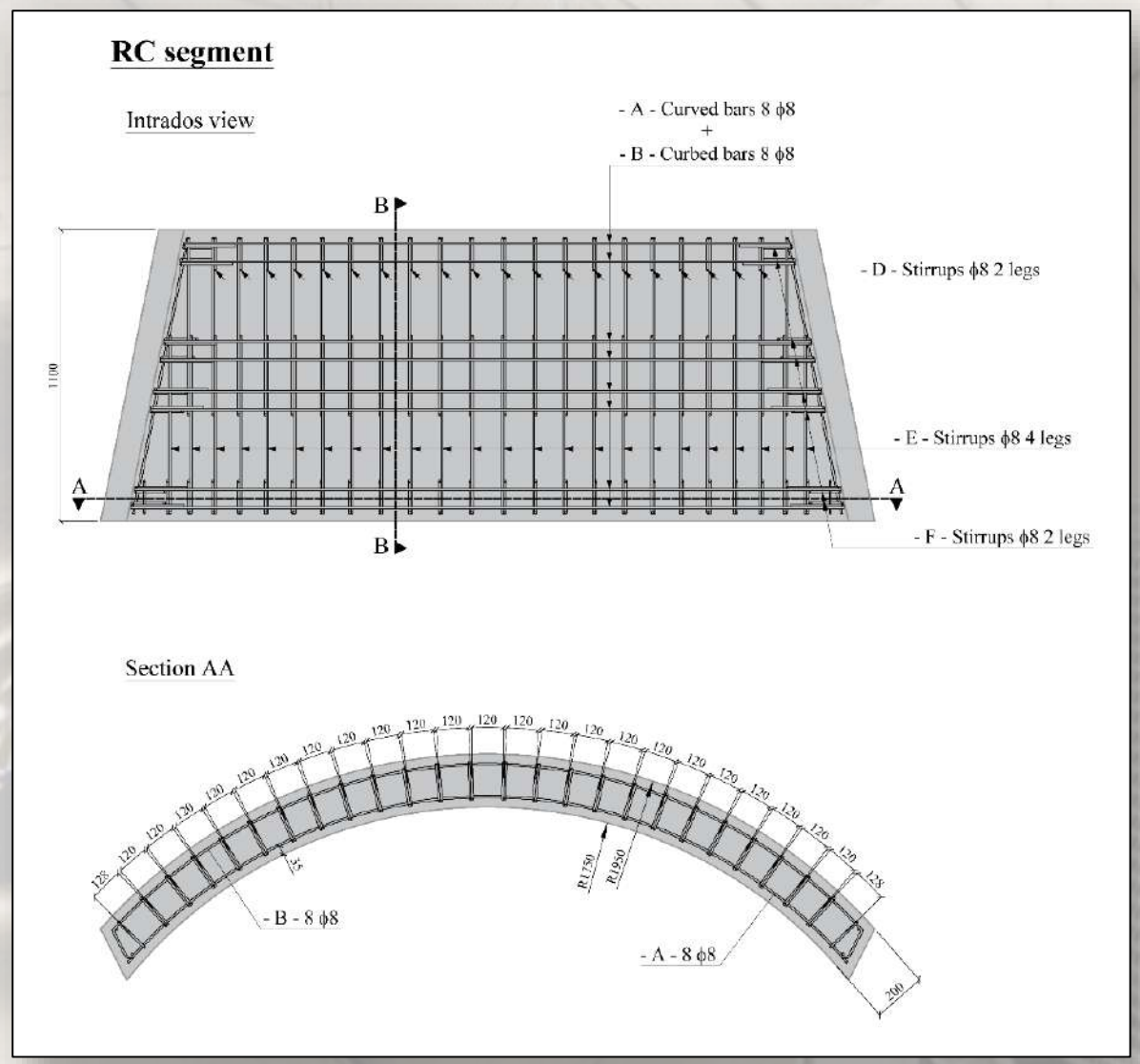
Concio con armatura ordinaria (RC)

- Classe di calcestruzzo: C50/60
- Barre di armatura longitudinali:
  - barre curve di acciaio, 8+8 ϕ8
  - percentuale di armatura, ρ_s=0.23%

- Armatura a taglio: staffe ϕ8 @ 12cm, 4 bracci, con percentuale equivalente ρ_{st}=0.15%
- Armatura di splitting: staffe locali ϕ8 @ 12cm, 2 bracci

- **Armatura totale:**

contenuto in barre pari a 110 kg/m^3



Concio con armatura ibrida (RCO+PFRC8)

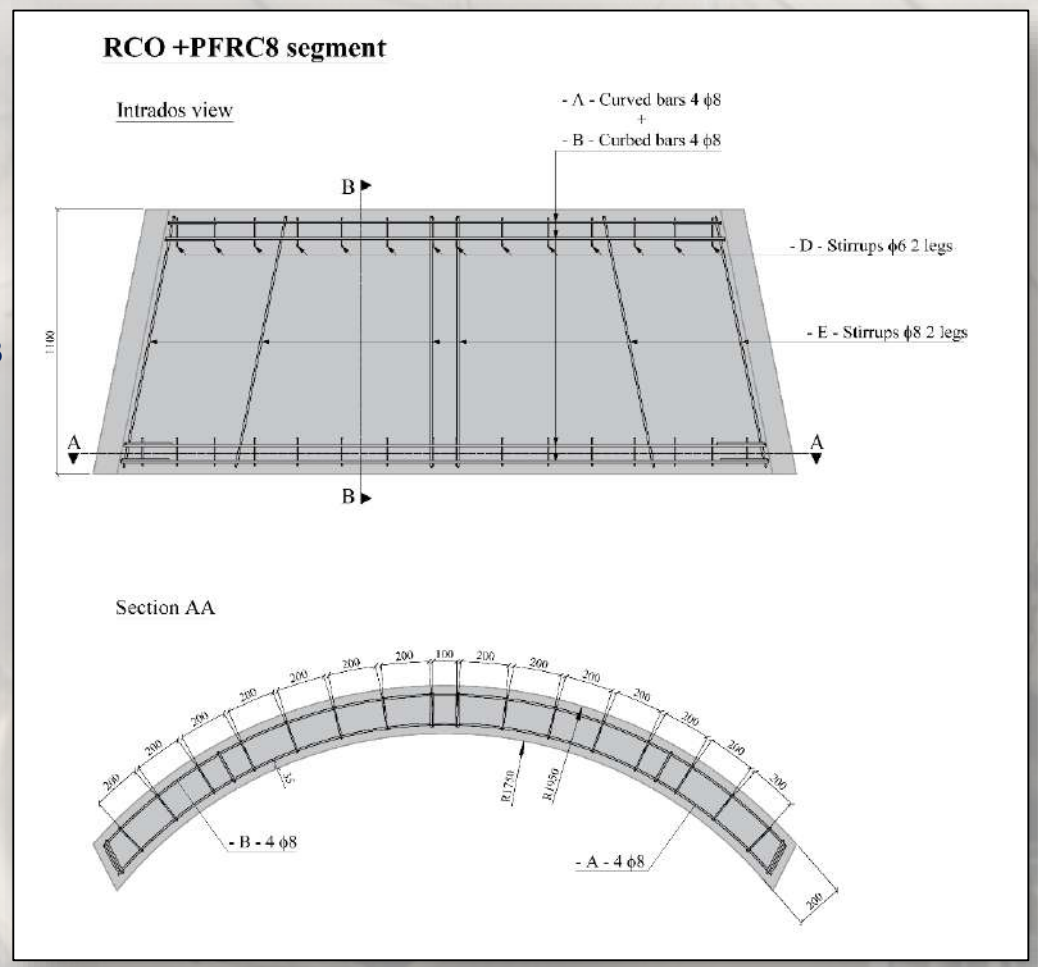
- Classe di calcestruzzo: C50/60
- Barre di armatura longitudinali:
  - barre curve di acciaio, 4+4 ϕ8
  - percentuale di armatura, ρ_s=0.11%
- Fibre macro-sintetiche, Fibre PP, 8 kg/m^3

- Armatura a taglio: fibre PP, 8 kg/m^3
- Armatura per comportamento locale di splitting: fibre PP, 8 kg/m^3

- **Armatura totale:**

8 kg/m^3 fibre PP

+ contenuto di barre di 35 kg/m^3



RC vs. RCO+PFRC8

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

Concio con armatura ibrida (RCO+PFRC8)

- **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:

