Danish Concrete Days, 2017

Control of cracks due to shrinkage and early age thermal actions

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Bridge design and Management

Agenda

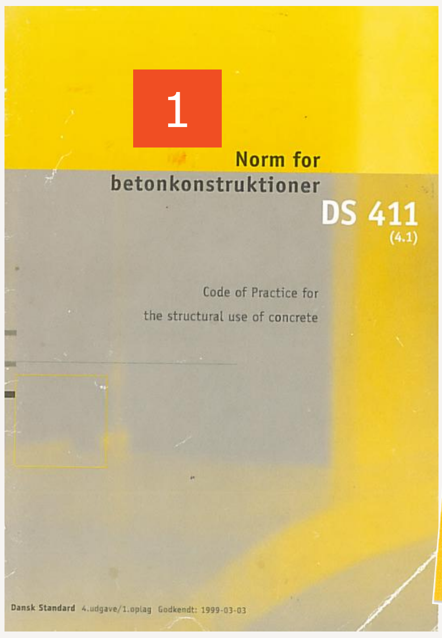
- Introduction
- The Danish formula, background and definitions
- Crack width specifications
- Controlling TCS crack widths in practice
- “Owners” of cracks
- Early age cracking – the Danish/Nordic way
- Specifications
- Experience and ideas for development
- Temperature and strength simulations
- Assessment
- Summary and closure

Concrete – one big problem: Cracks !

- Throughout my career (from 1986) – and before – cracks has been a cause of discussion in our industry
- With a simple formula/design rule we can design the minimum needed reinforcement to control the cracks to an agreed level
- But few know this "**big secret**" and even fewer use the design rule and obtain the advantages of it

Breakwater in Tangier with controlled cracks

The Danish Formula



3 ENERGI STYRELSEN

DS/EN 1992-1-1 DK NA:2013
Nationalt anneks til
Eurocode 2: Betonkonstruktioner –
Del 1-1: Generelle regler samt regler for bygningskonstruktioner

