www.abt.eu

Developing a CUR-CROW guideline for permanent SFRUWC floors

Lex van der Meer
DOV Technische Lezingenavond
15 september 2022

kennisplatform CROW
2020-nu

bam

Rijkswaterstaat

SBR CUR net
2015-2017

Royal HaskoningDHV

mobilis | TBI

Betonhuis

BEKAERT better together

Witteveen+Bos

DURA VERMEER

Gemeente Rotterdam

metal products STEELFIBER PRODUCER

MAX BÖGL

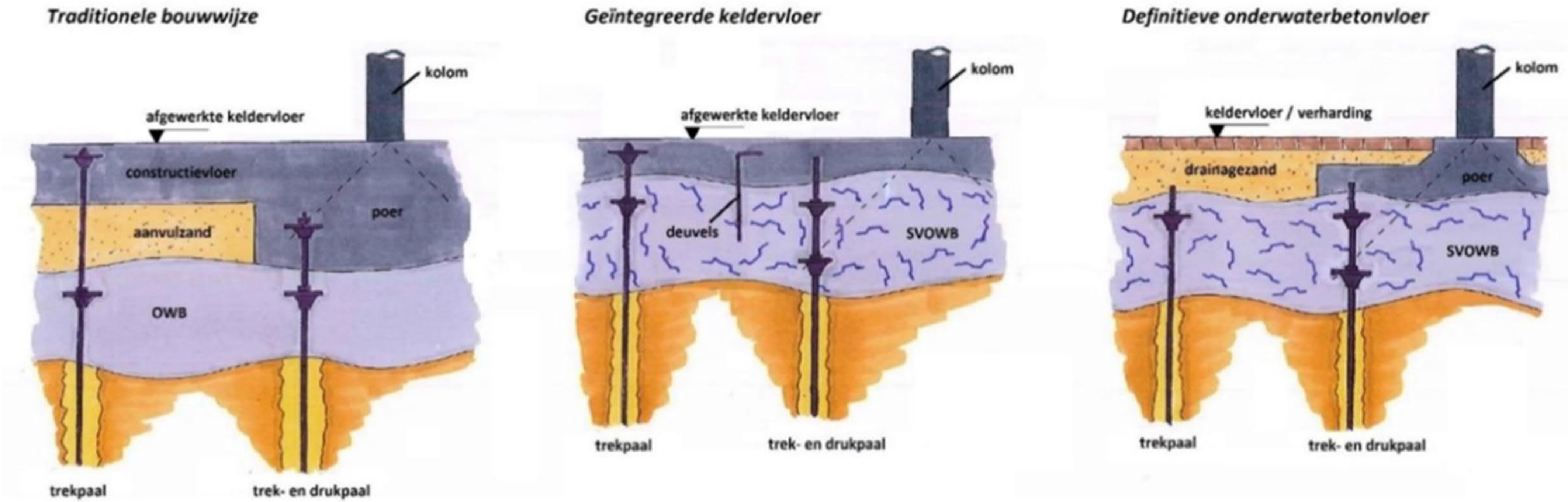
DIANA FEA

abt

heijmans

ArcelorMittal

Why?



Figuur: principeschetsen van keldervloeren voor (diepe) bouwkuipen met onderwaterbeton

abt

www.abt.eu

Why?

	Case Fase 1	Case Fase 2
	Keldervloer voor een ondergrondse parkeergarage	Vloer voor de verdiepte ligging/landtunnel voor een snelweg
Afmeting:	oppervlakte van 260x30 m^2	3,0 km lang en 35 m breed
Directe bouwkosten 	*€ 750.000,-*	*€ 10.120.000,-*
CO_2-uitstoot 	*1.100.000 kg**	*14.900.000 kg**
Vervoersbewegingen (via weg) 	*800*	*10.500*

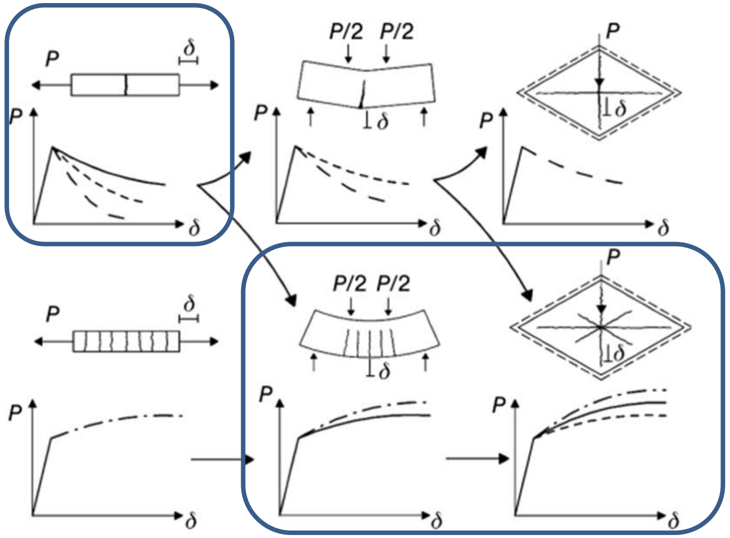
Tabel 2: Indicatie besparing definitieve SVOWB-vloer t.o.v. traditionele bouwwijze voor twee voorbeeldcases

* De CO_2-reducties komen overeen met de CO_2-opname van een bos ter grootte van het bebouwde oppervlak gedurende een periode van 142 jaar. Omgerekend naar de uitstoot van een vliegtuig tussen Amsterdam en Nieuw-Zeeland staat dit gelijk aan 60 retourvluchten voor de parkeergarage (Fase 1) en 819 retourvluchten voor de verdiepte snelweg (Fase 2).

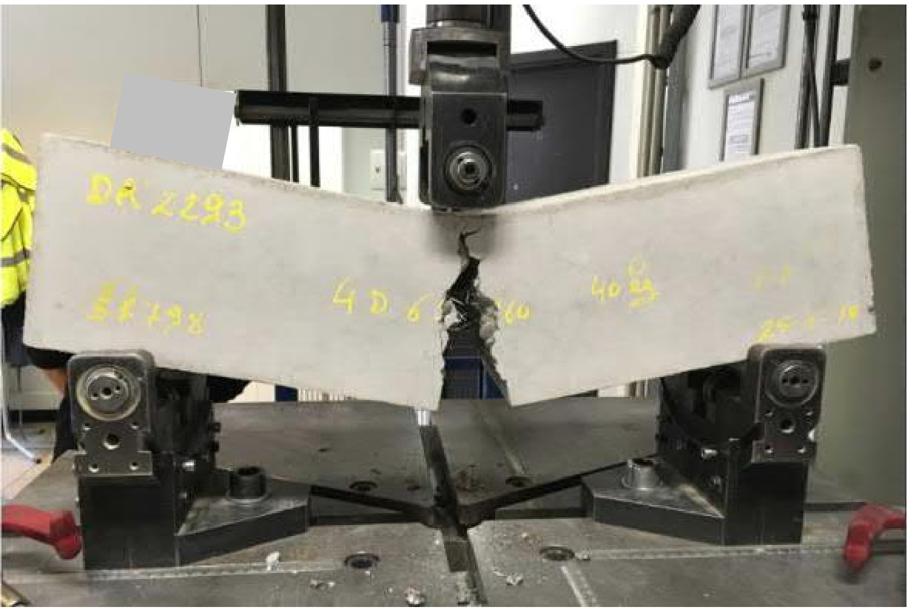
www.abt.eu

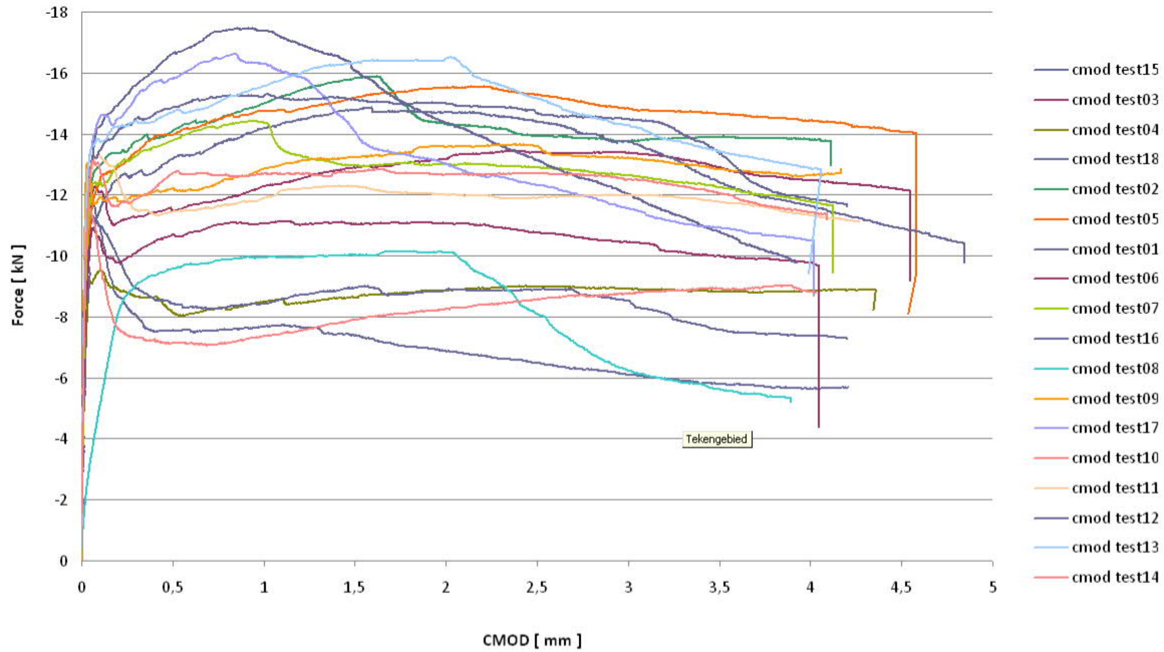
Why?

Why?


P
δ
P/2 P/2

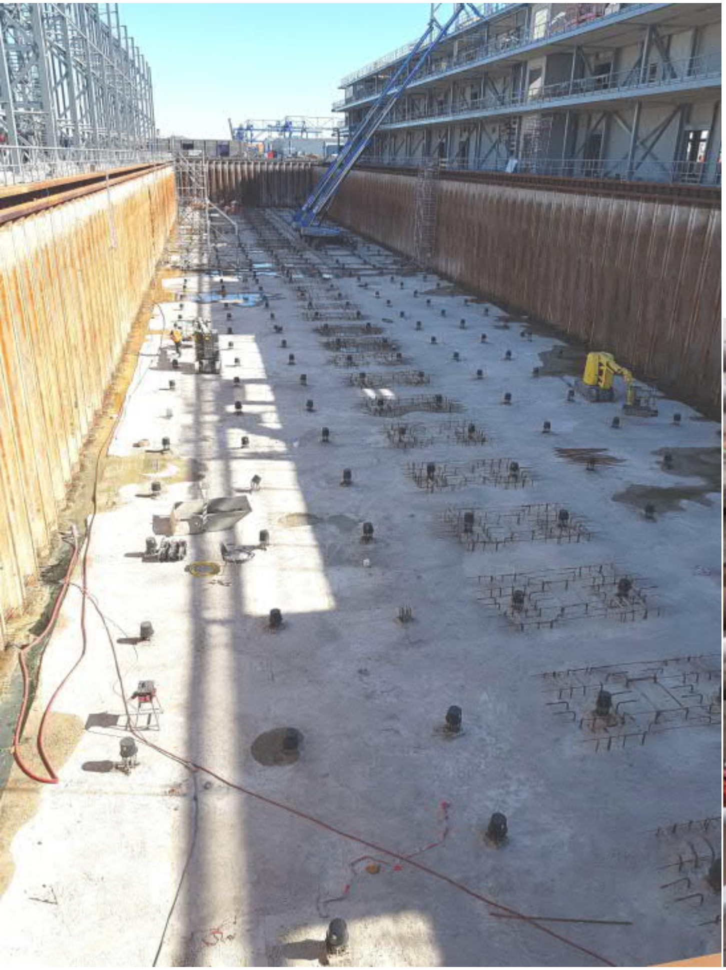

jonge fase
?
uitgeharde fase
?

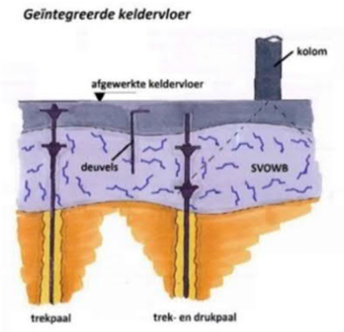



Force [kN]
CMOD [mm]
Tekengebied
cmod test15
cmod test03
cmod test04
cmod test18
cmod test02
cmod test05
cmod test01
cmod test06
cmod test07
cmod test16
cmod test08
cmod test09
cmod test17
cmod test10
cmod test11
cmod test12
cmod test13
cmod test14

www.abt.eu

Why?





Successes:

- Steel fiber reinforced under water concrete (SFRUWC)
- Added ductility
- Appropriate design choices
- Supervision on concrete technology & construction
- Extensive FEA with DIANA

Main challenges SFRUWC

- Shrinkage cracking
  - Brittle behaviour in spite of steel fibres
  - Leakage and possible damage to environment
  - Overestimating capacity in case of permanent structural function
- Fatigue
  - Mainly in case of application in infrastructural projects

abt

CROW committee organization

- SG1 – corrosion and durability
- SG2 – fatigue and scale factor
- SG3 – execution
- SG4 – shrinkage cracking
- SG5 – cases

SG4 output (background reports)
- Starting points and FEA basic model
- Sensitivity analysis
- Experiments (in-situ and laboratory)
- Validation

SG4 activities
- FEA to gain insight
- Validate by theory
- Validate by experiments

SG5 activities
- Develop design rules
- Analyze cases by design rules
- Analyze cases by FEA

SG4 output (guideline)
- Recommendations FEA (advanced)

SG5 output (guideline)
- Design rules (simple / conservative)

Main challenges FE modelling

Thermal

- Hydration heat development
- Thermal boundaries and properties

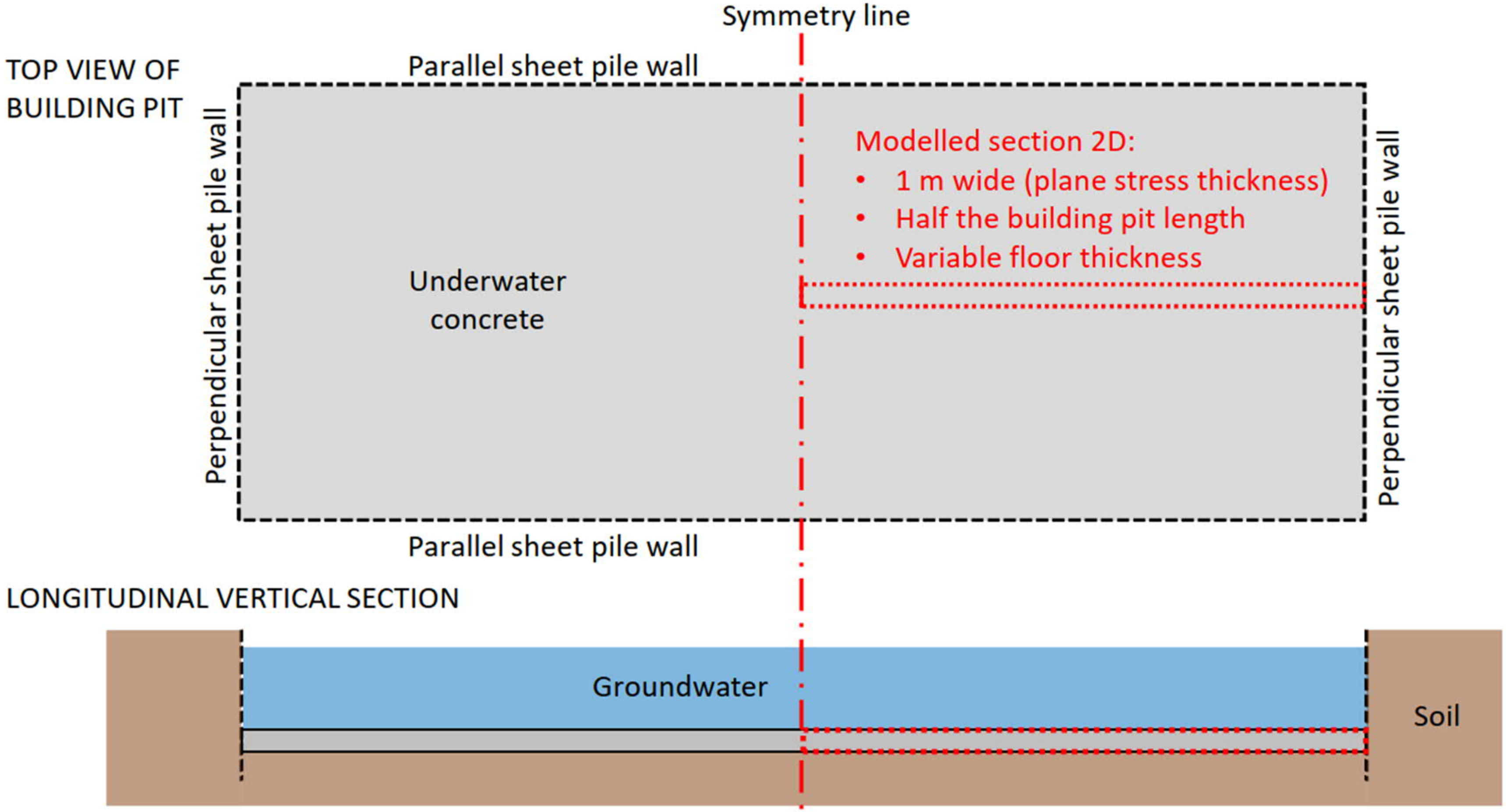
Structural

- (Autogenous) shrinkage
- Strength and stiffness development of YHC
- Degree of restraint
- Development of eigen stresses
- Relaxation particularly at early age
- Development of cracking
- Influence of steel fibres after cracking