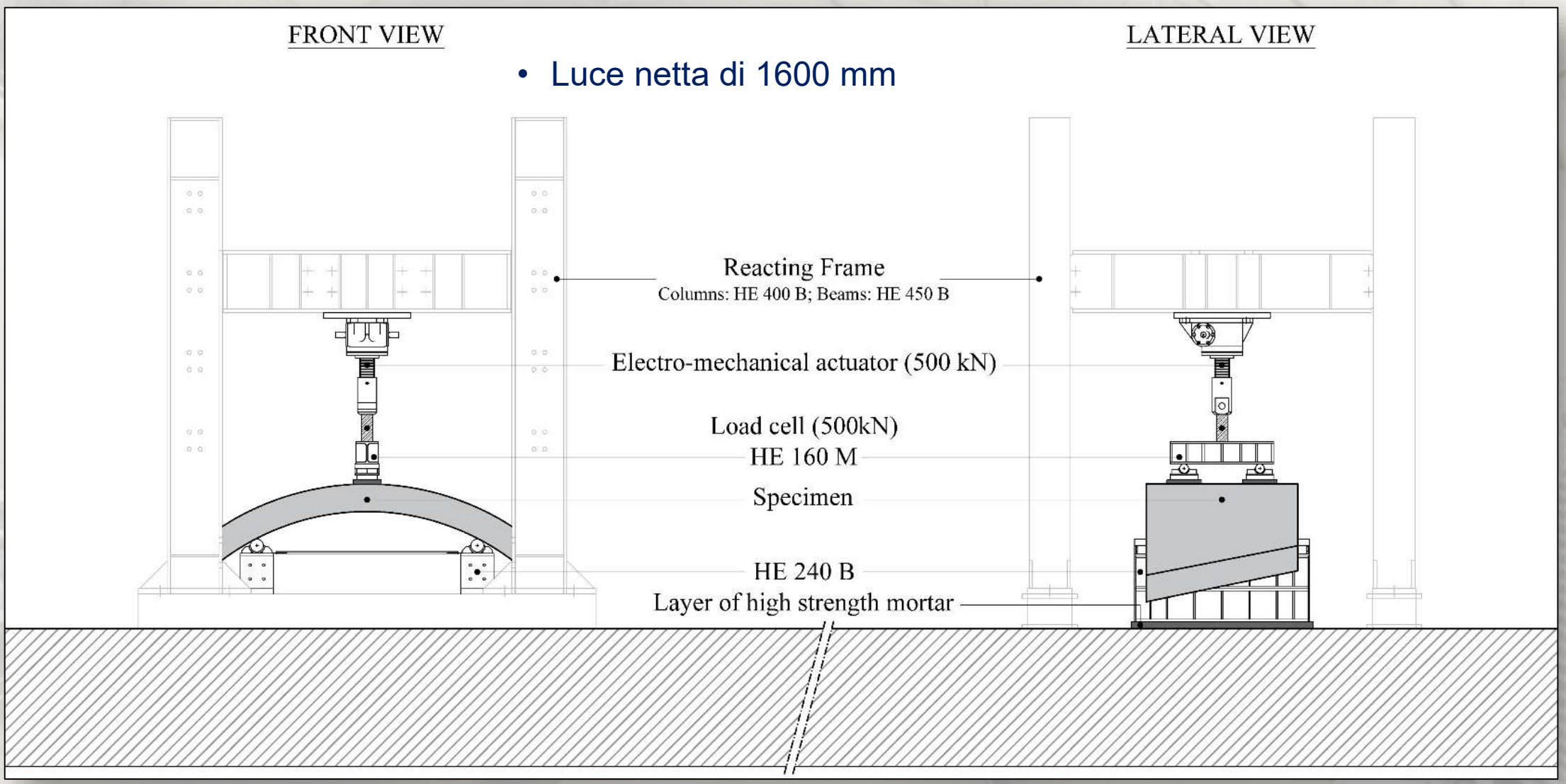
- un concio di riferimento RC

- due conci RCO+PFRC8 (configurazione ibrida)