$$\rho = \sqrt{\frac{\phi f_{ct,ef}}{4E_{sk}kw_k}}$$

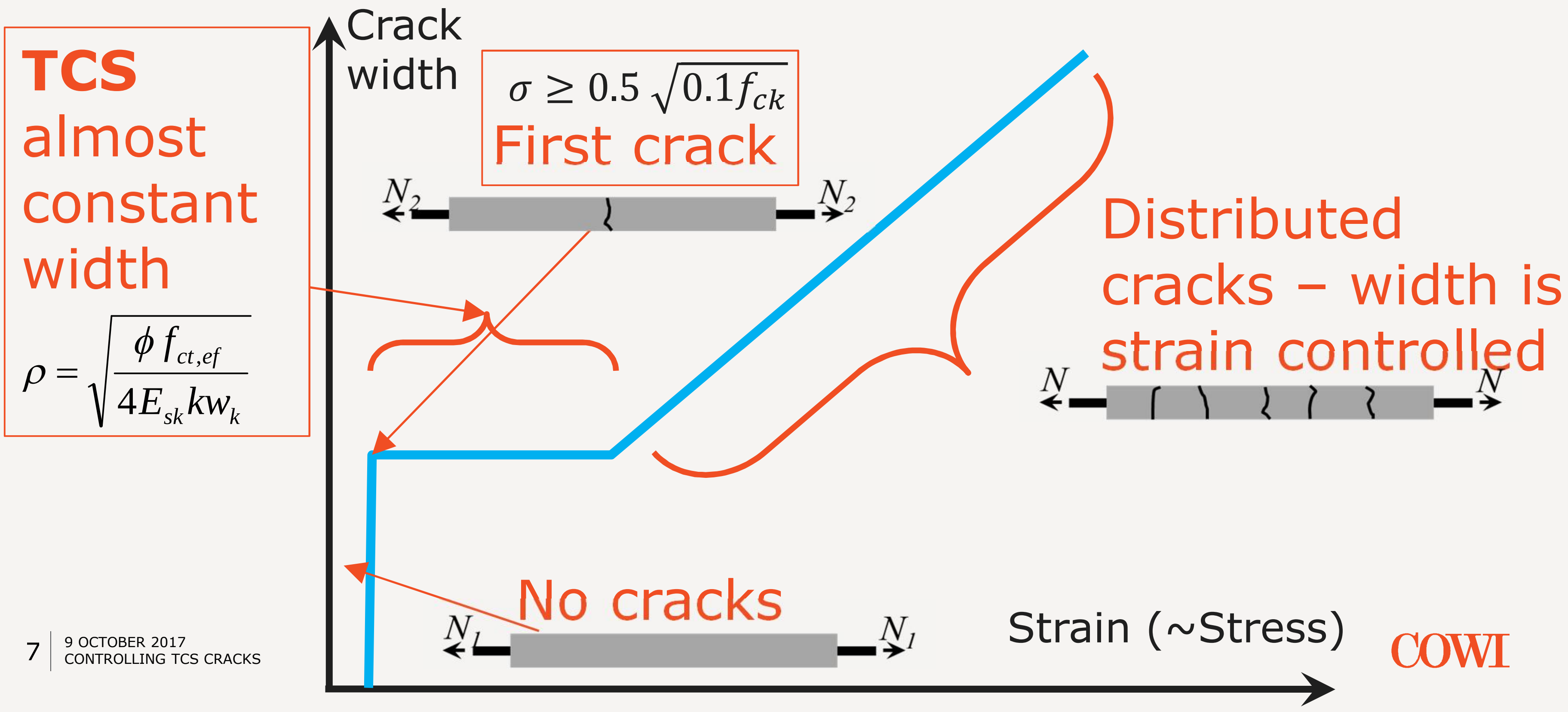
Polished floor in a shop
visible cracks – in spite of sectioning!

What went wrong ?

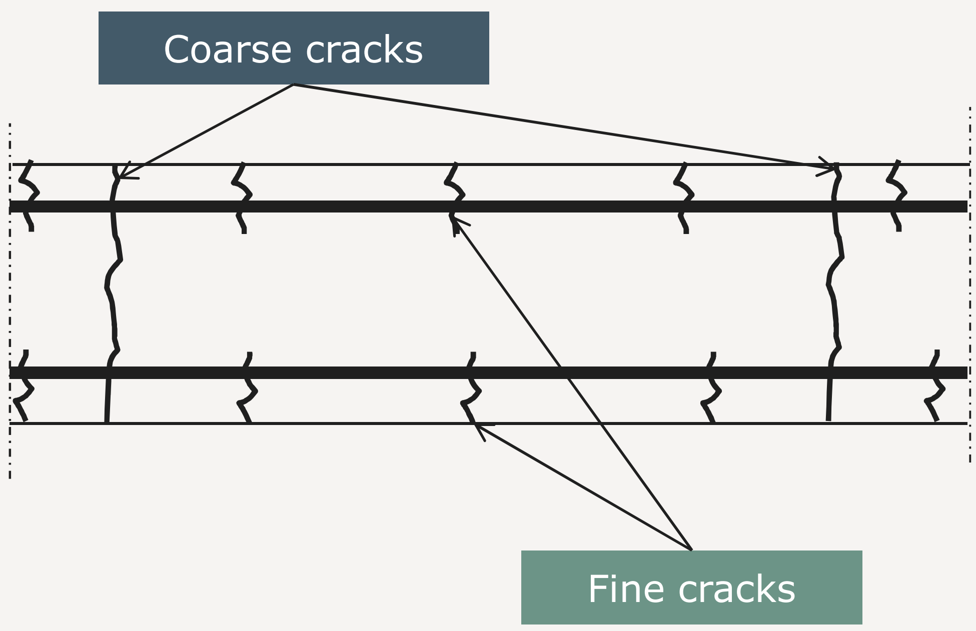
Definition of TCS cracks

- TCS actions are movements due to concrete's Shrinkage, Creep and Temperature changes – no external forces
- Concrete's TCS actions leads to **cracks** just because the structure has a certain size *or* because it's movements are restrained
- Concrete's temperature development during early hardening results in the same kind of cracks

