Sustainable CSA Cement-based Precast Concrete Tunnel Lining Reinforced with GFRP Bars: Challenges and Opportunities

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THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

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WHY AIM FOR THE CSA BINDERS IN TUNNELLING FIELD?

An average of over

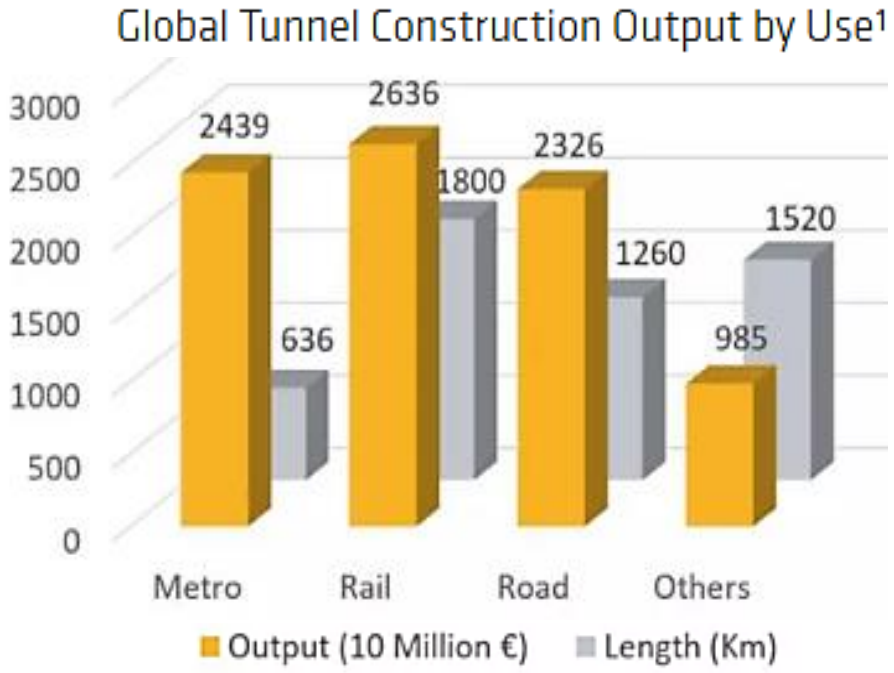
5,000 kilometers

of tunnels are constructed each year around the world.[1]

Approximately

86 billion

Euros are spent per year in tunnel and underground construction worldwide.[1]



60 million m^3/year

150 million $tons_{Concrete}$/year

24 million $tons_{Cement}$/year

24 millions tons CO_2/year
≈1% worldwide

[1] Source: Internantional Tunnelling Association (ITA), Tunnel Market Survey 2016