- due conci PFRC8

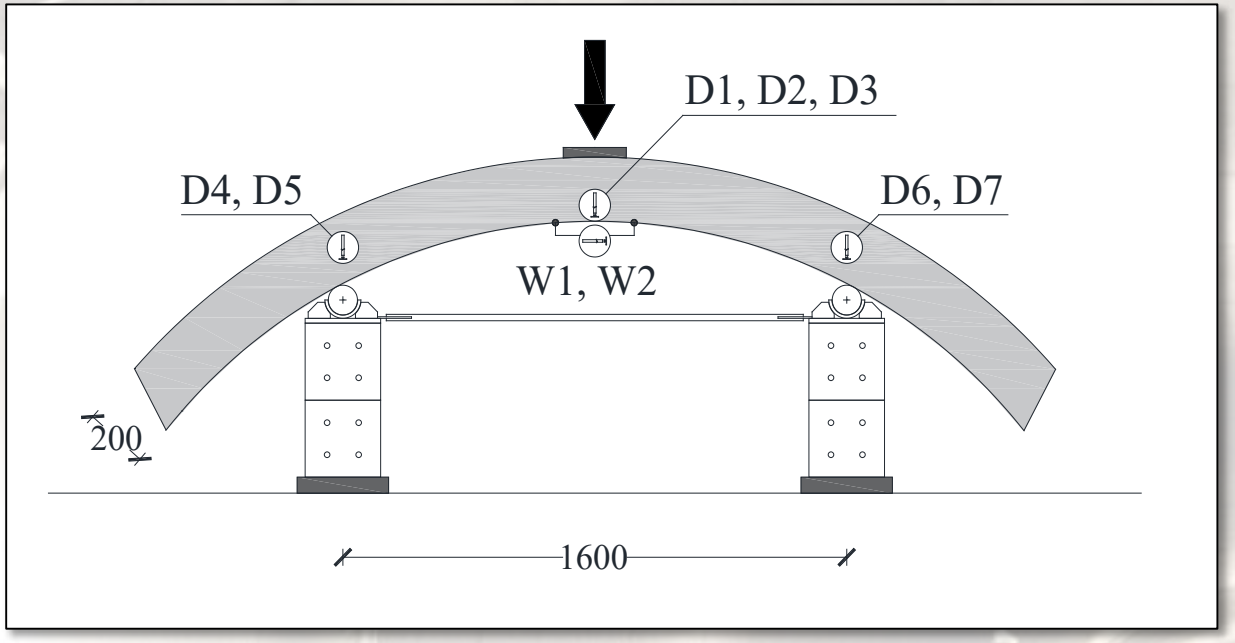
Prove di flessione

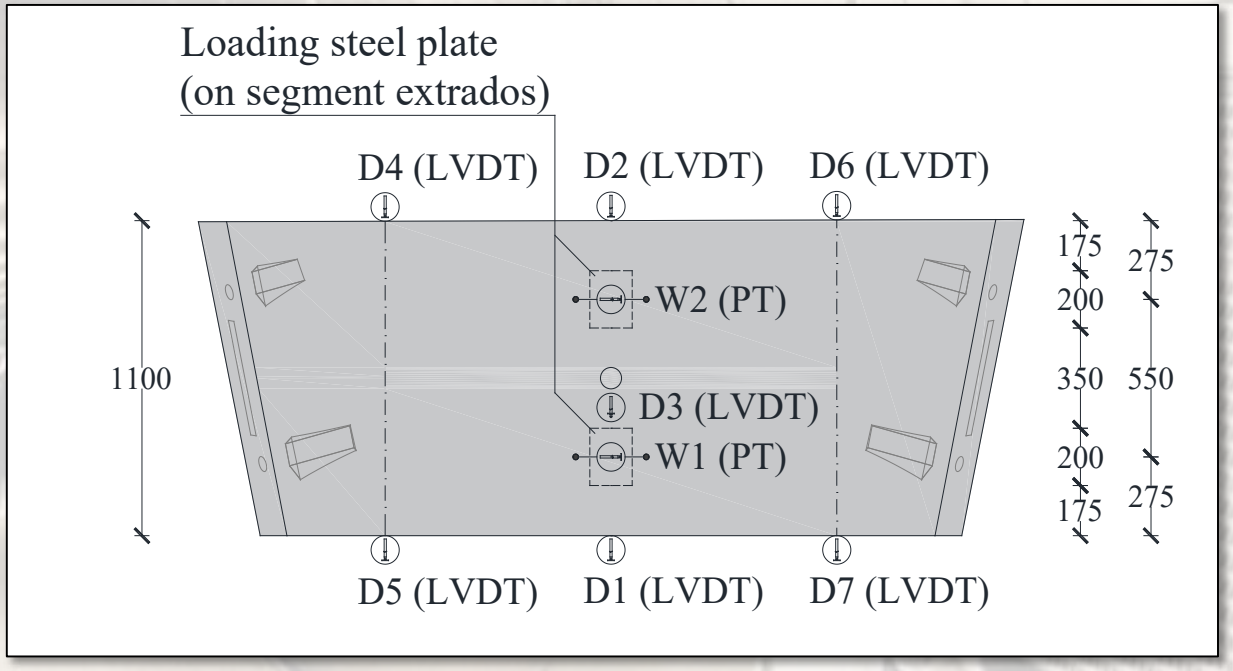
- Luce netta di 1600 mm



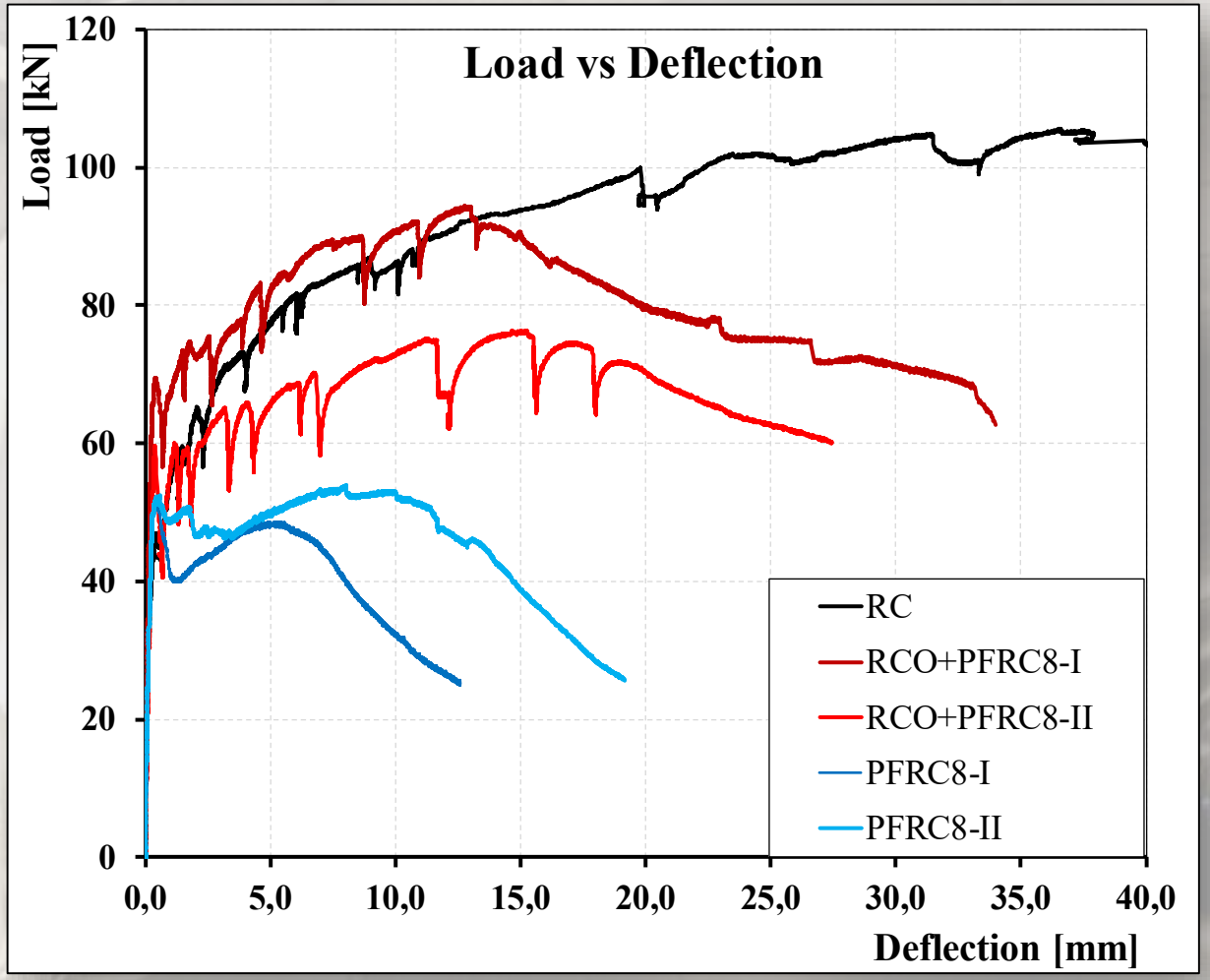
I due appoggi sono continui sull'intera lunghezza del concio, mentre il carico all'estradosso è stato applicato con due piastre (150x200 mm) posizionate su uno strato di malta ad alte prestazioni

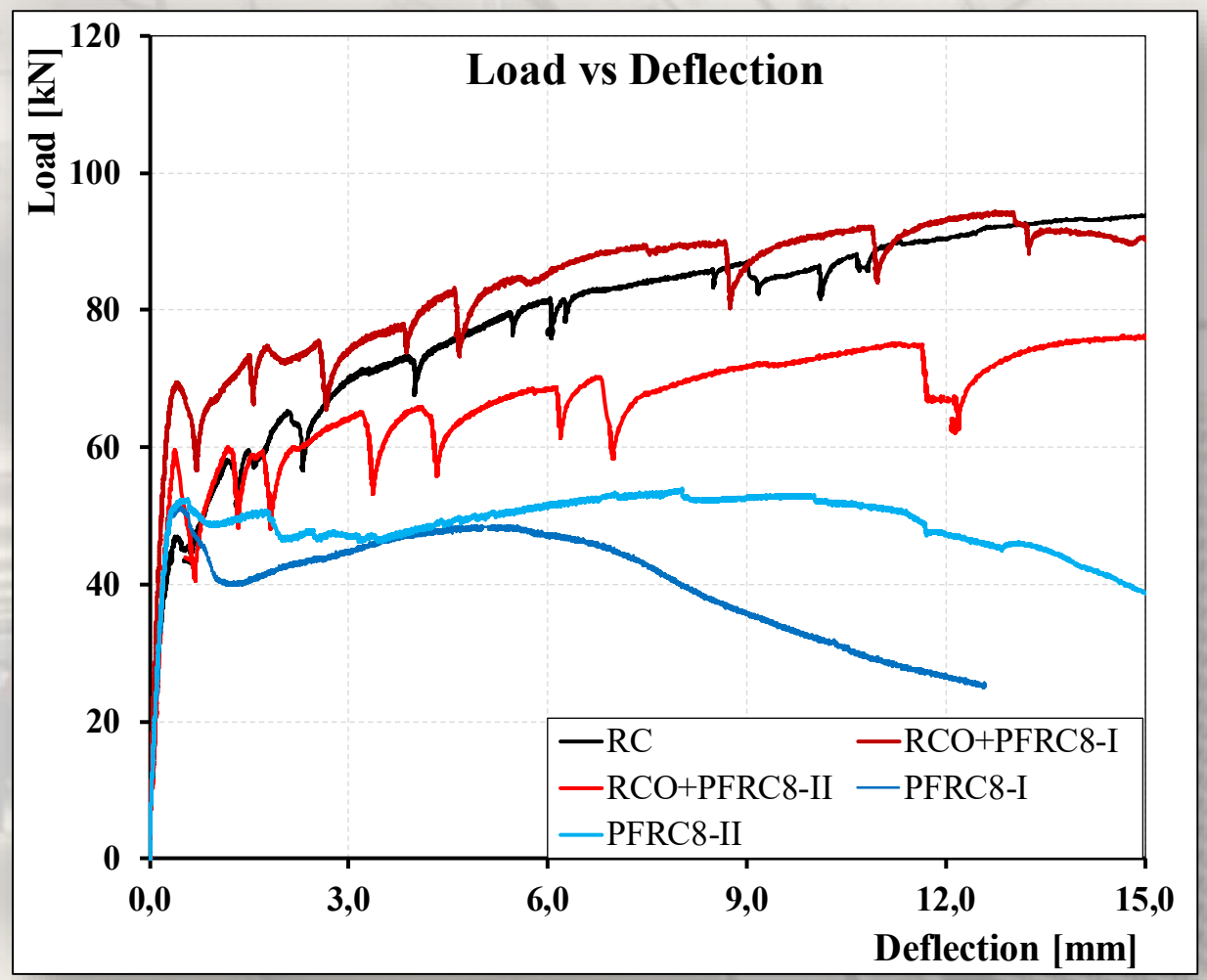
Strumentazione per le prove di flessione





