POLITECNICO
MILANO 1863

DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING

Un approccio olistico alla sostenibilità delle costruzioni in calcestruzzo armato: meglio, con meno, più a lungo

Liberato Ferrara

MUSA
The project MUSA, Multilayered Urban Sustainability Action has been funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strenghtening of research structures and creation of R&D “innovation ecosystems”, set up of “territorial leaders in R&D” ,5

Current societal challenge for civil engineering

WHICH SCENARIO?

55% world population lives in urban areas
(up to 80% in high income countries)

Every year about 1% of current world population (75 mln) relocates to urban areas

Within 2045 67% of the world population will live in urban areas

Liberato Ferrara, DICA, POLIMI
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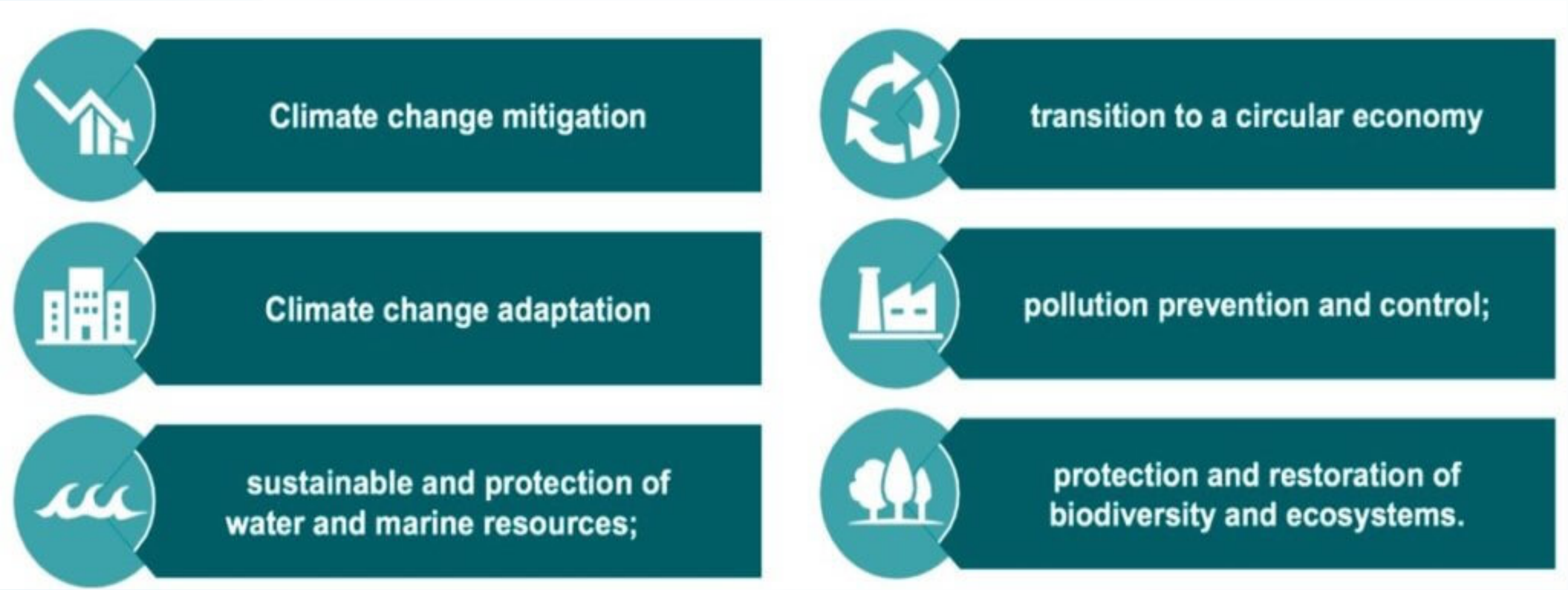
Current societal challenge for civil engineering

The new EU taxonomy environmental objectives



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Current societal challenge for civil engineering

Transportation Infrastructures :

1% GDP investment in infrastructures results into +1.5% GDP in 4 years

http://ec.europa.eu/growth/sectors/construction/index_en.htm

Every year road interruptions and traffic congestion delays cost an average of EUR 3000 to each household!

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Current societal challenge for civil engineering

Coastal protection: Europe has a 66000 km coastaline (3 times as much the one of US)

Coastal defense infrastructure market: 660 bn€/y + 4% year growth foreseen

a very likely increase of the European average 100-year extreme sea level of 34–76 cm under a moderate mitigation scenario, and of 58–172 cm under a high emissions scenario

Nearly 700000 EU citizens exposed to coastal flooding

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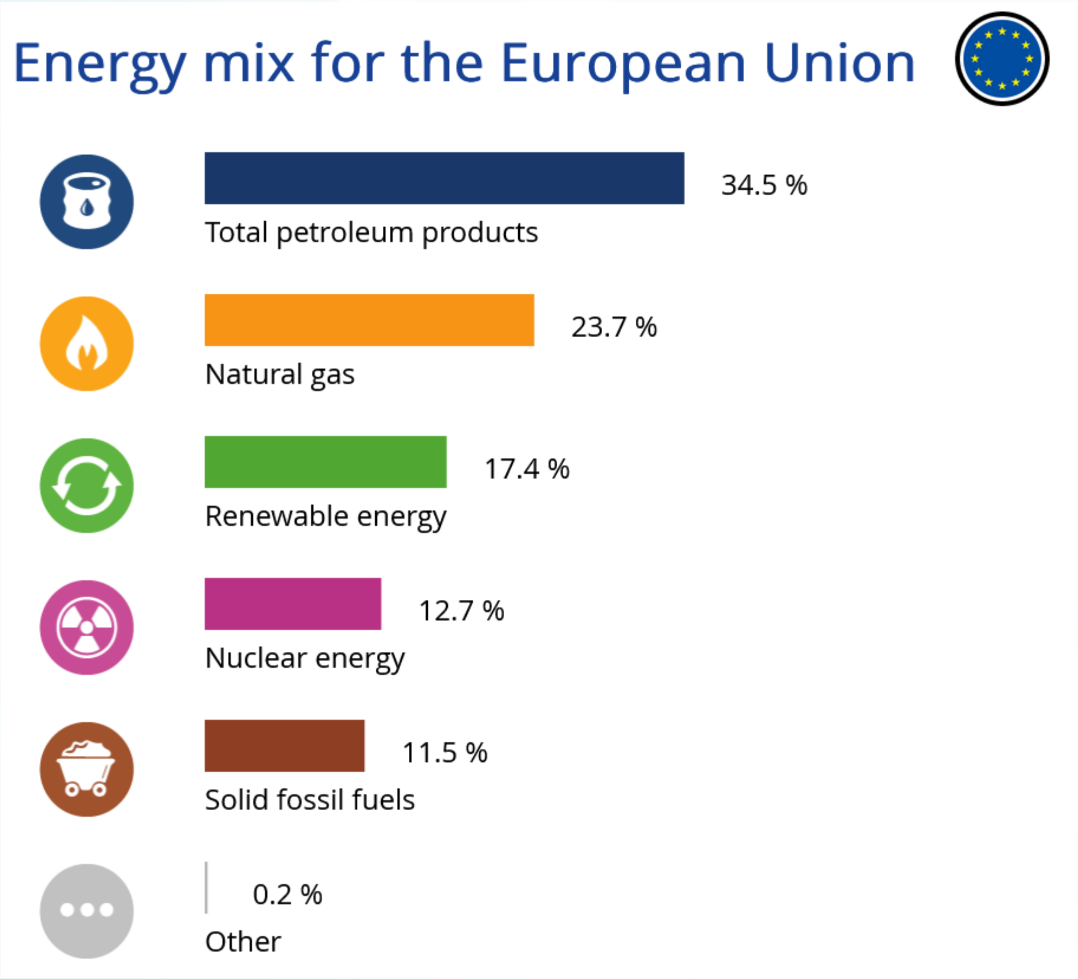
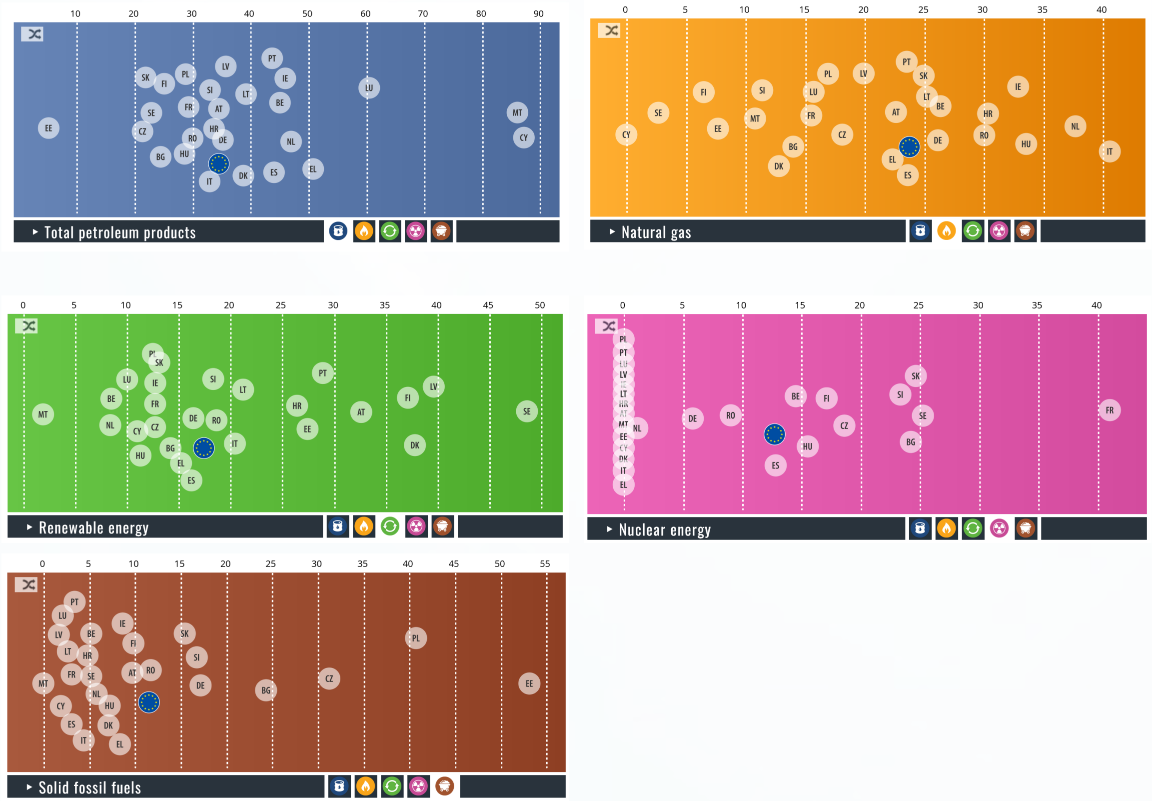
Current societal challenge for civil engineering

https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html





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Current societal challenge for civil engineering

Green growth: promoting the growth of clean energy production

Offshore wind

https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en

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Current societal challenge for civil engineering

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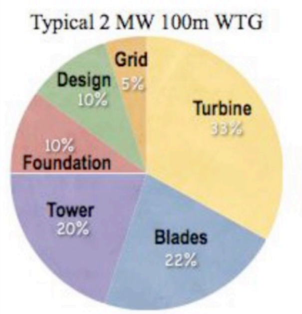
Offshore wind

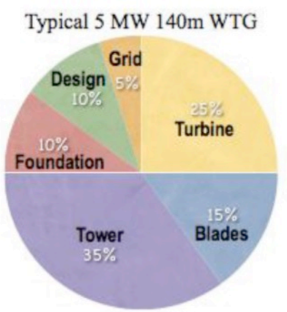
https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en

Small size (1-200 kW): rotor diameter, 1-20 m; tower height, 10-30 m.
Medium size (200-800 kW): rotor diameter, 20-50 m; tower height, 30-50 m.
Large size (oltre 1000 kW): rotor diameter: 55-80 m; tower height: 60-120 m.

Multi-megawatt generators have rotors that works at frequencies around 1/4 Hz.

The steel towers, limited by a base diameter of around 4 m by the transport needs, have a first frequency that approaches to the critical resonant 1/4 Hz as the heigh of the tower approaches to 100 m.
Being the bottom diameter limited, the only option to increase the tower stiffness, and therefore rise its main frequency, is to increase the shell thickness, but this is a very expensive way, and at the end, also an inefficient one, since thickness increase rise stiffness linearly but also increases linearly the mass compensating the frequency increase, that depends on the ratio between stiffness and mass.





Plancha et al., 2014

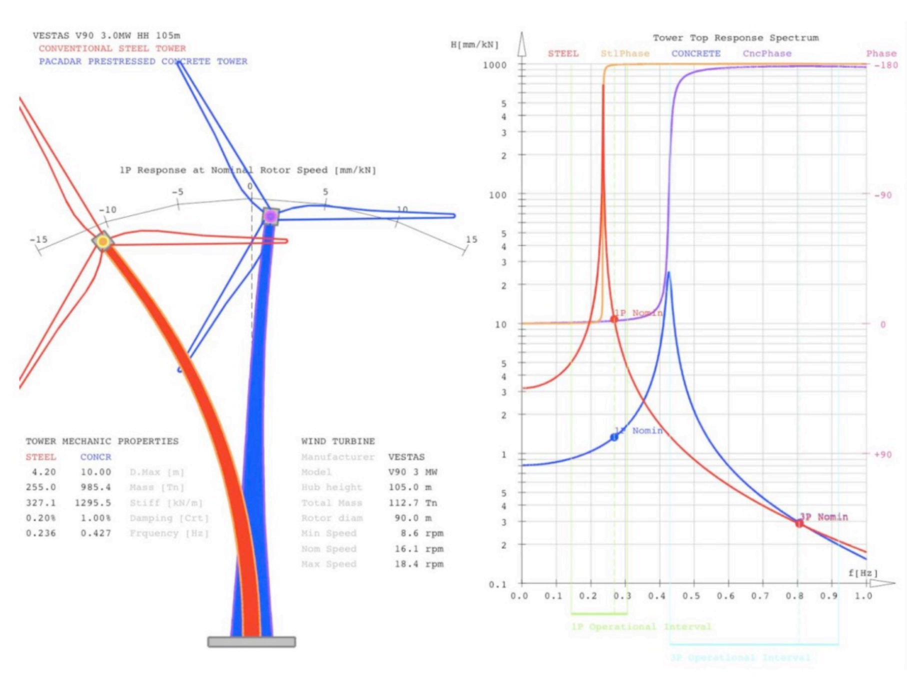
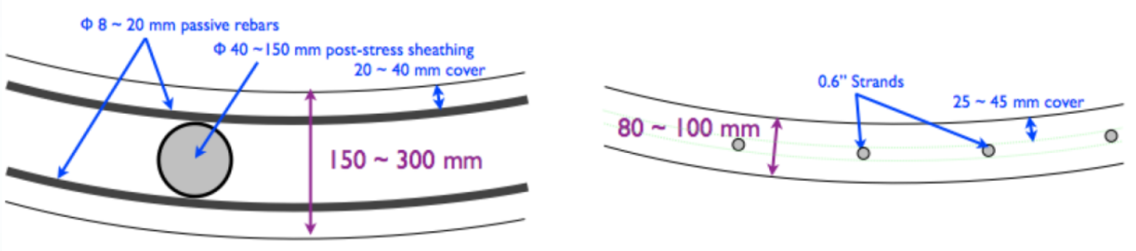


Figure 1: Comparison between steel and concrete towers frequency response



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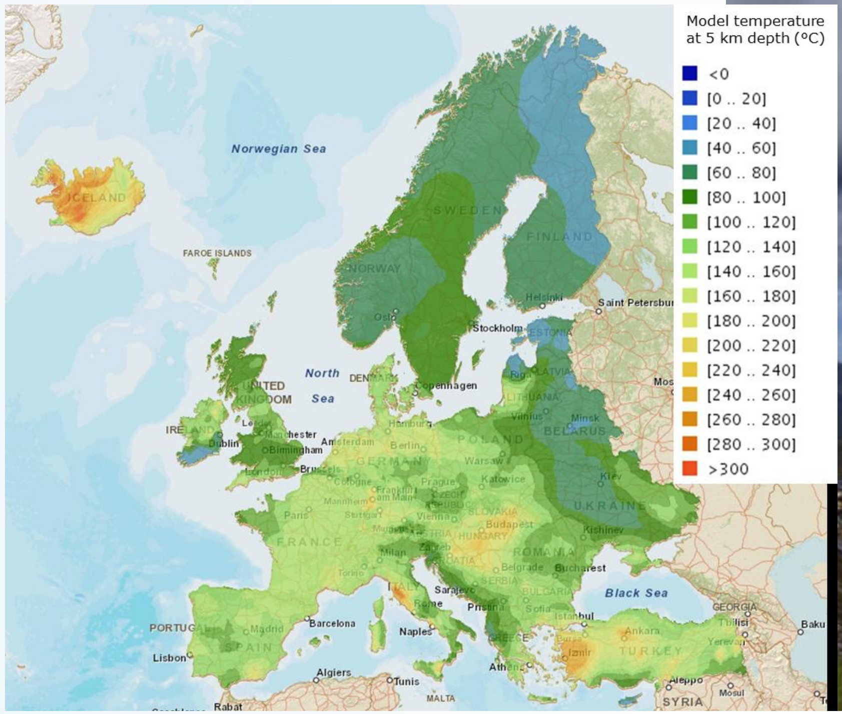
Current societal challenge for civil engineering

Green growth: promoting the growth of clean energy production

EGS: engineered geothermal system - stimulating deep hot resources that are otherwise not exploitable - provided technological challenges are overcome, the installed capacity of EGS technology could reach between 1200 GW to 12000 GW worldwide (currently it is 60 GW) https://ec.europa.eu/jrc/en/news/new-report-analyses-geothermal-energy-sector



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Current societal challenge for civil engineering

WHICH SCENARIO?