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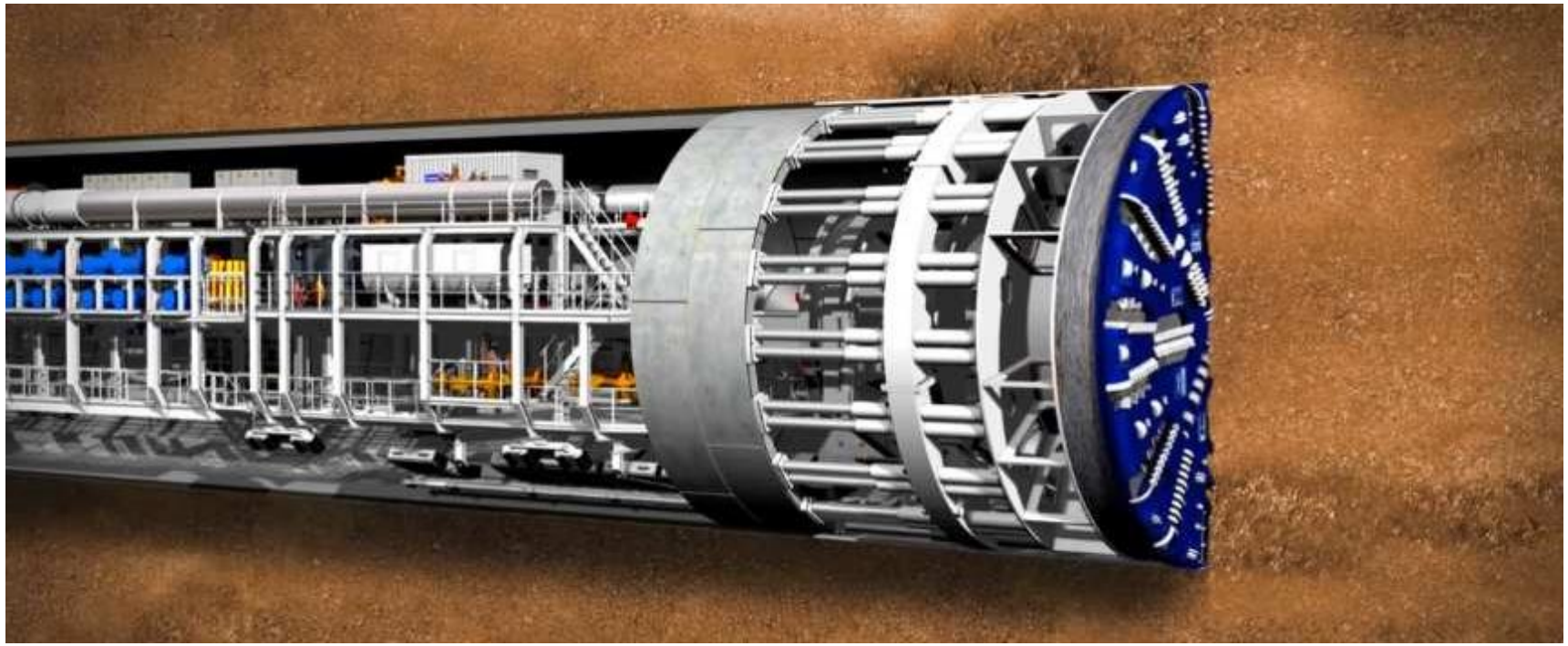
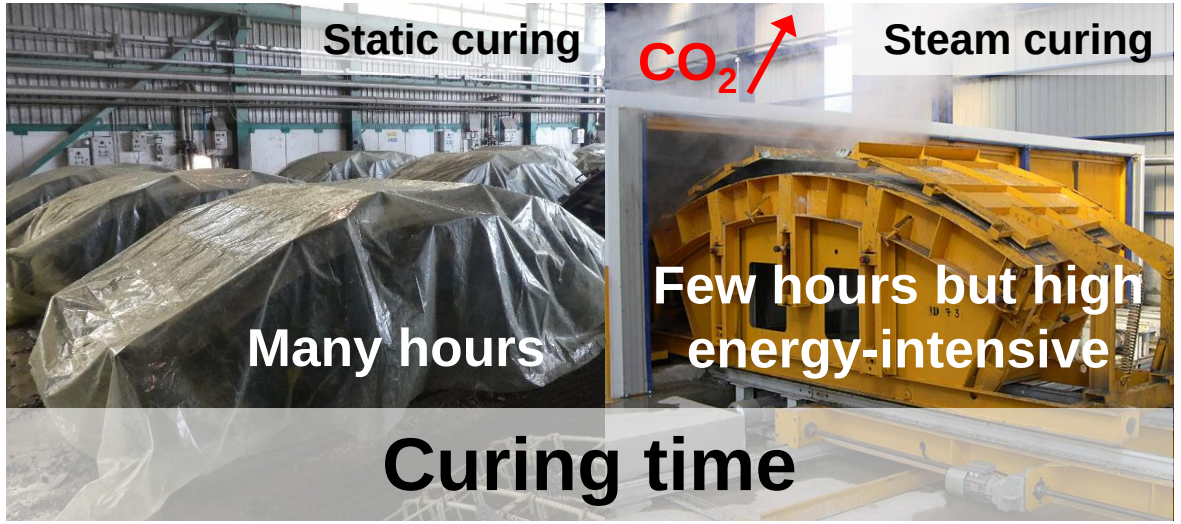
Mechanized tunnelling

Increasing use of mechanized tunnelling

Tunnel boring machines are very advanced equipment used as an alternative to drilling and blasting through rock and conventional mechanical excavation in soft ground. Mechanized tunneling has become more important with the rapid growth and expansion of underground construction in recent years.



Production of the precast segments



Work-site storage area: can be a problem?

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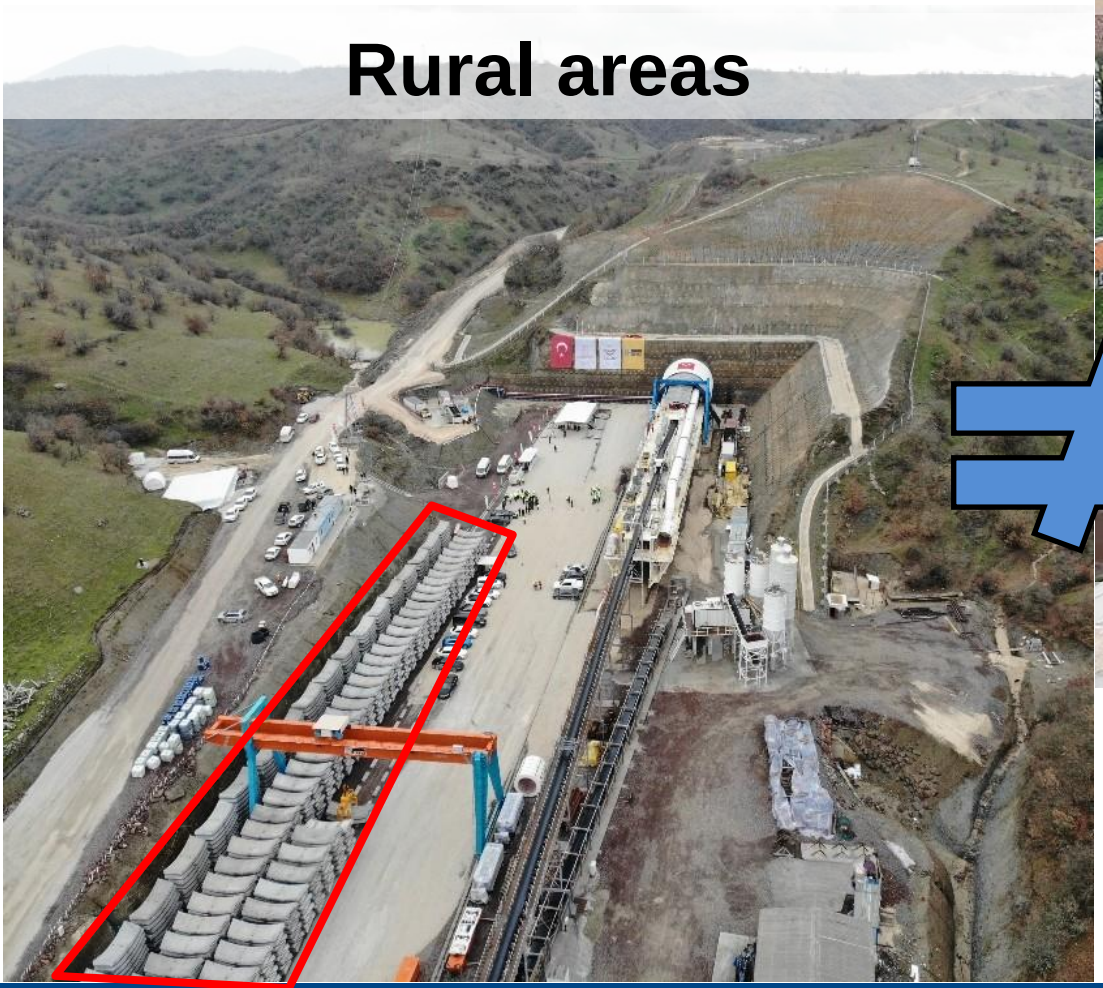
Stacking on the construction-site