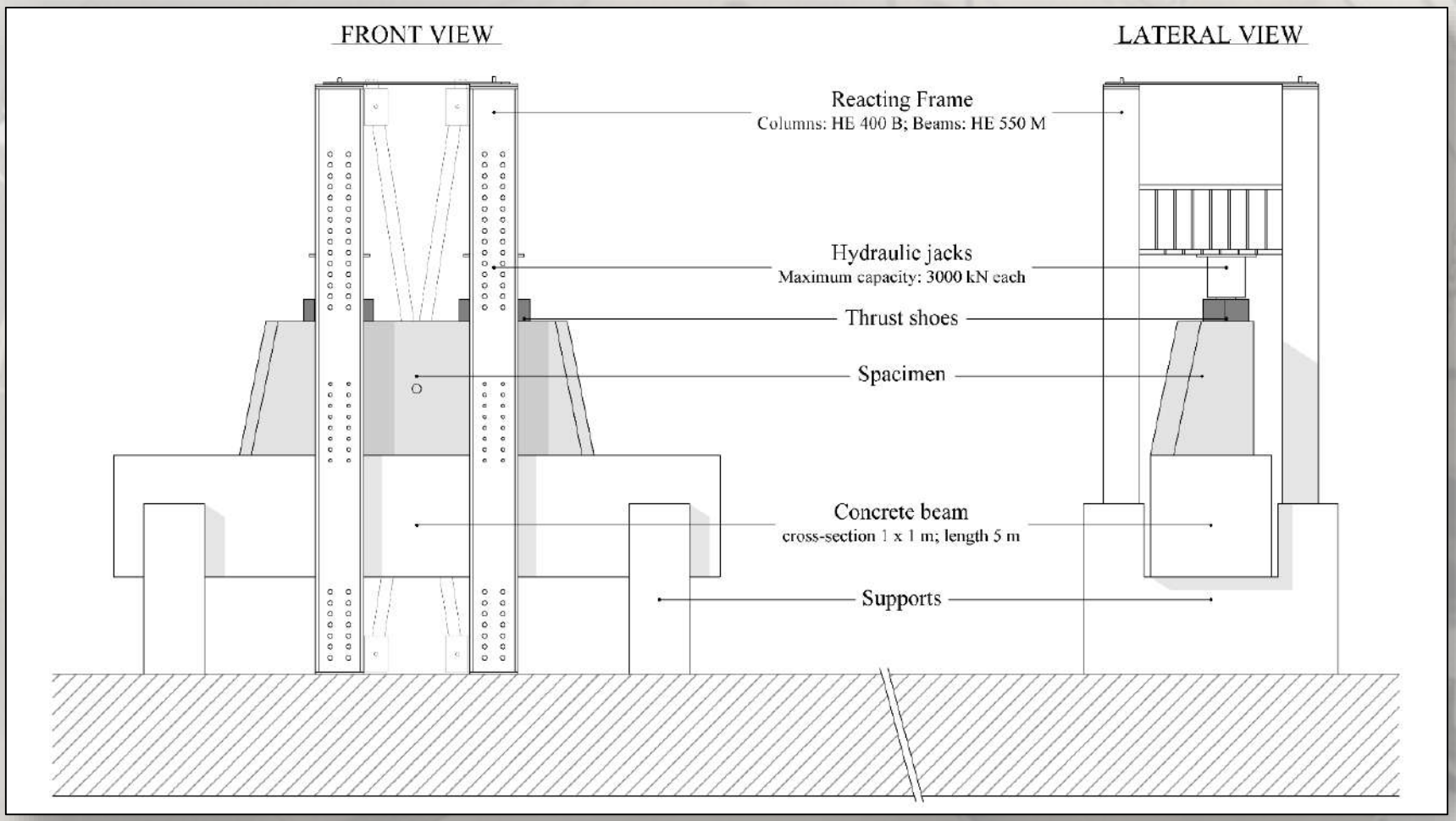
Risultati sperimentali

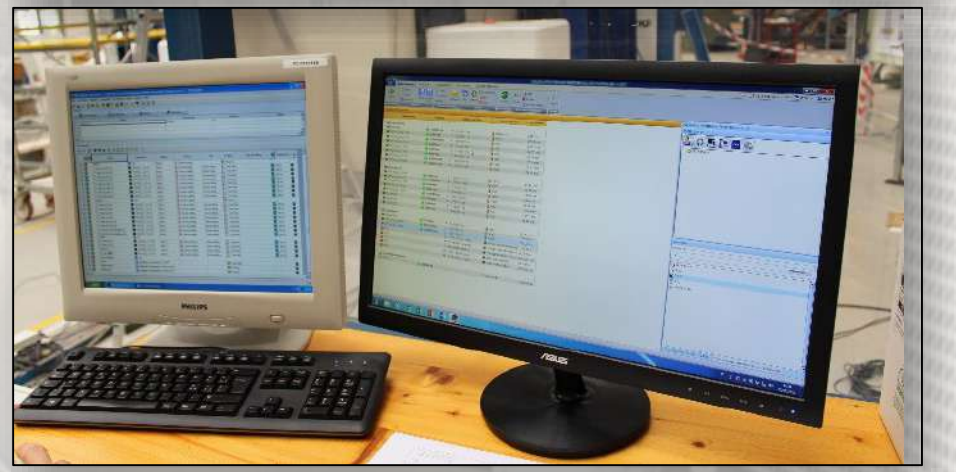


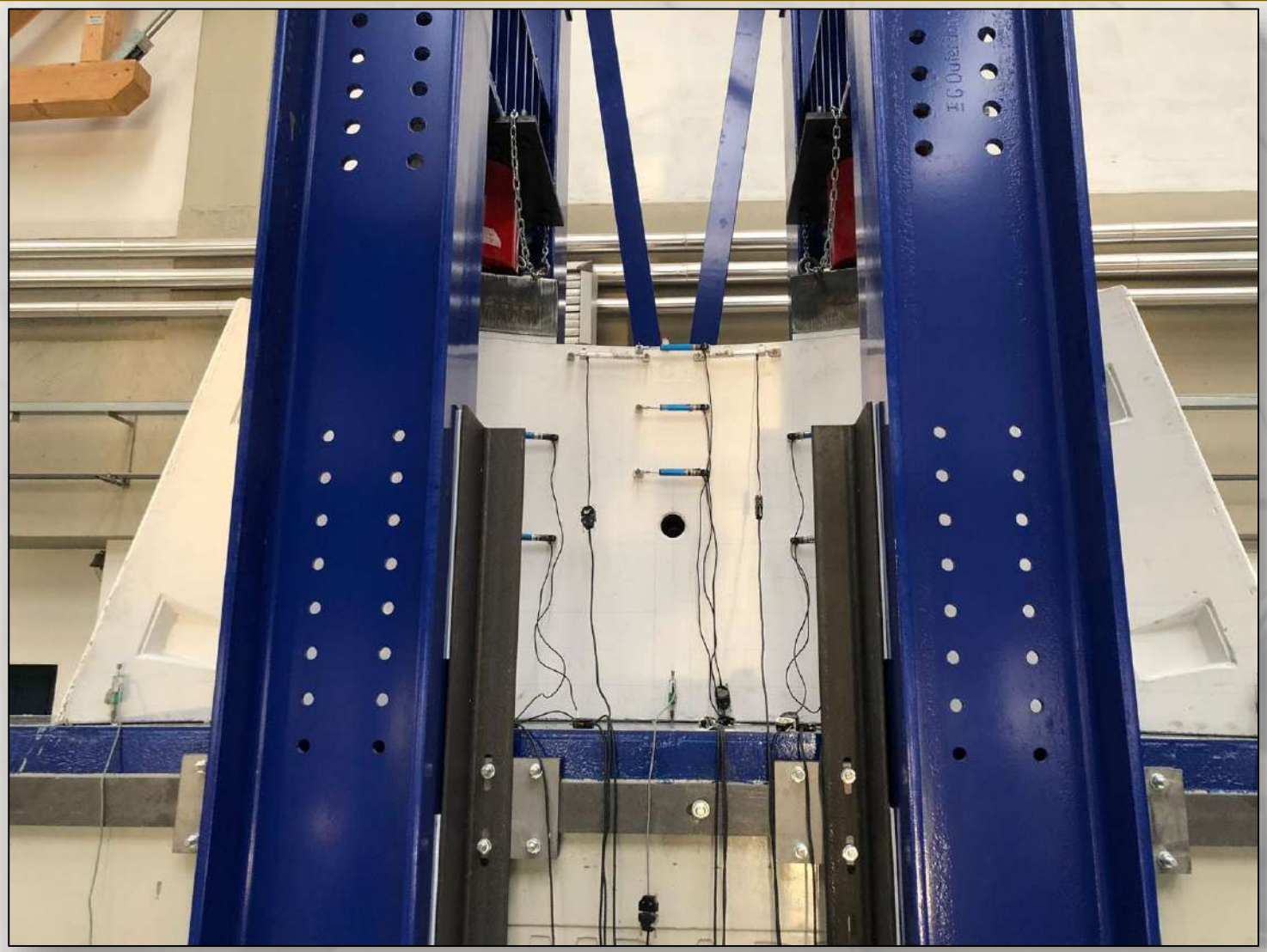


Prove di compressione

Le forze esercitate dalle **scarpe di spinta della TBM** sui conci durante il processo di scavo sono state simulate mediante martinetti idraulici ed un banco di prova auto-equilibrato