CONCRETE: … a remarkably good building material
made with locally available constituents and raw materials
ideal candidate for tailored "scenario-based" solutions

10 bln tons each year: the second largest used material worldwide
twice as much than the total of all other building materials
10 bln tons/year concrete: 4 bnl t/y cement and 48 bln t/y aggregates

«IF YOU REPLACE CONCRETE WITH ANOTHER MATERIAL, IT WOULD HAVE A BIGGER CARBON FOOTPRINT»

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Current societal challenge for civil engineering

The new EU taxonomy environmental objectives

Reduce CO_2 from clinker production

Reduce clinker in cement

Reduce cement in concrete

Reduce concrete in buildings and structures

More efficient (re) use of buildings and structures

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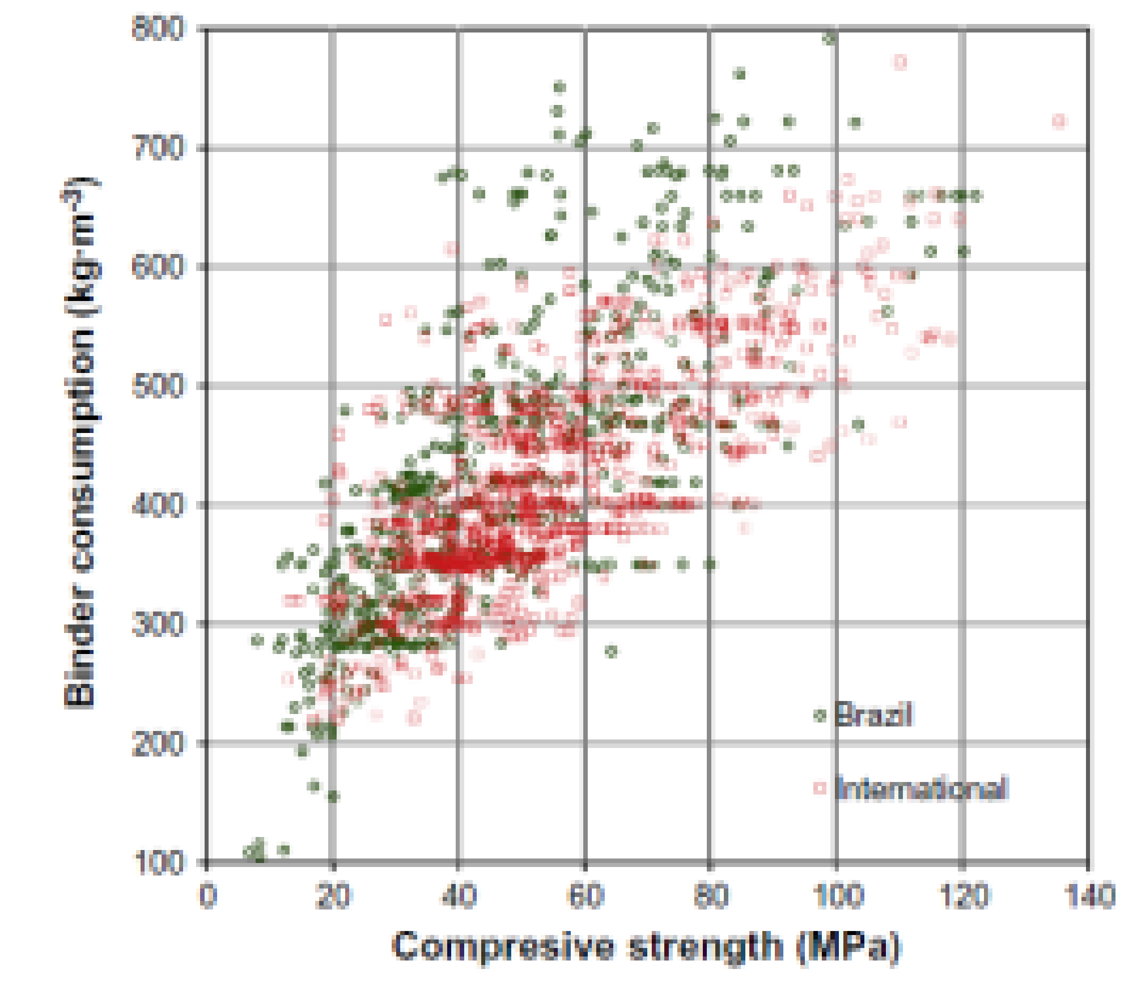
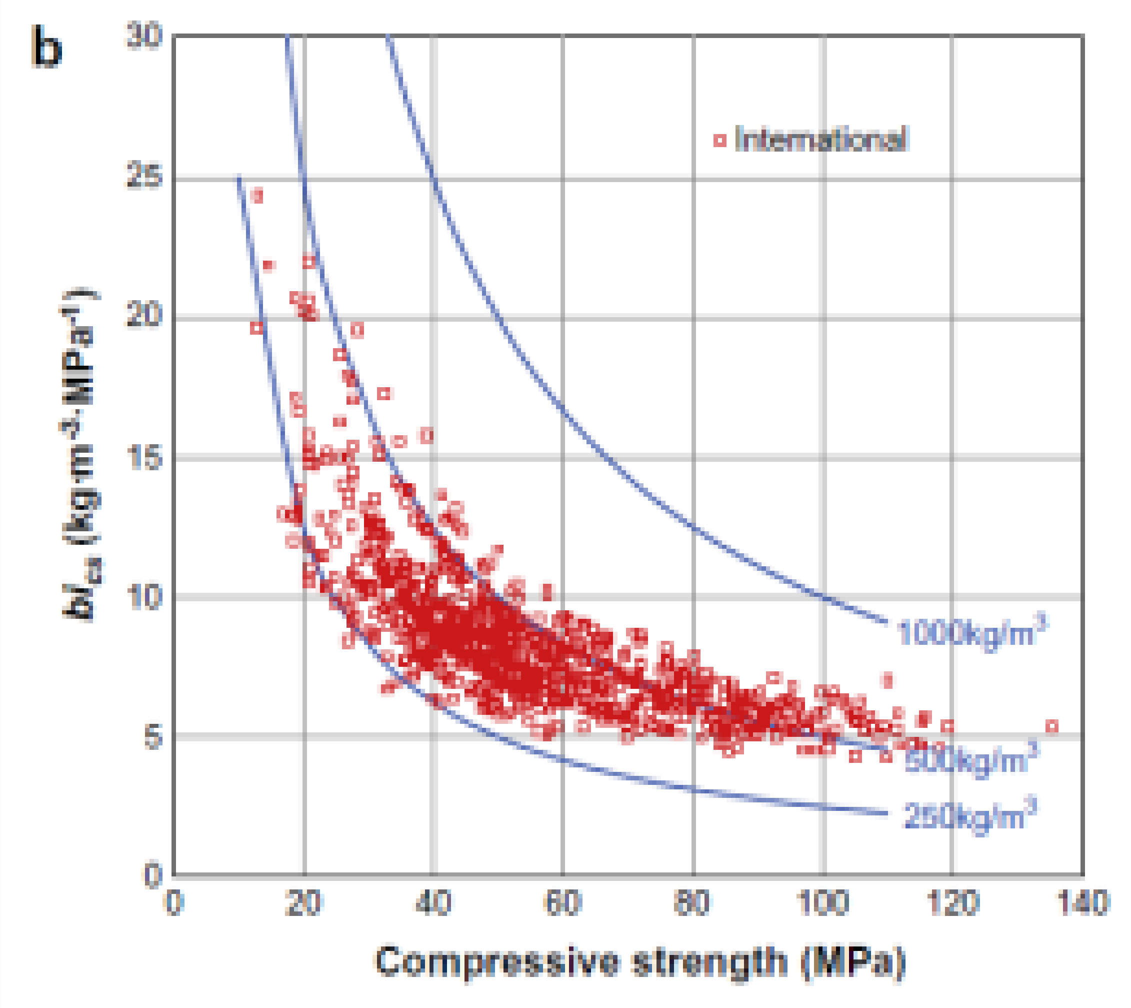
What kind of performance are we looking for?





Damineli et al., CCC, 2010

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What kind of performance are we looking for?

INCREASE **SERVICE LIFE** by:

- Adequate service life design
- Monitoring and inspection
- Adequate rehabilitation

Keep structure attractive to user!

INCREASE **PERFORMANCE** by:

- Use concretes with enhanced durability and improved «in structure» performance
- Use concretes with additional functionalities (self-sensing, self-cleaning, self-healing, METAMATERIAL)

IMPROVE RESILIENCE

$$SUSTAINABILITY = \frac{Service\ Life \times Performance}{Environmental\ footprint}$$

$$APATHY = \frac{Environmental\ footprint}{Performance}$$

REDUCE **ENVIRONMENTAL FOOTPRINT** by:

- Use of raw materials with reduced footprint
- Developments of concretes with «optimum» binder content
- Development of environmentally friendly production and construction techniques

Mueller et al., 2018, ACI SP
Gettu et al.,2018, ACI SP

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Introduction

50% of repaired concrete structures were damaged again: **25% in the first 5 years**, **75% within 10 years** and **95% within 25 years**.

Matthews (2007)

(Google images)

EN 206

Exposure class		Max. w/c	Min. strength. [MPa]	Min. cement [Kg/m³]	min. cover [mm]
Zero risk	X0	-	C12/15	-	10
Carbonation corrosion	XC1	0,65	C20/25	260	15
	XC2	0,60	C25/30	280	25
	XC3	0,55	C30/37	280	25
	XC4	0,50	C30/37	300	30
Chloride corrosion	XD1	0,55	C30/37	300	35
	XD2	0,55	C30/37	300	40
	XD3	0,45	C35/45	320	45
Corrosion by chlorides from seawater	XS1	0,50	C30/37	300	35
	XS2	0,45	C30/37	320	40
	XS3	0,45	C35/45	340	45
Freeze-thaw	XF1	0,55	C30/37	300	15
	XF2	0,55	C25/30	300	25
	XF3	0,50	C30/37	320	25
	XF4	0,45	C30/37	340	30
Aggressive exposure	XA1	0,55	C30/37	300	35
	XA2	0,50	C30/37	320	40
	XA3	0,45	C35/45	340	45

Any FRC would satisfy these prescriptions! (not to speak about UHPC)

So how accounting for the benefits related to their use?

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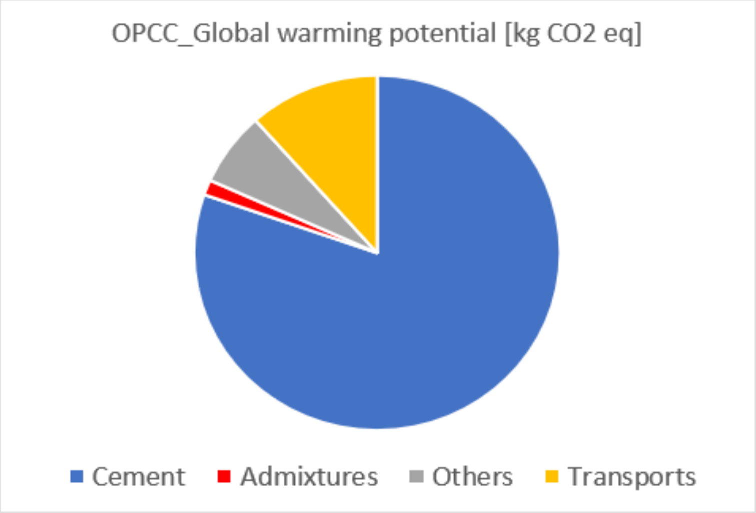
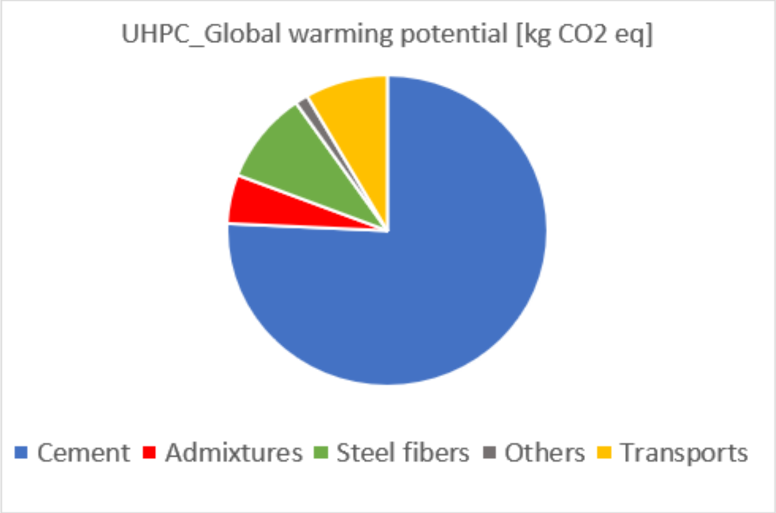
What kind of performance are we looking for?

UHPC MIX DESIGN	
Components	**kg/m^3**
Sand <= 0.5 mm	302
Sand 0.6 - 1.2 mm	600
Cem I	950
Silica fume	175
Water	160
VC 20HE	30
Steel microfibres	120

OPCC MIX DESIGN	
Components	**kg/m^3**
White Sand	211
Red Sand	897
Cem I	370
Water	150
VC 5970	3
Aggregate 7/10	354
Aggregate 12/20	377

- Cradle-to-gate system boundary for both the m^3 of material
- Use of CML-IA impact method to address consequences on a local/regional/global scale
- The distances taken into account for the supply of the raw materials have been estimated





Global warming environmental impact for both OPCC and UHPC. 1 m^3 has been assessed **407 kg CO2 eq. for OPCC and 1,108 kg CO2 eq. for UHPC**.

di Summa et al, fib Symposium Istanbul 2023

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Material «Sustainability» Index:

$$\frac{20 \cdot \text{structural performrmance}}{\sum_1^{10} CML\ impacts + 10 \cdot costs}$$

Normalize UHPC «performance» to the one of OPCC

Parameters	MI
Compressive strength	**40 MPa** (OPCC), **150 MPa** (UHPC)
Cost	111 €/m^3 (OPCC), 689 €/m^3 (UHPC)

MI= 0.41

Is UHPC really «sustainable»?

di Summa et al, fib Symposium Istanbul 2023

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Objective

1. Overcome the prescription-based durability paradigm through the use of durability-focused design and new degradation prediction models;

2. Use UHPC (Ultra-High-Performance Concrete) to reduce raw material consumption, maintenance frequency, and costs.

3. Utilizing Life Cycle Sustainability Analysis (LCSA) as an integral part of the “conceptual” design pathway and as a decision-making tool.

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The "metrics" does matter!

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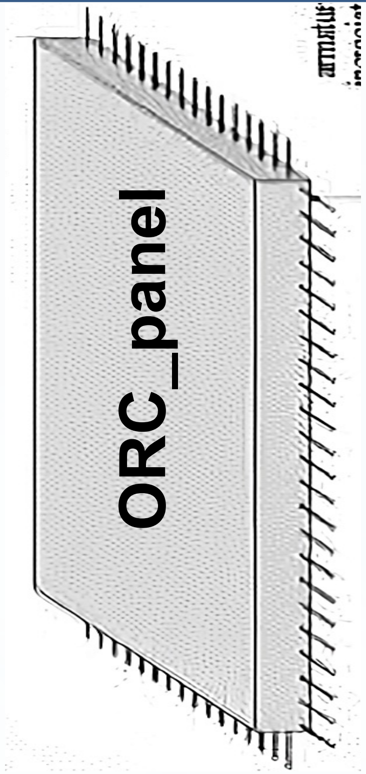
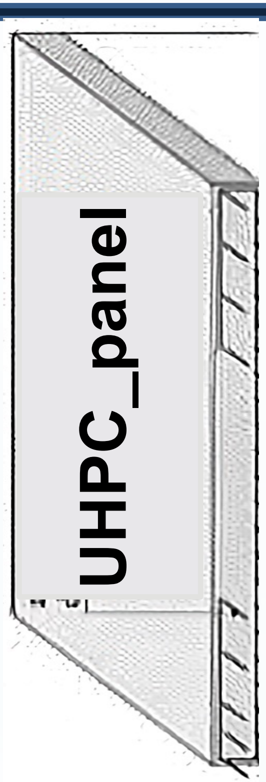
Bending capacity 2.45 kNm/m

3+3ϕ16 bars per meter (flexural) with 6 ϕ 6/m bars per meter (ORC_panel) (about 110 kg/m³ of steel bars)

4.55 m x 2.24m x **0.08 m**
(L X H X **W**)



Vs



4.55 m x 2.24m x **0.035m**
(L X H X **W**)

di Summa et al, fib Symposium Istanbul 2023

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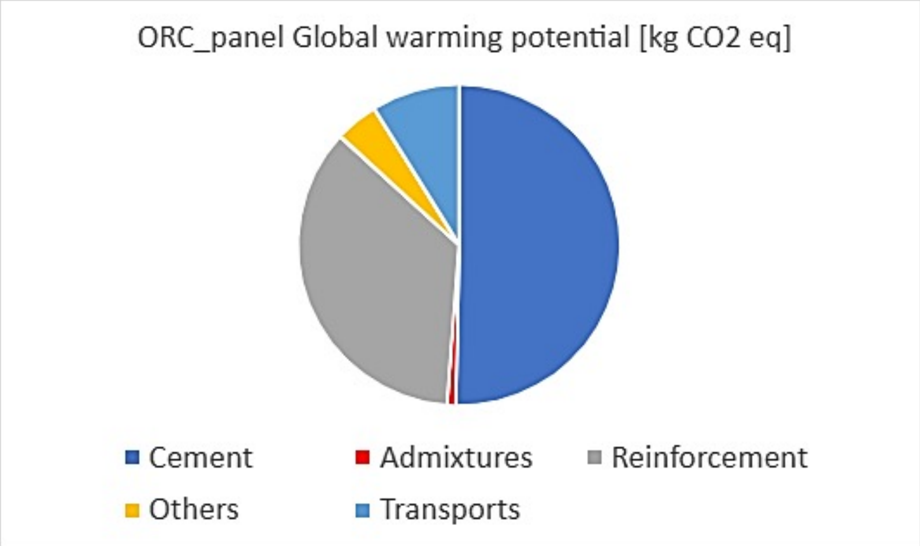

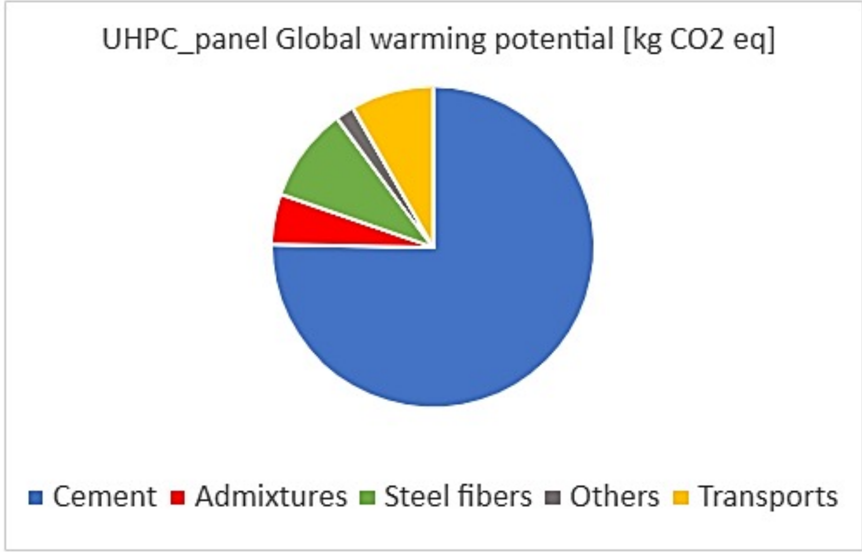

Global warming environmental impact for both ORC_panel and UHPC_panel.
519 kg CO_2 eq. for ORC_panel and 390 kg CO_2 eq. for UHPC_panel.

di Summa et al, fib Symposium Istanbul 2023

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Structural Sustainability Index (per Functional Unit)

$$\frac{\dfrac{\sum_1^n \text{durability parameters}}{\text{n}} + \dfrac{\sum_1^r \text{structural performance}}{\text{r}}}{\sum_1^{10} CML\ impacts + 10 \cdot costs} \cdot 10$$