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Concrete mix design based on CSA cement

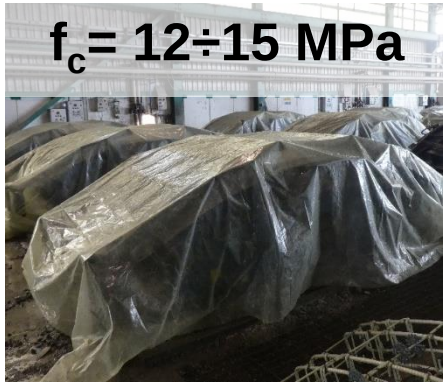
Main advantages…

- More sustainable production process (lower firing temperature)

- **Development of high mechanical strengths in short-term**

- Low shrinkage

…connected to mechanized excavation



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Fast static-curing
4÷5 hours

No
Steam-curing

Speed up demoulding

Installation: 7 days for the required strength (instead of 28 days)

Increase in production per workshift and fast clearing of the storage areas

Concrete mix design based on CSA cement

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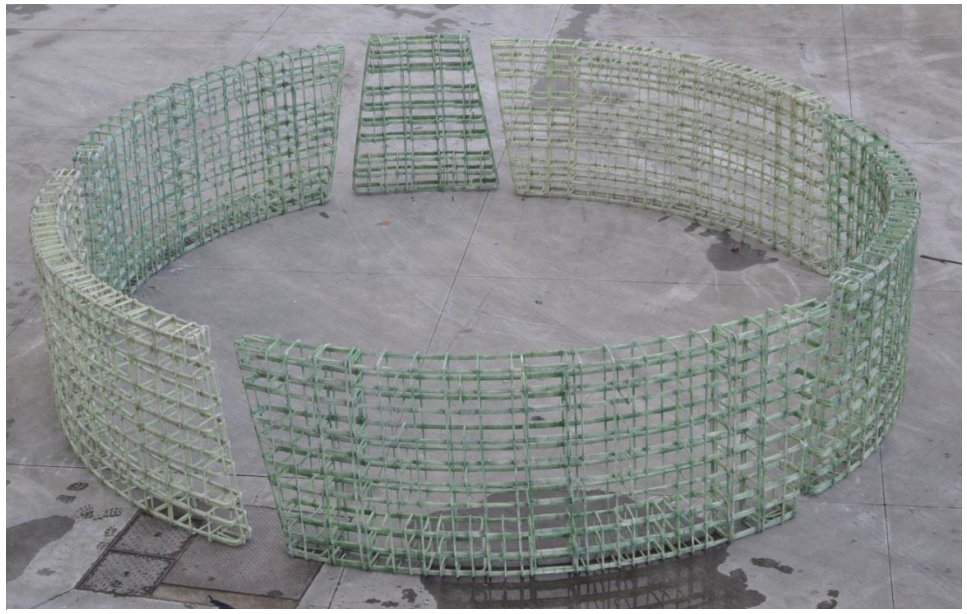
Main disadvantages…