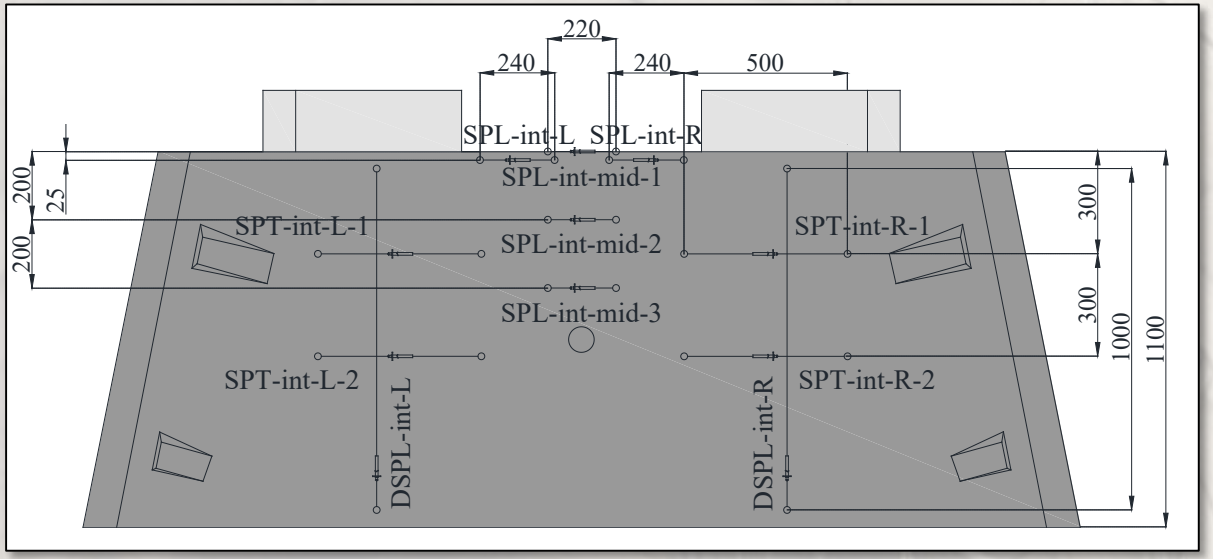


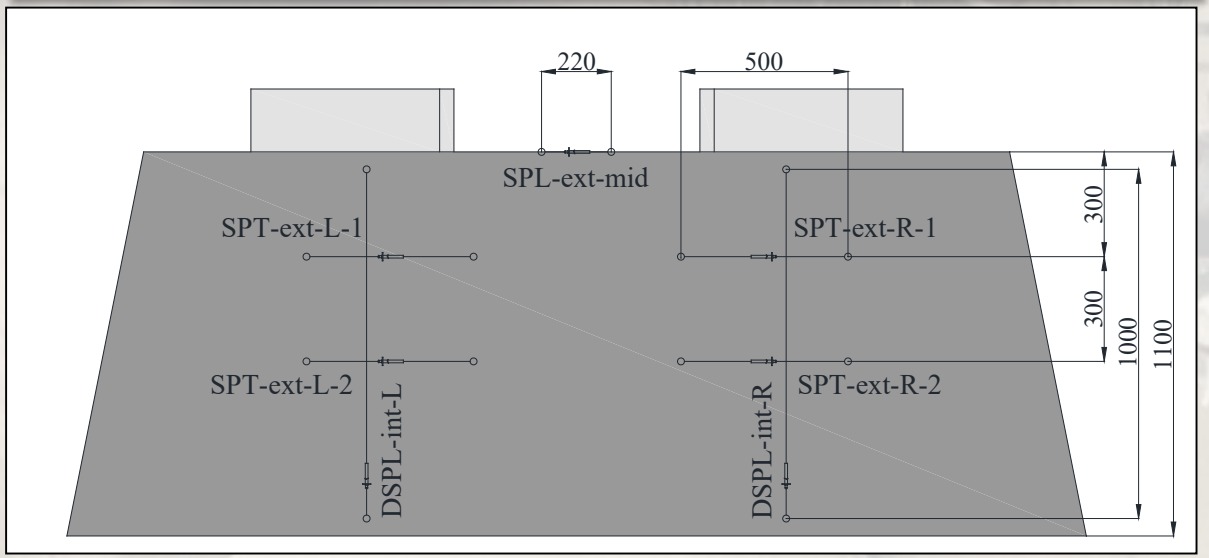


Dati dal progetto originale

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

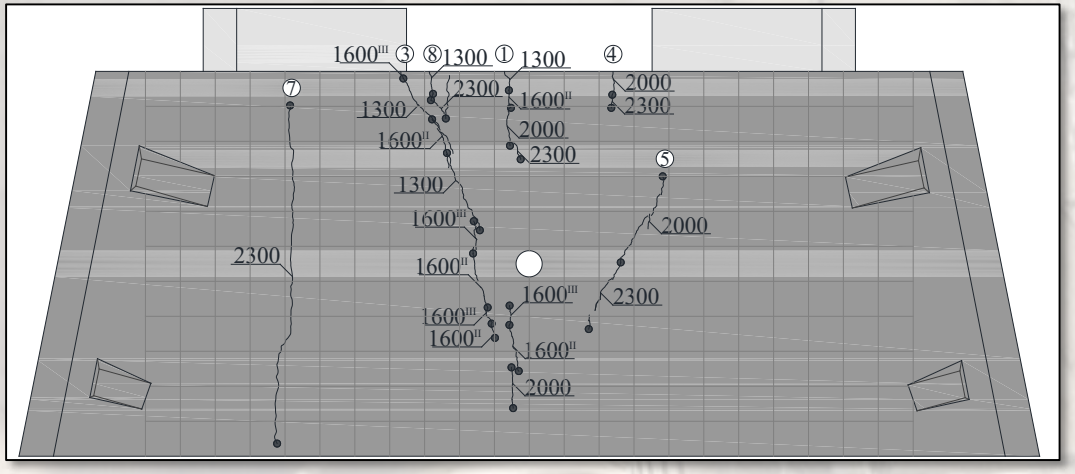
Strumentazione per la prove di compressione (TBM)

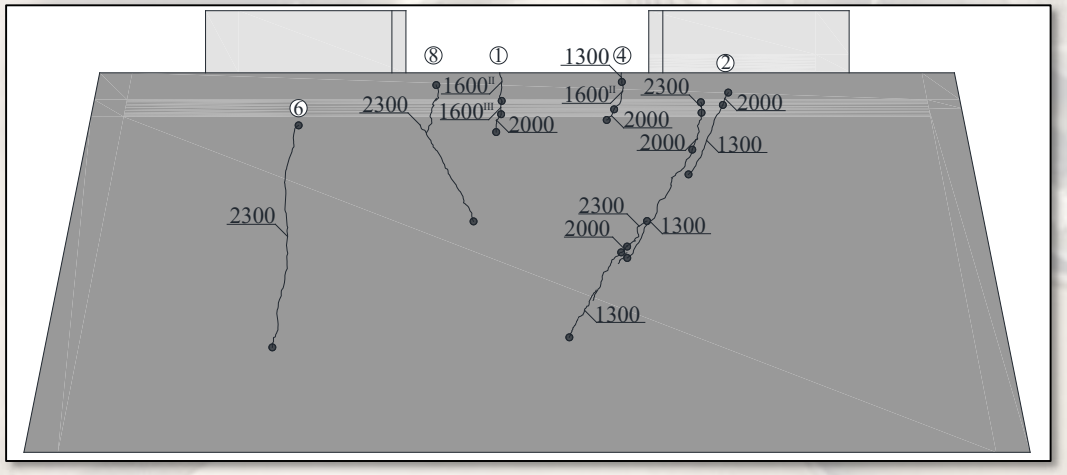




Quadro fessurativo finale del concio RCO+PFRC-08

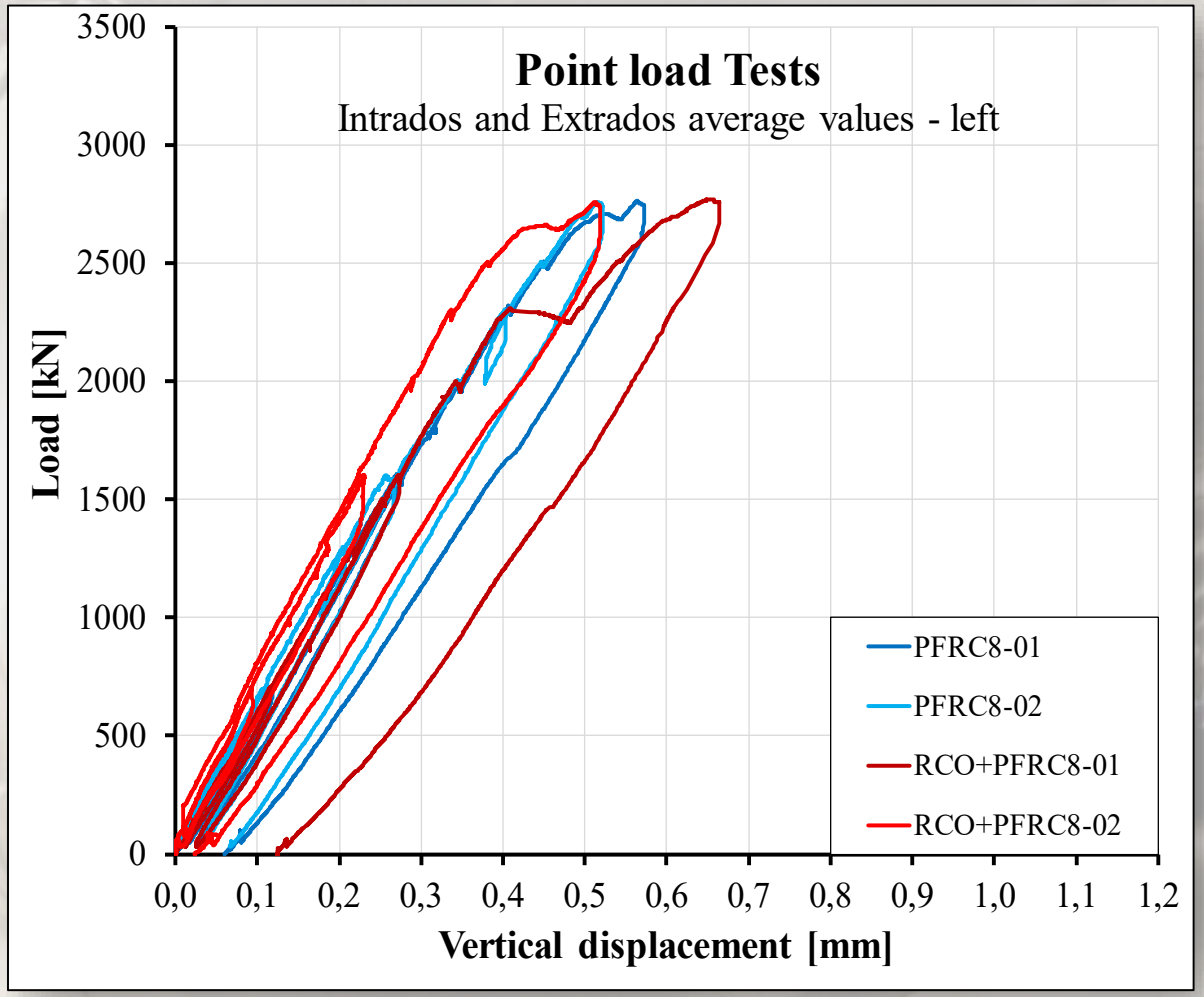
- A titolo di esempio, si riporta il **panorama fessurativo finale del** concio RCO+PFRC-08