Compressive strength	Tensile strength	Cost	Dapp
40 MPa (ORC_panel), **150 MPa** (UHPC_panel)	**3.5 MPa** (ORC_panel), **10 MPa** (UHPC_panel)	**363€** (ORC_panel) **241€** for (UHPC_panel)	**10^{-11} m/s^2** (ORC_panel) **10^{-13} m/s^2** (UHPC_panel

SI=1.36

di Summa et al, fib Symposium Istanbul 2023

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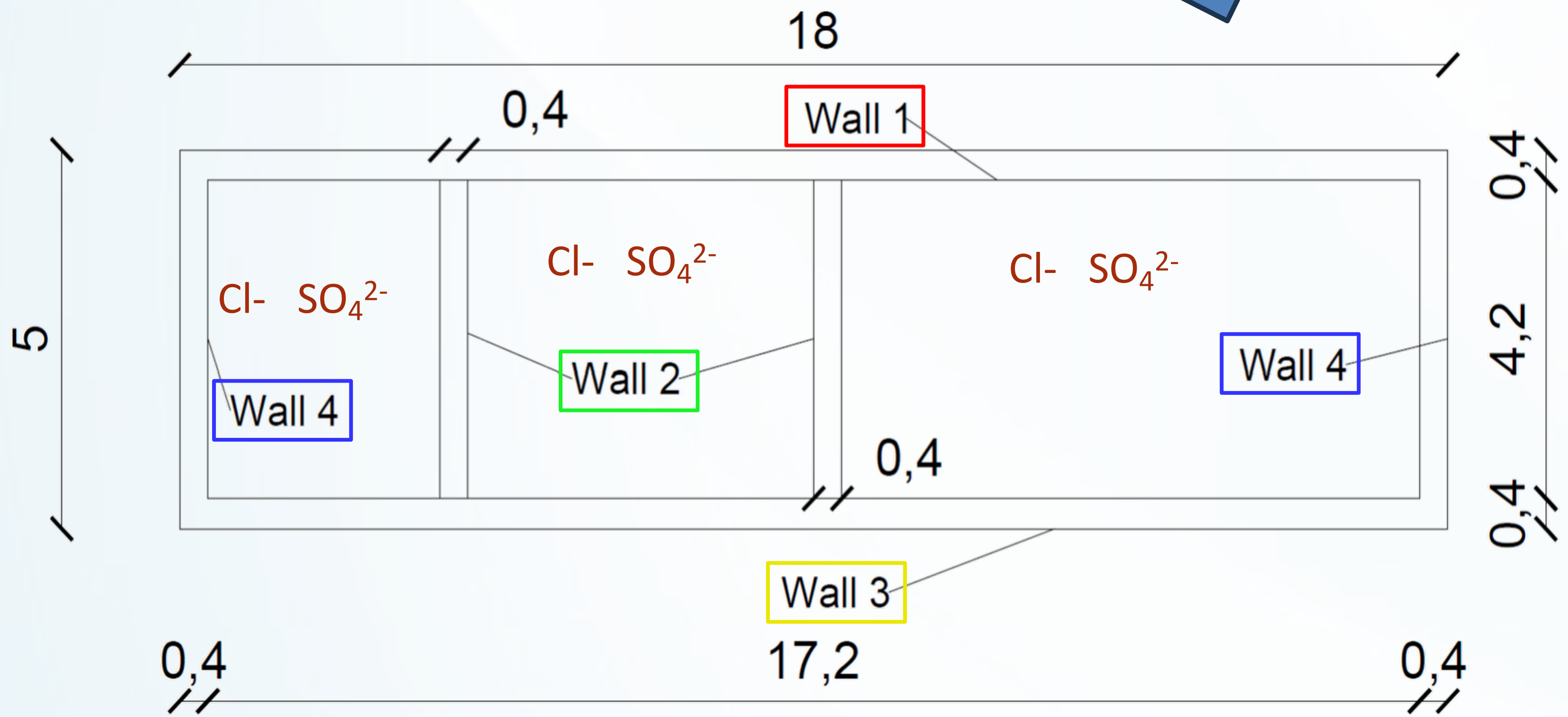
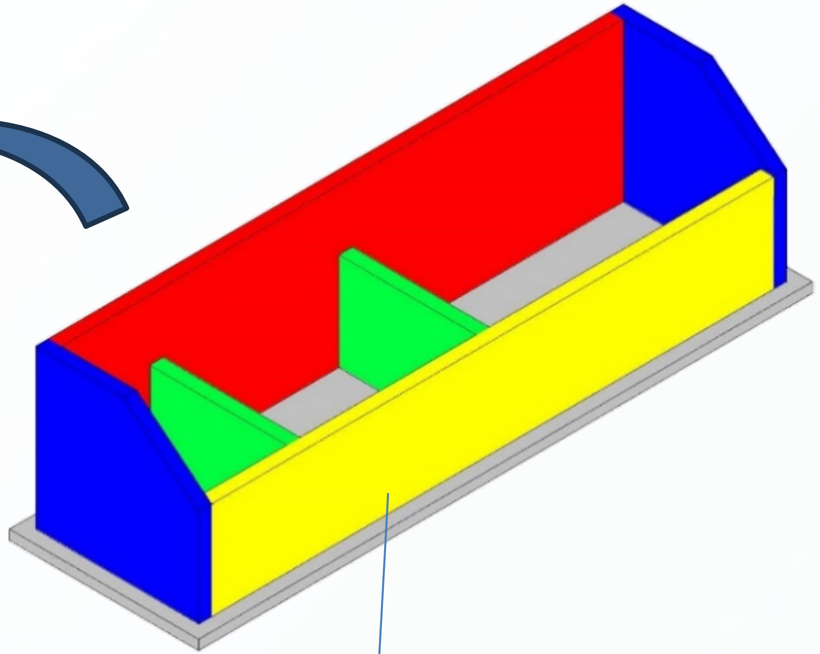
Case Study

Water tank in a geothermal power plant





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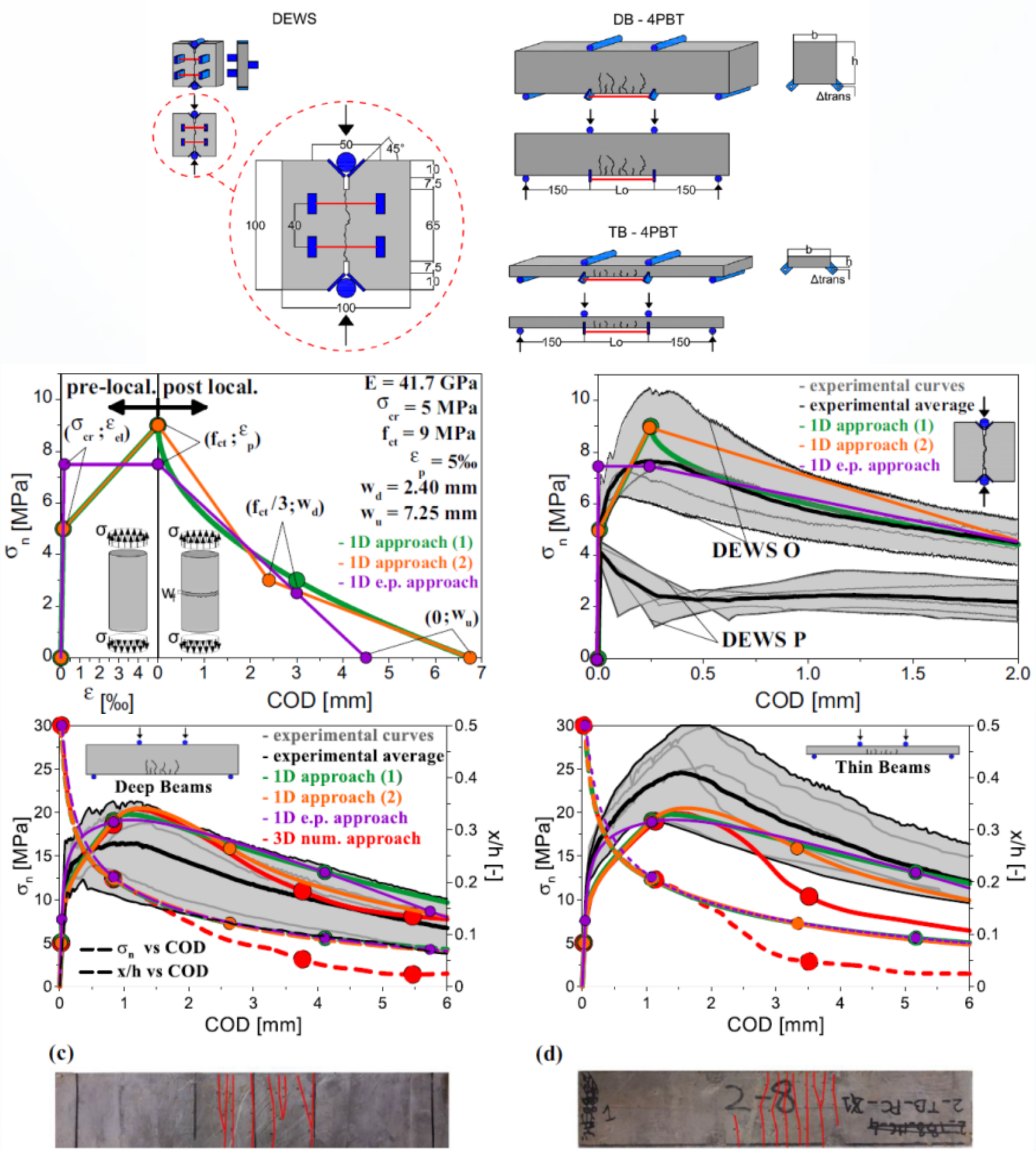
Case Study

Water tank in a geothermal power plant

Investigated mix-designs

Constituents $\left[\frac{Kg}{m^3}\right]$	ORC	UHPC
CEM I 42.5 R	350	
CEM I 52.5 R	/	600
Slag	/	500
Water	207	200
Coarse aggregates	900	/
Fine aggregates Sand	959	982
Limestone filler	60	/
Superplasticizer	/	33
Steel fibres	/	120
Crystalline admixture	/	4.8

Lo Monte and Ferrara, M&S 2020



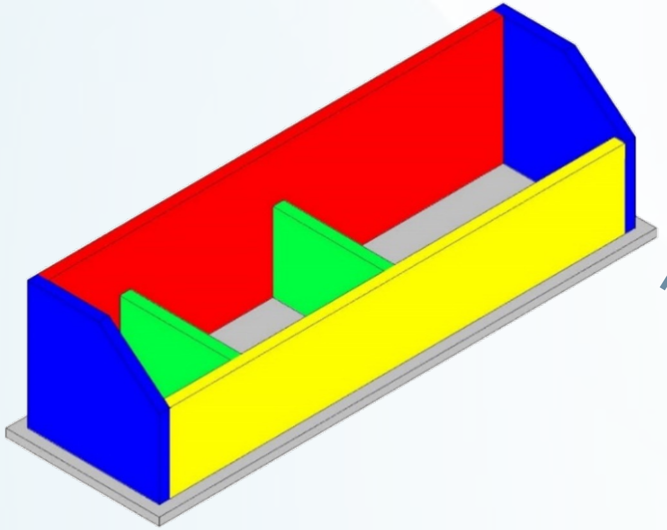
European Commission

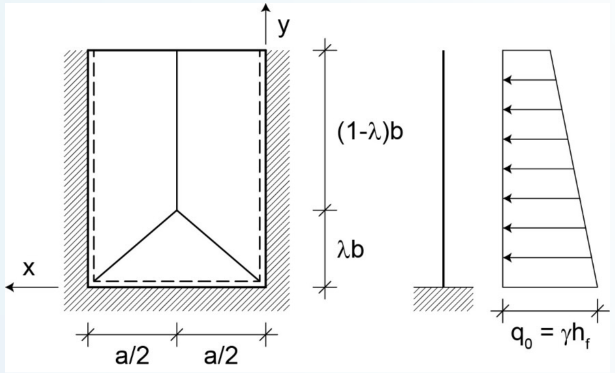
Horizon 2020
European Union funding
for Research & Innovation

RESHEALIENCE
Ultra High Durability Concrete

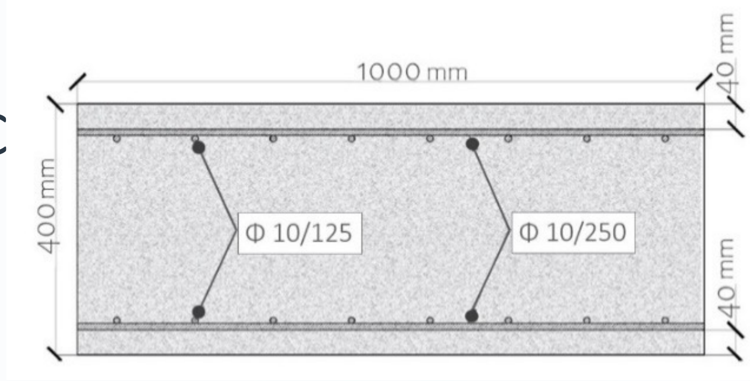
Design

«Classical» structural design +
Durability prescriptive approach

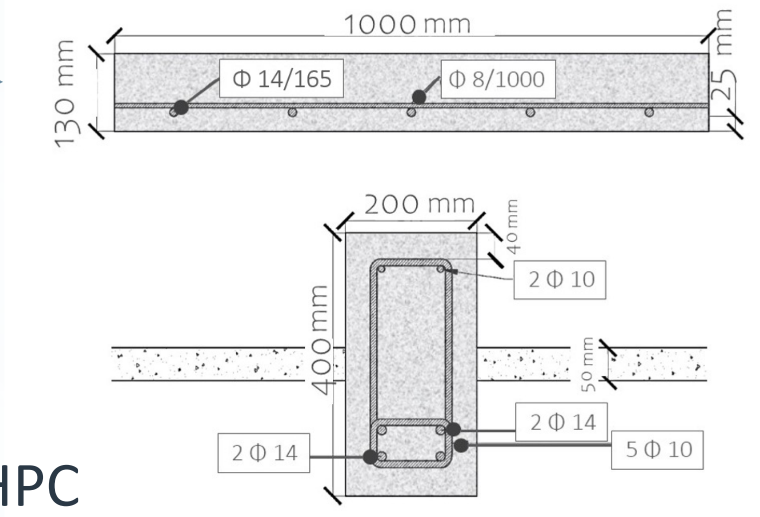




ORC

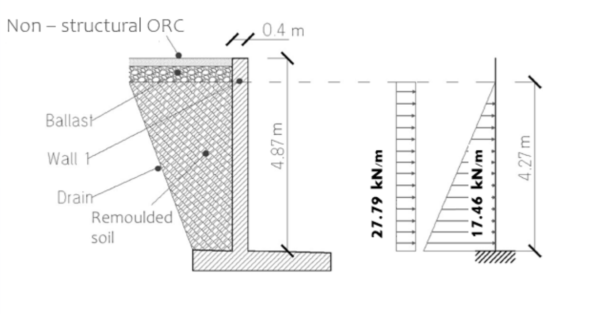


UHPC
walls



UHPC
precast slabs +
ORC «buttresses»

How thin can we go?



Cl^-
SO_4^{2-}

+

Model of degradation

Durability Assessment based Design

Liberato Ferrara, DICA, POLIMI

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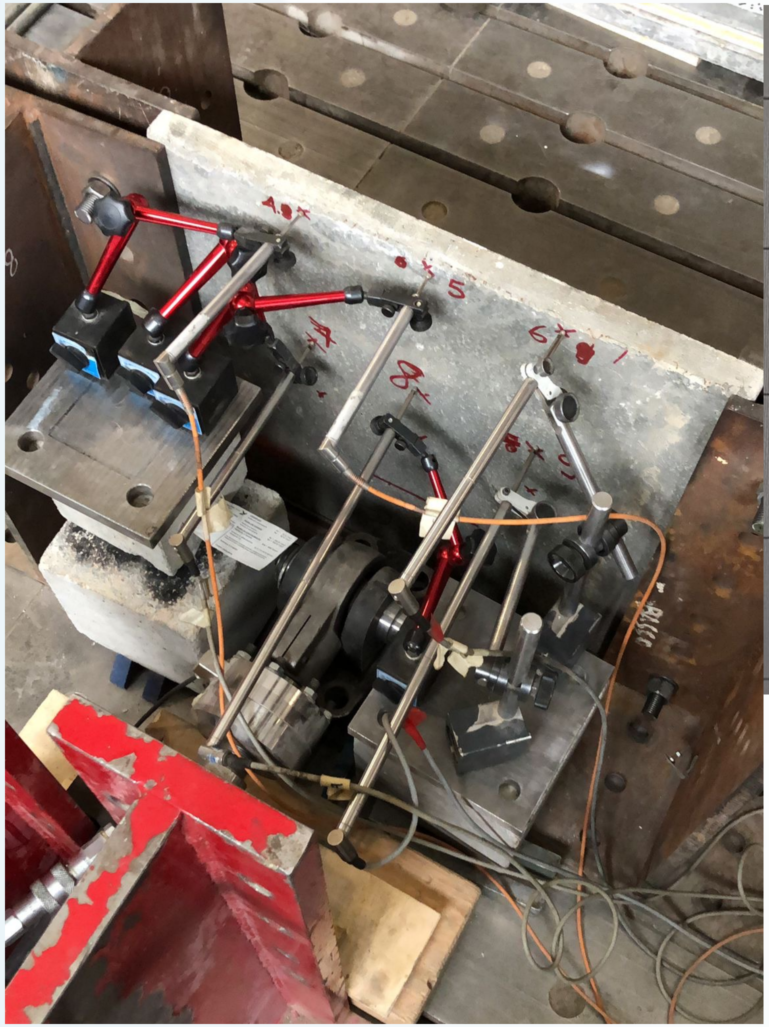
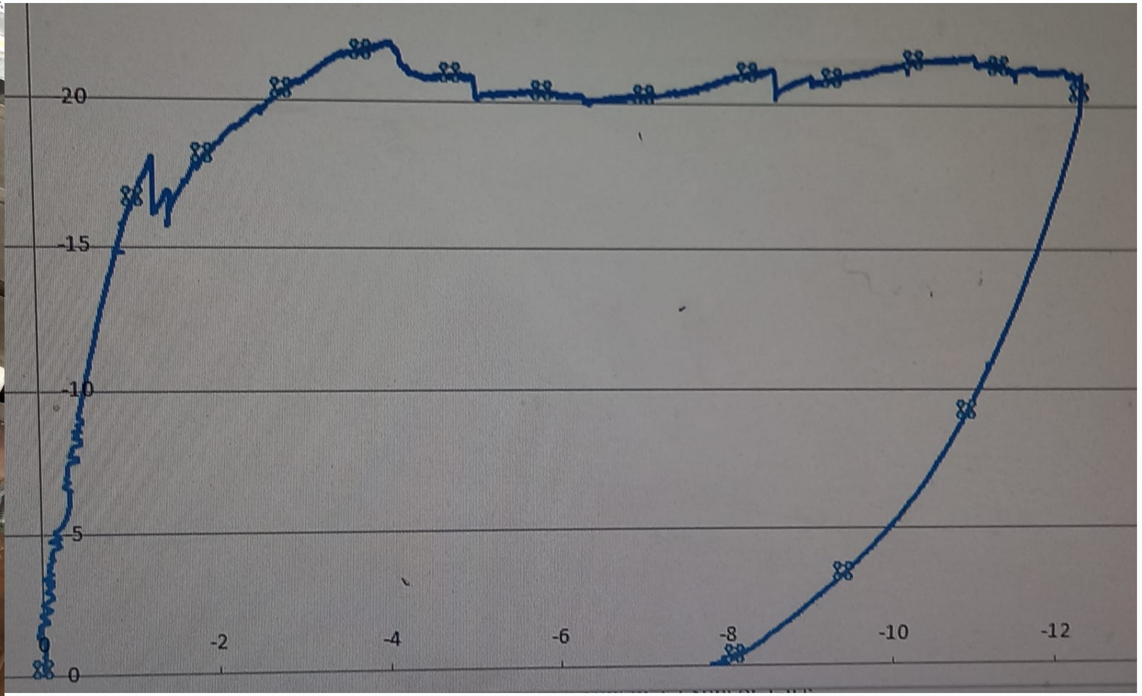
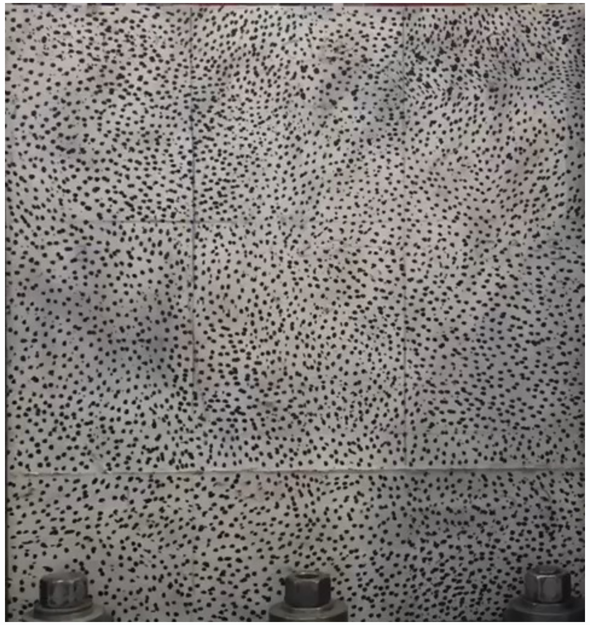
Yield line design validation