- Low workability
- Low pH value

…solved in mechanized excavation

Sufficient for the prefabrication

Traditional Steel reinforcement



New GFRP closed-ring reinforcement

GFRP closed-ring reinforcement

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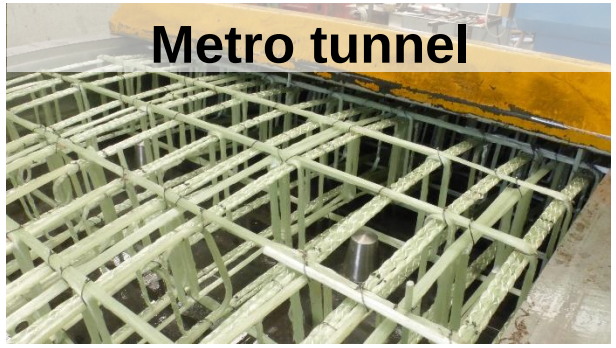
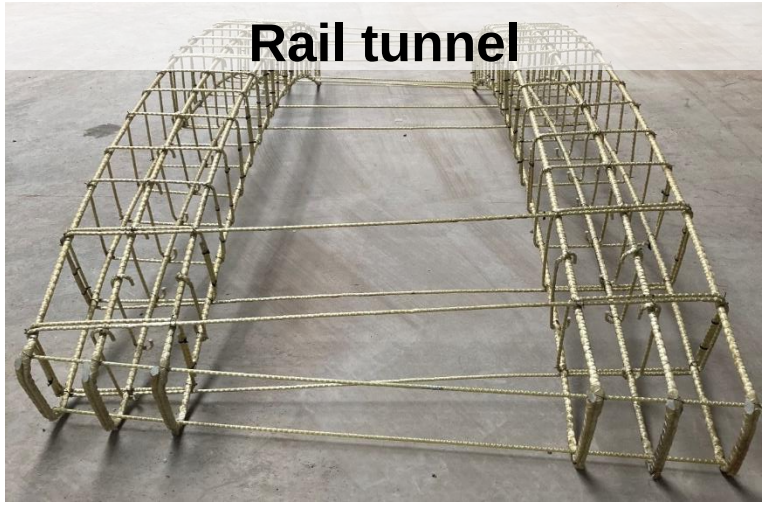
Full-scale test with several GFRP dimensions/configurations

Hydro tunnel

Metro tunnel



Rail tunnel

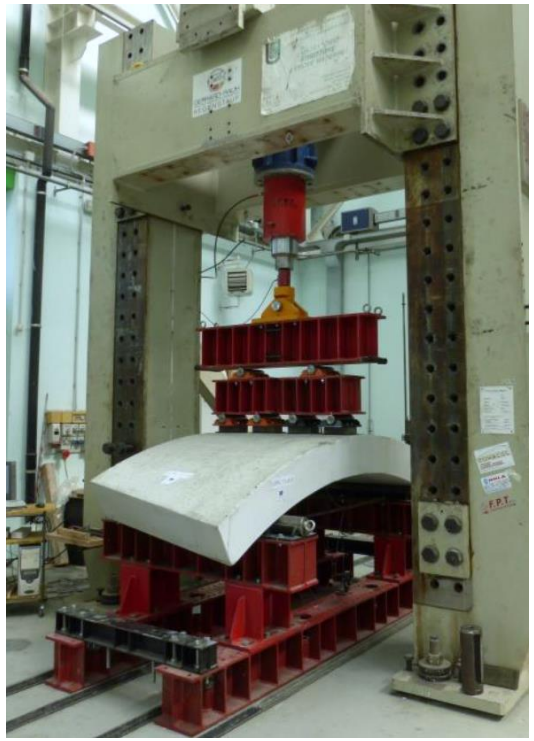


Road tunnel

GFRP closed-ring reinforcement

Full-scale test on several tunnel dimensions: Bending test

Hydro tunnel



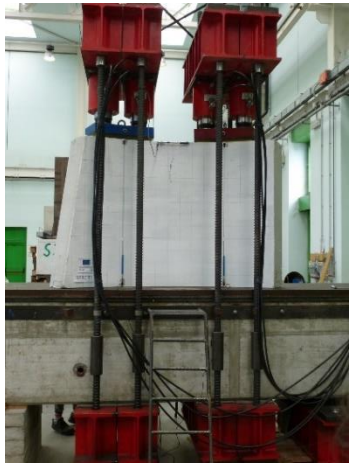
Metro tunnel

Rail tunnel

Road tunnel

GFRP closed-ring reinforcement

Full-scale test on several tunnel dimensions: TBM thrust test



Hydro tunnel

Metro tunnel

Rail tunnel

Road tunnel

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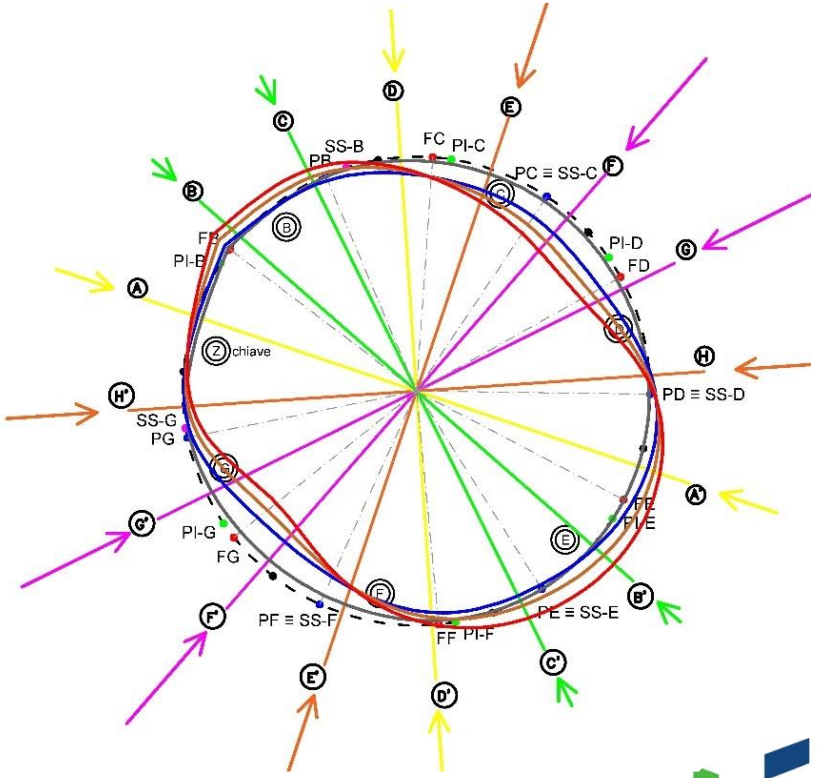
Full-scale test on metro tunnel ring: Earth pressure