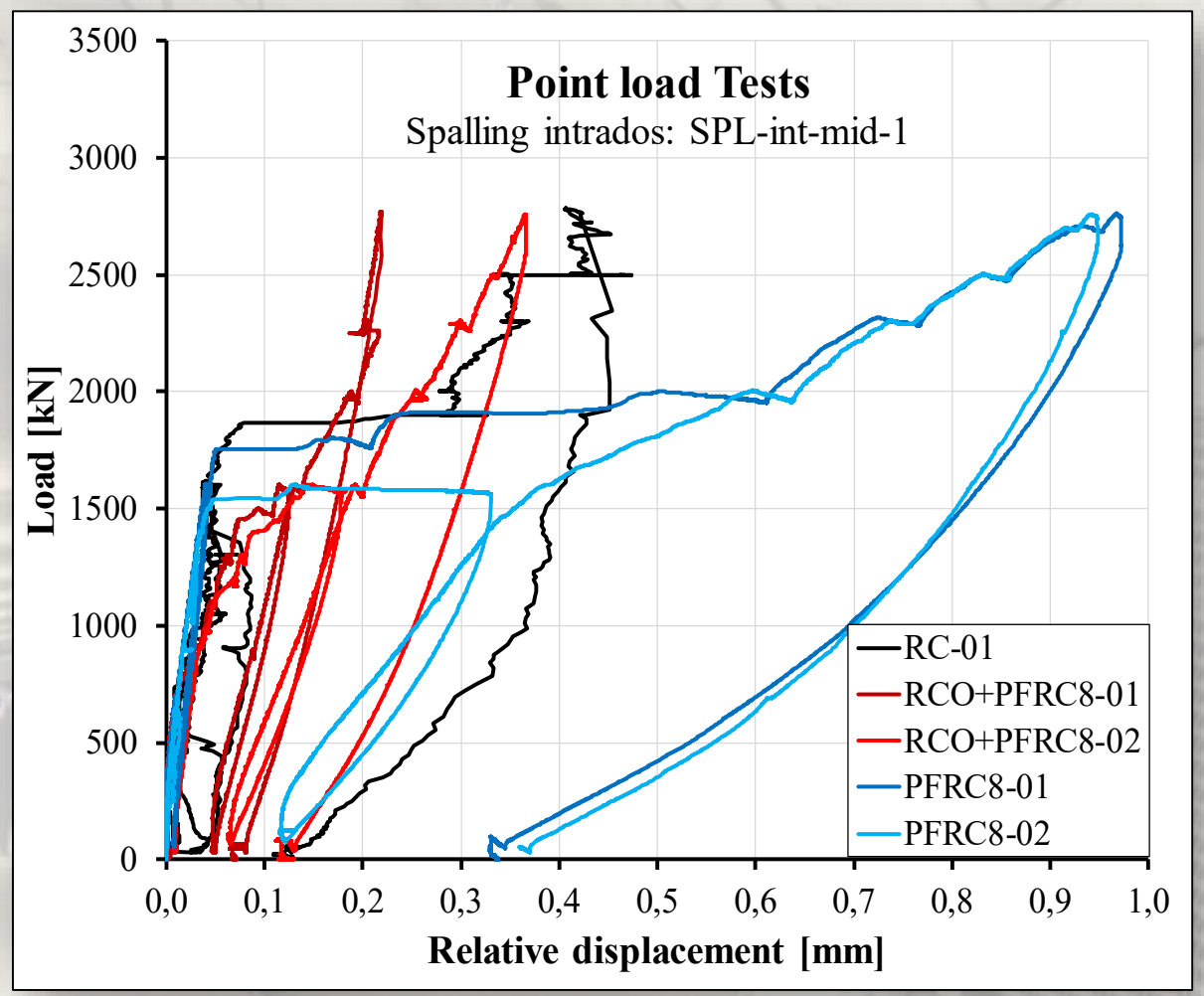


Risultati sperimentali

Carico-spostamento verticale



Carico-apertura di fessura



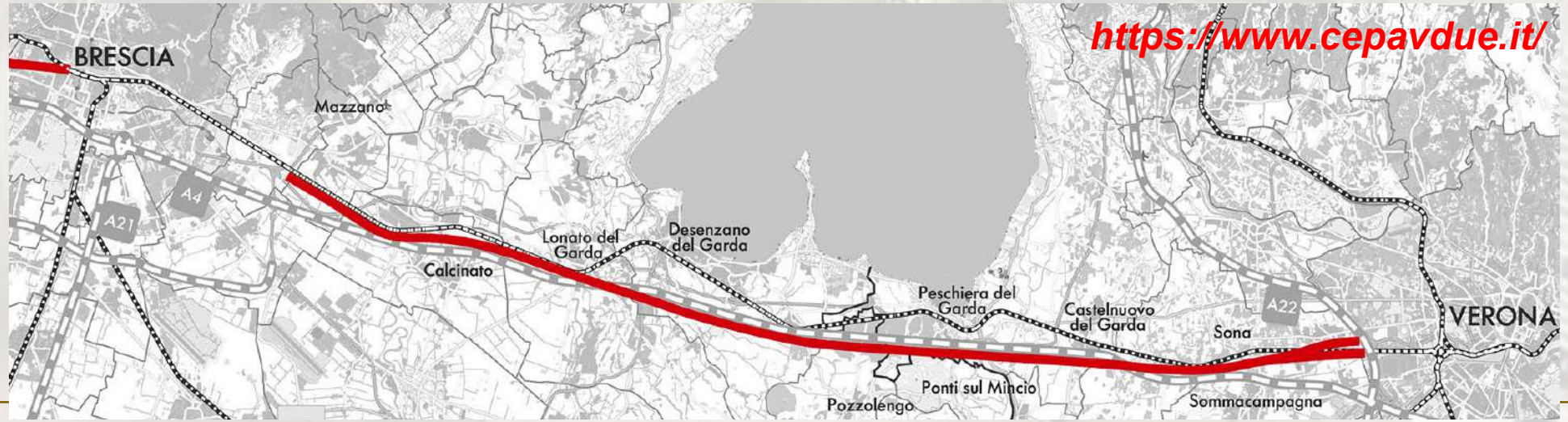
La sperimentazione per il controllo in opera