Al Obaidi et al., unpublished results

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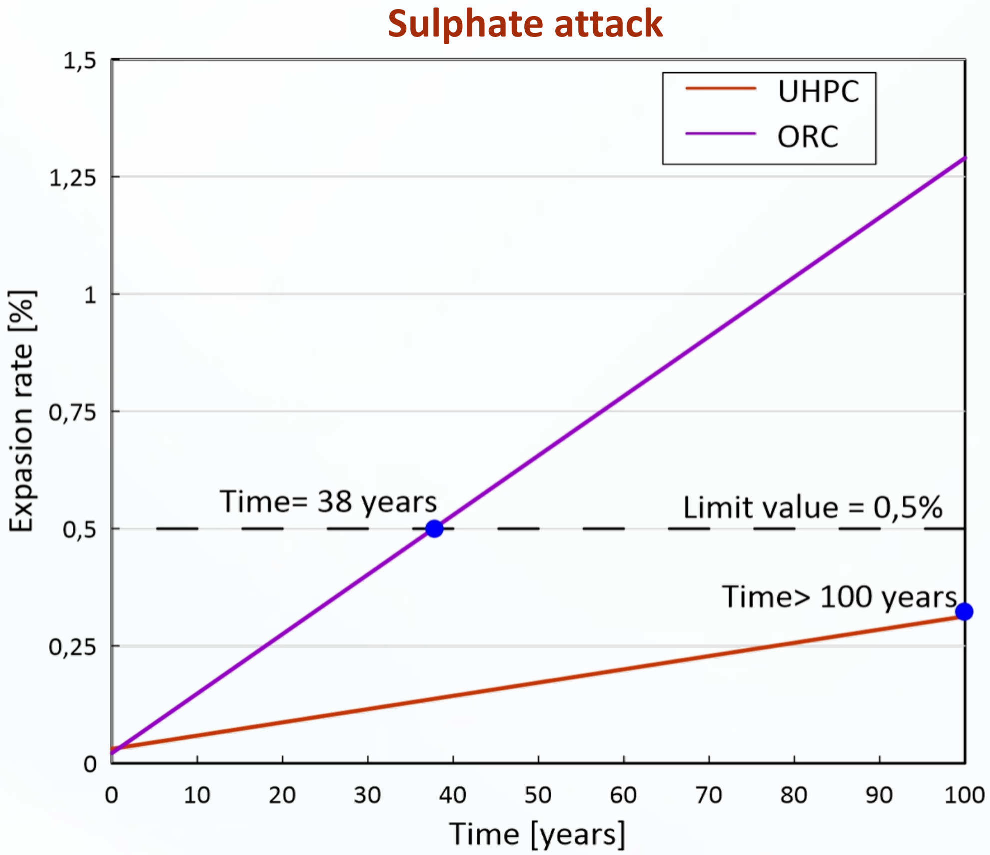
Sulphate Attack

Chemical composition cement

		ORC	UHDC
Cement	$\left[\frac{Kg}{m^3}\right]$	450	600
C_3S	[%]	63,6	63,6
C_2S	[%]	7,6	7,6
C_3A	[%]	7,6	7,6
C_4AF	[%]	8	8
$\frac{W}{C}$	[−]	0,45	0,18

$$EXP = 0.0293(W/C * T) + 0.000975(C3A) * T + 0.0216$$

$$EXP = 0{,}157\left(\frac{W}{C} * T\right) + 0{,}0305$$



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Chloride Attack

Model for Ordinary reinforced concrete/Hybrid FRC-UHPC

$$t_{crit} = \frac{x^2}{12D_{app}\left(1-\sqrt{\frac{(C_{crit}-C_i)}{C_s-C_i}}\right)}$$

Apparent chloride diffusion coefficient
Durability performance
(Environmental Resistance Classes)
in new EN-206 (uncracked concrete!)

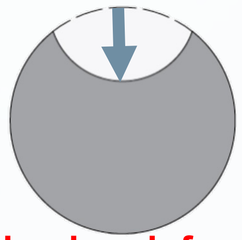
D_{app} = 1.0 x 10^{-10} m^2/s for ORC
Dapp = 5.0 x 10^{-13} m^2/s for UHPC

Time of initiation

II Fick's law

Time of propagation

Hemispherical Pitting



Reduction in reinforcement cross section area

SLS

SLU

Crack-opening verification

M_{Rd} verification

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Chloride Attack

Model for Ordinary Reinforced Concrete

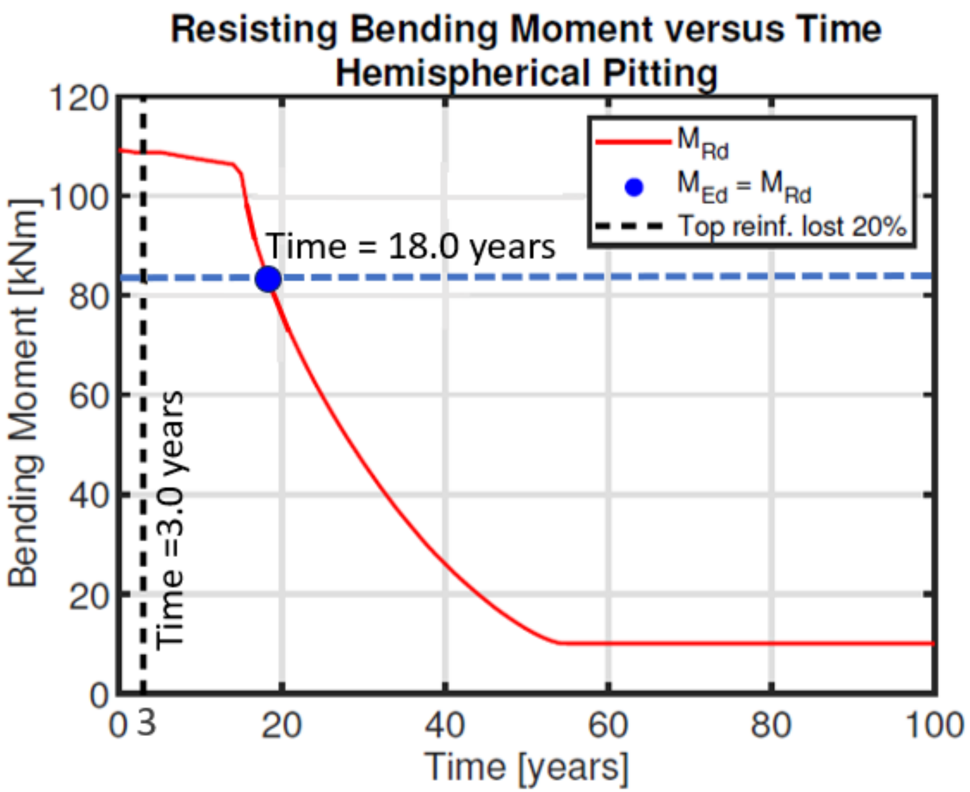
- Corrosion starts on the taut side of the walls
  Dapp = 10^{-10} m^2/s almost instantaneous

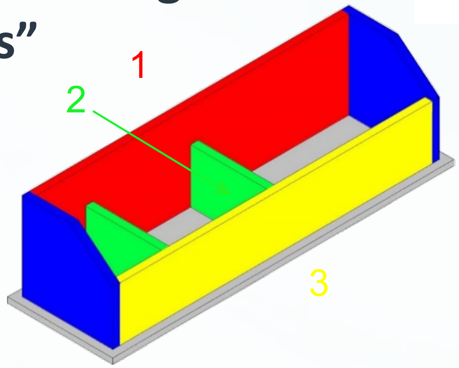
- Hemispherical pit corrosion more severe than uniform
  (carbonation induced corrosion)

- Maintenance carried out when a 20% reduction
  of the reinforcement cross section is reached
  → **Maintenance every three years (!!!)**
  → **service life much shorter than what through "deemed to satisfy prescriptions"**

di Summa et al., Structural Concrete 2023

Bending moment resistance over time





	$M_{Rd,0}/M_{Ed}$	Calculated service life
Wall 1	1.04	18 years
Walls 2	1.03	25 years
Wall 3	1.09	21 years
Walls 4	1.05	23 years

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State of fact

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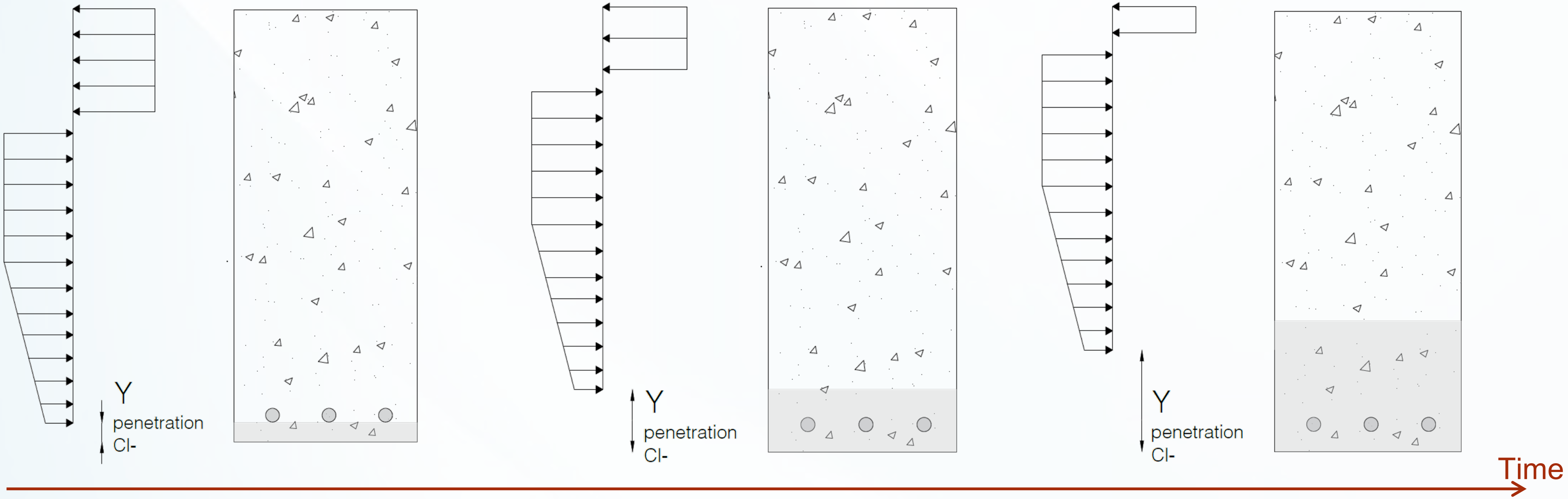
Layer removal model

Old degradation model for the expected behaviour of FRC/UHPC



Al-Obaidi et al., Infrastructures 2020
Al-Obaidi et al., Sustainability 2021

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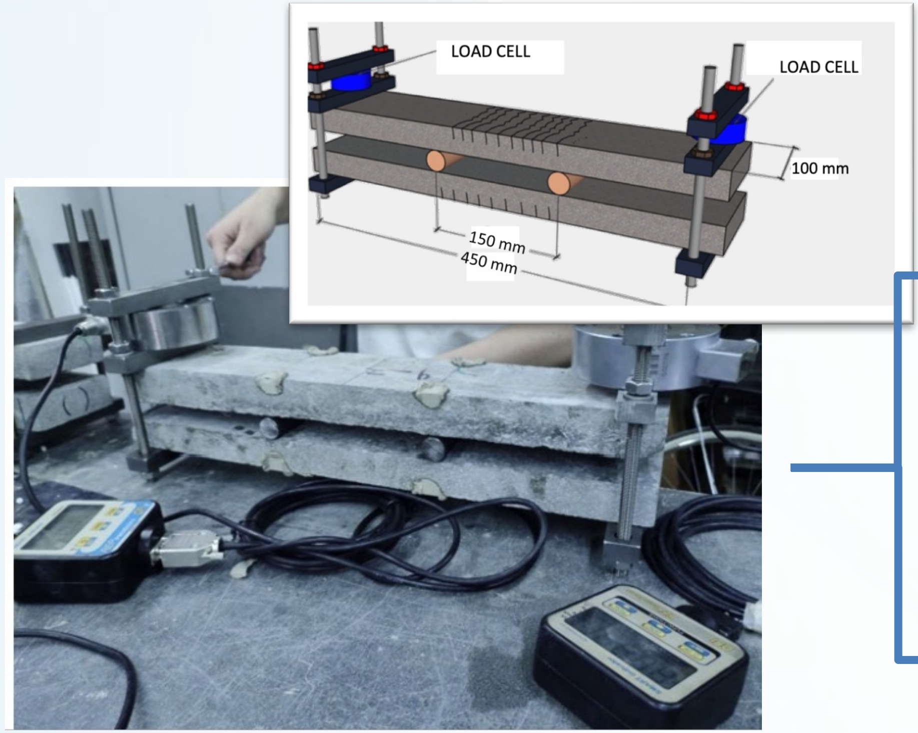
Experimental campaign

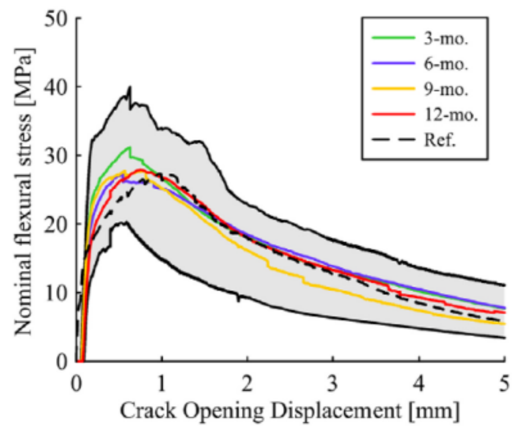
Mechanical tests on cracked specimens exposed under sustained load (targeted to a cracked serviceability limit state) to geothermal water (XA) and saline solution (XS) up to 12 months

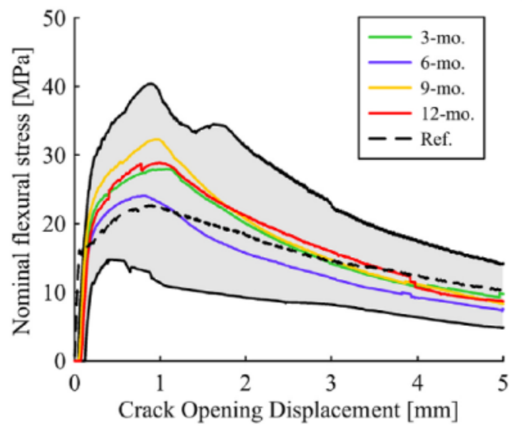


1 → 12 month XA/XS exposure under sustained flexural load

Four-point bending test

Direct tensile test





Davolio et al., CCC 2023

at the surface!

Inside the crack!