Experimental program: Concrete Mix design & Reinforcement

Mix design	Unit	20°C	Ref.
Binder (CSA Next-SL05)*	kg/m^3	380	380
Sand	kg/m^3	892	892
Rubble	kg/m^3	445	445
Gravel	kg/m^3	503	503
Additive CC39/P22	%	0.7	0.7
Water	l/m^3	160	160
w/c	-	0.42	0.45
Workability loss (Consistency class: S4)			
t_0	mm	195	200
t_{30}	mm	190	200
t_{60}	mm	180	190

* Replaces CEM IV/A(PV) 42.5N SR pozzolanic cement, normally adopted to cast tunnel segments.

Buzzi Unicem

CE ETA13/0419

Property	Unit	Value
12 Longitudinal Ø13 (#4) GFRP closed-loop ring		
Average tensile strength	MPa (ksi)	1100 (160)
Guaranteed tensile strength	MPa (ksi)	850 (123)
Design tensile strength	MPa (ksi)	397 (57)
Tensile modulus	GPa (ksi)	46 (6672)
Average tensile strain	%	2.39
Guaranteed tensile strain	%	1.85
Design tensile strain	%	0.77
Fiber volume fraction	%	60
Plus 16 Transversal Ø8 (#2) GFRP closed-loop stirrup		