Development of cracks in reinforced concrete



Be aware of the terminology



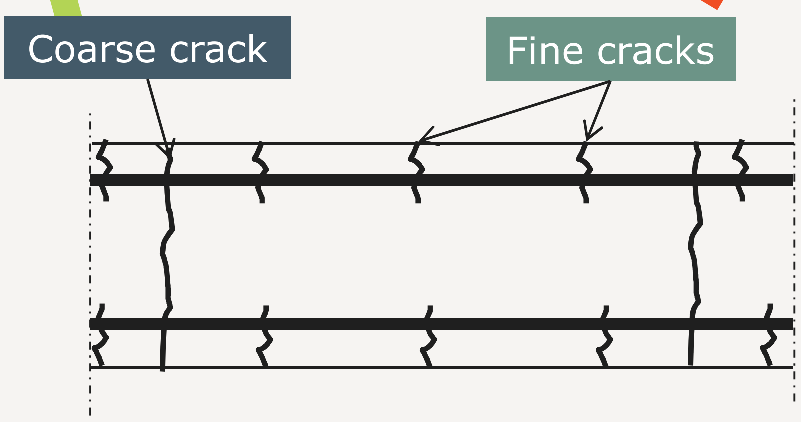
- The "*coarse cracks*" pass through the section…
- …and can have a smaller width than…
- …the "*fine cracks*" that are only present around the reinforcement

Fine and the coarse cracks – the Danish way:

COARSE CRACKS	FINE CRACKS
If $\zeta \geq 0.6 : \rho_1 = \sqrt{\dfrac{\phi f_{ctef}}{8 E_{sk} w_k}}$	If $\zeta \geq 0.6 : \rho_2 = \sqrt{\dfrac{\phi f_{ctef}}{4 E_{sk} w_k}}$

$$\rho = \sqrt{\frac{\phi f_{ct,ef}}{4 E_{sk} k w_k}}$$

k is 1 for the fine crack system and 2 for the coarse crack system



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Allowable crack widths, DS/EN 1992 FU:2013:

(5) Der bør fastlægges en grænseværdi, w_{max}, for den beregnede revnevidde, w_k, der tager hensyn til konstruktionens foreslåede anvendelse og art samt omkostningerne ved revnebegrænsning.

Tabel 7.1NA – Anbefalede maksimale værdier af beregnede revnevidder w_{max} (mm)

Miljøklasse	Slap armering	Spændarmering
Ekstra aggressiv	0,2 mm	0,1 mm
Aggressiv	0,3 mm	0,2 mm
Moderat	0,4 mm	0,3 mm

Hvis der ikke stilles særlige krav (fx vandtæthed), kan det antages, at en begrænsning af revnevidden til w_{max}-værdierne anført i tabel 7.1NA under kvasipermanent lastkombination generelt vil være tilfredsstillende for armerede betonkonstruktionsdele i bygninger med hensyn til udseende og holdbarhed.

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Control crack widths!