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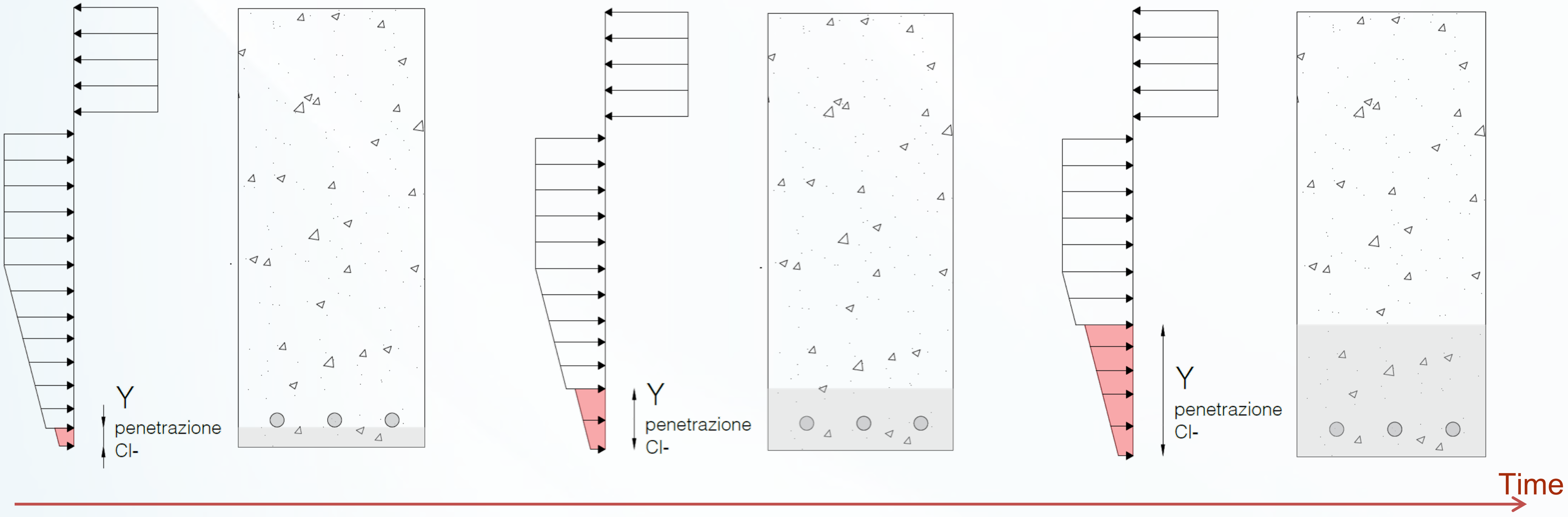
Evolutionary constitutive law model

New degradation model based on experimentally identified behaviour of FRC/UHPC



Soave et al., FRC workshop 2023

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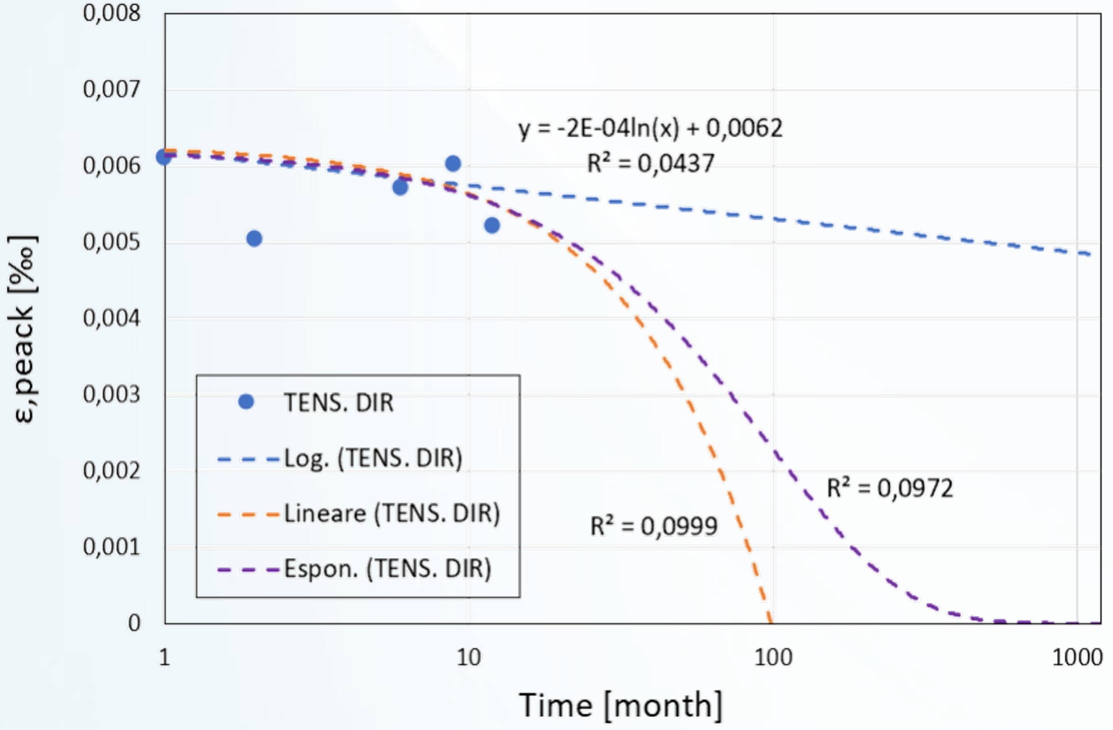
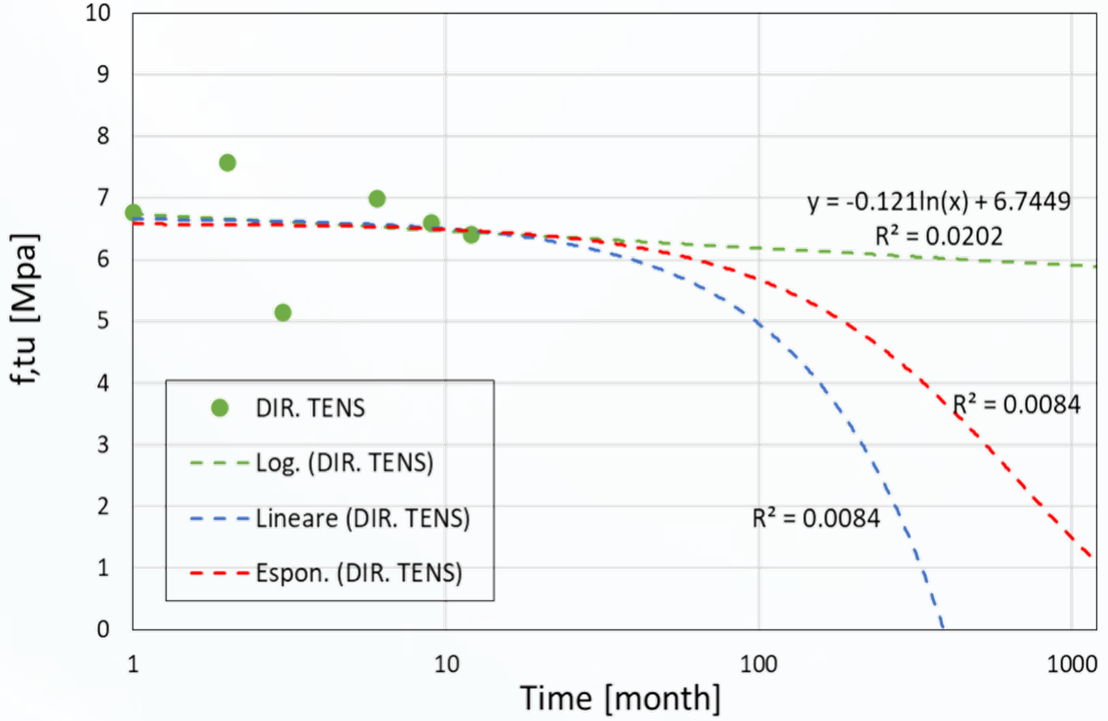
Evolutionary constitutive law model

Regressions supported by multiphysics modelling

Exposure (XA) – Peak strain



Exposure (XA) – Ultimate tensile strength



Soave et al., FRC workshop 2023

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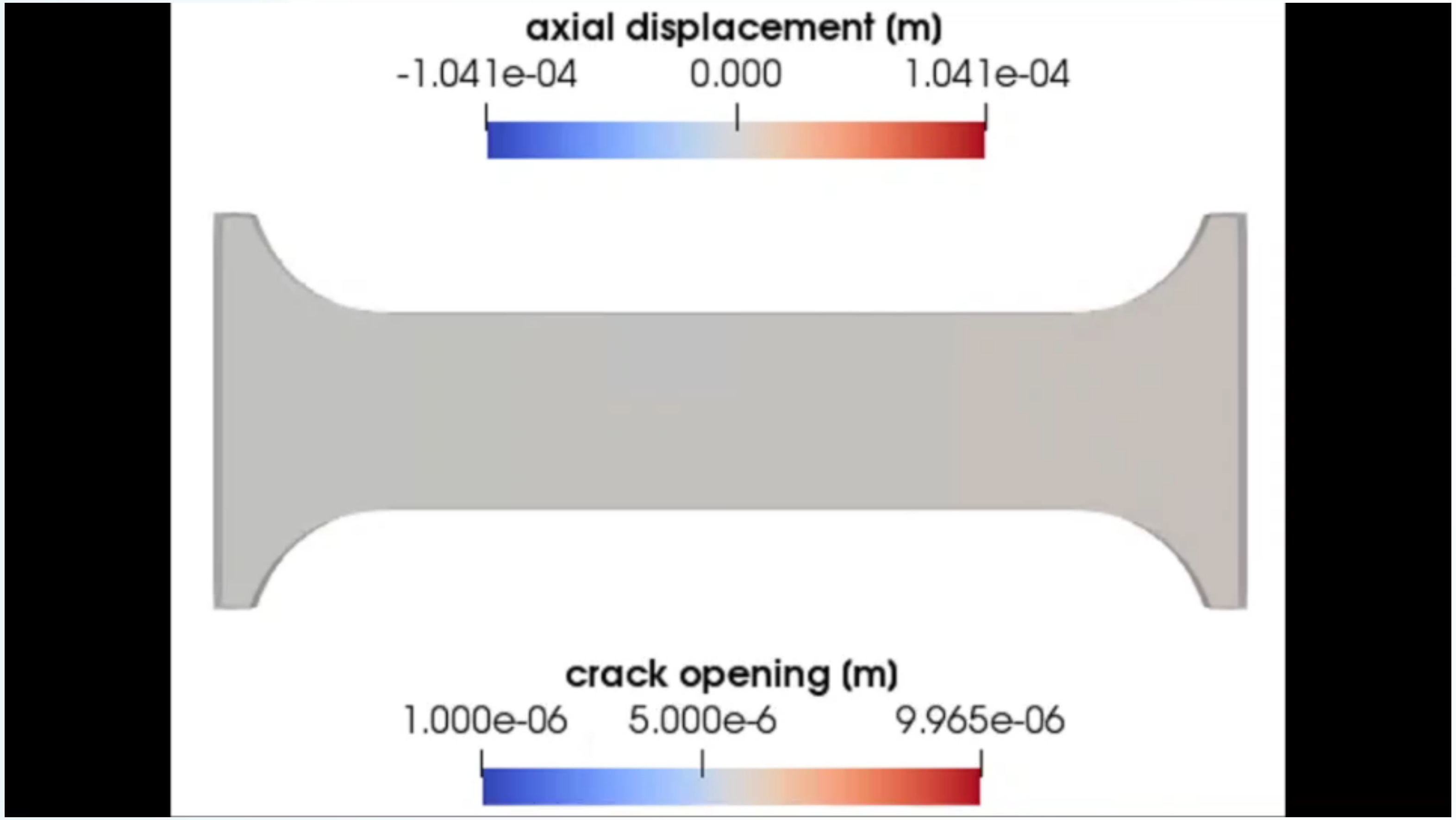

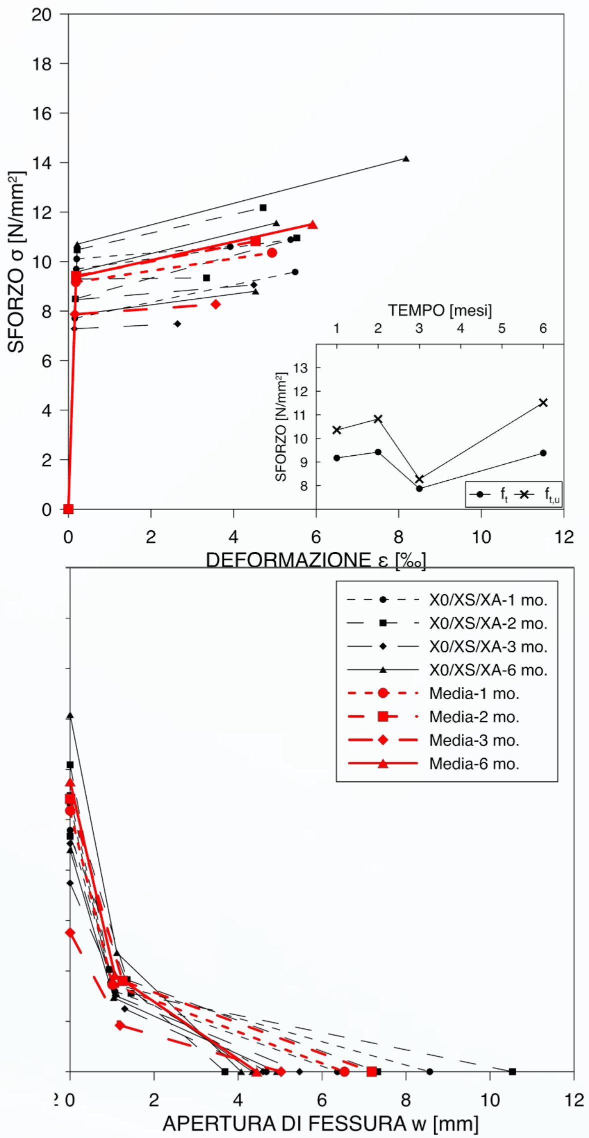

Cibelli et al., EFM 2022
Cibelli et al., ASCE JEM 2023

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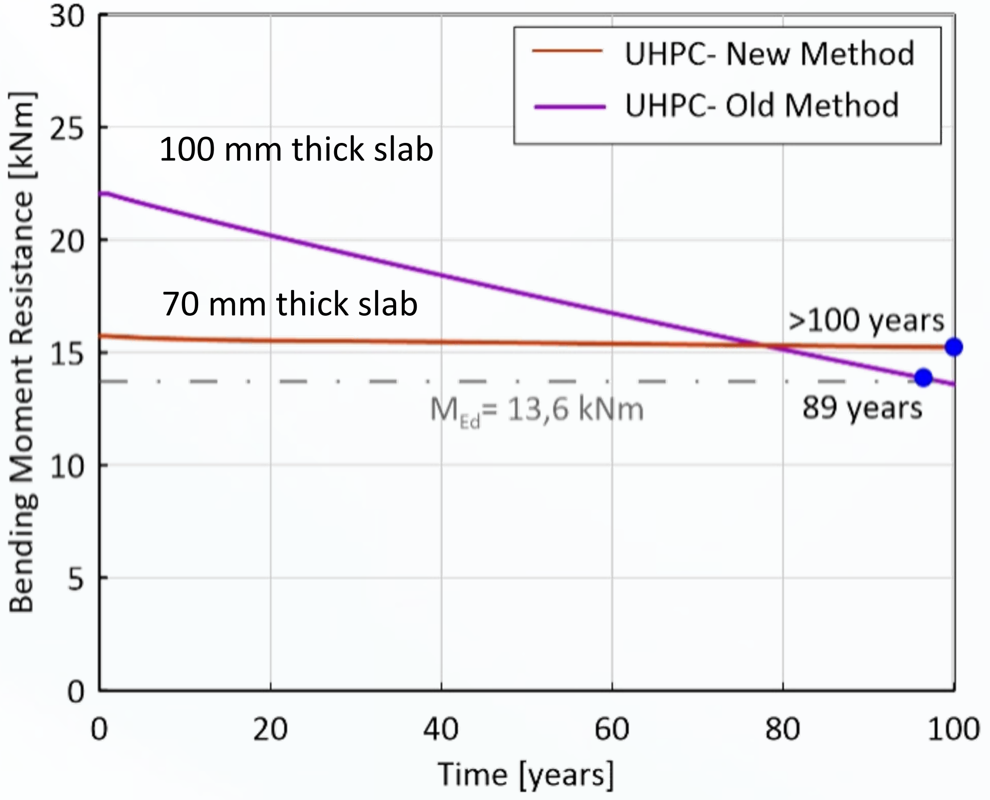
Evolutionary constitutive law model

- “Pure” structural design: 70 mm thin UPHC slabs (same safety factors as for ORC design)

- Layer removal model →
  To guarantee safety over time for a service life > 50 years it would be necessary to thicken the section
  70 mm → 100 mm

- Evolutionary constitutive law model
  70 mm thin cross section for a service life > 100 years

Bending moment resistance in time



Soave et al., FRC workshop 2023

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How realistic it is?

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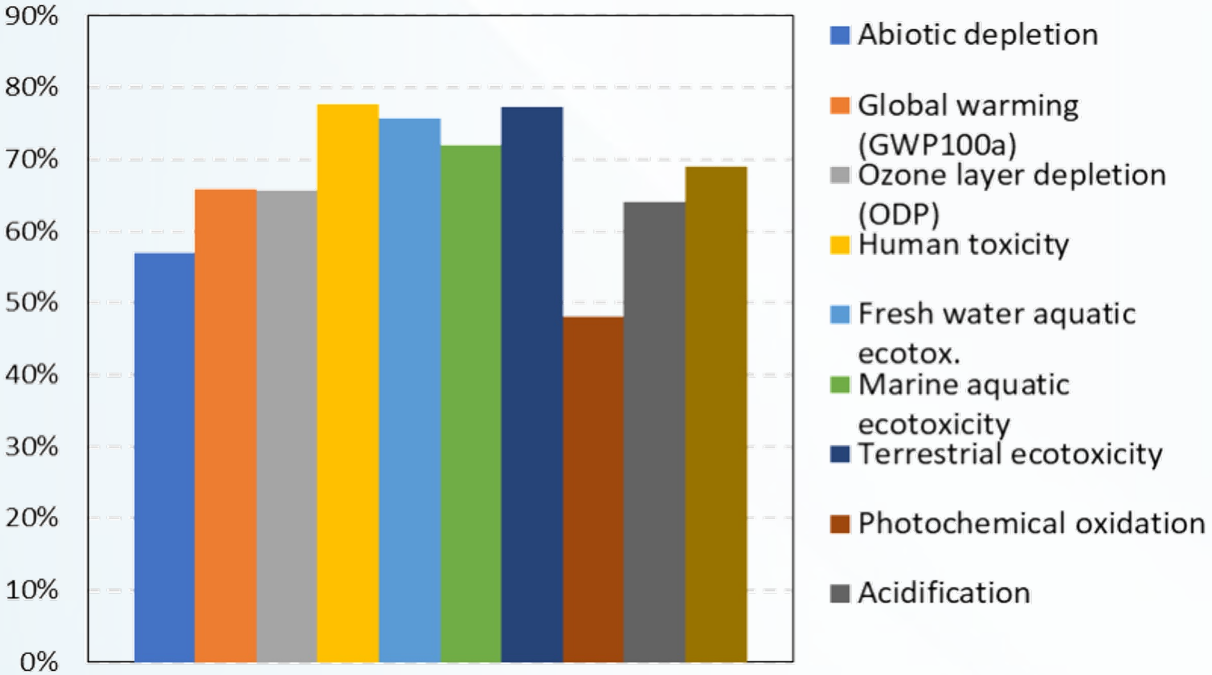
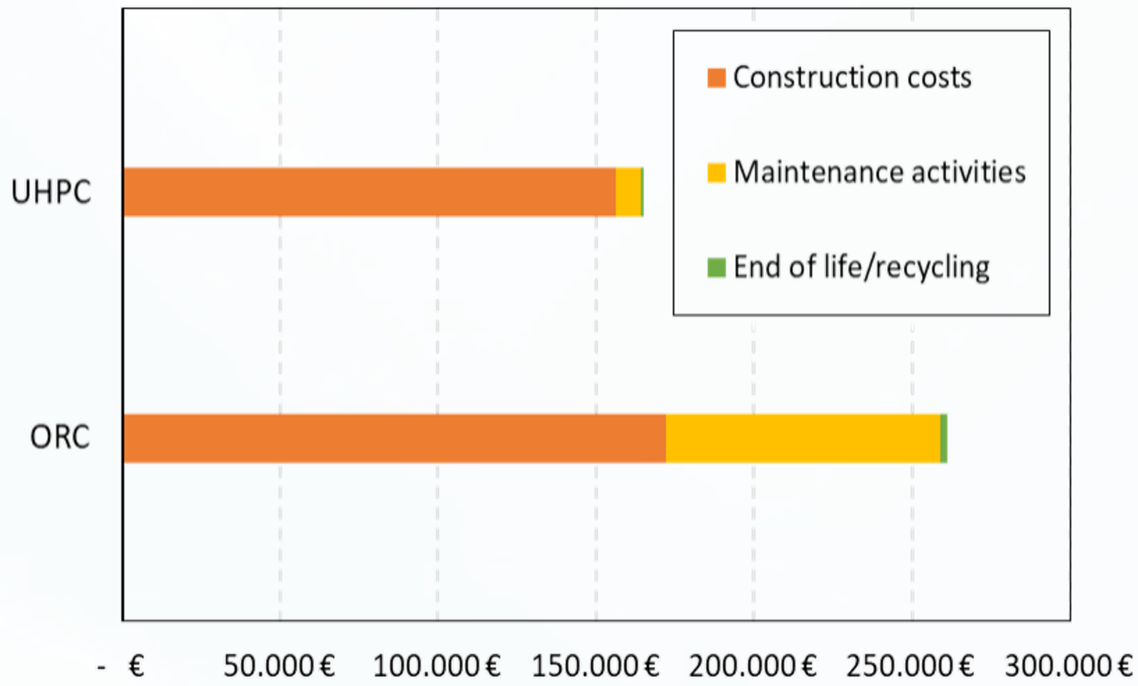
LCA/LCC