Stochastic variation

- Random field

(Thermal) shrinkage cracking in underwater concrete

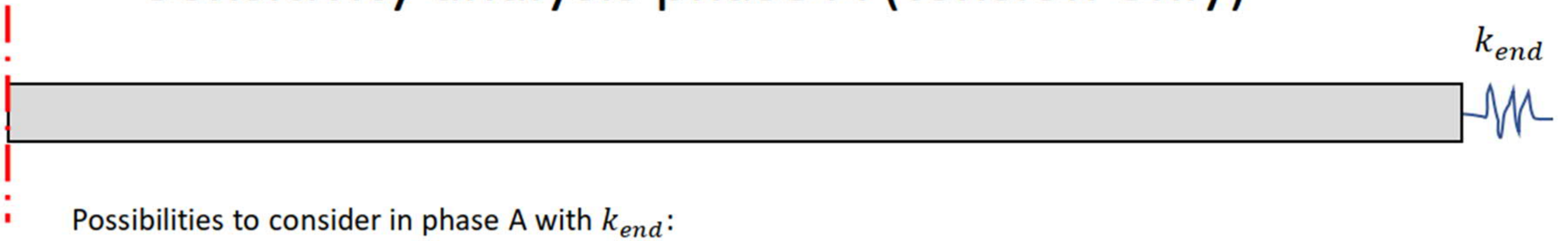


(Thermal) shrinkage cracking in underwater concrete

Sensitivity analysis phase A:
- Tension only
- Theoretical, worst case
- Easier to interpret
- Horizontal restraint at the end or distributed over the length
- Variations in degree of horizontal restraint
- Relevant during underwater phase only (heating + cooling)

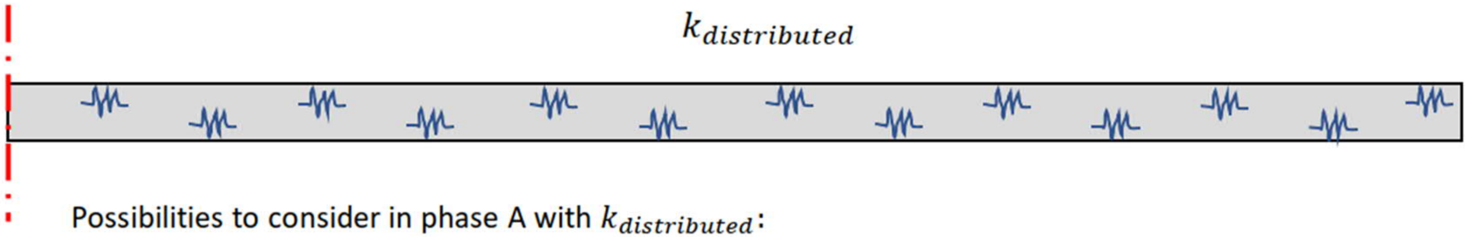
Sensitivity analysis phase B:
- Tension + bending
- More realistic, compression from bending is beneficial to prevent through-and-through cracking
- More difficult to interpret
- Various sources of bending
- Varying ratio of bending to normal (tensile) stresses
- Additional phase to be considered: water pressure and vertical resistance by piles/anchors after pumping

Sensitivity analysis phase A (tension only)



Possibilities to consider in phase A with k_{end}:

- Worst case: $k_{end} = \infty$ (shrinkage fully restrained)
- $k_{end} < \infty$ (shrinkage not fully restrained)
- In both cases: <u>constant normal force</u> from start to end
- This is a theoretical case, assuming the longitudinal floor section has no interactions except at the end



Possibilities to consider in phase A with $k_{distributed}$:

- Different $k_{distributed}$ values to account for restraint by parallel sheet pile walls
- Can also account for horizontal pile or bedding stiffness (without the eccentricity)
- Normal force can build up at the free end and between cracks
- This case is more realistic, except that is it still pure tension, no bending

www.abt.eu

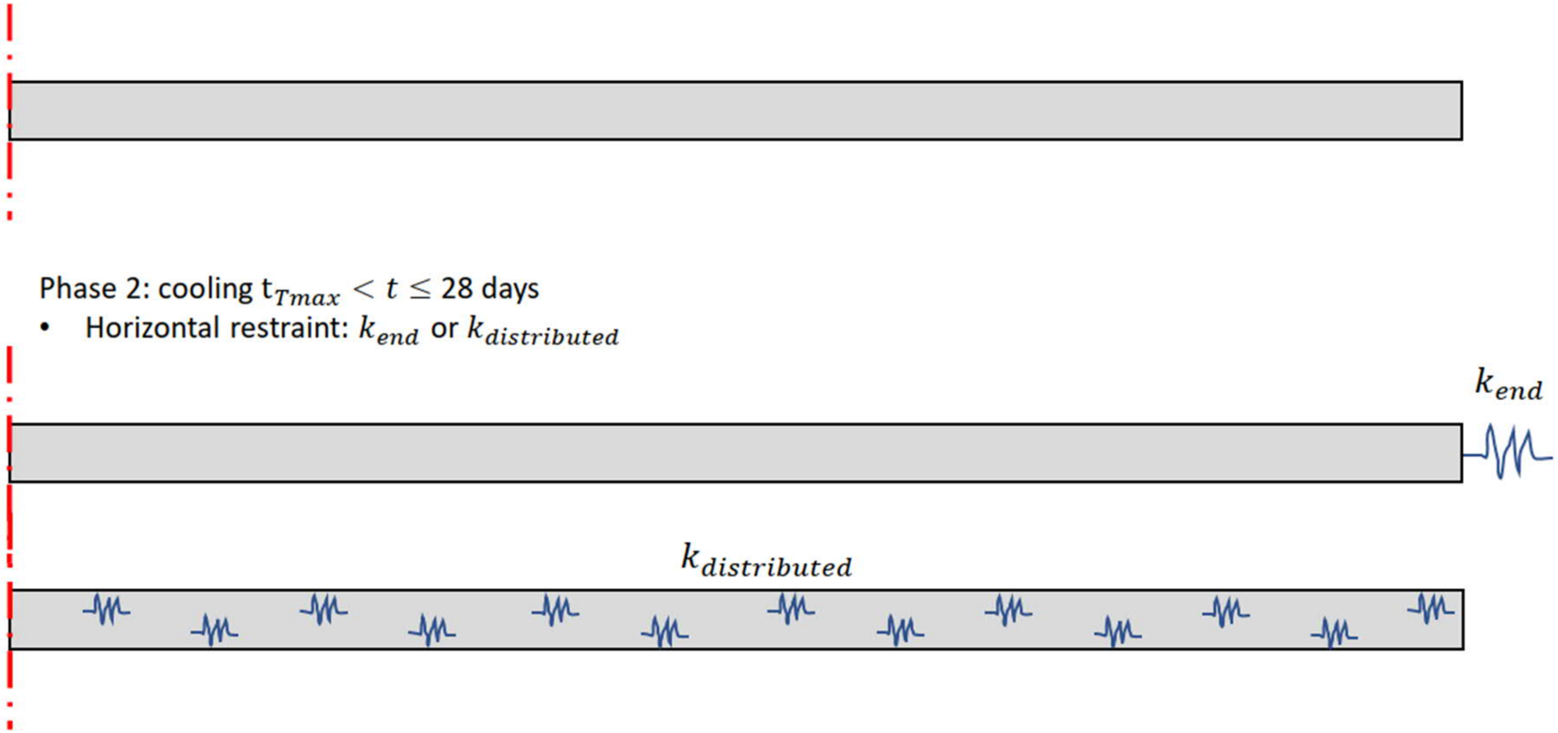
Sensitivity analysis phase A (tension only)

Phase 1: heating $0 \le t \le t_{Tmax}$

- No restraints

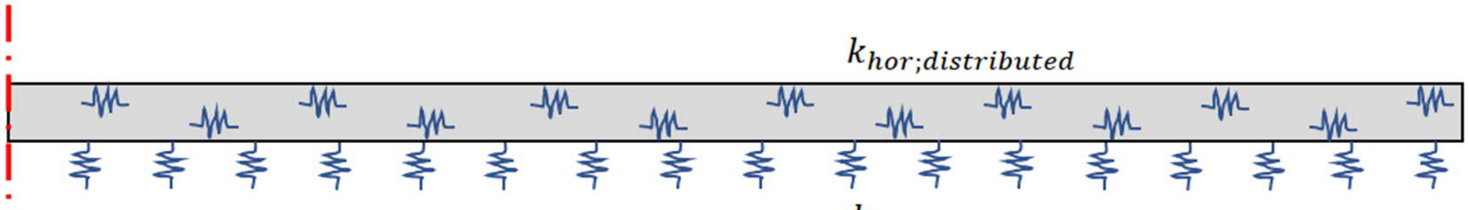
Phase 2: cooling $t_{Tmax} < t \le 28$ days

- Horizontal restraint: k_{end} or $k_{distributed}$



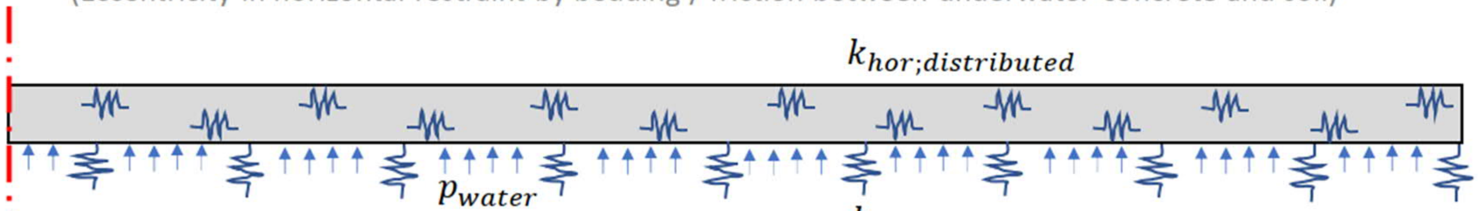
www.abt.eu

Sensitivity analysis phase B (tension + bending)



Possible sources of bending in the heating and cooling phase:

- Self weight + vertical bedding
- Non-symmetric thermal boundary conditions
- (Stochastic variation of material properties through-thickness)
- (Eccentricity in horizontal restraint by bedding / friction between underwater concrete and soil)



Possible sources of bending in the phase after pumping:

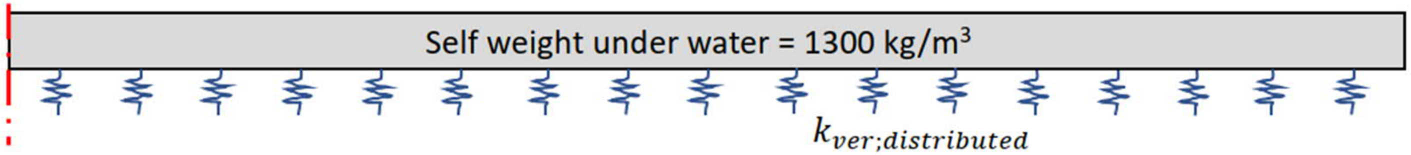
- Water pressure + vertical resistance by piles / anchors
- (Drying shrinkage)
- (Vertical loads)
- (Eccentricity in horizontal restraints)

Sensitivity analysis phase B (tension + bending)

www.abt.eu

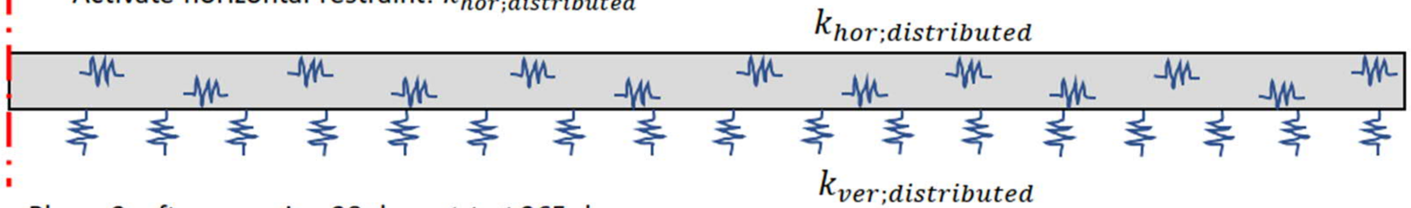
Phase 1: heating $0 \leq t \leq t_{Tmax}$

- No horizontal restraints
- Vertical restraints: bedding + self weight under water



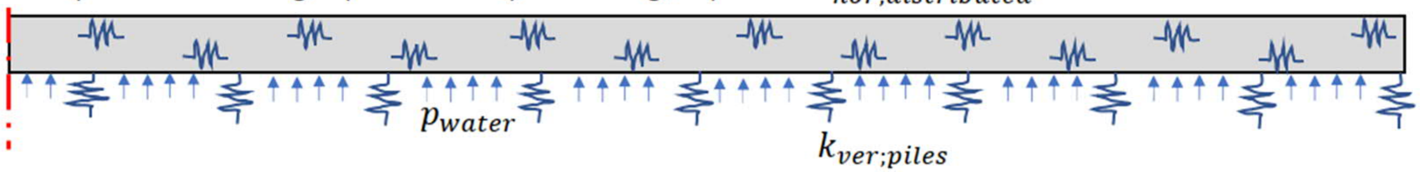
Phase 2: cooling $t_{Tmax} \leq t \leq 28$ days

- Activate horizontal restraint: $k_{hor;distributed}$



Phase 3: after pumping 28 days $< t \leq 365$ days

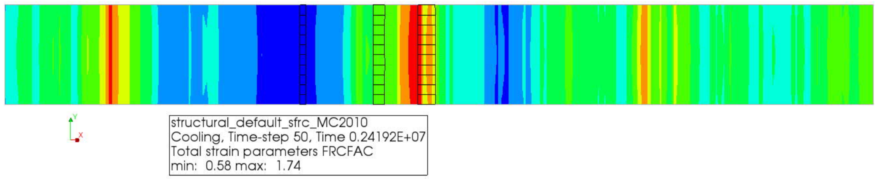
- Deactivate vertical restraint: $k_{ver;distributed}$
- Activate vertical restraint: $k_{ver;piles}$
- Activate water pressure
- (Increase self weight (above water) to 2300 kg/m³)

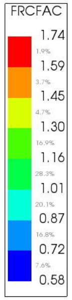


www.abt.eu

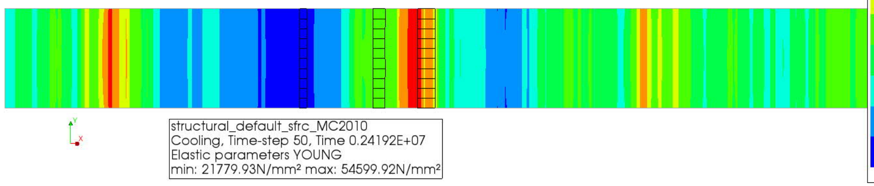
Results base model fase A (tension only)