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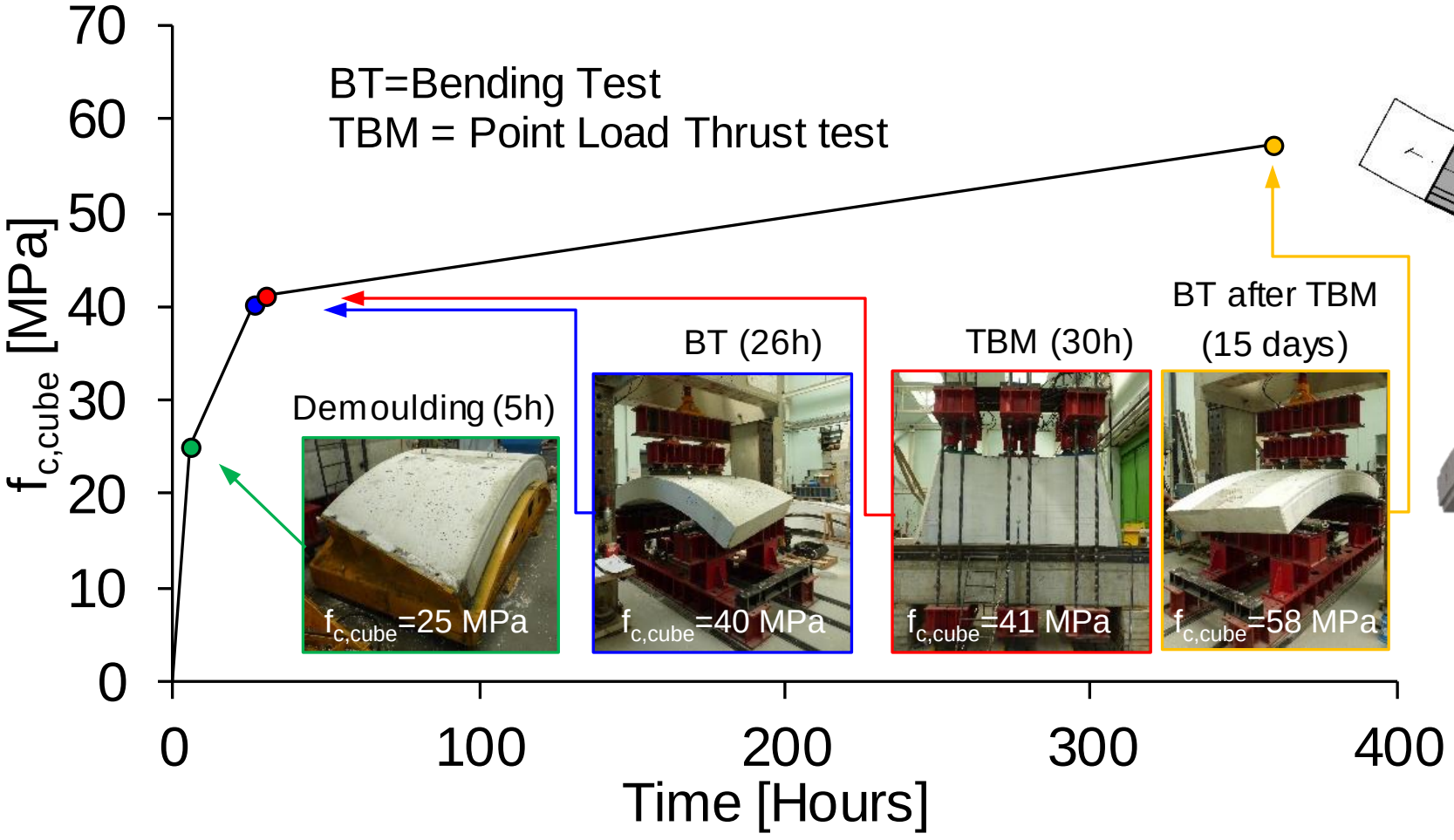
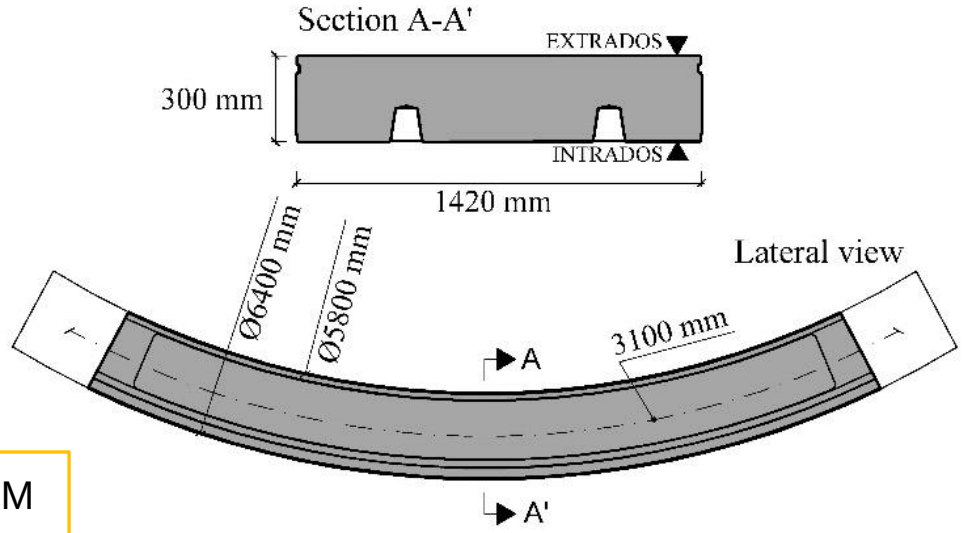
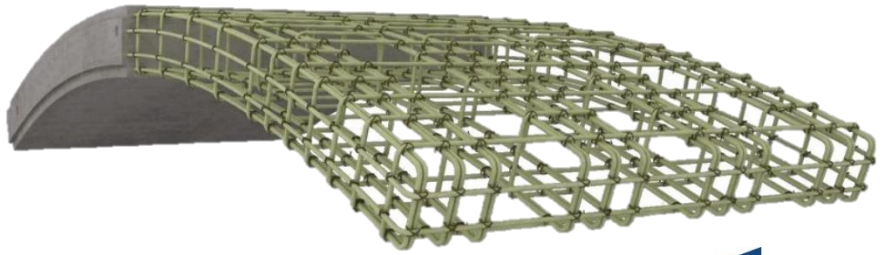
Experimental program: sequences and full-scale tests