Comparison between **UHPC** solution with **ORC** solution





The **OCR basin's poor durability** with a **consequent increase in the frequency of maintenance** interventions requires additional raw materials to restore the structure's functionality, **contributing to an increase in the impact.**

di Summa et al., Structural Concrete, 2023

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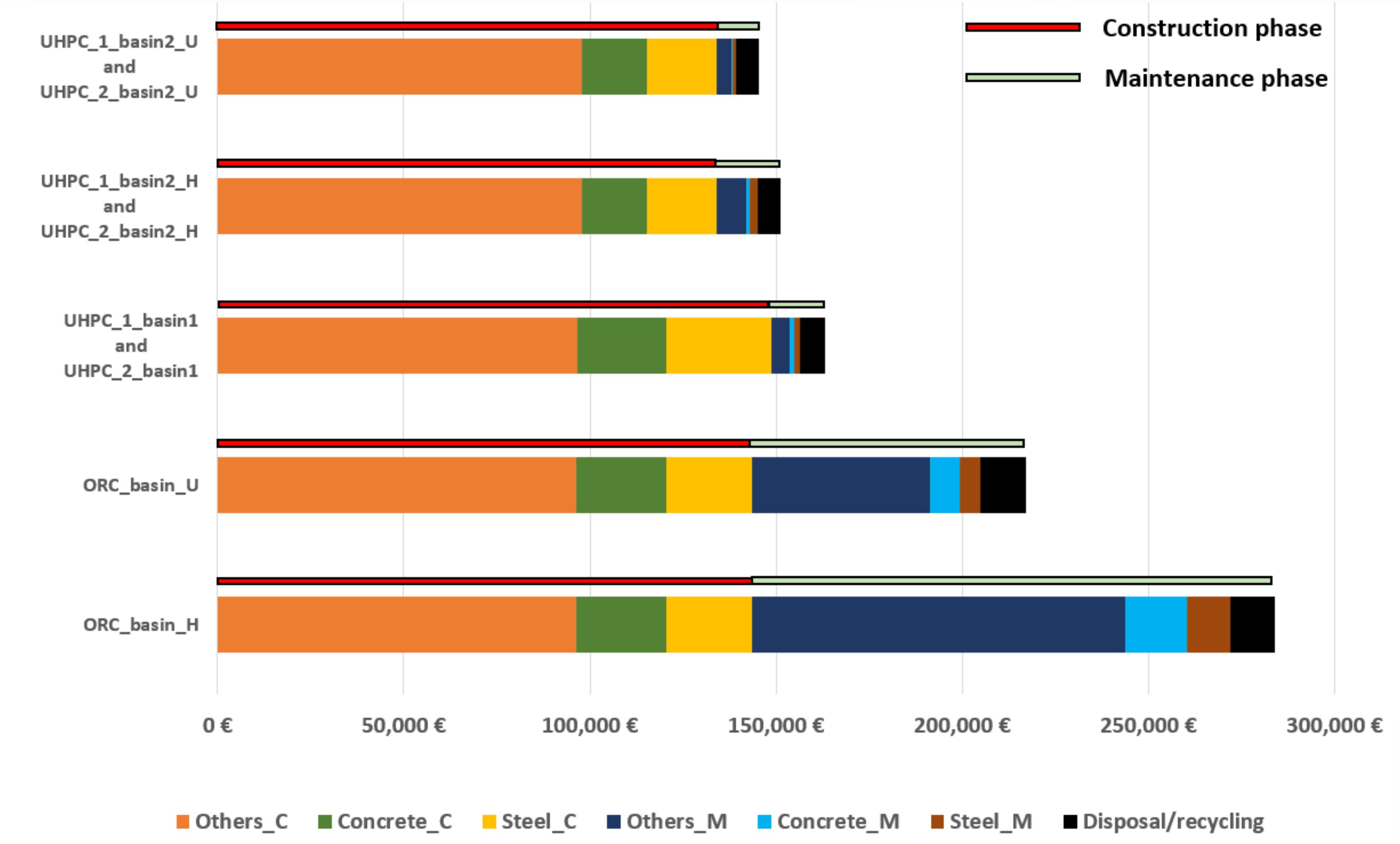

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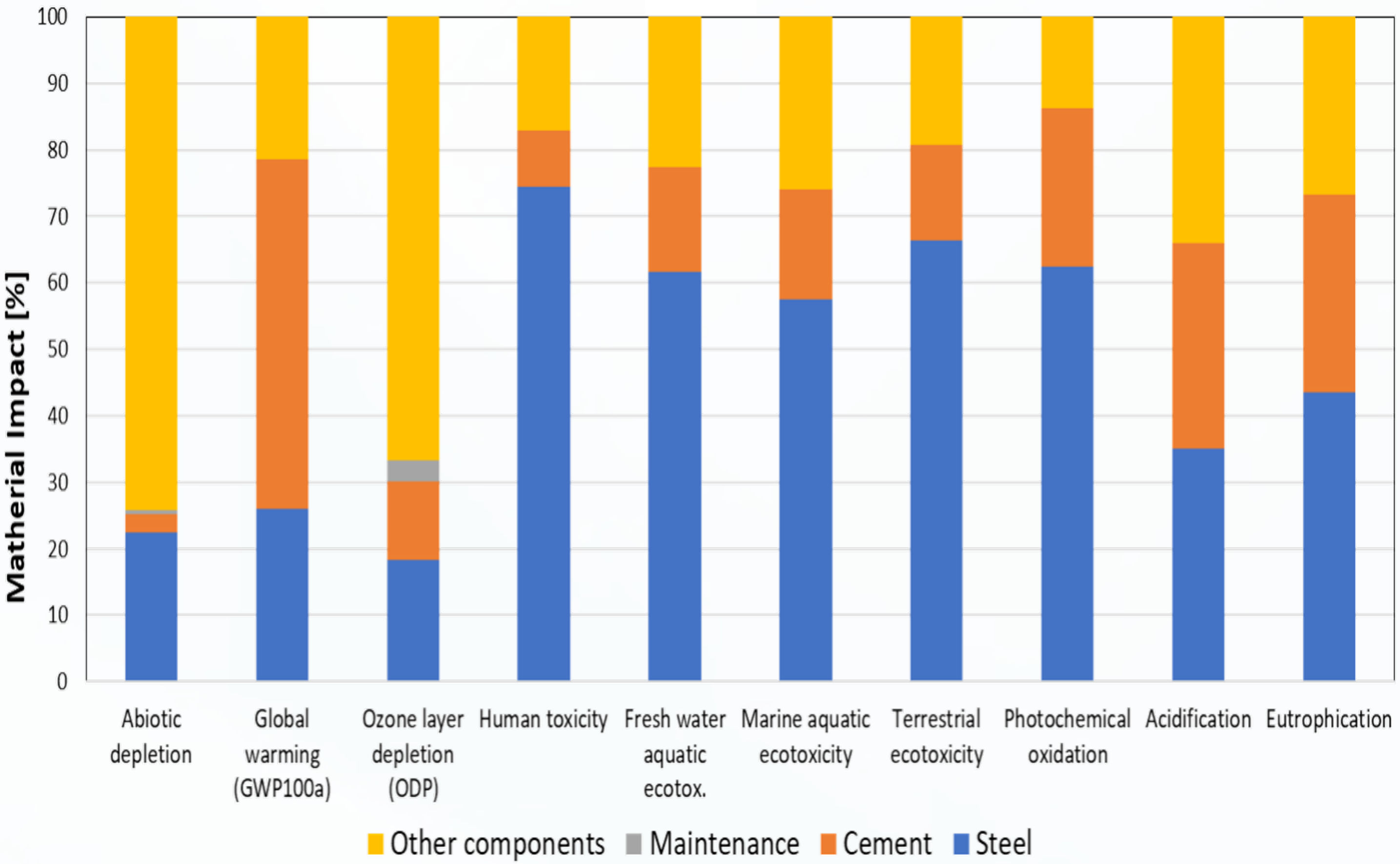
LCA

Impact of every material for **UHPC solution**

- **Cement** is the most important parameter for the **GWP** indicator,
- **Steel** either from the ordinary reinforcement or from fibres, **plays the most significant role for the largest part of other indicators**;



di Summa et al., Structural Concrete, 2023

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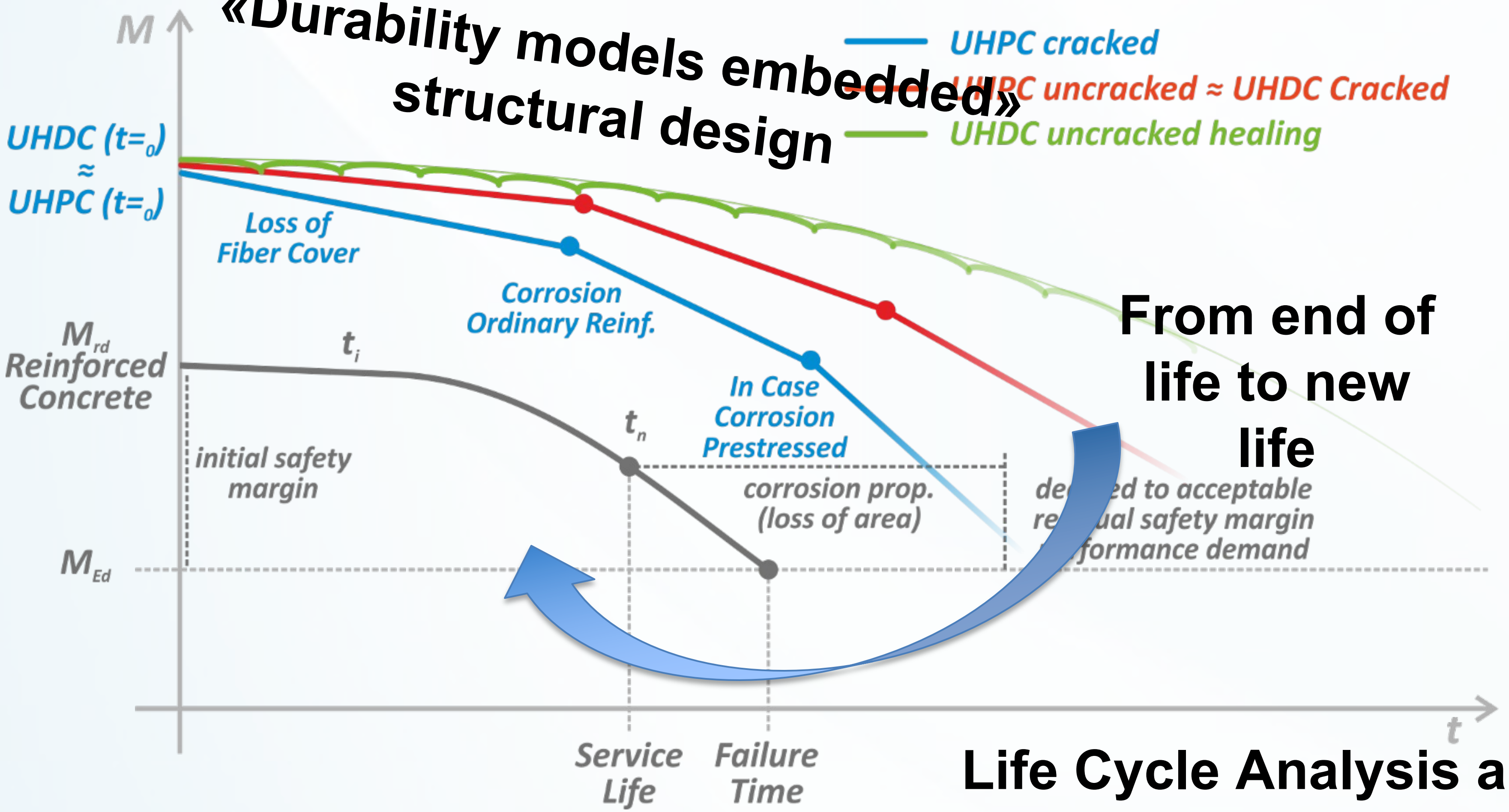
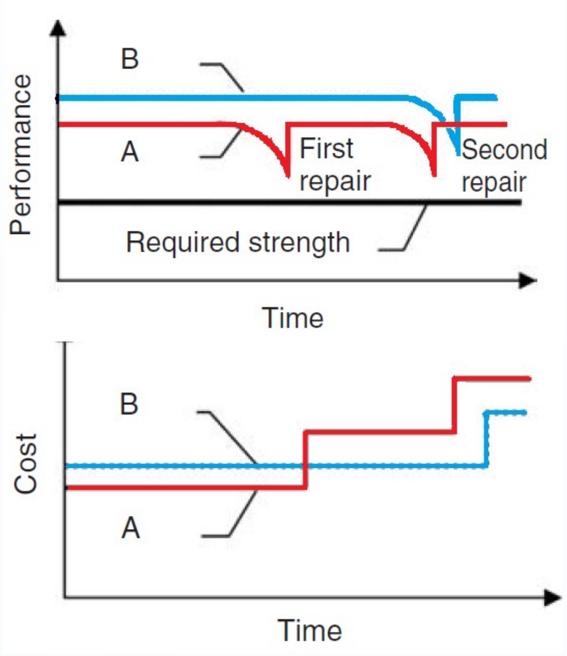
Towards a novel holistic design approach for reinforced concrete structures

«Classical» structural design

«Durability models embedded structural design»



From end of life to new life



Life Cycle Analysis and Life Cycle Cost

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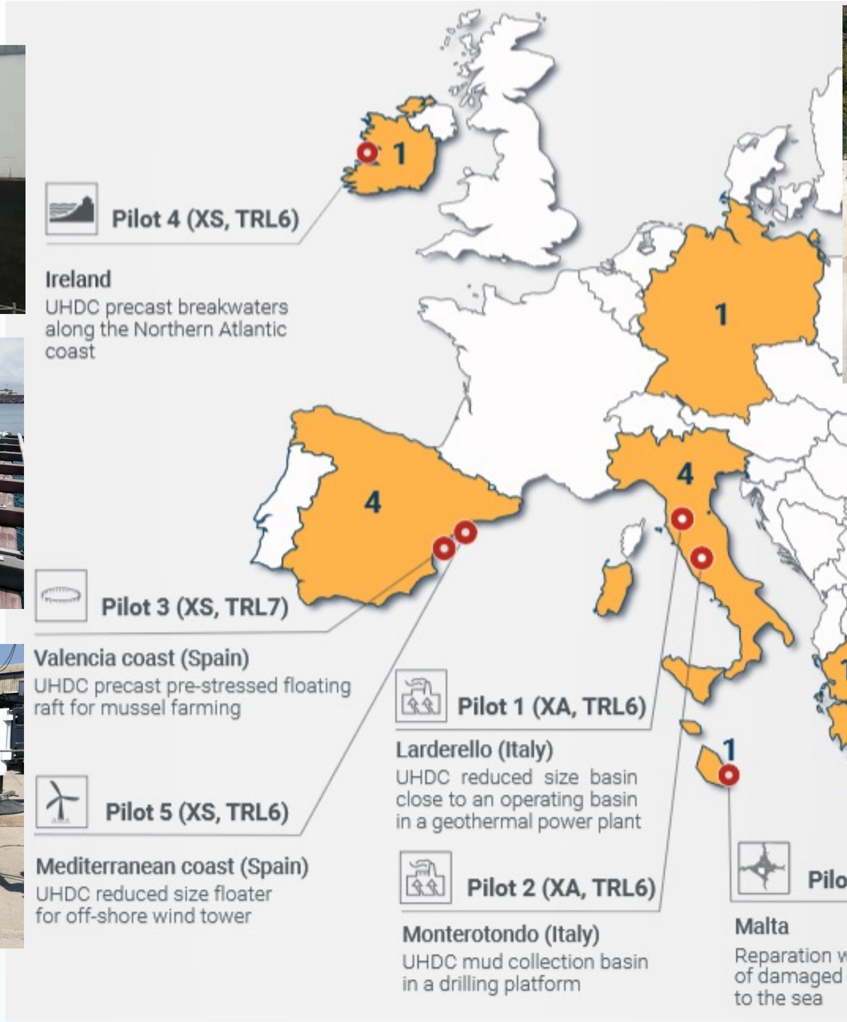