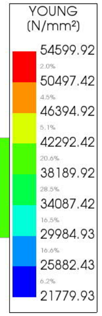
Random field SFRC stress-strain



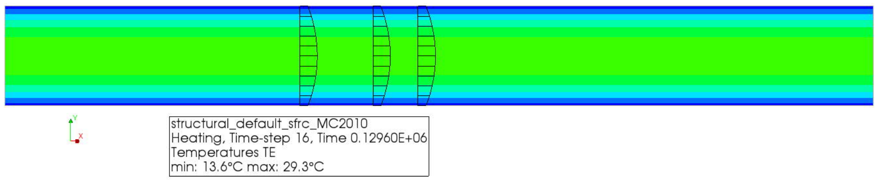


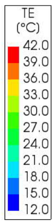
Random field Young's modulus



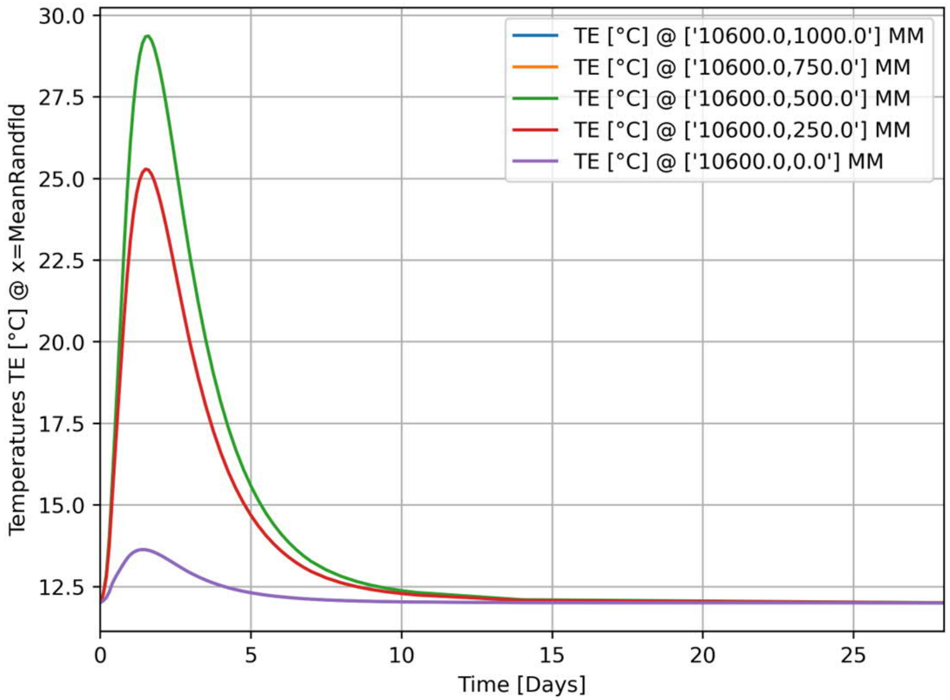


Temperature distribution at peak





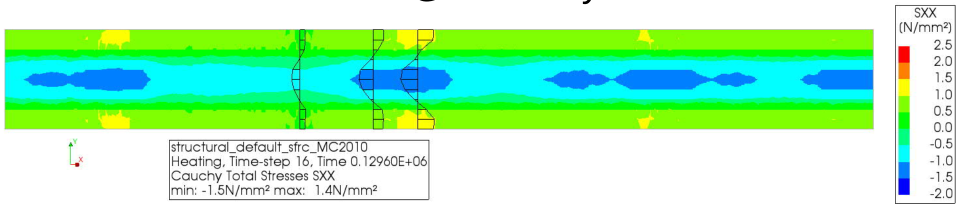
Temperature development in time



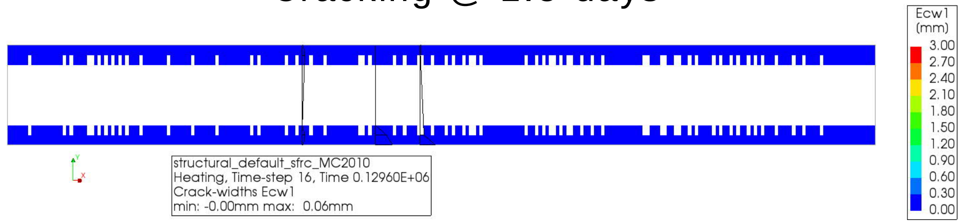
www.abt.eu

Results base model fase A (tension only)

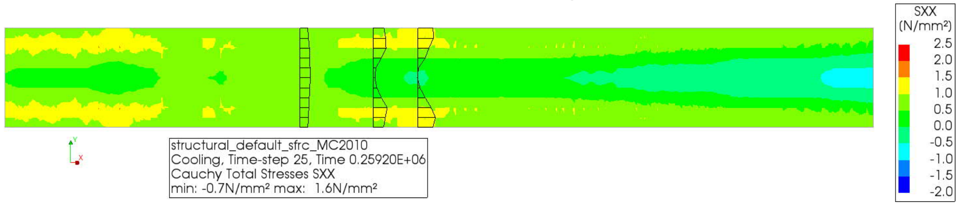
Stresses @ 1.5 days



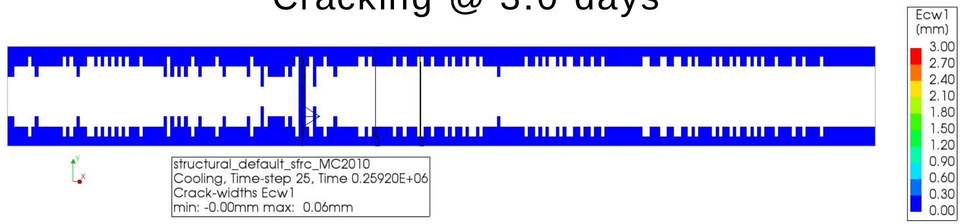
Cracking @ 1.5 days



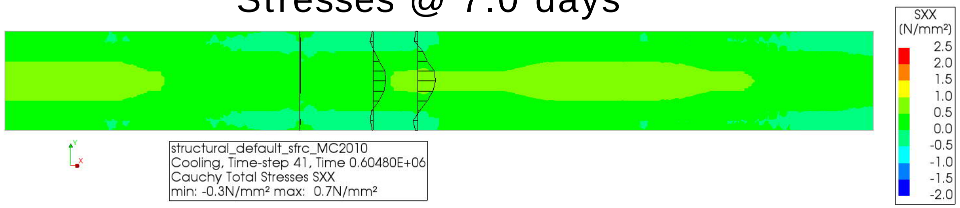
Stresses @ 3.0 days



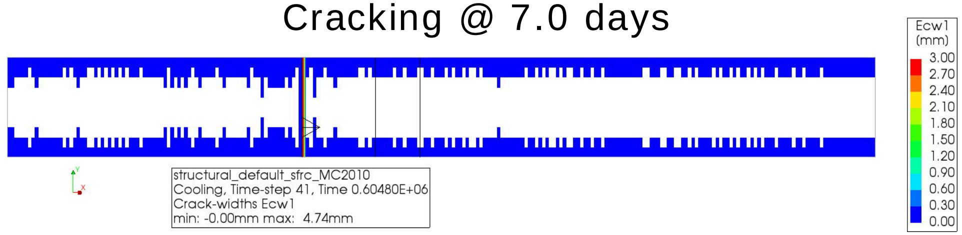
Cracking @ 3.0 days



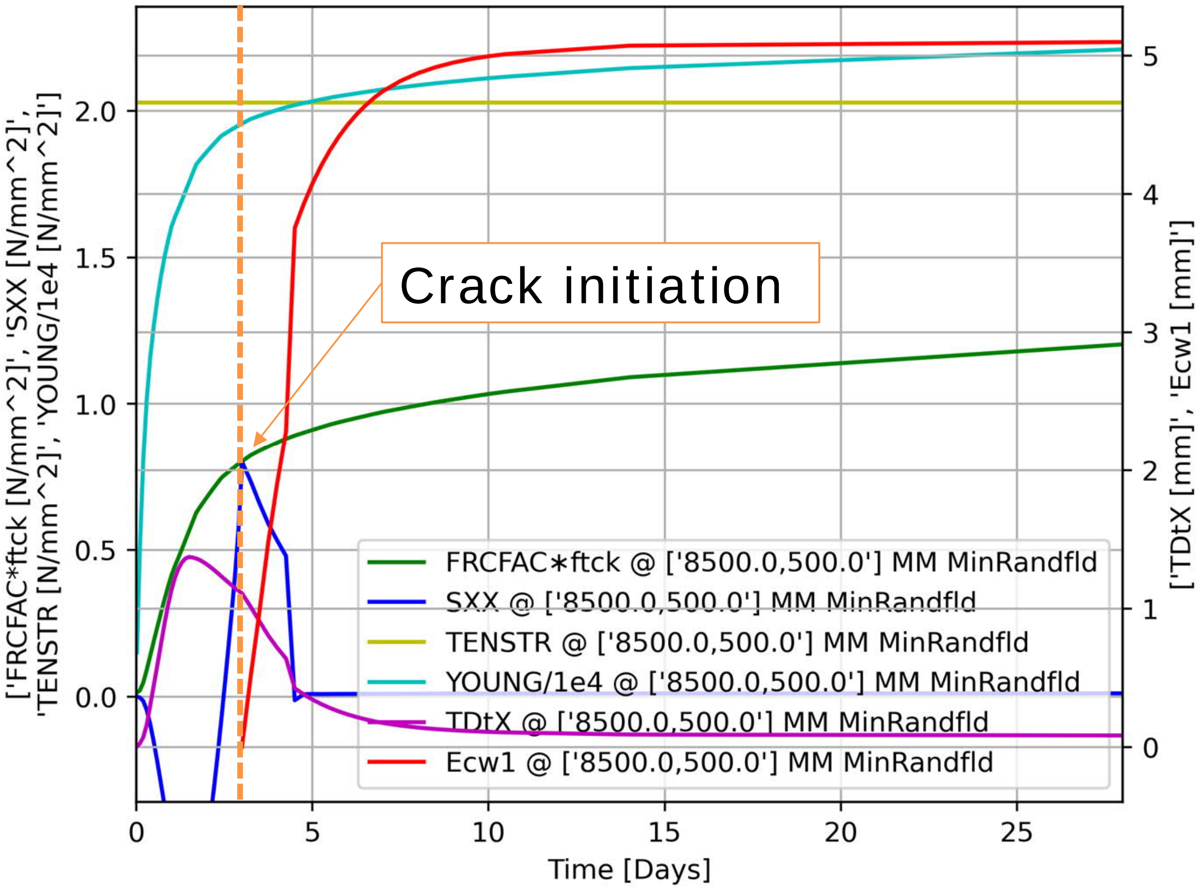
Stresses @ 7.0 days



Cracking @ 7.0 days



Results base model fase A (tension only)

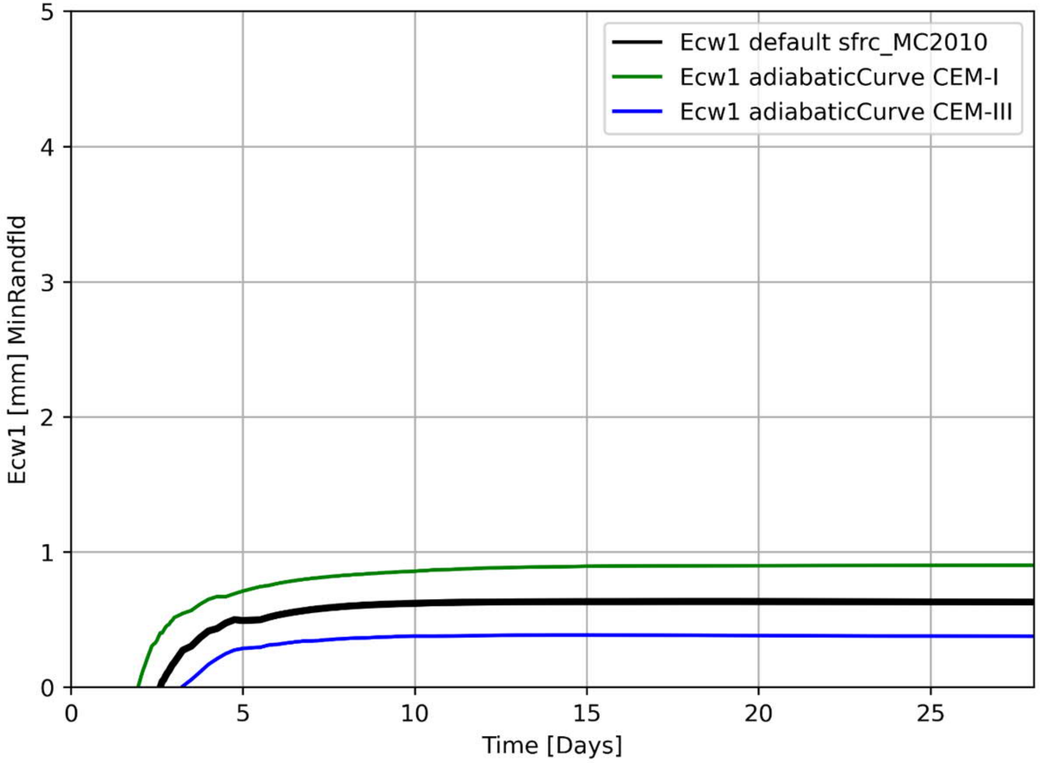


abt

Sensitivity analysis phase A

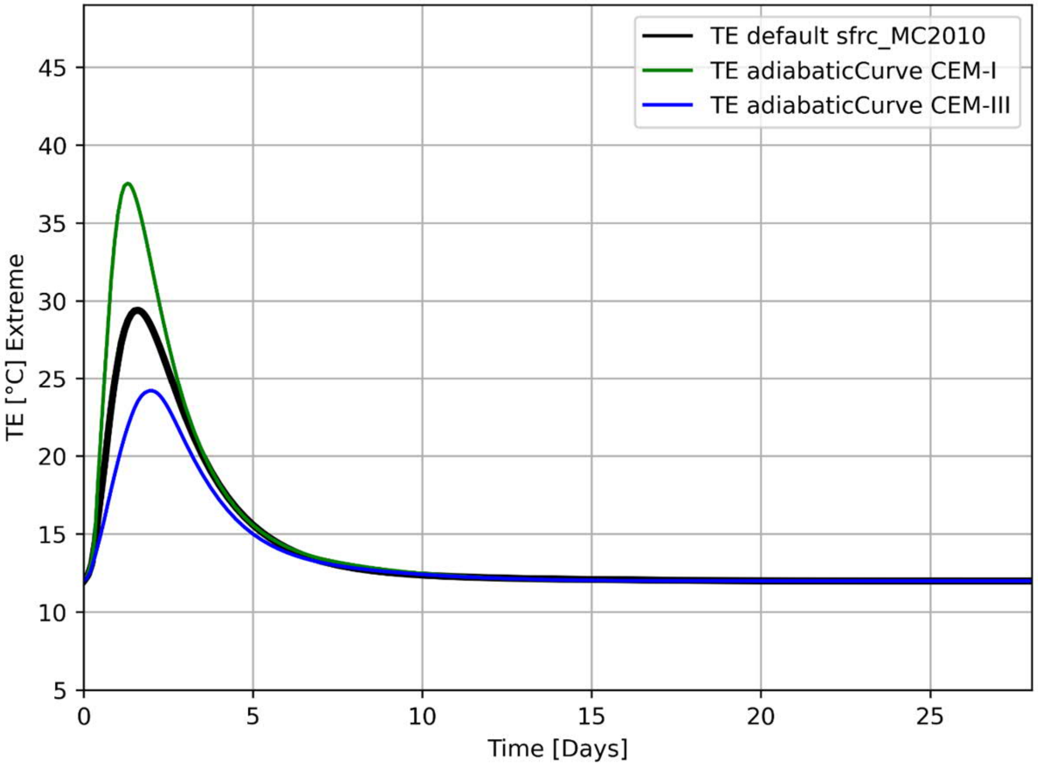
Categorie	Parameter	Basismodel	Variatie fase A
Geometrie	Dikte	1,0 m	0,5 – 0,8 – 1,0 – 1,25 – 1,5 – 2,0 – 2,5 – 3,0 m
Thermische eigenschappen en randvoorwaarden	Warmteovergangs-coëfficiënt boven/onder	100 / 100 W/(m²K)	5/5 – 100/100 – 700/700 W/(m²K)
	Adiabaat	60˚C (CEMIIIa)	50 - 60 - 70˚C
	Stort-/omgevingstemperatuur	12/12˚C	12/12 – 25/12 ˚C
Mechanische eigenschappen	Betonsterkteklasse	C30/37	C20/25 - C25/30 - C30/37 - C35/45
	Nascheurgedrag (SVB classificatie MC2010)	4c	Ongewapend 2a – c – e 3a – c – e 4a – c – e 5a – c – e
	Vorm spanning-scheurwijdte diagram	Model Code 2010	Model Code 2010, DIANA FEA (met dip)
	Rijpheidsafhankelijke mechanische eigenschappen	Cementklasse N (s = 0,25)	Cementklasse S (s = 0,20) N (s = 0,25) R (s = 0,38)
	Stochastische verdeling sterkte en stijfheid	Correlatielengte 5,0 m	Correlatielengte 0,5 – 2,0 – 5,0 m
	Relaxatie	-	n.t.b.
Mechanische randvoorwaarden	Horizontale verhindering door kopse damwanden	Zuivere trekstaaf vanaf afkoelfase, uiteinde volledig verhinderd	-
	Horizontale verhindering door parallelle damwanden	-	Centrische bedding vanaf afkoelfase, afschuifstijfheid 3,5 – 30 – 120 MN/m³ (niet i.c.m. verhindering kopse damwanden)
	[illegible]		