- Reinforced and unreinforced concrete structures above a certain dimension or restrained will crack
- We don't want side-effects like:
  - Poor appearance on e.g. facades, high quality floors, outdoor pavements
  - Lack of durability in balconies, basins, bridges, tunnels and marine structures
  - Leakages and lack of function

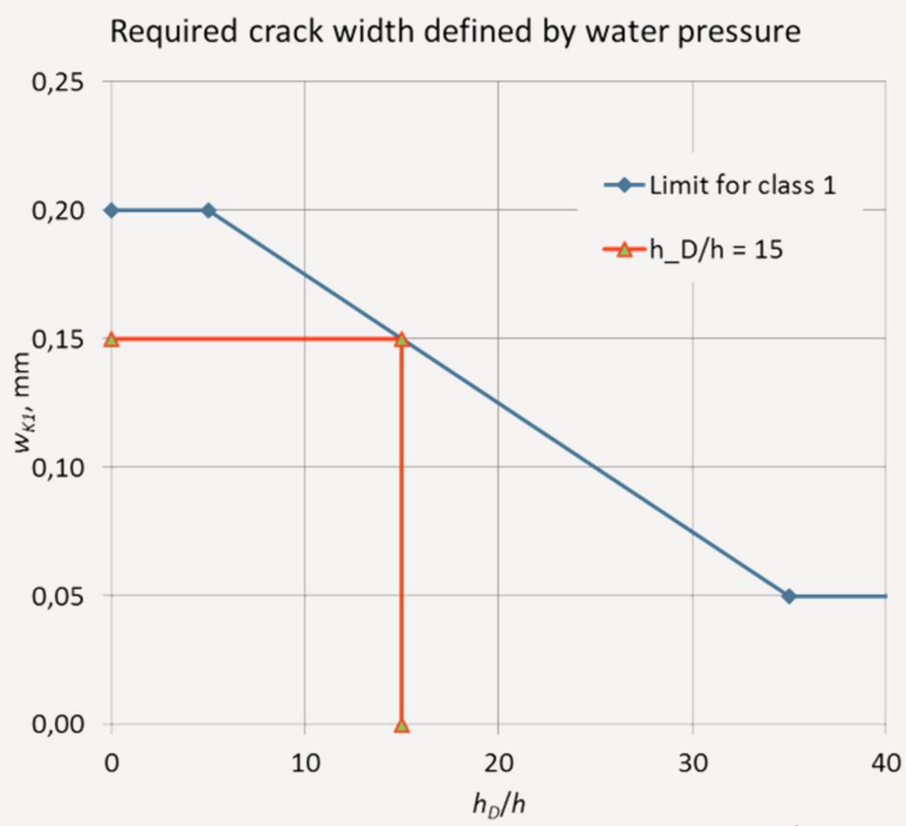
Does crack free concrete exist? To my experience it all depends on the distance of observation

Controlling crack widths to obtain self healing according to DS/EN 1992-3:2009

TABLE 7.105 – CLASSIFICATION OF TIGHTNESS

TIGHTNESS CLASS	REQUIREMENTS FOR LEAKAGE
0	Some degree of leakage acceptable, or leakage of liquids irrelevant
1	Leakage to be limited to a small amount. Some surface staining or damp patches acceptable
2	Leakage to be minimal. Appearance not to be impaired by staining
3	No leakage permitted

Controlling crack widths to obtain self healing according to DS/EN 1992-3:2009, Class 1



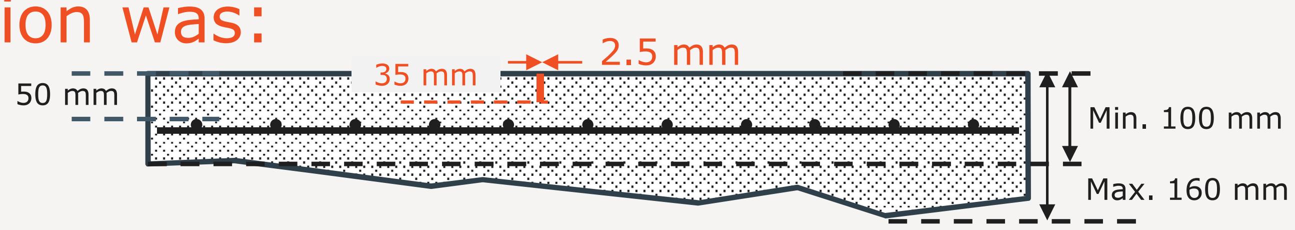
Reading for

- pressure height, h_D= 6 m
- and wall thickness h = 0.4 m

The cover thickness is one important parameter to control

When expectations to the crack width are not met it may well be due to a too large cover depth – cf. the following example from reality