La nuova linea ferroviaria AV/AC Brescia Est – Verona

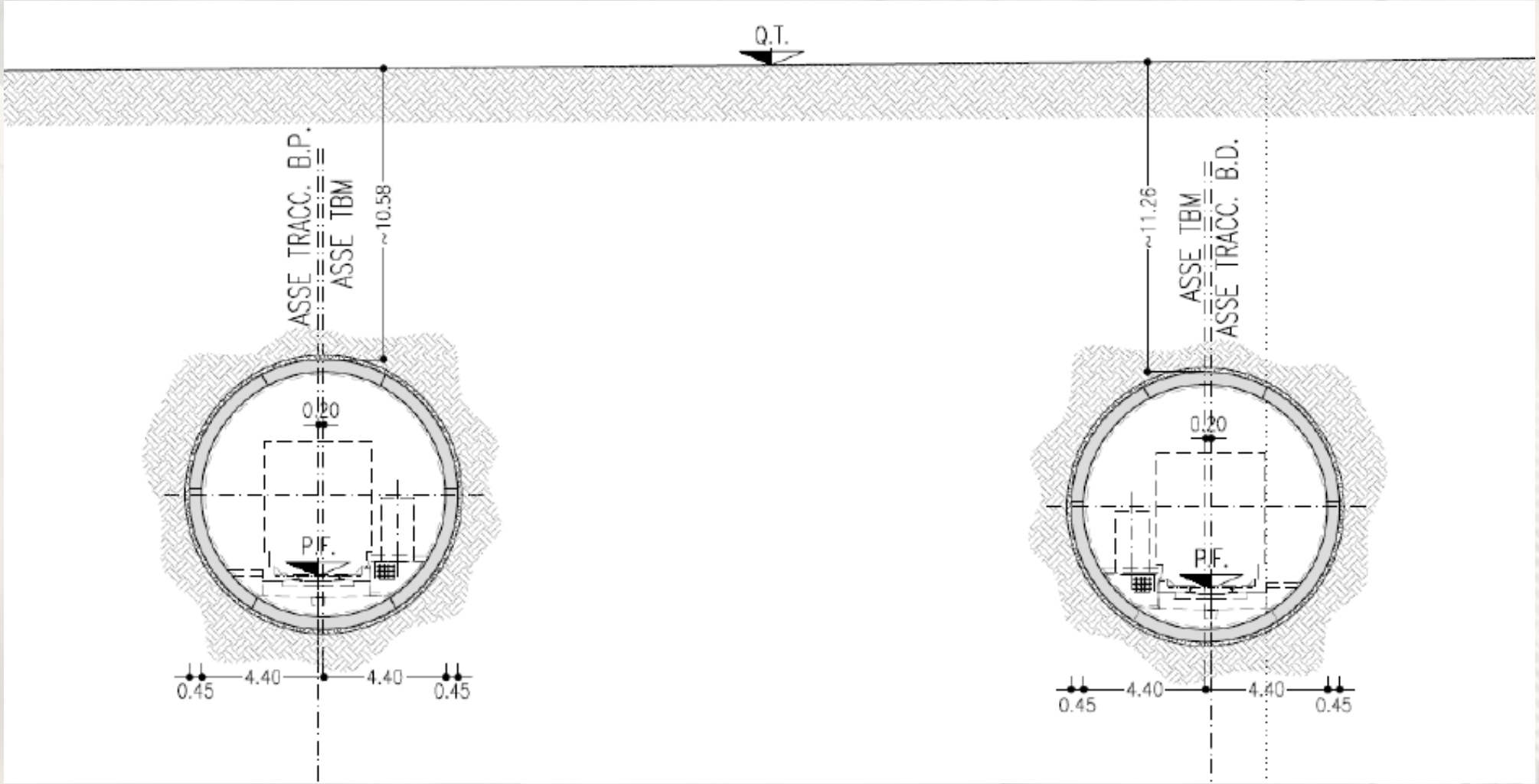
- La nuova linea ferroviaria AV/AC Brescia Est – Verona si sviluppa per circa 48 km, iniziando il percorso nel comune di Mazzano, in provincia di Brescia, sino a raggiungere il comune di Verona nel lato occidentale con i nuovi binari AV e la nuova interconnessione di Verona Merci.
- Il tracciato ferroviario attraversa:

  - Regione Lombardia e Regione Veneto

  - Province di Brescia, Mantova e Verona

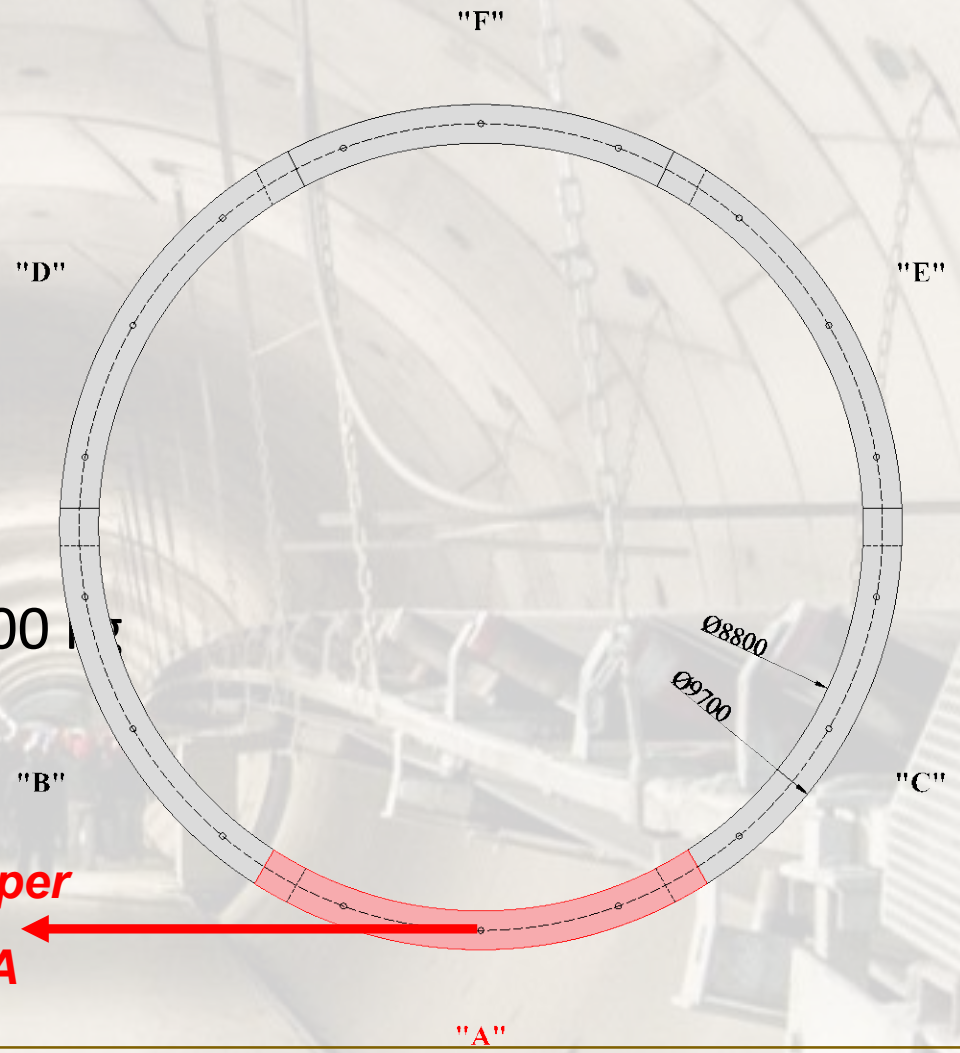


GALLERIA A DOPPIA CANNA A SINGOLO BINARIO



Galleria naturale di Lonato

- diametro interno: 8.8 m
- diametro esterno: 9.7 m
- spessore del rivestimento: 0.45 m
- numero di conci per anello: 6
- peso medio di ciascun concio: 10500 kg



Elemento di riferimento considerato per le prove di laboratorio: CONCIO TIPO A

Principali caratteristiche geometriche del rivestimento

- Principali caratteristiche geometriche del rivestimento:

- 18 scarpe di spinta della TBM per anello

- 3 scarpe di spinta per ogni concio

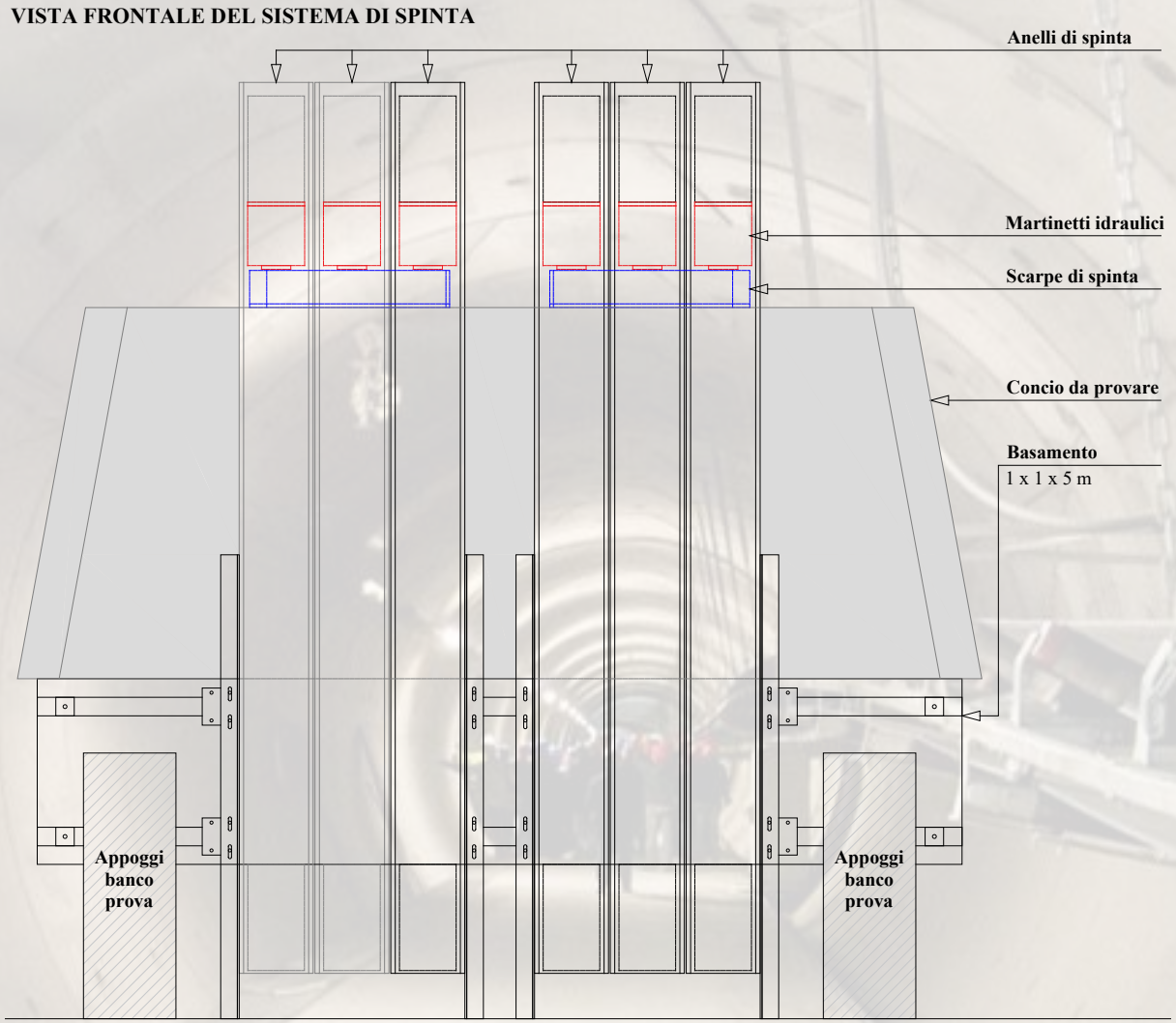
- Nelle sezioni più sollecitate del tracciato: spinta per scarpa di spinta pari a circa 600 – 750 ton