Sensitivity analysis phase A

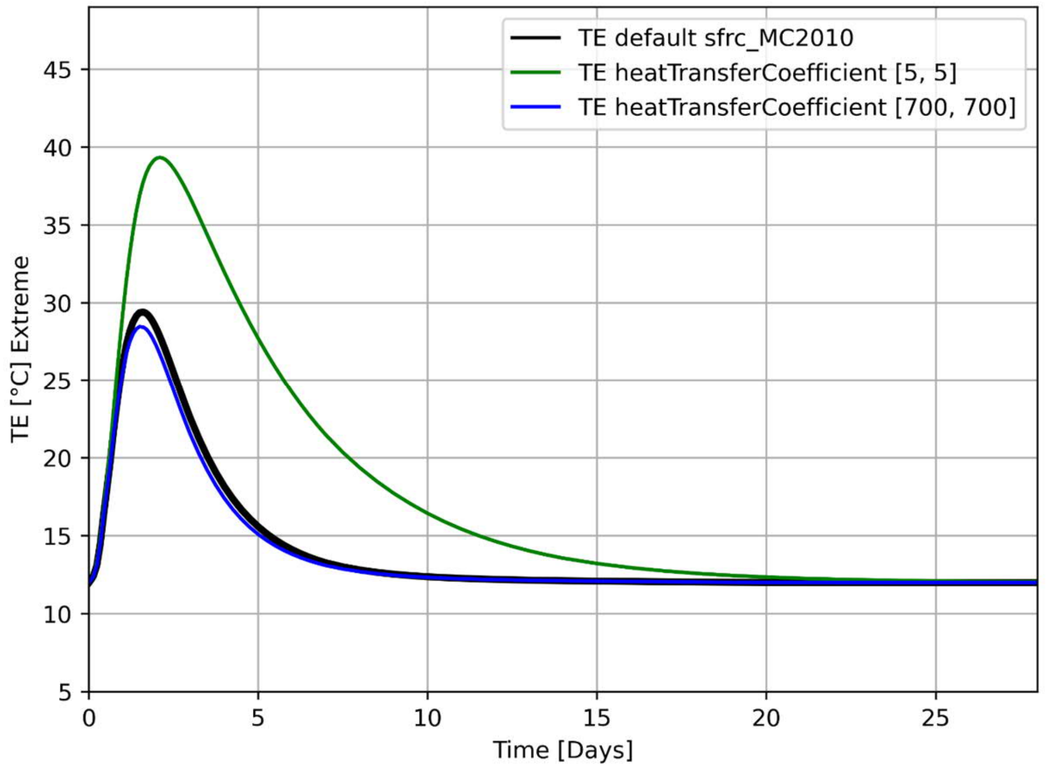


www.abt.eu

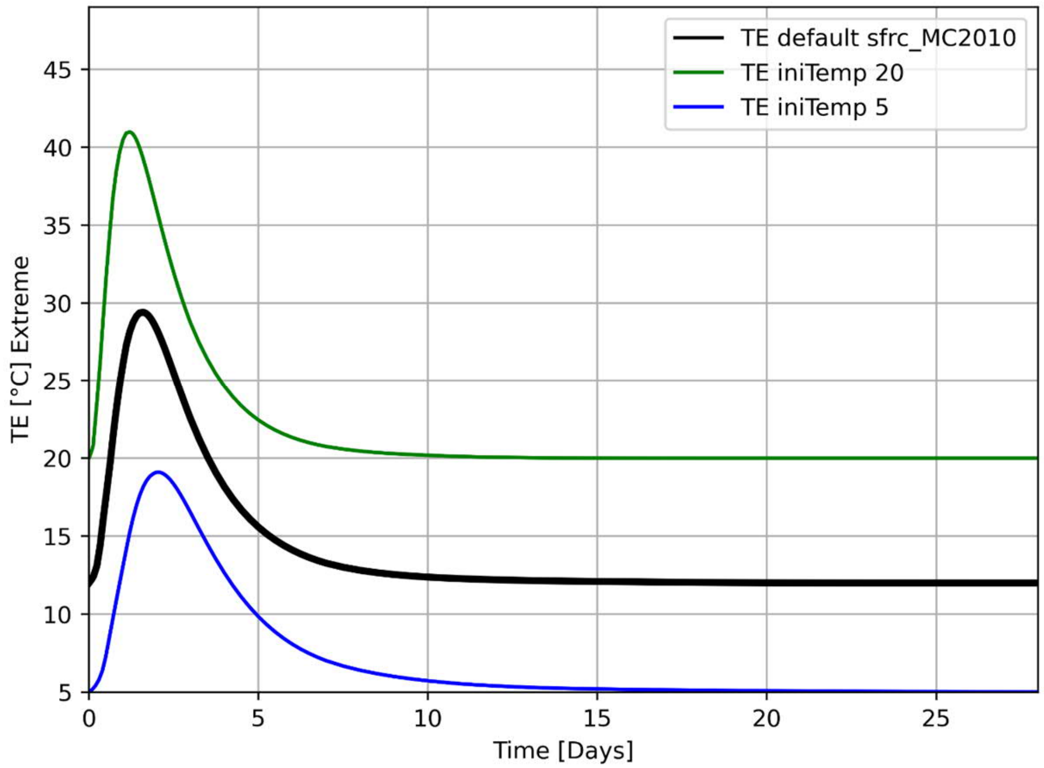
Sensitivity analysis phase A



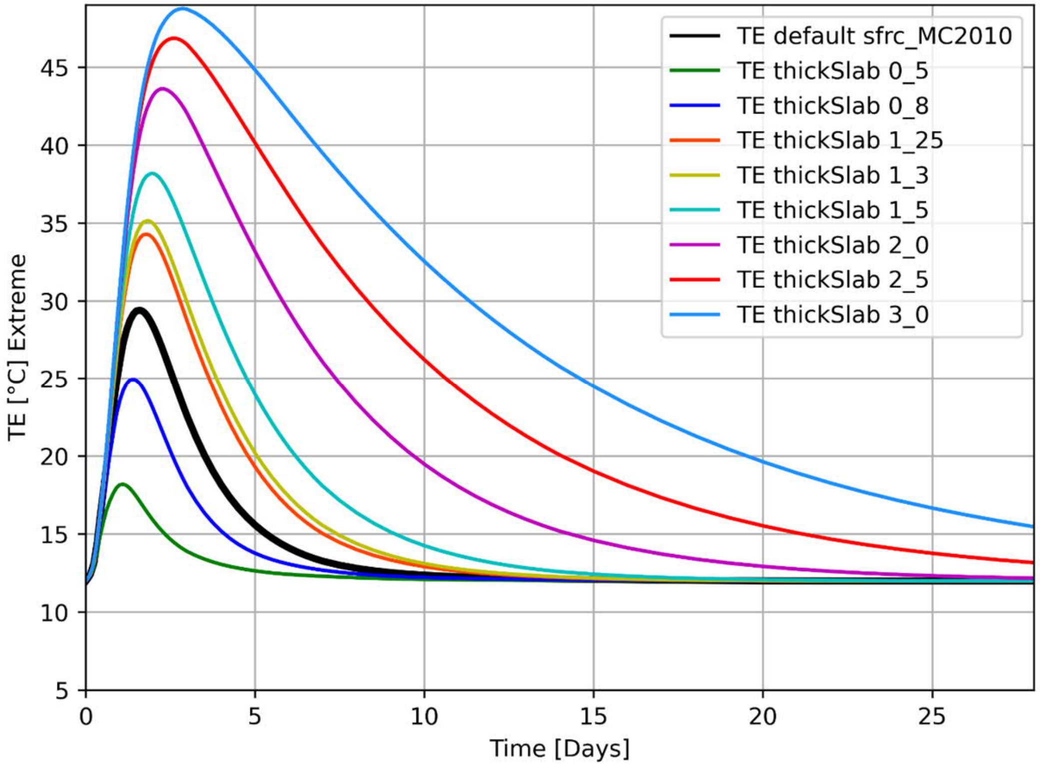
Sensitivity analysis phase A



Sensitivity analysis phase A

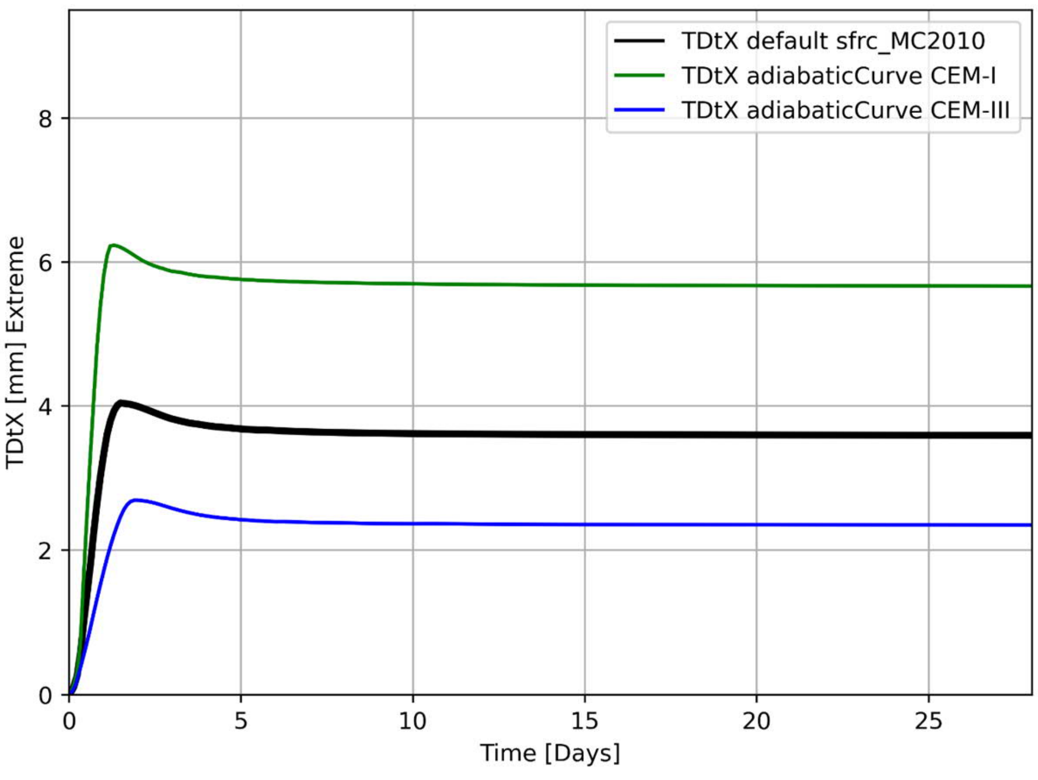


Sensitivity analysis phase A

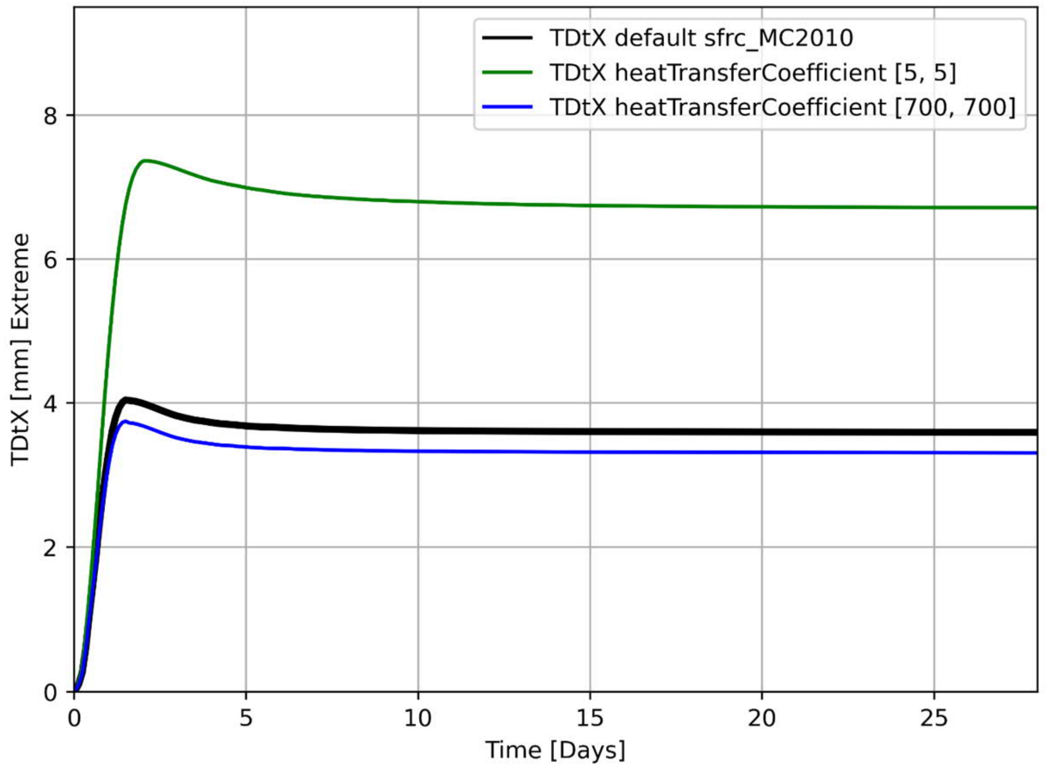


www.abt.eu

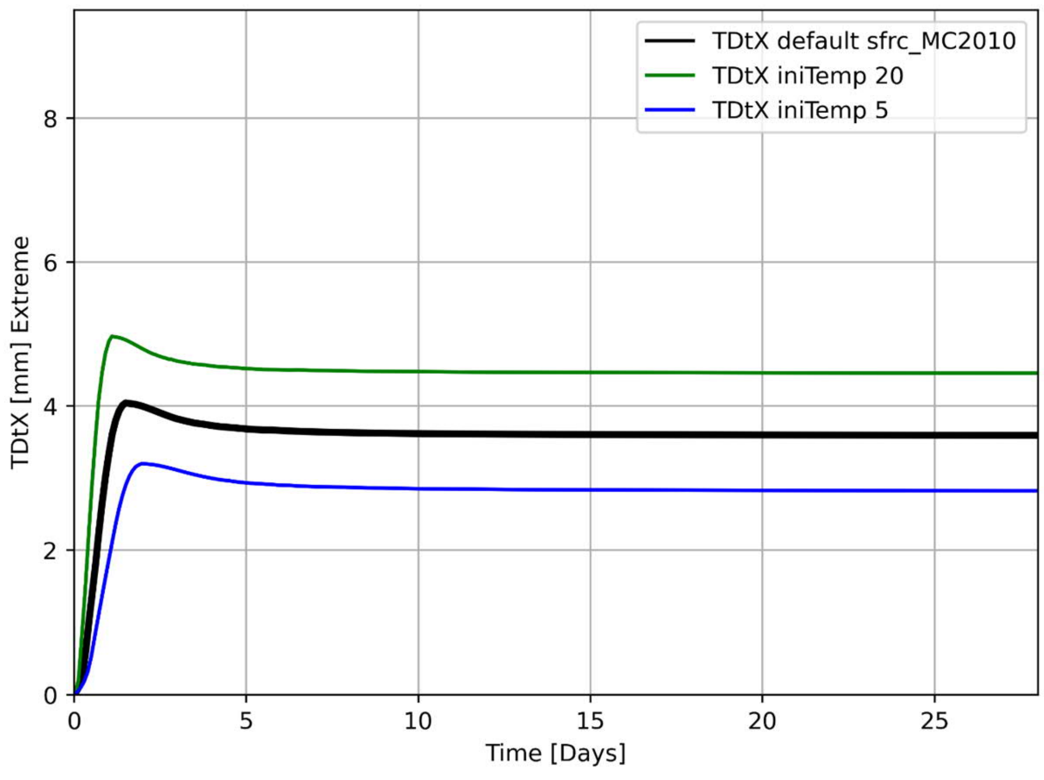
Sensitivity analysis phase A



Sensitivity analysis phase A

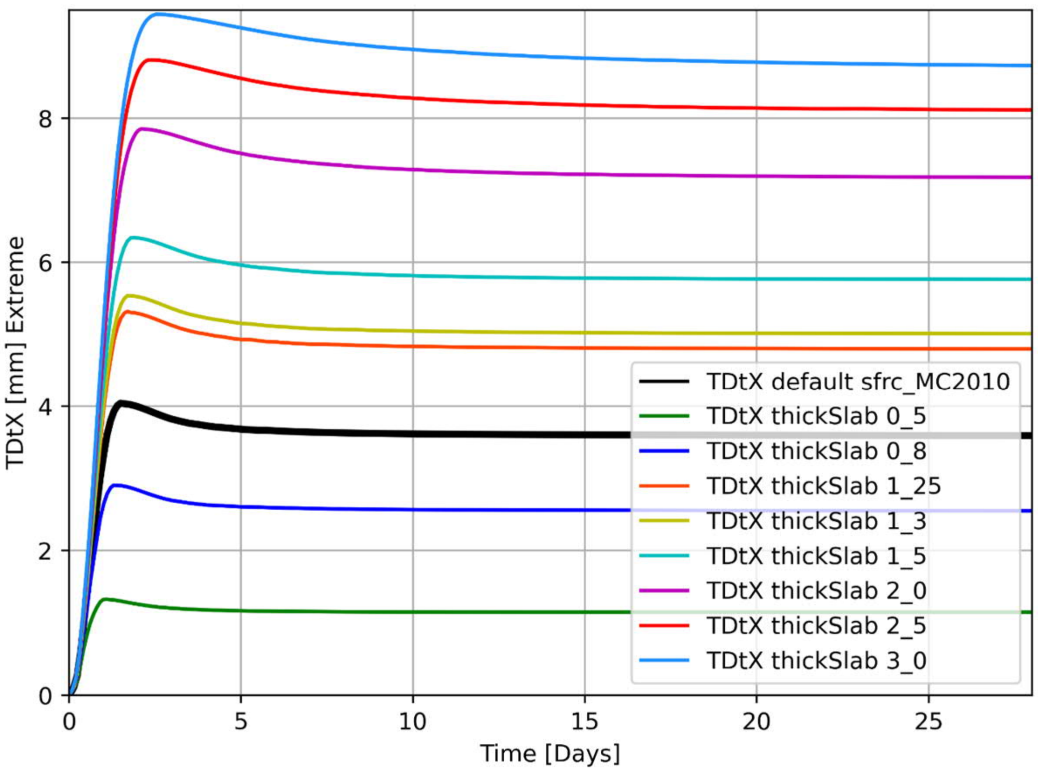


Sensitivity analysis phase A

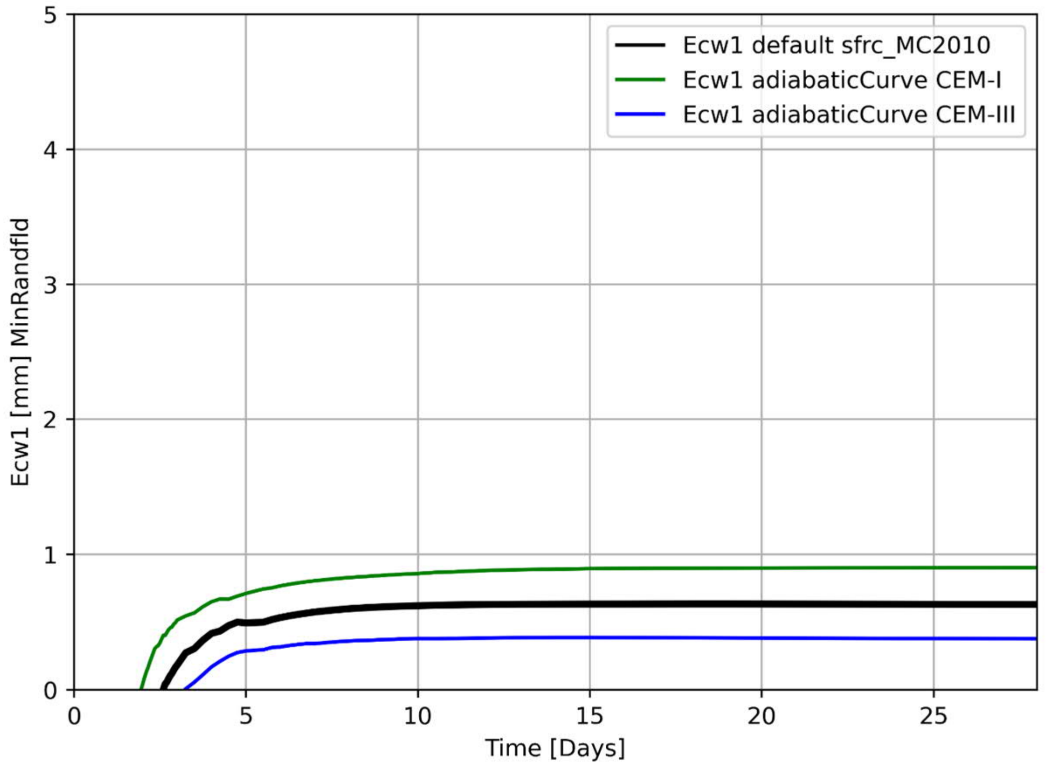


www.abt.eu

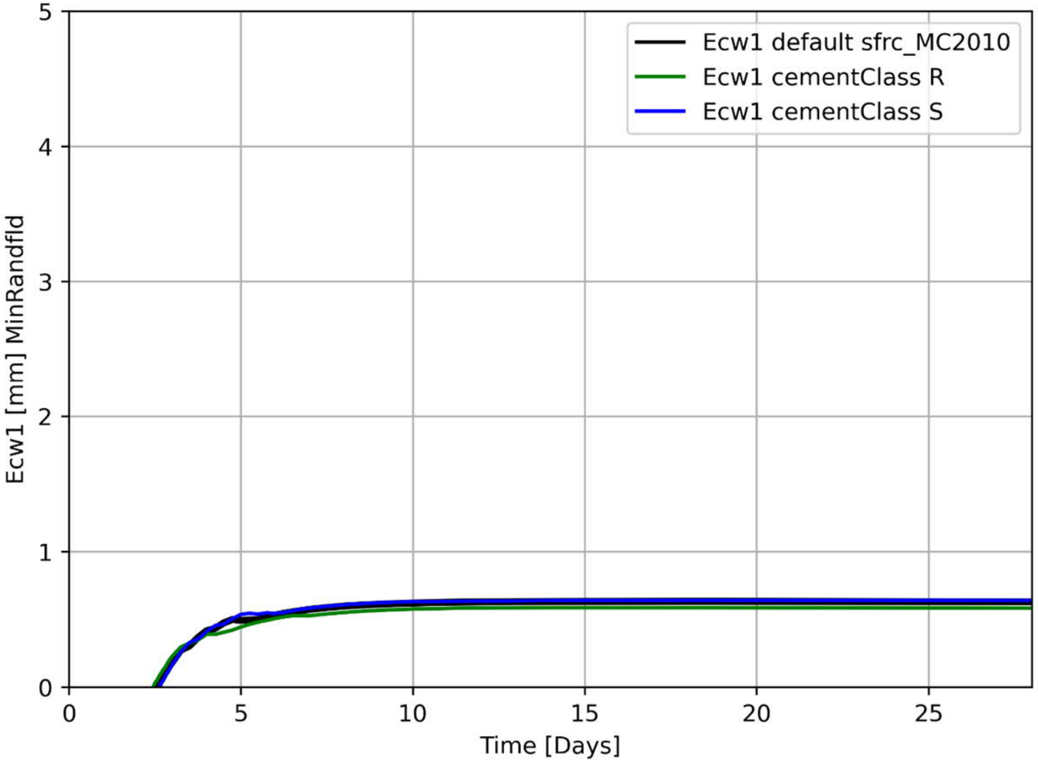
Sensitivity analysis phase A



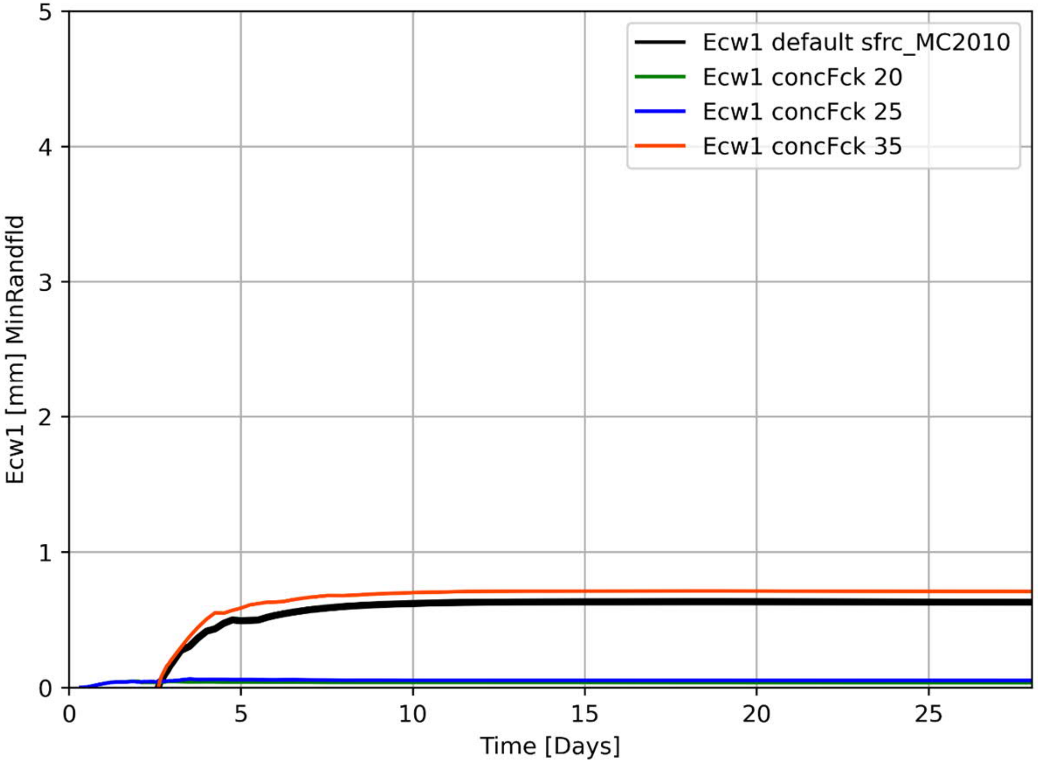