The specification was:



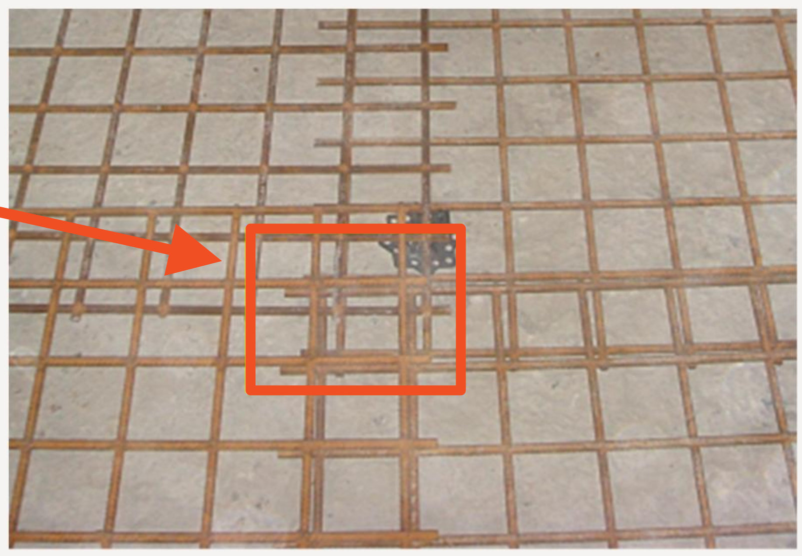
- Minimum thickness 100 mm
- Reinforcement Y10/100 mm
- Concrete: Fast self-desiccating C40/50 inclusive steel fibres 25 kg/m³
- Time for cutting crack inducers depends on temperature
- To be cut when the concrete has set 10-16 hours after casting

As built:
- Cover up to 100 mm
- Crack width measured up to 0.8 mm

Complaining customer

The cover thickness was not in control

- Reinforcement meshes takes up height – here it is 20+20+20+20 = 80 mm!
- The specification said 50 mm