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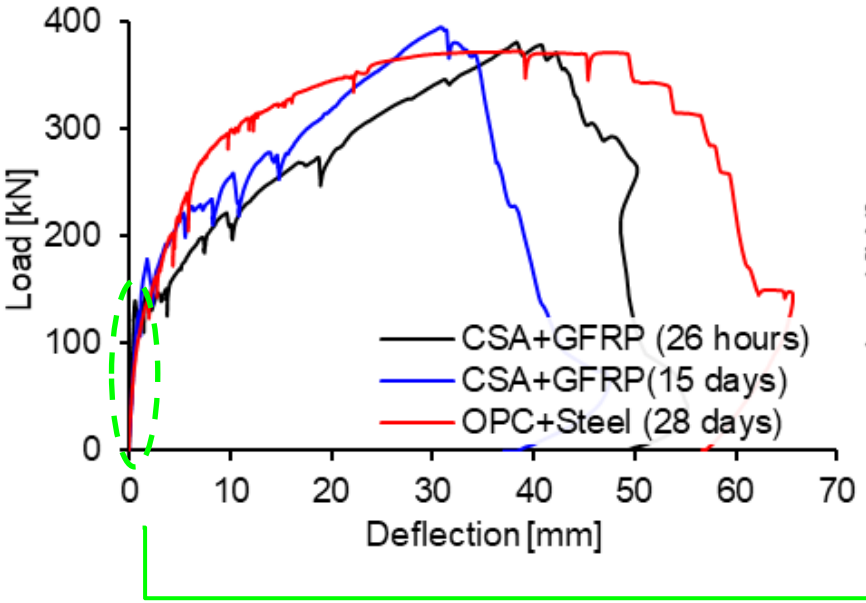
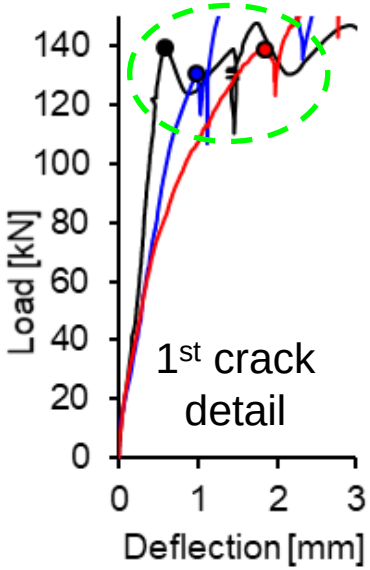
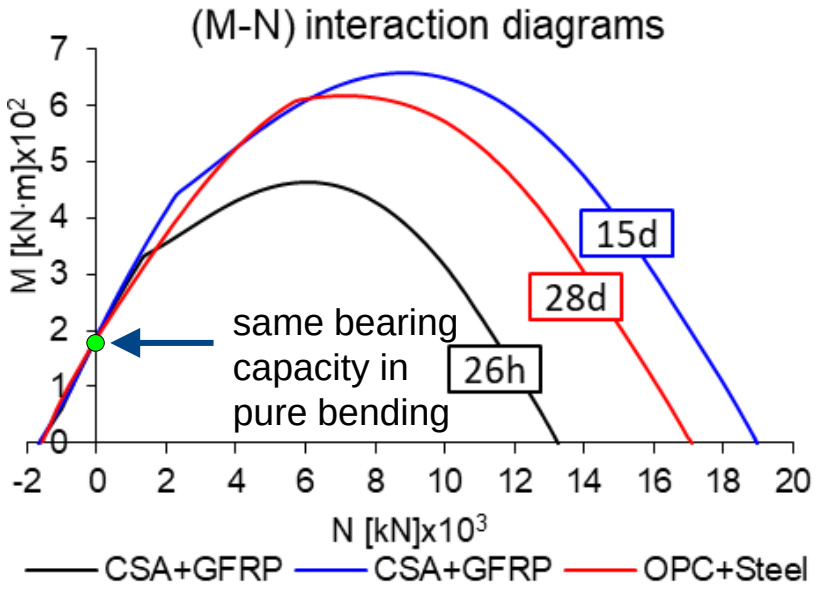
Experimental program: three-point bending test

26 hours after segment casting (compare to 28 days of the traditional solution)







Property →		Cross-area	Reinforcement					Concrete		Exp. Load		Bending moment		
Solution ↓	Curing time	Height x width	Type	Longitudinal	Transversal (stirrups)	f_{ym}	f_{fum} [a]	Type	$f_{cm,cube}$	$F_{1st\ crack}$	F_{max}	$M_{u,exp}$	$M_{u,ana}$	ΔM
		[cm²]	[-]	[sup+inf]		[MPa]	[MPa]	[-]	[MPa]	[kN]	[kN]	[kN·m]	[kN·m]	[%]
OPC + Steel	28 days	30x142	Steel	(12+12) Ø12 [#4]	[#2] Ø8/20	510	-	OPC	48	137	373	186	188	-1.0
CSA + GFRP (I)	26 hours		GFRP	12 rings Ø13 [#4]		-	524	CSA	40	140	380	190	187	+1.6
CSA + GFRP (II)	15 days		GFRP	12 rings Ø13 [#4]		-	524	CSA	58	130	395	197	190	+3.9

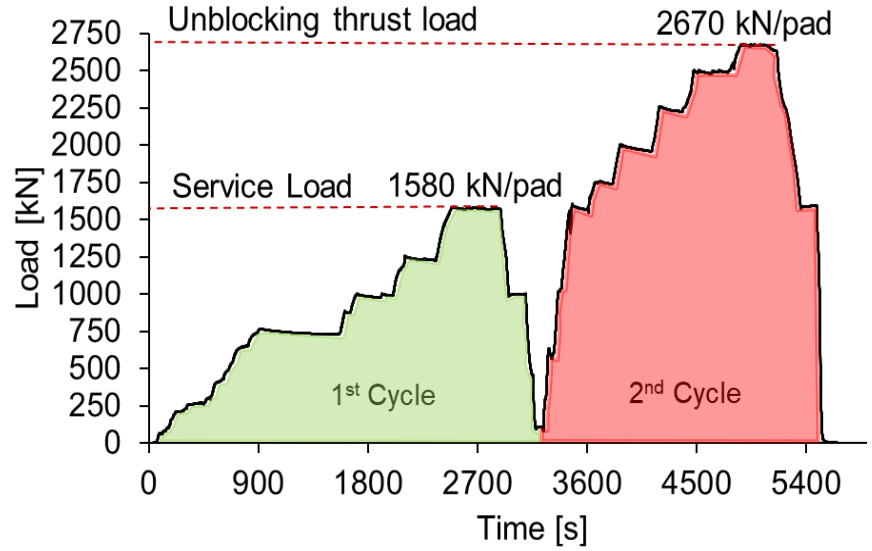
Note: [a] $f_{fum}=f_{fm}/\gamma_{f,\varnothing}=1100/2.1$

Experimental program: TBM point load test

30 hours after segment casting (compare to 28 days of the traditional solution)