Sensitivity analysis phase A



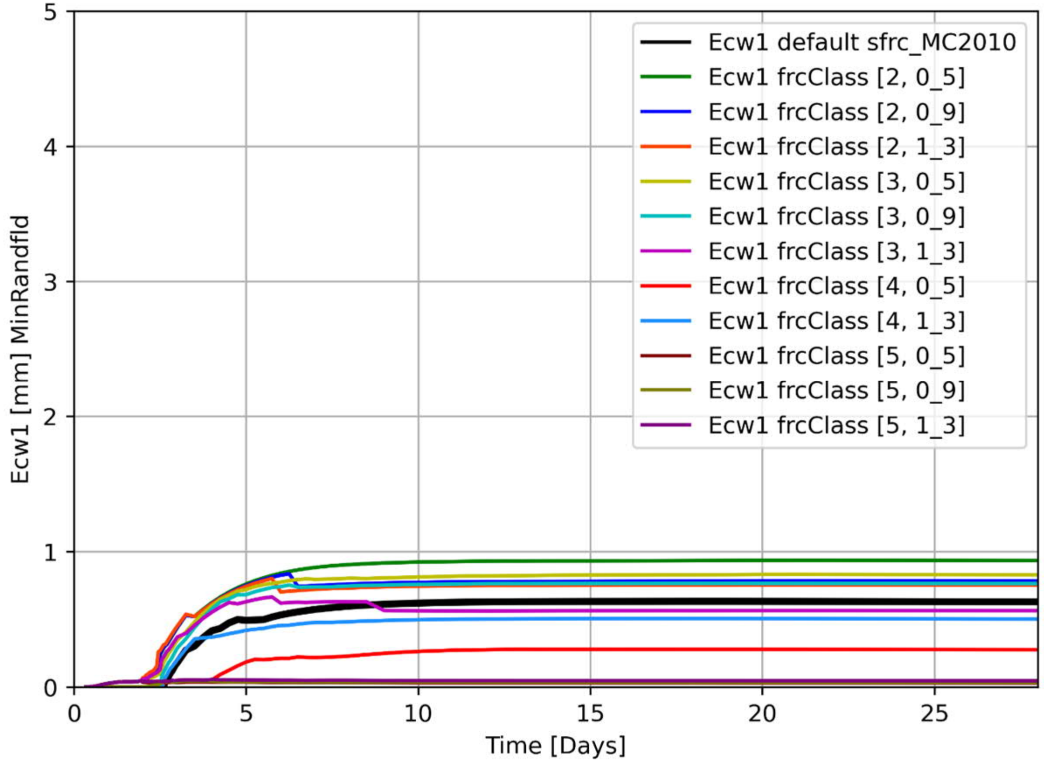
Sensitivity analysis phase A



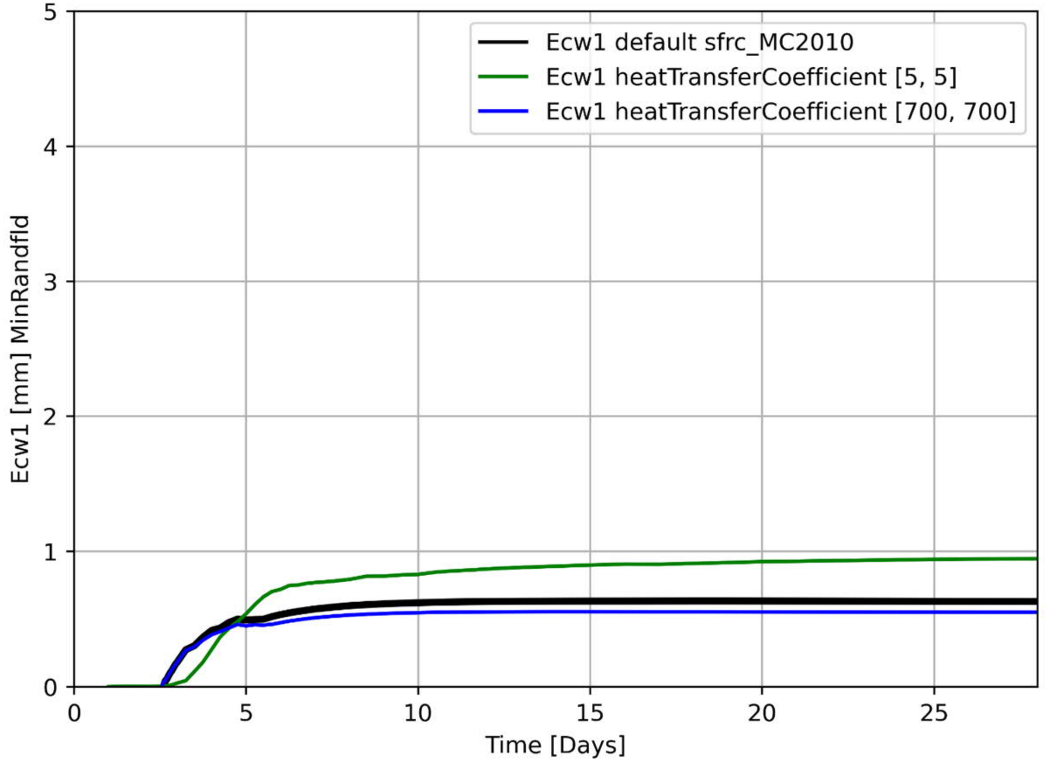
Sensitivity analysis phase A



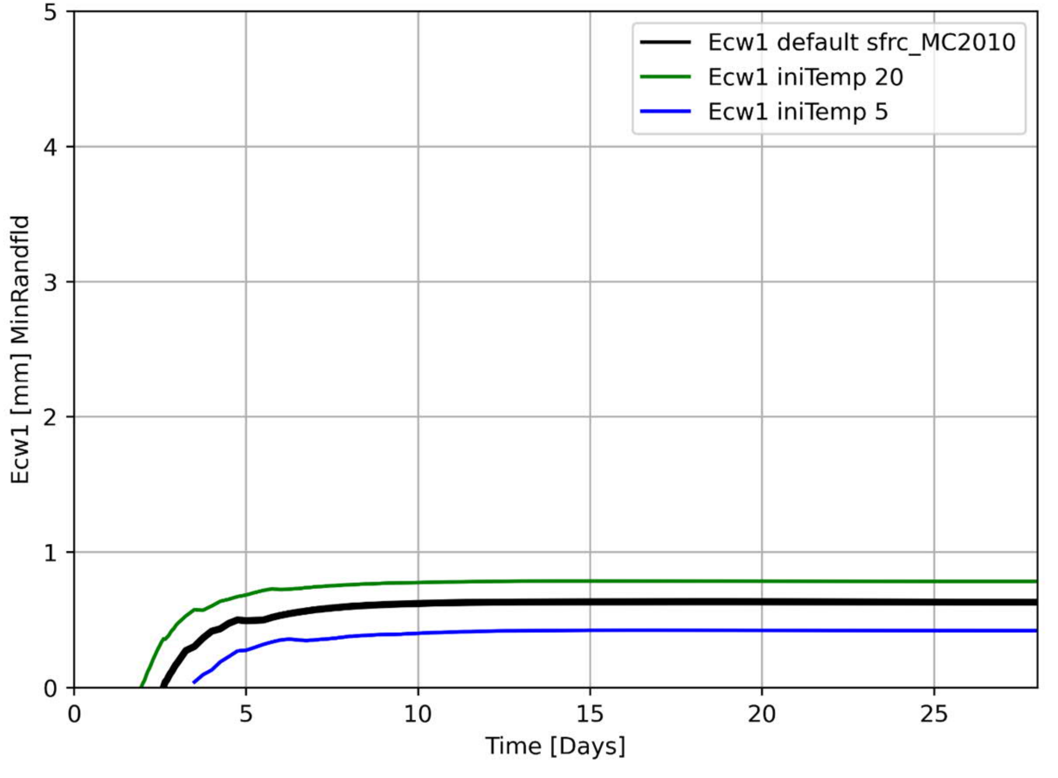
Sensitivity analysis phase A



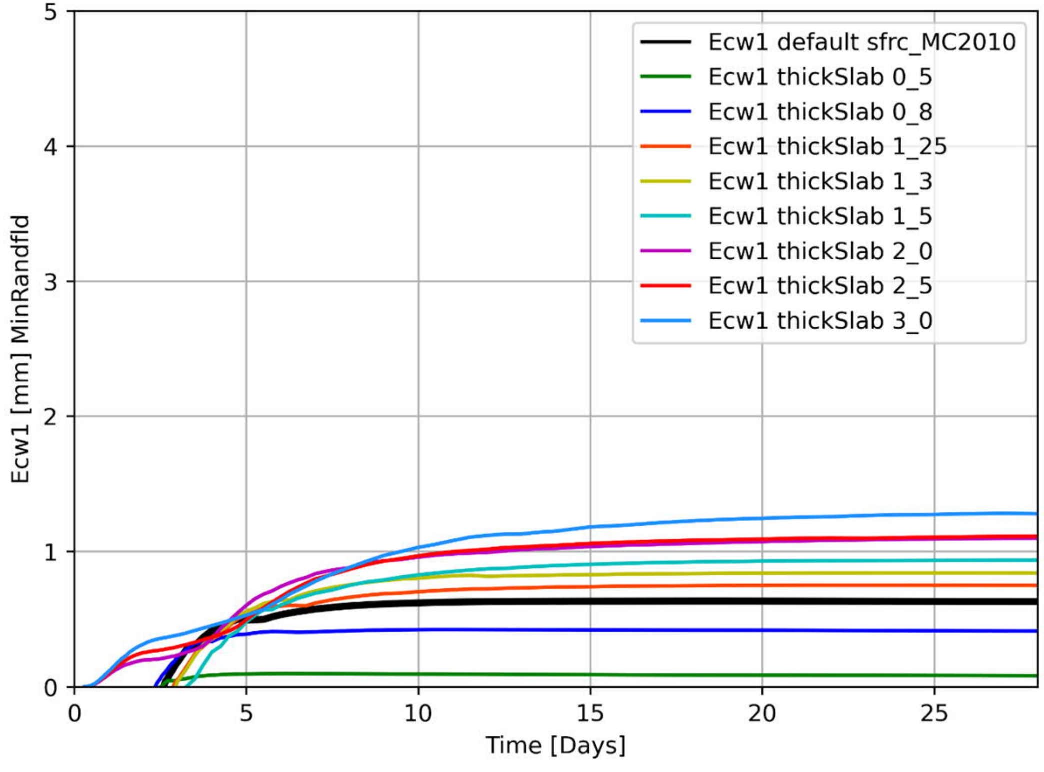
Sensitivity analysis phase A



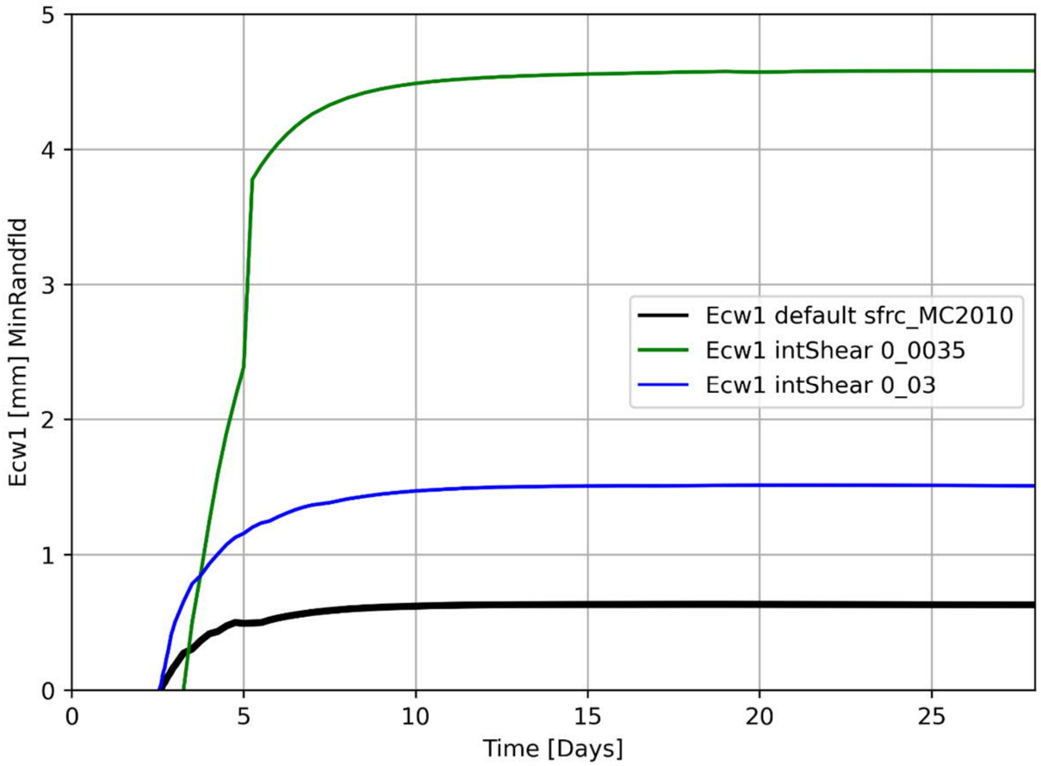
Sensitivity analysis phase A



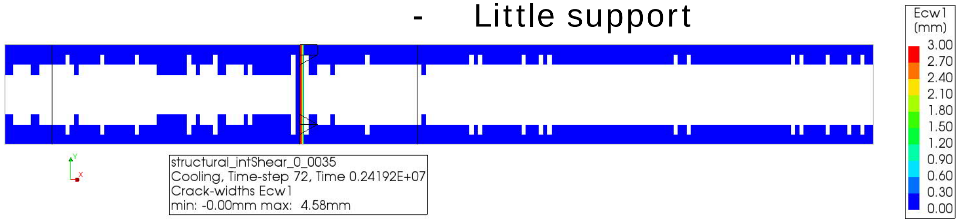
Sensitivity analysis phase A

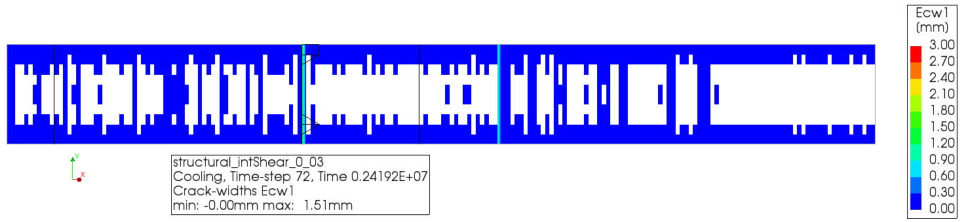


Influence of parallel sheet pile walls



Far away from sheet pile wall
- Little restraint
- Little support





Close to sheet pile wall
- A lot of restraint
- A lot of support (reinforcement)