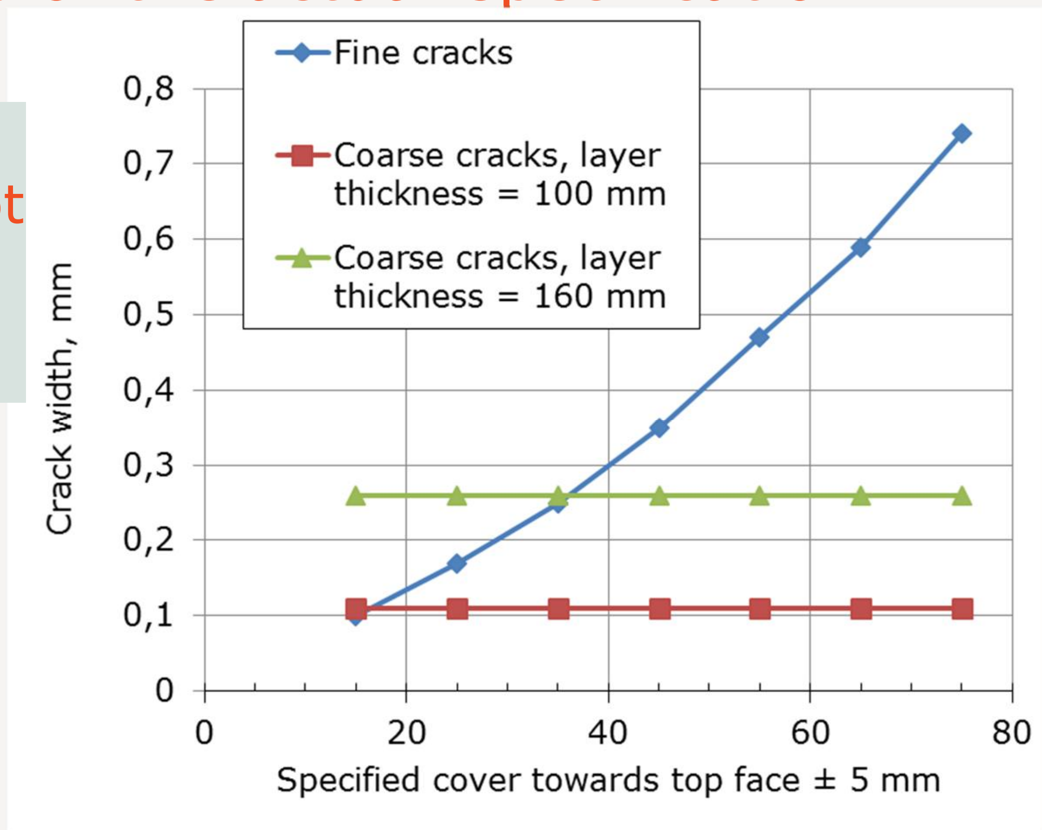


Do not allow overlaps of meshes

I.e. no crack control but a lot of effort put into the job!!

Calculated effects of the *actual* specification

I.e. in reality no crack control but a lot of effort and money put into the job



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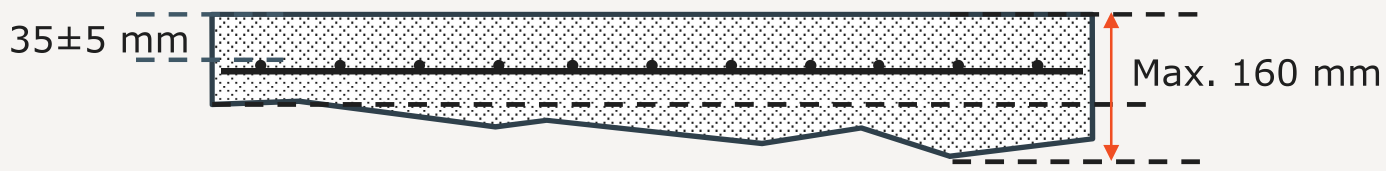
A simple and less expensive solution would be:



- ~~Minimum~~ Maximum thickness 160 mm ~~100~~
- Reinforcement Y10/100 mm
- Concrete: Fast self-desiccating C40/50 ~~incl~~ ~~steel fibres 25 kg/m³~~
- ~~Time for cutting crack inducers depends on temperature~~
- ~~To be cut when the concrete has set 10-16 after casting~~

Most likely result:

- Less expensive materials (no steel fibres)
- Less work (no cutting)
- **No need for joints for dilation**
- Crack widths max. 0.3 mm