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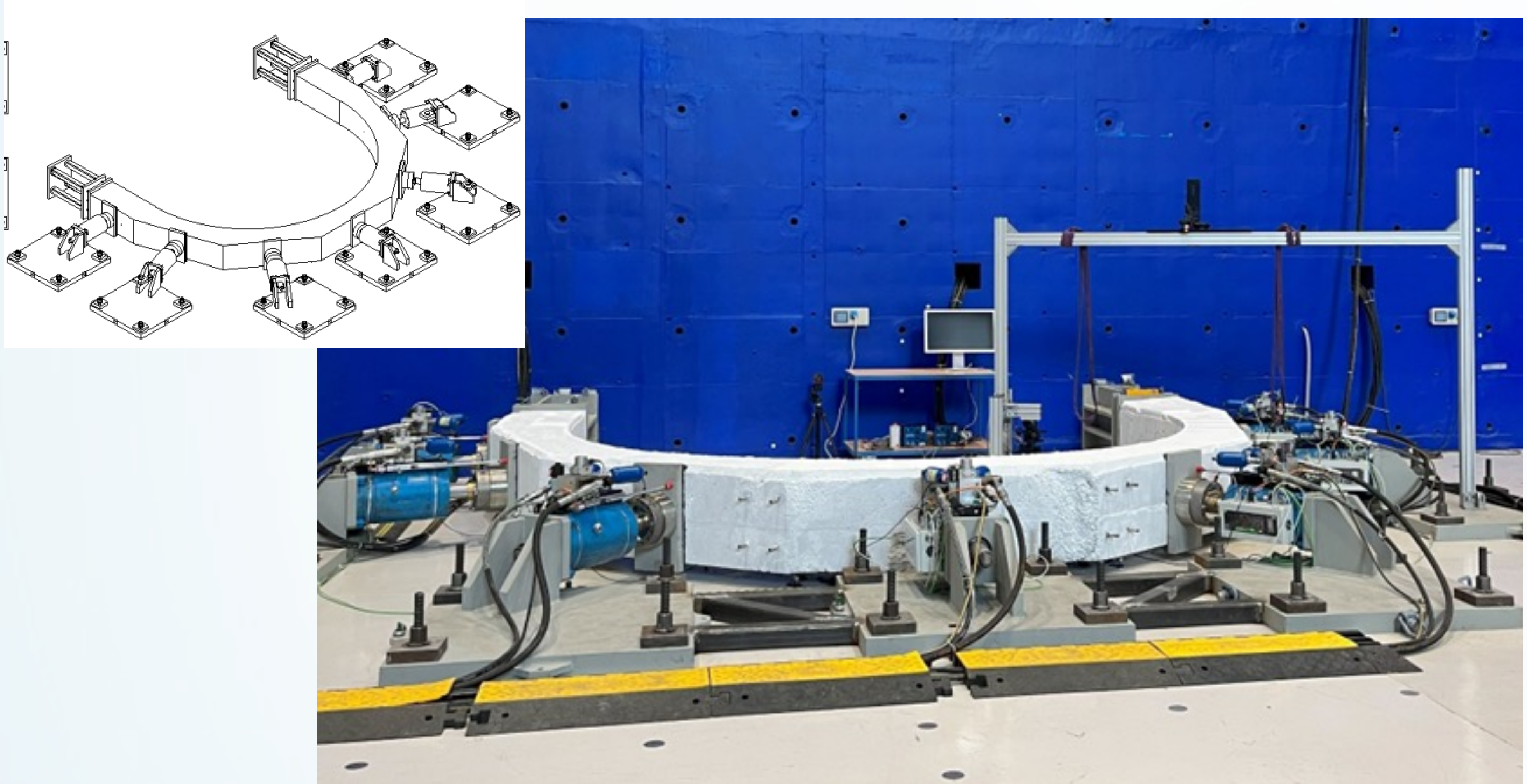

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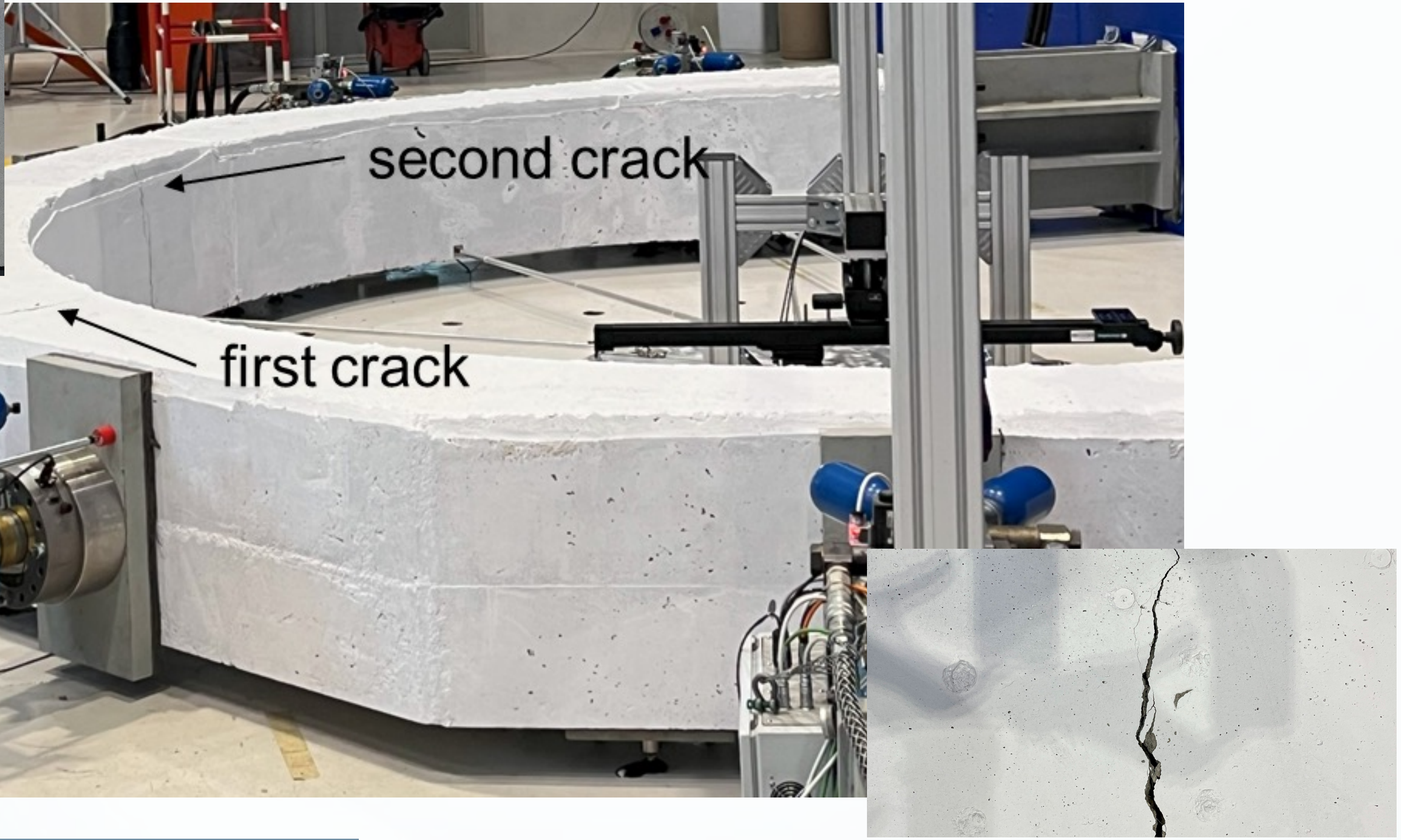

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The Large Scale Digital Concrete Extrusion Project

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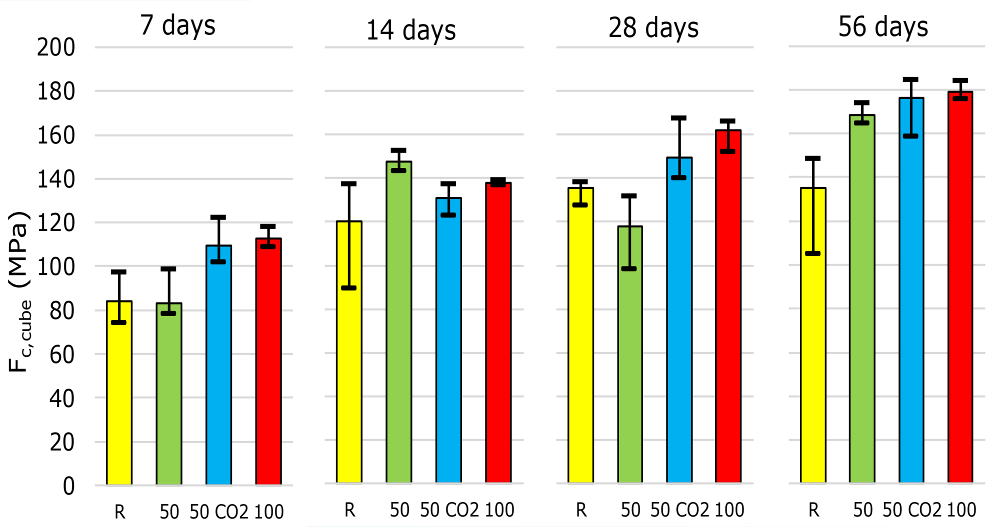
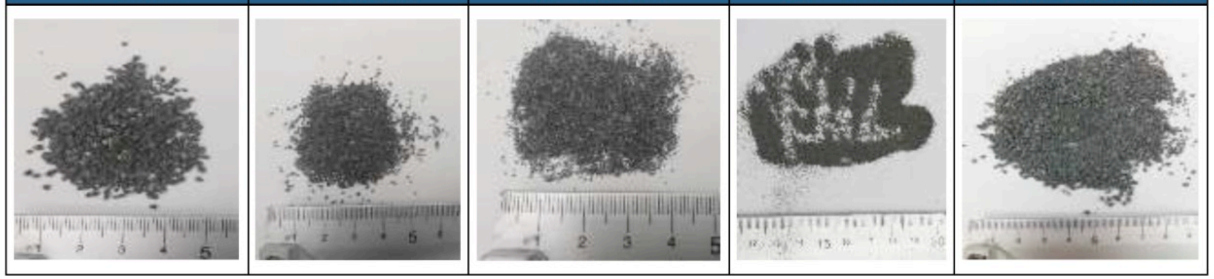
Towards a novel holistic design approach for reinforced concrete structures: upcyling

Constituents	Dosage (kg/m³)		
	Reference	50% R-UHPC R-UHPC-C	100% R-UHPC
Cement 52.5 R	700	700	700
Silica Fume	400	400	400
Superplasticizer (ACE 442)	64	64	64
Water	231	231	231
Natural aggregate 117/F	286	143	0
Natural aggregate 103	409	205	0
Natural aggregate 113	122	61	0
Recycled aggregate	0	409	817
Steel fibres (l_f = 22 mm, d_f = 0.2 mm)	160	160	160
Crystalline admixture (Penetron Admix ®)	5,6	5,6	5,6



1 - 2 mm	1 - 0.6 mm	0.6 - 0.3 mm	0.3 – 0mm	Blended aggregate



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Borg et al., FBE, 2022

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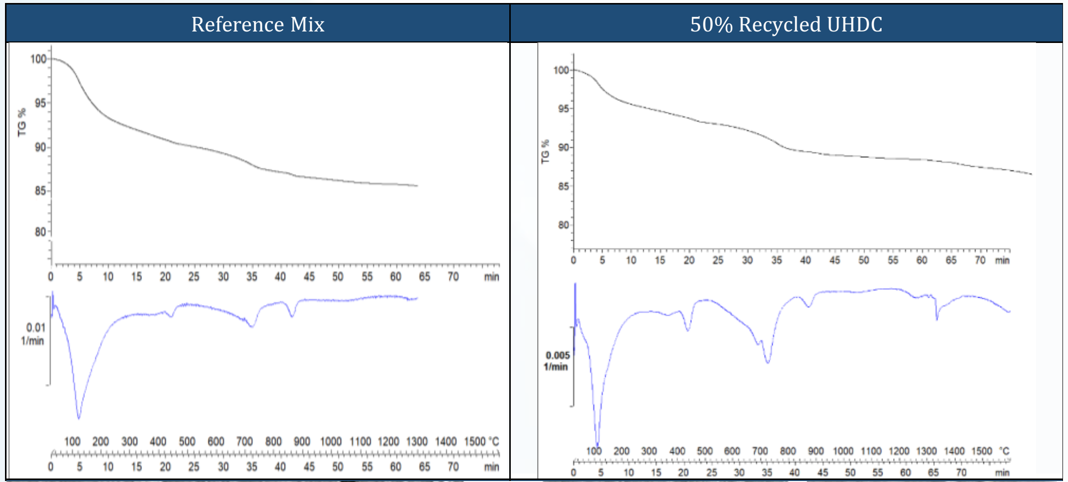

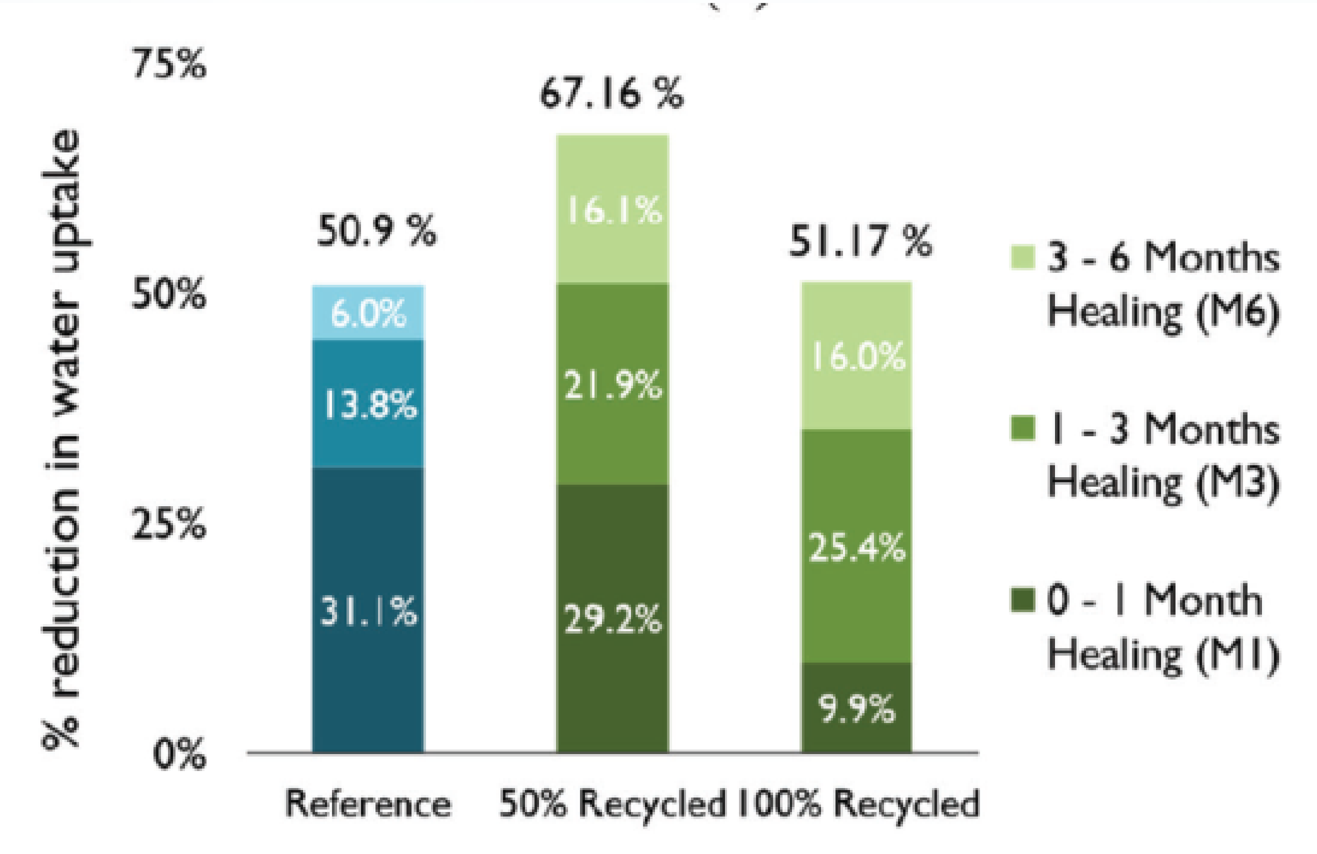

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Borg et al., FBE, 2022
Kannikachalan et al., ACI J, 2023

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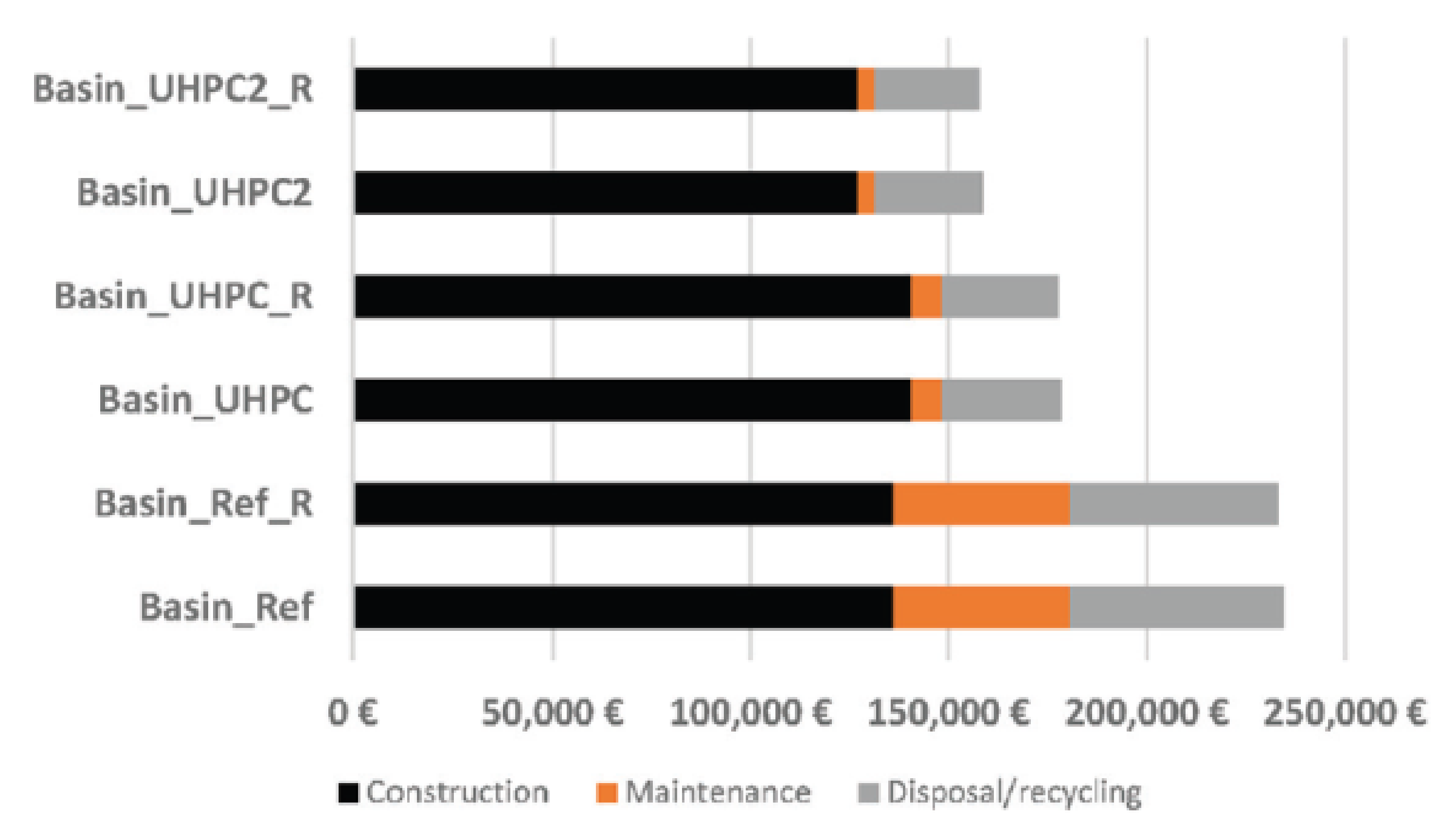