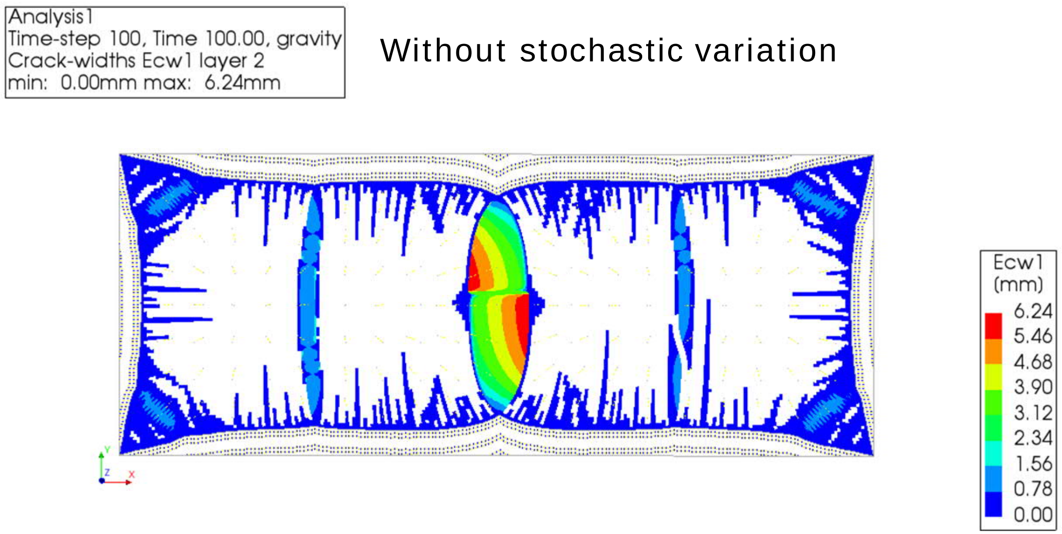
abt

www.abt.eu

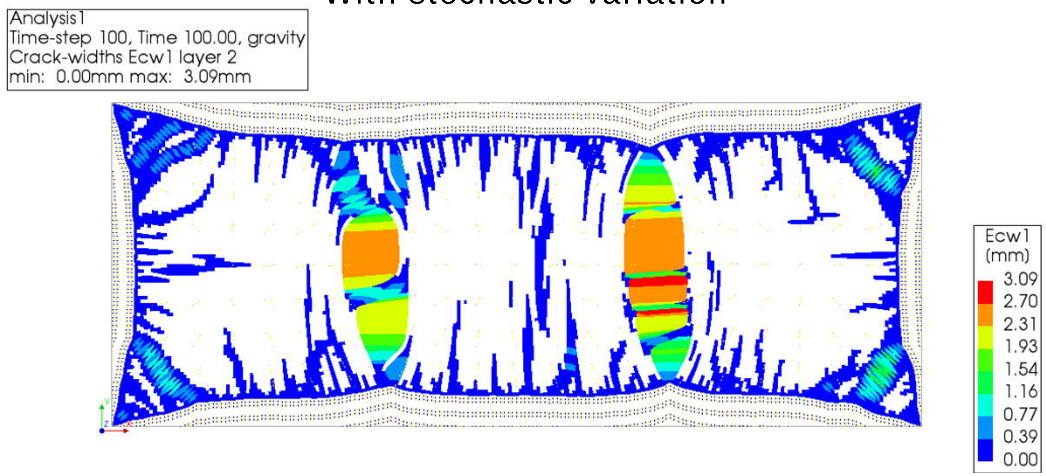
Influence of aspect ratio and BCs (2.5D model)

- Building pit 50 x 20 m
- At sheet pile walls: high shear stiffness, low normal stiffness
- 1/3 strength, 2/3 stiffness
- C30/37 with steel fibres (4c) but no eigen stresses ~ unreinforced concrete

Without stochastic variation



With stochastic variation

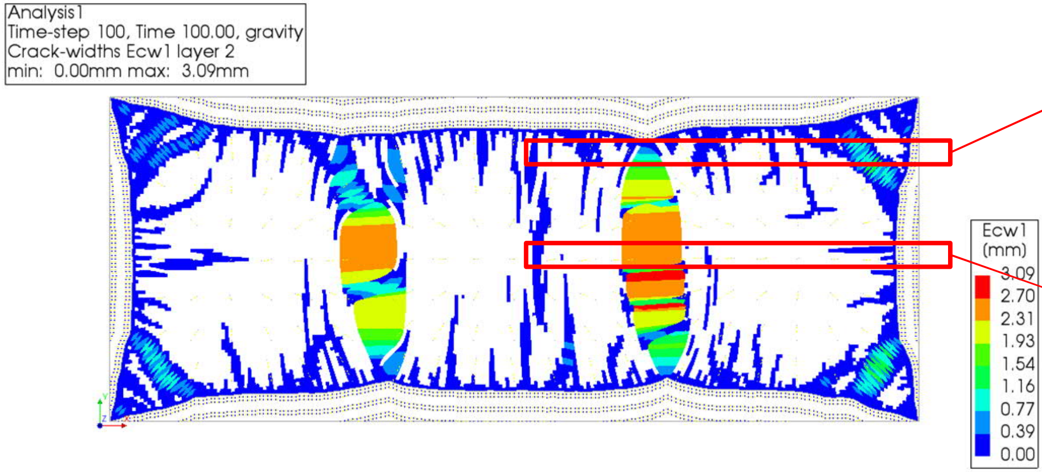


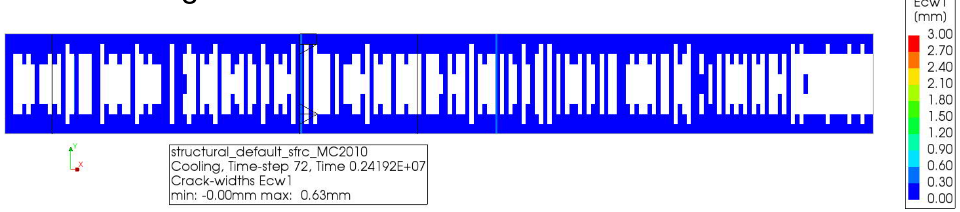
abt

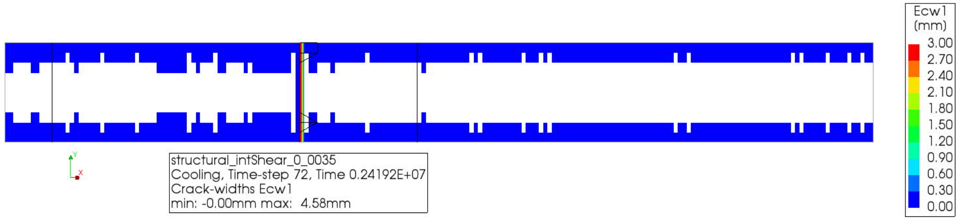
www.abt.eu

Influence of aspect ratio and BCs (2.5D model)

Close to sheet pile wall:
- A lot of restraint
- Also a lot of support (reinforcement)
- High shear stiffness 2D model realistic?