Satisfied customer

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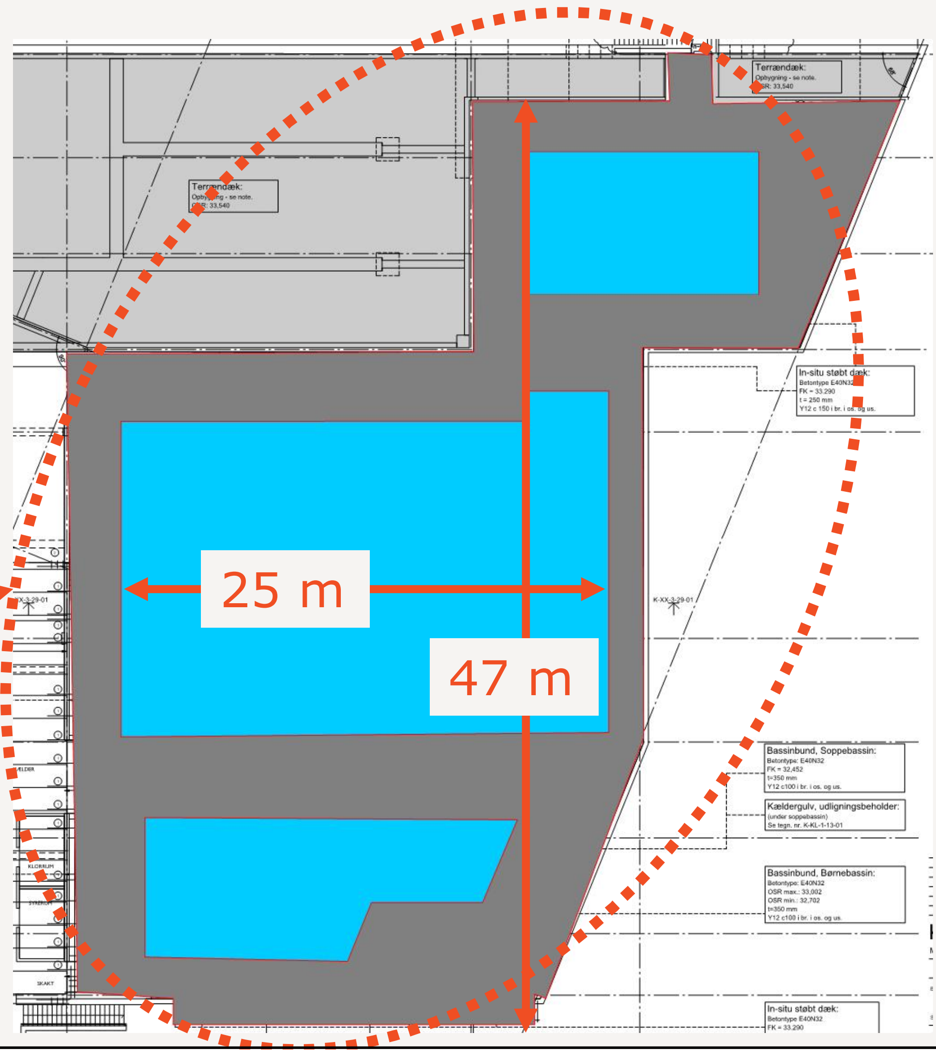
Reinforcement for crack control in simple shaped industrial floors – be aware of box outs

- f_{ck} = 30 MPa
- Crack width: ≤ 0.2 mm
- Cover towards top face (and bottom side if two meshes) = 25 ± 5 mm
- Anchoring factor ≥ 0.6
- **Do not exceed 140-150 mm spacing due to workers safety when walking on the meshes**

LAYER THICKNESS mm	NUMBER OF MESHES	REBAR DIAMETER mm	MAXIMUM DISTANCE mm
60	1	6	60
80	1	8	80
100	1	8	90
120	2	8	90
150	2	8	90
180	2	8	90
200	2	8	90
250	2	10	115
300	2	10	100
400	2	14	125
500	2	16	120