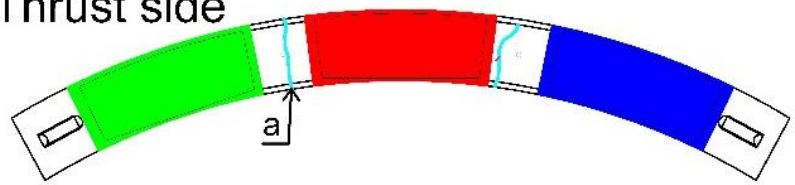
1st cycle: TBM progress thrust			Admissible residual crack width
	Service Load (1580 kN/pad)	Unloading (100 kN/pad)	
Solution ↓	Maximum crack width [mm]	Residual crack width [mm]	[mm]
OPC + Steel	0.10	**0.10**	**0.15**
CSA + GFRP	0.42	**0.15**	**0.50**

2nd cycle: TBM unblocking thrust (Exceptional load)			Admissible residual crack width
	Max TBM capacity (2670 kN/pad)	Unloading (0 kN)	
Solution ↓	Maximum crack width [mm]	Residual crack width [mm]	[mm]
OPC + Steel	0.25	**0.10**	**0.15**
CSA + GFRP	0.80	**0.15**	**0.50**



Crack pattern

Thrust side

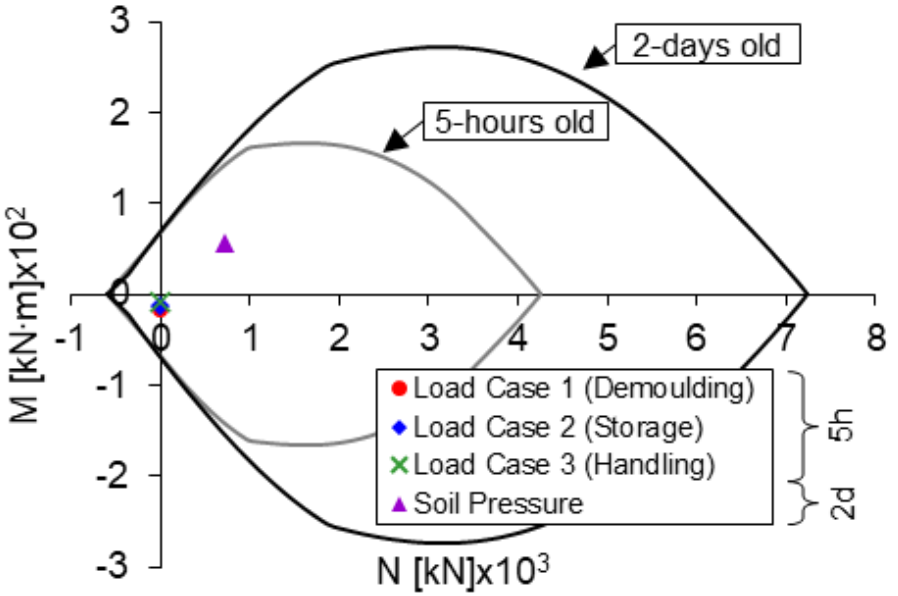


Case study

Summary of required design checks and factors for transient and final stages (ULS) according to ACI544.7R-16.

Load Case	Phase	Dynamic shock factor β	Key design parameter f_{ck} (f_{cd}) (*MPa*)	M_{Ed} (*kN·m*)	N_{Ed} (*kN*)	V_{Ed} (*kN*)	V_{Rd} (*kN*)
1	Demoulding	2.0	15 (10) (5 hours)	-16.7	0	47.8	107
2	Storage[a)]	-		-13.1	0	106	
3	Handling	2.0		-7.3	0	21	
4	Soil pressure (ULS)	-	30 (17) (2 days)	55.8	711	67	135

Note: a) Possible temporary storage on construction-site (which follows demoulding) is accounted for.

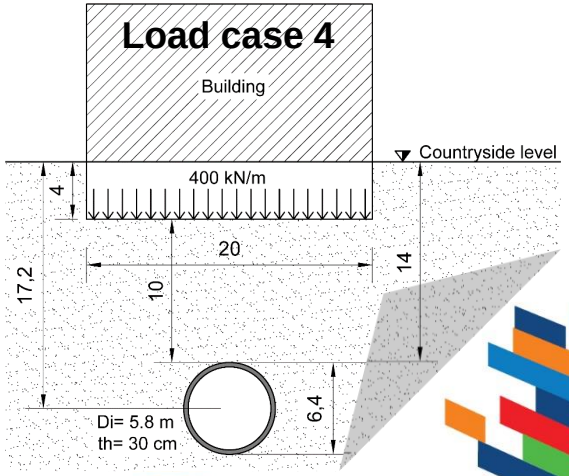


Load case 1

Load case 2

Load case 3

Load case 4



Note: Transportation phase is neglected for the purpose of using the CSA

Conclusions: CSA+GFRP

1) **Speed up** the **production** (4÷5 hours) without any energy-intensive steam-curing process

→ switch from 2 work-shift/day to 4 work-shift/day

2) **Reduction** of **segments stacked** waiting for the required strengths→ **Segments on demand**;

3) Possibility to establish a **work-site full prefabrication** (including ad-hoc modify pultrusion process)

improving the health and socio-economic aspects tied to the **reduction** of **pollution** and **traffic congestion** of the urban areas.

(**NO transports by trucks** of the reinforcement cages from the manufacturing plant to the prefabrication one and the segments from the latter to the construction-site)

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THANK YOU

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