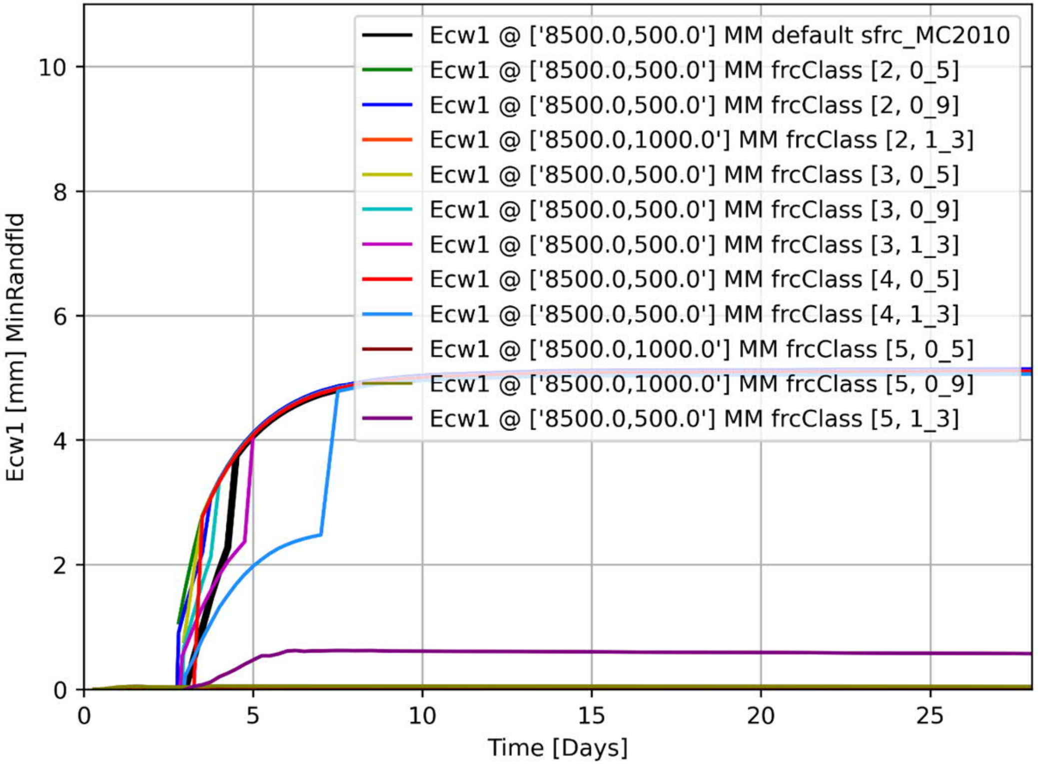


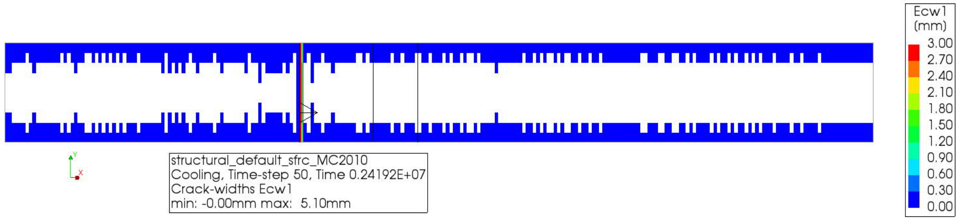


Far away from sheet pile wall:
- Little restraint
- Little support
- Low shear stiffness 2D model realistic?

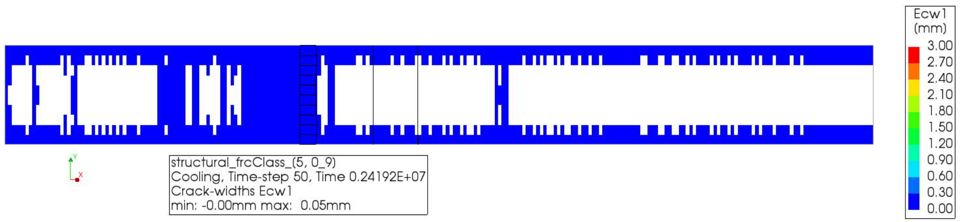
abt

Influence of steel fibres





Concrete: C30/37
SFRC MC2010: 2a t/m 4e
Result: a single big through-crack (leakage)



Concrete: C30/37
SFRC MC2010: 5a t/m 5e
Result: distributed smaller cracks

Correlation concrete strength class – SFRC performance

alpha_k=0,6

C20/25	a	b	c	d	e
1	0	3	4	2	0
1,5	0	6	6	2	0
2	0	2	4	4	0
2,5	0	0	4	2	0
3	0	0	1	1	0
3,5	0	0	0	1	0
4	0	0	0	0	0

C25/30	a	b	c	d	e
1	0	3	4	0	0
1,5	0	4	5	3	0
2	0	1	7	4	0
2,5	0	0	3	3	0
3	0	0	1	3	0
3,5	0	0	0	1	0
4	0	0	0	0	0

C30/37	a	b	c	d	e
1	0	2	4	0	0
1,5	0	1	9	3	2
2	0	0	7	2	2
2,5	0	0	4	4	1
3	0	0	1	4	1
3,5	0	0	0	1	0
4	0	0	0	1	0

C35/45	a	b	c	d	e
1	0	1	4	0	0
1,5	0	0	9	2	2
2	0	0	7	3	1
2,5	0	0	5	3	1
3	0	0	2	3	2
3,5	0	0	0	3	0
4	0	0	0	1	0

Source: Bekaert

alpha_k=0 C20/25-C35/45	a	b	c	d	e
1	0	9	16	2	0
1,5	0	11	29	10	4
2	0	3	25	13	3
2,5	0	0	16	12	2
3	0	0	5	11	3
3,5	0	0	0	6	0
4	0	0	0	2	0
4,5	0	0	0	0	0
5	0	0	0	0	0

Special attention concrete mixture i.r.t. type/dosage steel fibres
+ 0,5 a 1,0 MPa

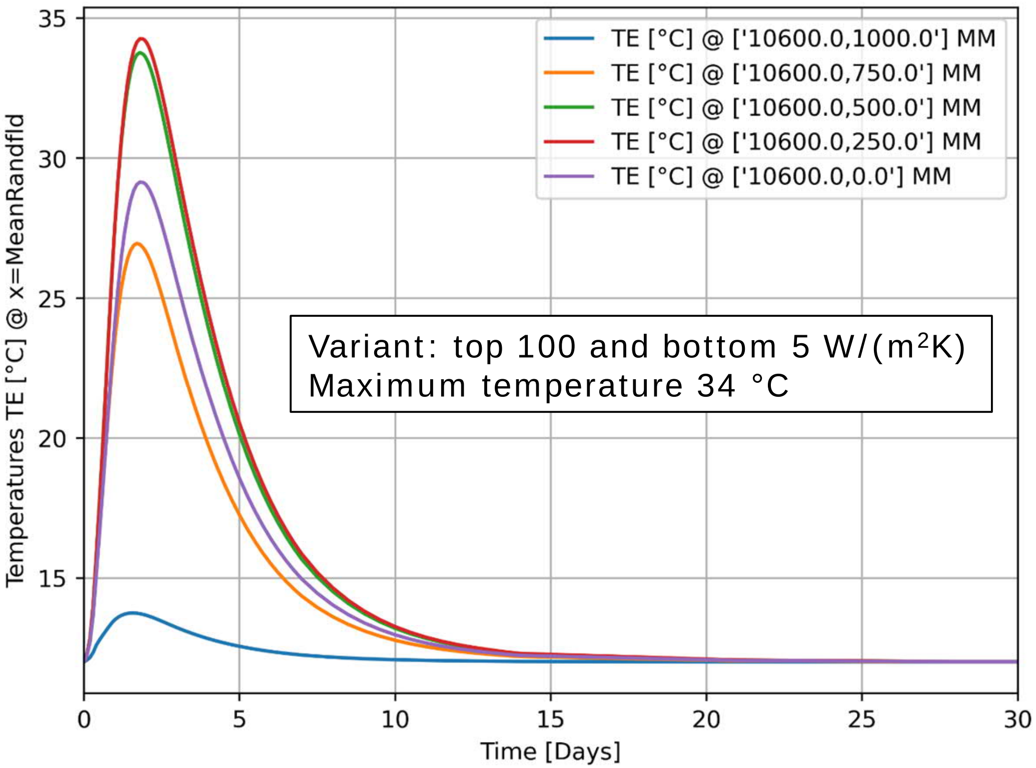
Indicative: successful projects SFRUWC

Result DIANA: one big crack

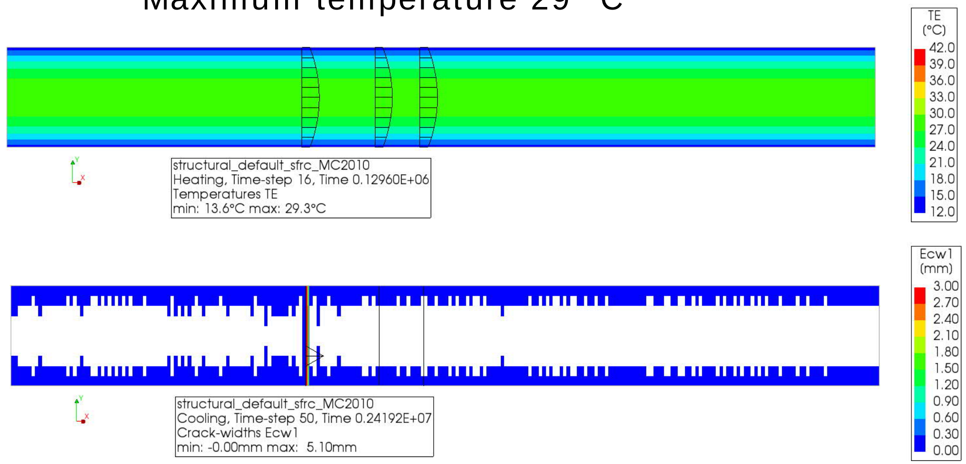
Result DIANA: several smaller cracks

www.abt.eu

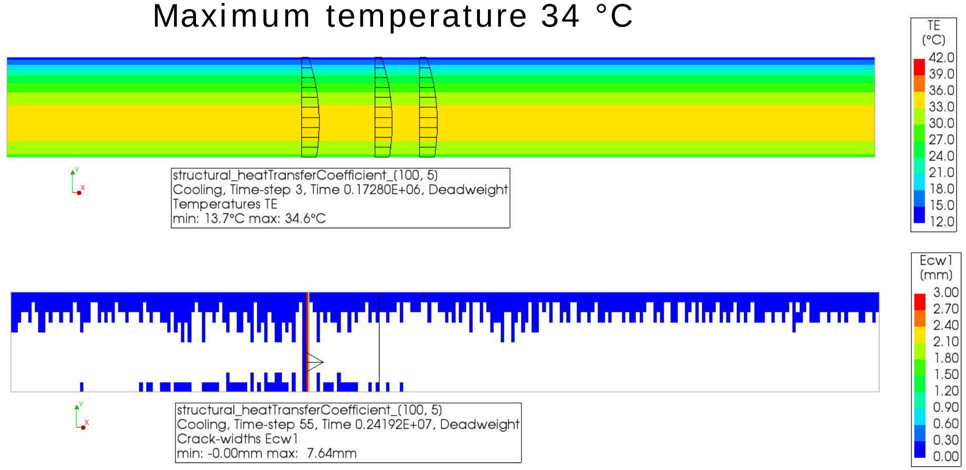
Influence of restraint curvature at early age



Base model: top and bottom 100 W/(m²K)
Maximum temperature 29 °C



Variant: top 100 en bottom 5 W/(m²K)
Maximum temperature 34 °C



Validation

Goal: gain confidence in numerical model and analyses (DIANA) and validate with theory / cases from practice / experiments

- DIANA vs theory
- DIANA vs cases from practice (SG5)
- DIANA vs experiments from literature
- DIANA vs lab experiments TUD / in-situ measurements Singelgrachtgarage

Validation is very important because of:

- Large uncertainty in input and assumption for FE model
- Results strongly depend on the assumed input
- Convergence problems in the FEA

abt

Validation temperature analysis

Cement & Concrete Composites 40 (2013) 48–58

Contents lists available at SciVerse ScienceDirect

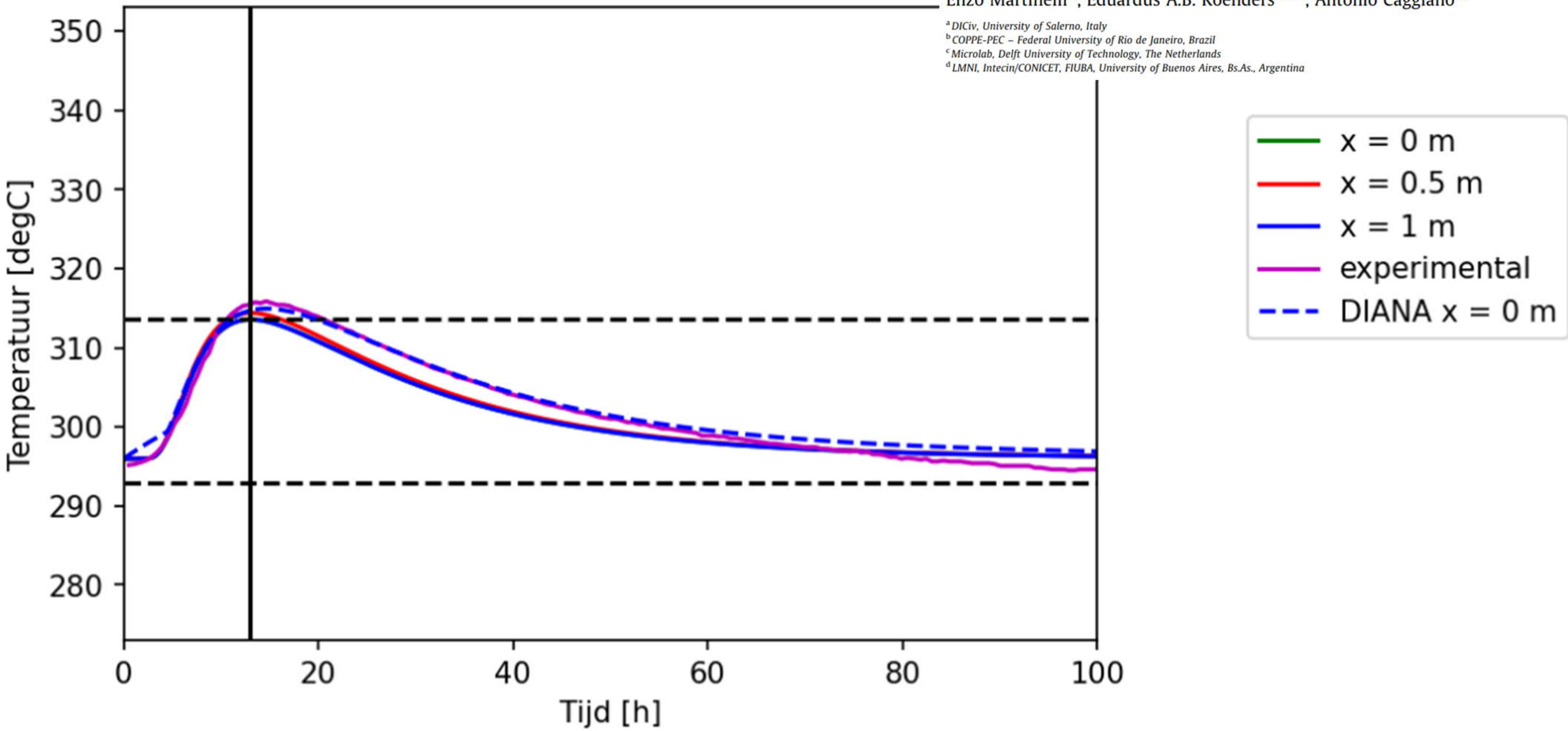
Cement & Concrete Composites

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

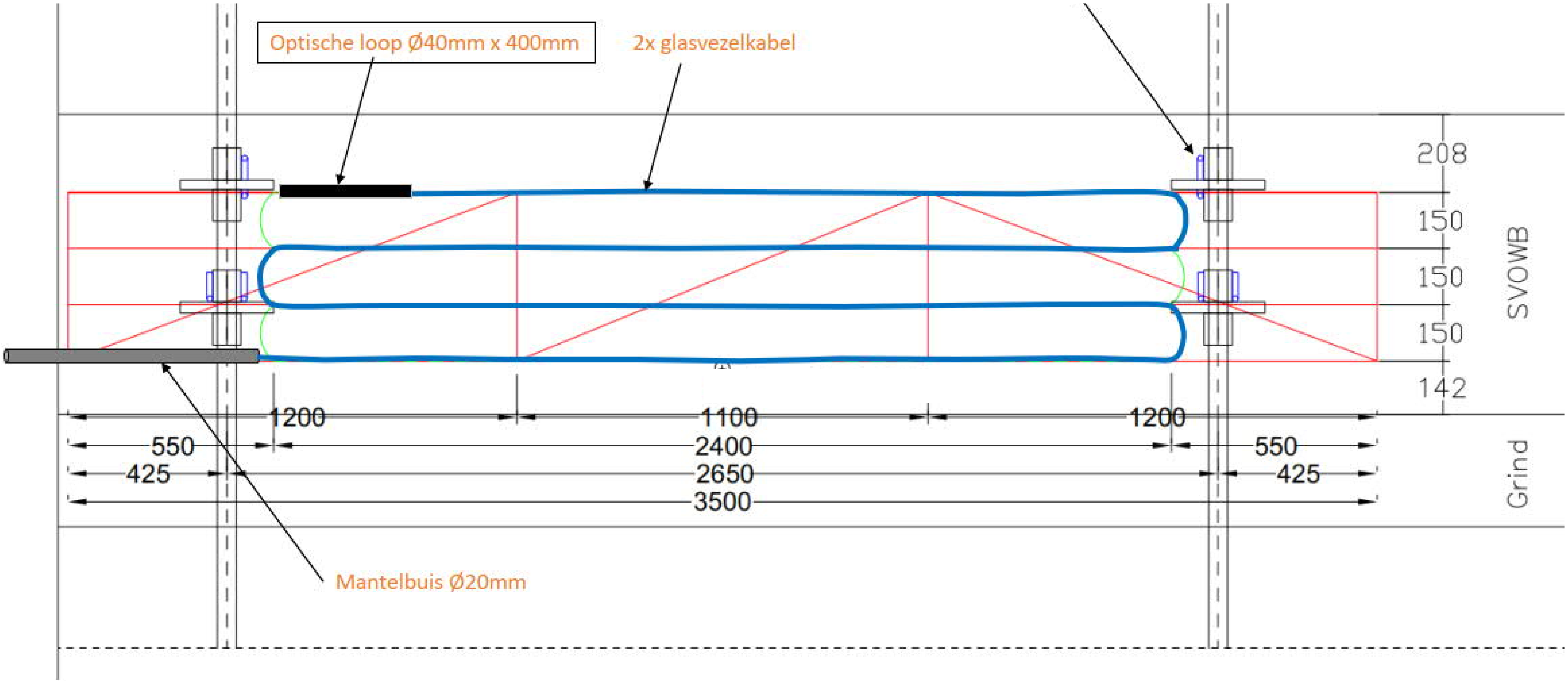
A numerical recipe for modelling hydration and heat flow in hardening concrete