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Kannikachalan et al., ACI J, 2023

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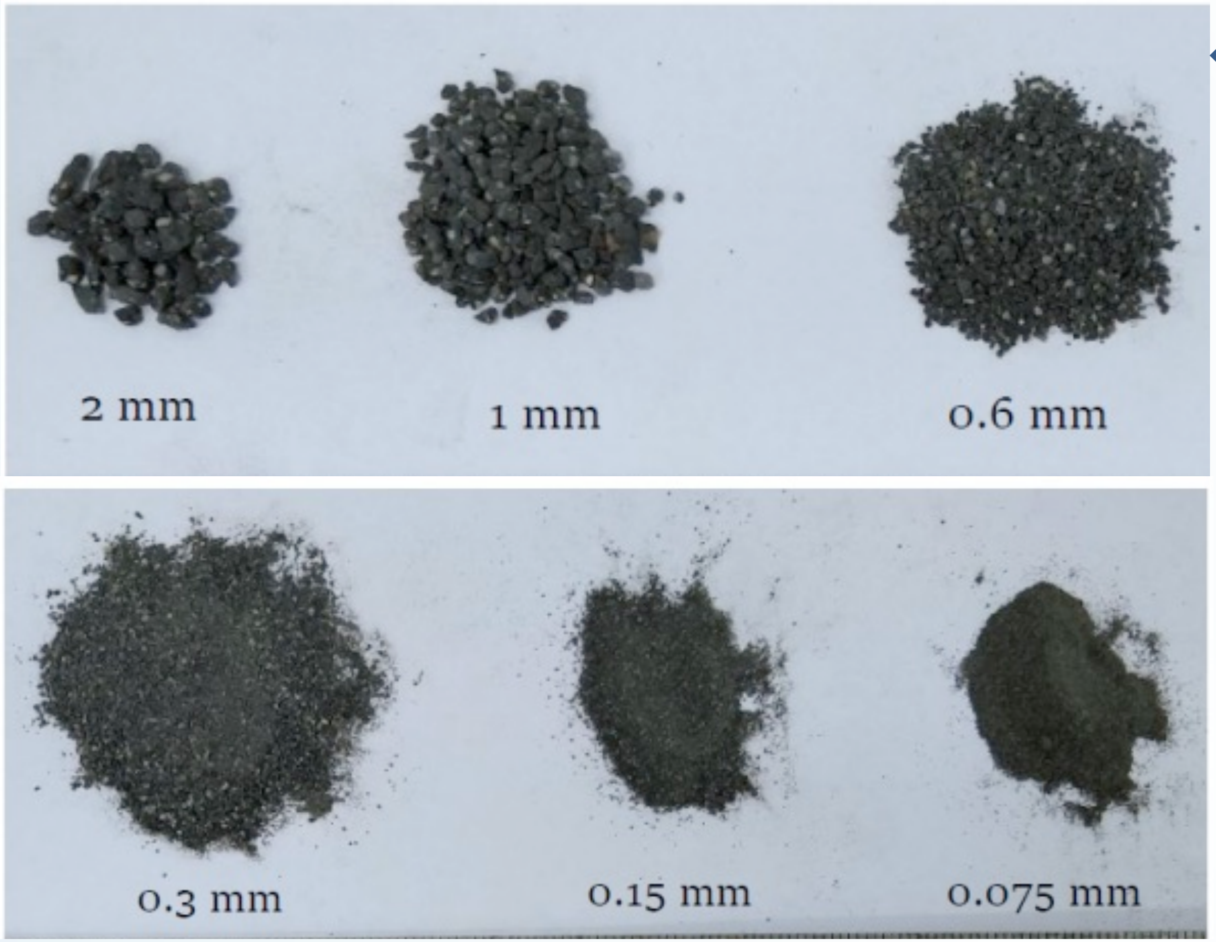
Towards a novel holistic design approach for r/c structures: upcyling to reduce cement demand?



Recycled UHPC as aggregate and cement (no size sorting)

	Ref	Mix 1 – S.F.	Mix 2 – U.F.
Constituent	kg/m³	kg/m³	kg/m³
CEM I 52.5R	700	490	490
Silica fume	400	400	400
SP Glenium ACE 442	64	64	64
Water	231	231	231
Sand 117/F	286	=	=
Sand 103	409	=	=
Sand 113	122	=	=
Steel fibers 20/0.22	160	160	160
Crystalline admixture	5.6	5.6	5.6
Recycled aggregates	=	817	1027
Recycles fines	=	210	=
Recycled fibers	=	=	=

Recycled «coarse» UHPC as aggregates and recycled uhpc fines as cement

Borg et al., fib Symposium, 2023

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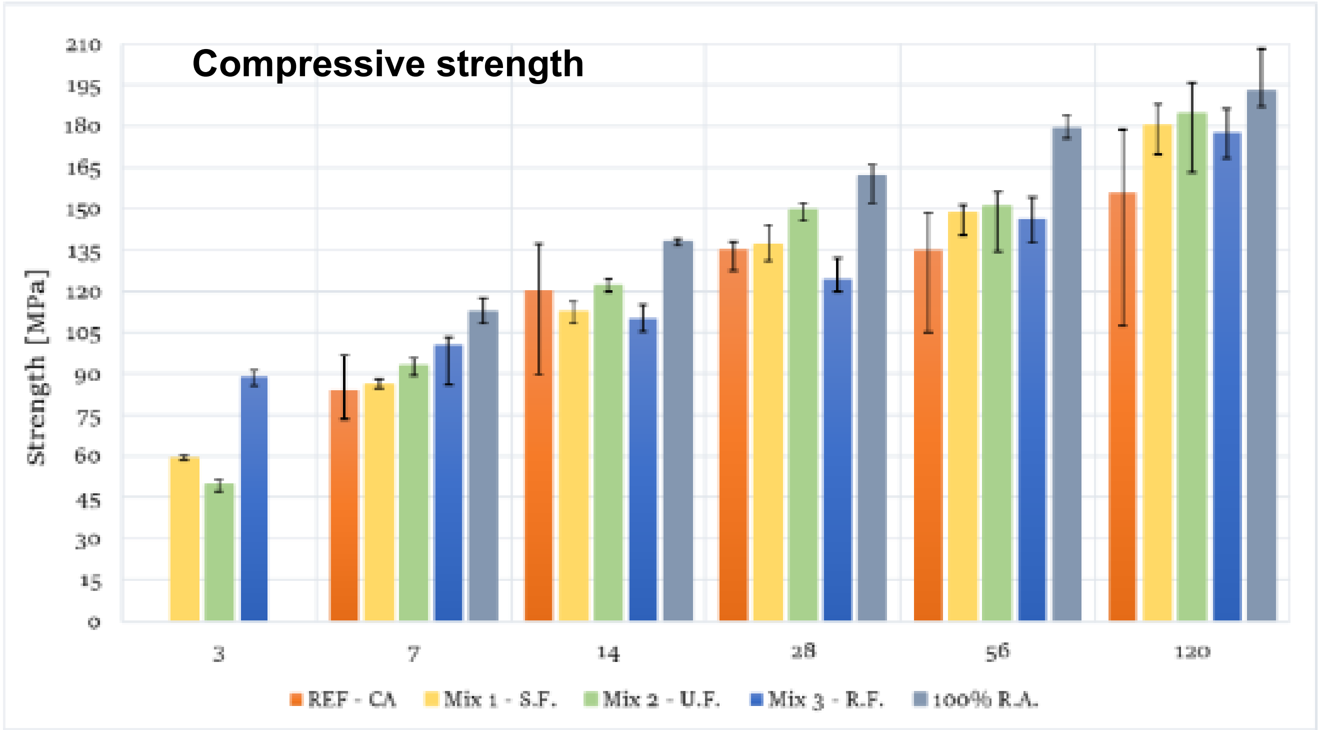

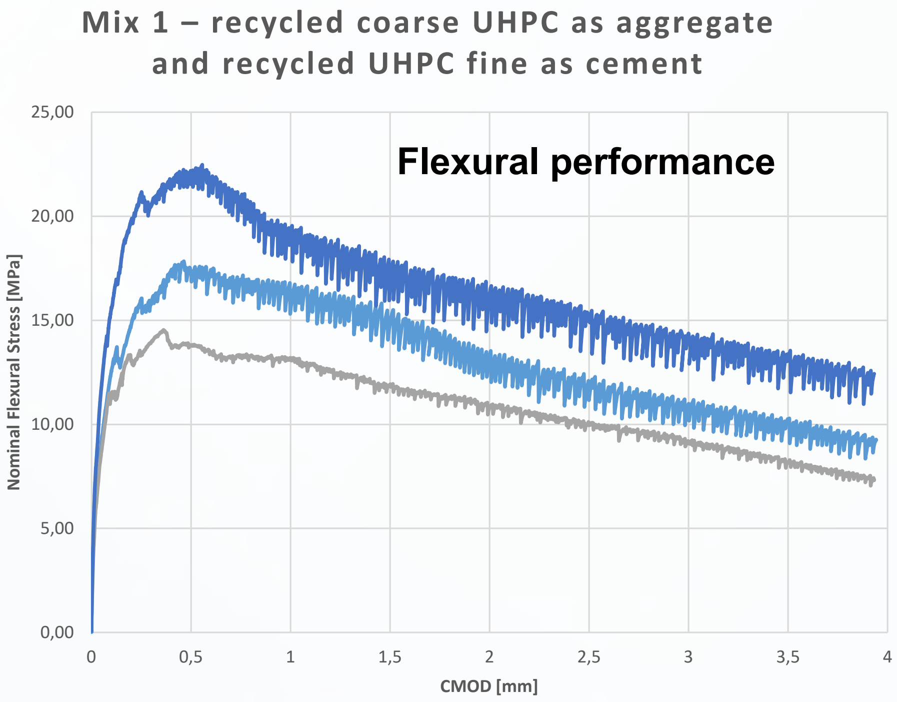

- the **presence of unhydrated binder cement** attached to recycled aggregate particles makes **mechanical and durability performance of recycled-aggregate UHPC comparable** if not higher than that of **parent UHPC**, including a **"latent" activatable autogenous self-healing capacity and** may also reliably imply the possibility of reducing the "fresh" cement in UHPC mix-designs with increased sustainability signature (size adjustment of recycled UHPC grains and increased grinding needed);

Borg et al., fib Symposium, 2023

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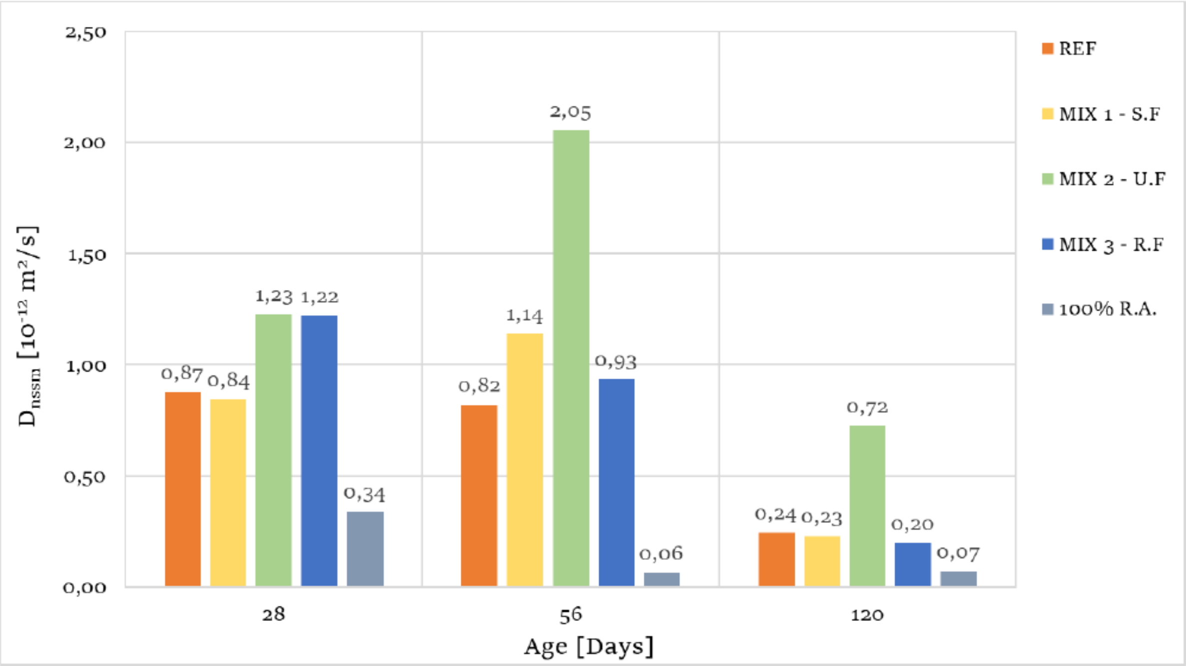
Towards a novel holistic design approach for r/c structures: upcyling to reduce cement demand?

Apparent chloride diffusion coefficient



- Shall we keep “testing at 28 days” as customary?
- On average costs and impacts of recycling UHPC (higher energy) are comparable to those of “disposing” it (database must be anyway populated)

Borg et al., fib Symposium, 2023

The project MUSA, Multilayered Urban Sustainability Action has been funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strenghtening of research structures and creation of R&D “innovation ecosystems”, set up of “territorial leaders in R&D” ,5

Conclusions

- Discard the "… per cubic meter of material" evaluation which undervalues innovative materials, neglecting long-term benefits: we design and build structures not cubes of 1 m side!
- The proposed Durability Assessment-based Design (DAD) approach comprehensively **assesses the structural design and service live of UHPC structures under extremely aggressive scenarios** combining constitutive laws identified from "real structural service scenarios" tests and projected to long-time service life through multi-physics modelling and life cycle sustainability analysis
- **DAD approach** capitalizes the benefits advanced cementitious materials' uniqueness, like **UHPC**, **enabling maintenance-free service life**, providing a paradigm shift from traditional prescriptive "deemed to satisfy" methods.
- The difference is clear at the construction stage, thanks to comparable construction costs due to exceptional savings in material volumes and most of all in a life cycle perspective, where **maintenance strongly impacts environmental and economic factors**, affecting total costs and use of natural resources and raw materials and hence overall environmental impacts.
- **Exploit the higher recyclability potential of UHPC**, also to reduce the demand of "fresh cement" in UHPC mixes

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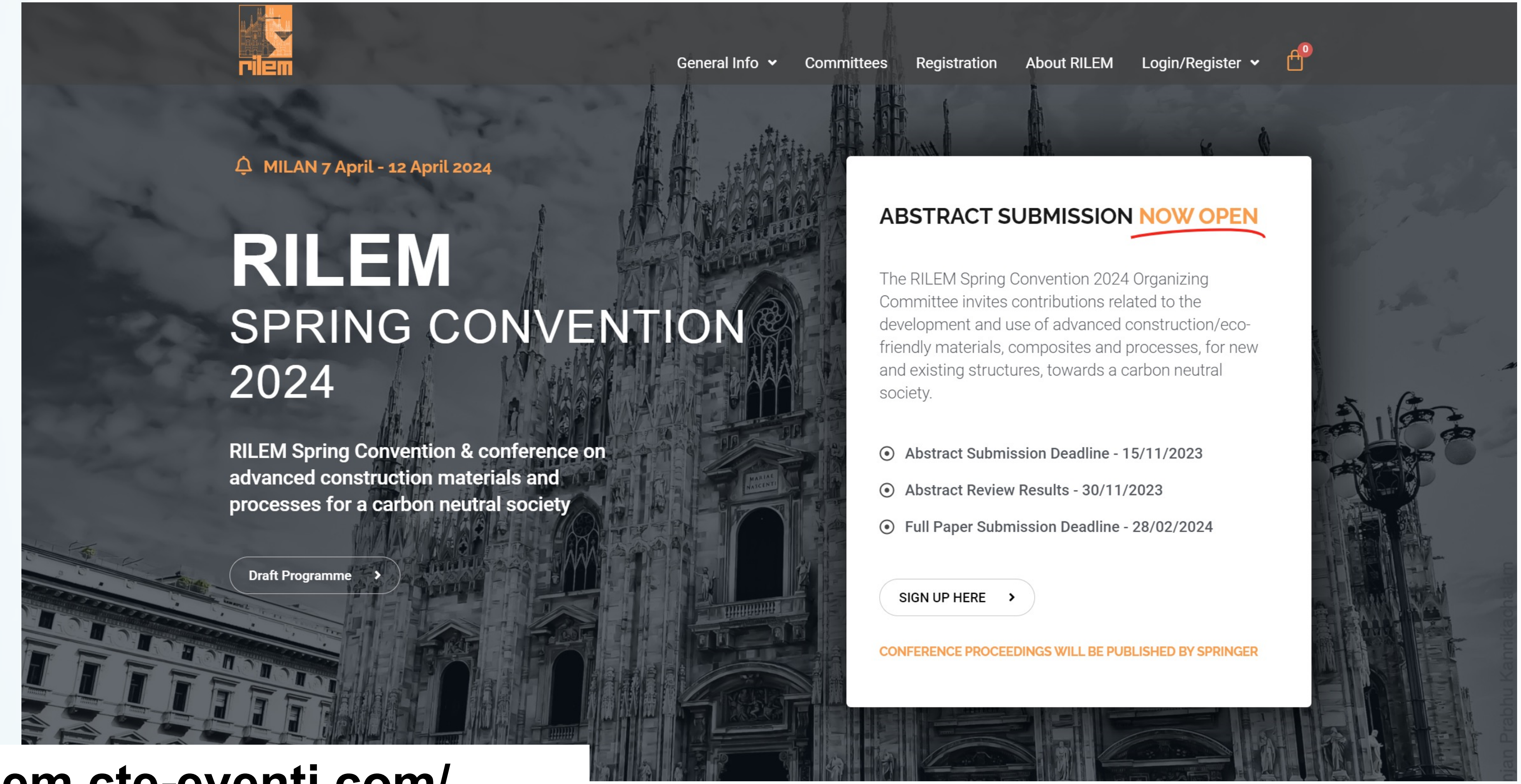
RILEM spring convention and conference - Milan, April 10-12 2024
Advanced construction materials and processes for a carbon neutral society



https://rilem.cte-eventi.com/

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Thank you for your attention

Liberato Ferrara, DICA, POLIMI

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Thank you for your attention

If you always do what you always did, you'll always get what you always got!

Liberato Ferrara, DICA, POLIMI

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MULTILAYERED URBAN SUSTAINABILITY ACTION

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European Commission | Horizon 2020 European Union funding for Research & Innovation

RESHEALIENCE Ultra High Durability Concrete

This project has received funding from the European Union's Horizon H2020 research and innovation programme under grant agreement Nº 760824

SMARTINCS
SELF-HEALING - MULTIFUNCTIONAL - ADVANCED REPAIR TECHNOLOGIES IN CEMENTITIOUS SYSTEMS

MARIE SKLODOWSKA-CURIE ACTION

European Commission

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