Le prove di collaudo

PROVA DI COMPRESSIONE
vuole rappresentare le azioni applicate dalla TBM durante le operazioni di scavo

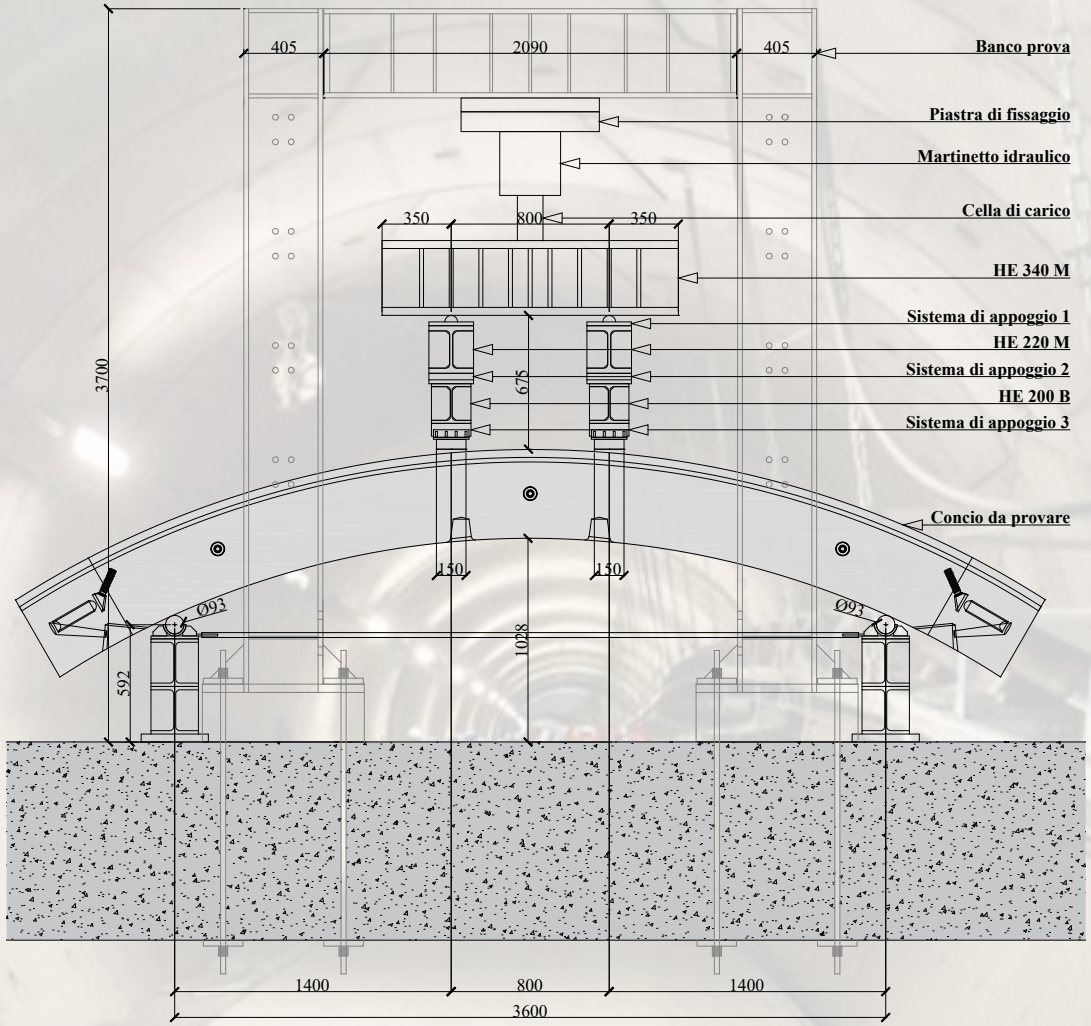
PROVA DI FLESSIONE
va a riprodurre le sollecitazioni che i conci subiscono durante le operazioni di movimentazione e stoccaggio

Prove di compressione



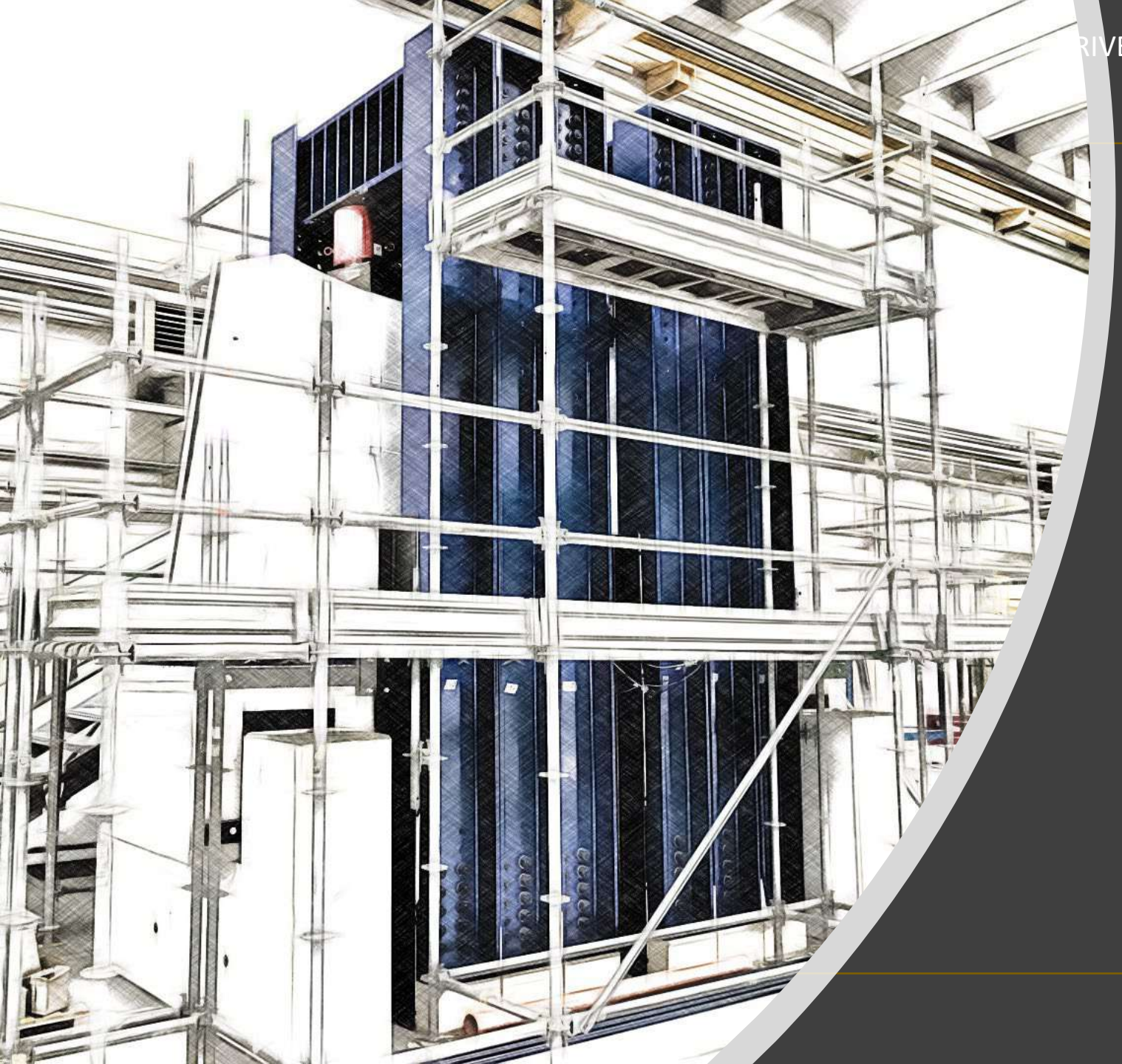
Prove di flessione

VISTA FRONTALE DEL SISTEMA DI CARICO



- Massima azione esercitabile su singolo concio (se di dimensioni adeguate): circa 16500 kN
- Dimensioni massime concio che può essere provato: sviluppo di circa 5m, altezza 2m

- Massima azione esercitabile su singolo concio (se di dimensioni adeguate): circa 1400 kN
- Dimensioni massime concio che può essere provato: sviluppo di circa 5m, altezza 2m



Grazie per l'attenzione !!