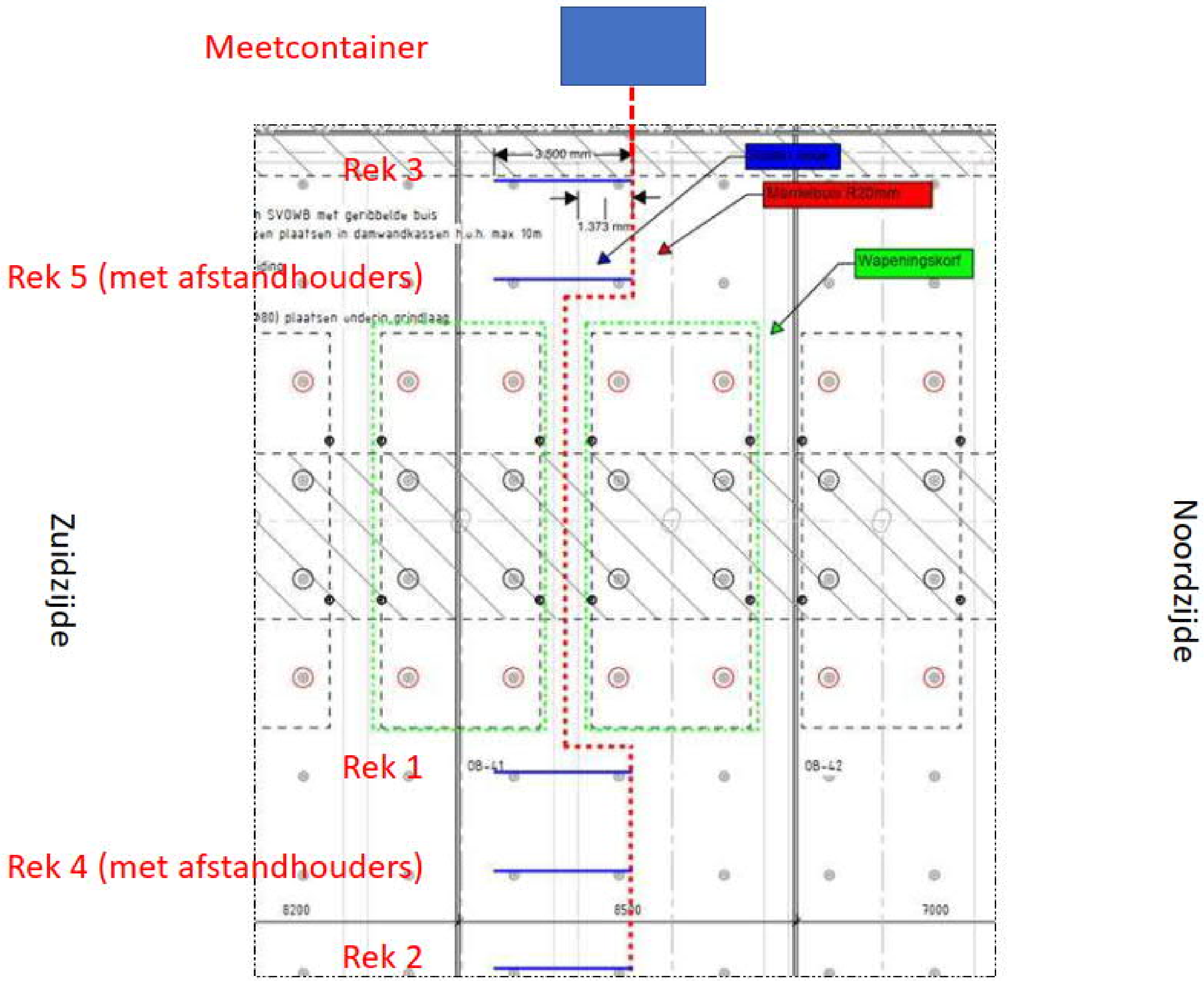
Enzo Martinelli [a], Eduardus A.B. Koenders [b,c,*], Antonio Caggiano [d]

[a] DICiv, University of Salerno, Italy
[b] COPPE-PEC – Federal University of Rio de Janeiro, Brazil
[c] Microlab, Delft University of Technology, The Netherlands
[d] LMNI, Intecin/CONICET, FIUBA, University of Buenos Aires, Bs.As., Argentina

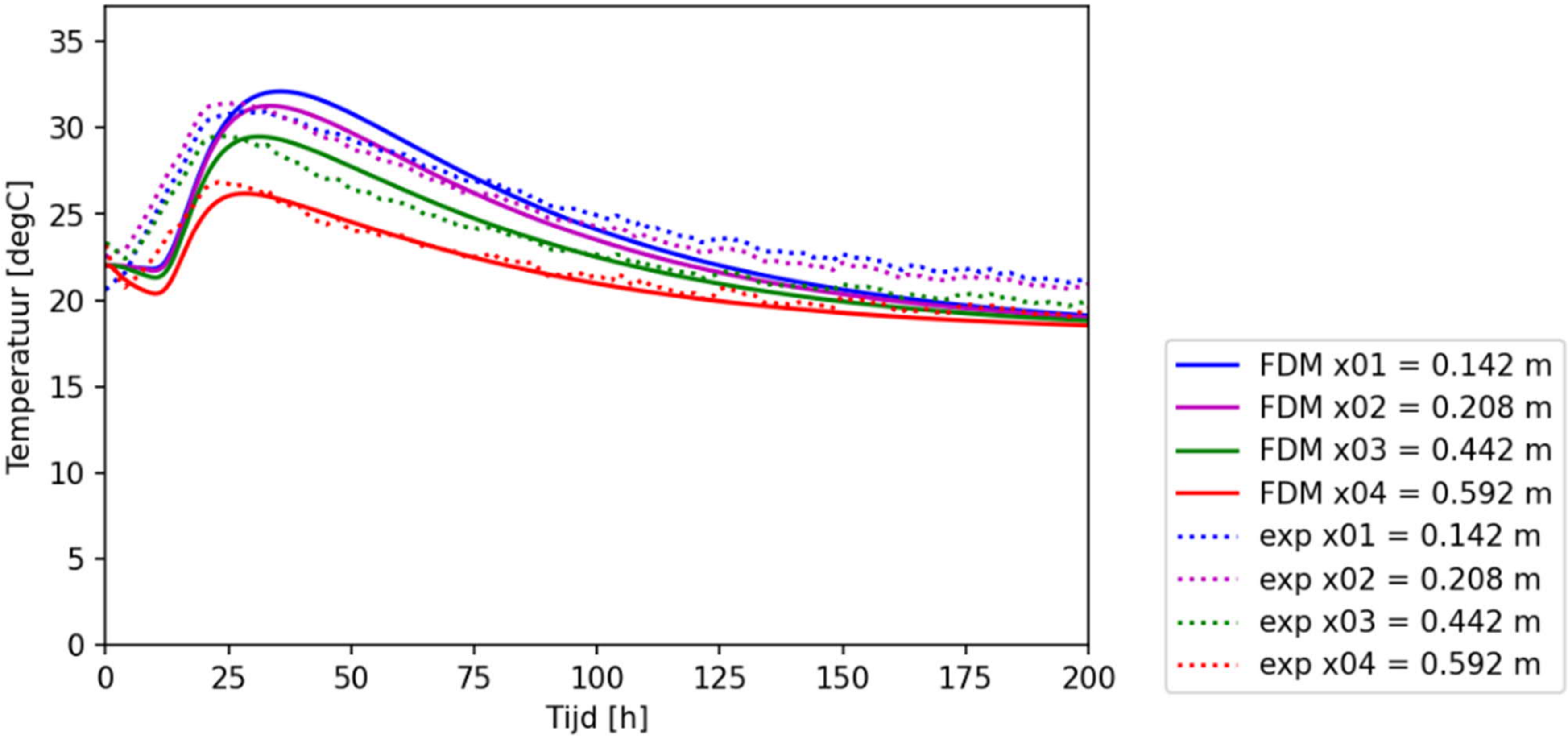


Measurement setup Singelgrachtgarage




Meetcontainer
Rek 3
3.500 mm
1.373 mm
Rek 5 (met afstandhouders)
Wapeningskorf
Zuidzijde
Noordzijde
Rek 1
OB-41
OB-42
Rek 4 (met afstandhouders)
8200
7000
Rek 2

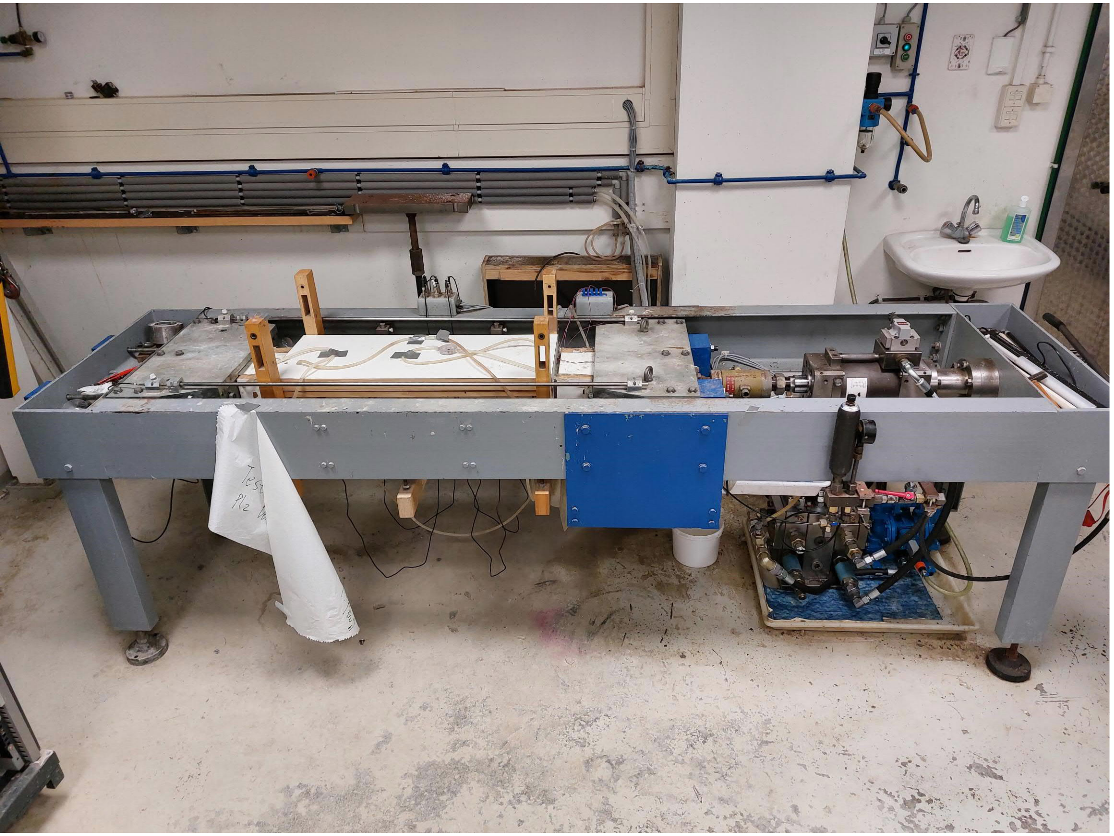
Singelgrachtgarage vs FDM (literature)

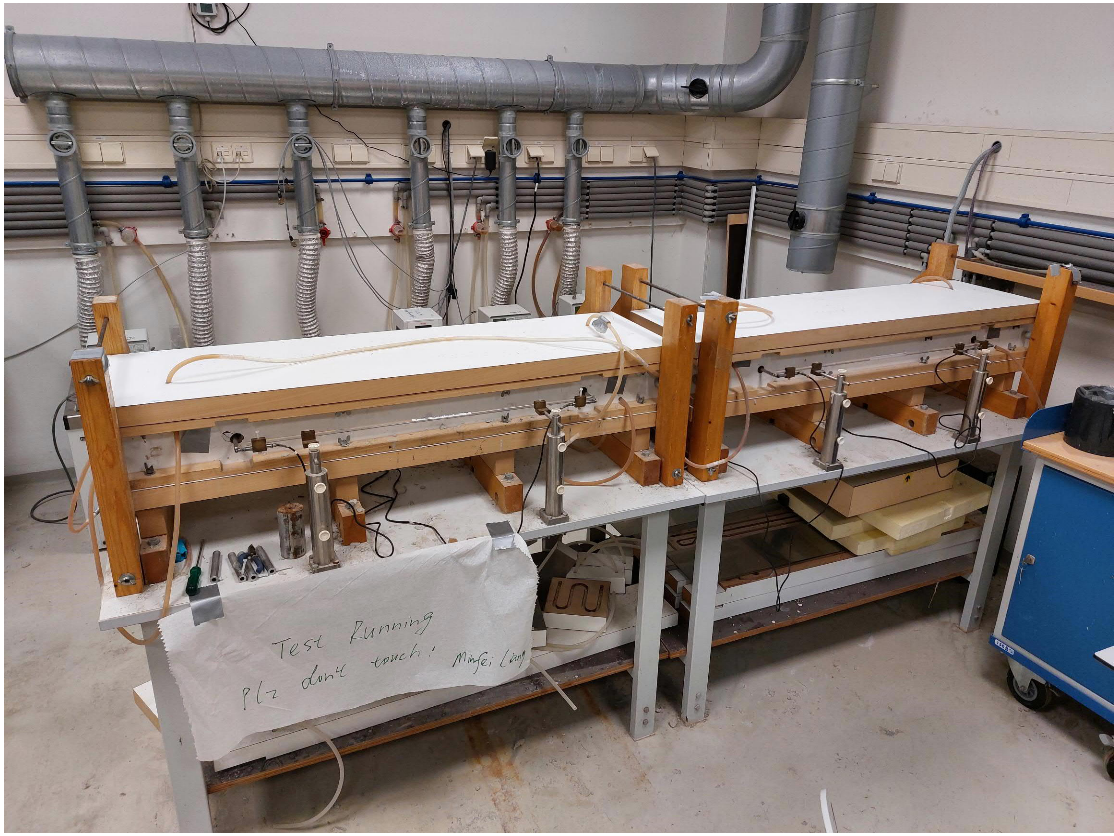


abt

www.abt.eu

TU Delft autogenous shrinkage / temperature / relaxation





To-do / remaining challenges for CUR-CROW guideline

SG4 validation:

- Understand Singelgracht / TU Delft experiments and compare to FEA
- Wrap-up and report theoretical validation

SG4 FEA:

- Update starting points based on latest findings (may be too conservative now)
- Re-run sensitivity analysis and update conclusions

SG5:

- Further develop design rules and test on cases

www.abt.eu

Challenges FEA

- Use 1D coupled analysis as input for 2.5D shell model
- Implement relaxation of YHC
- Implement autogenous shrinkage
- Fix convergence problems

Separate:

- Research project (Master thesis) Dennis Slockers using PROBAB / probabilistic analysis

www.abt.eu

Lex van der Meer
l.vd.meer@abt.eu
DOV Technische Lezingenavond
15 september 2022