Swimming pools without membranes

A monolith **without** joints for dilation



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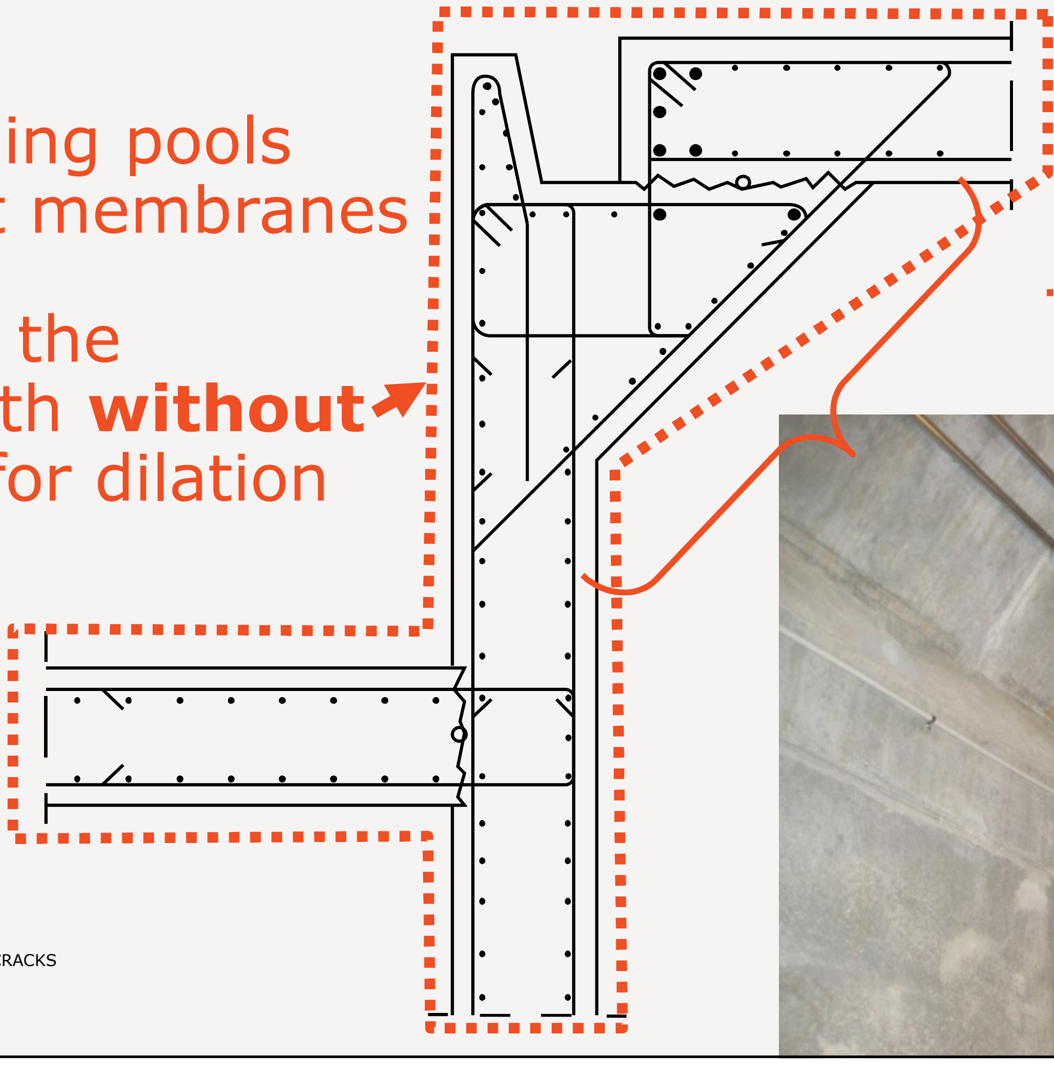
Swimming pools without membranes

Part of the monolith **without** joints for dilation



… and no leaks!

Specified crack widths for swimming pools without membranes

Structural member, concrete \ Exposure	Face towards Basin water, XD2	Face towards soil XC2	Face towards Service aisle XD1/XC2
Basin/tank walls E40	0.1 mm (0.2 mm)	-	0.2 mm (0.3 mm)
Bottom slabs E40	0.1 mm (0.2 mm)	0.2 mm (0.4 mm)	-
Promenade decks, E40	0.2 mm (0.2 mm)	-	0.3 mm (0.3 mm)
Slabs on soil, M30	-	0.3 mm (0.4 mm)	0.3 mm (0.4 mm)
Outer walls of basement, M30	-	0.3 mm (0.4 mm)	0.4 mm (0.4 mm)

Numbers in brackets are the requirements for crack widths in the structural members according to DK-NA/EN 1992

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Outdoor pavement

Controlling TCS cracks in outdoor pavements

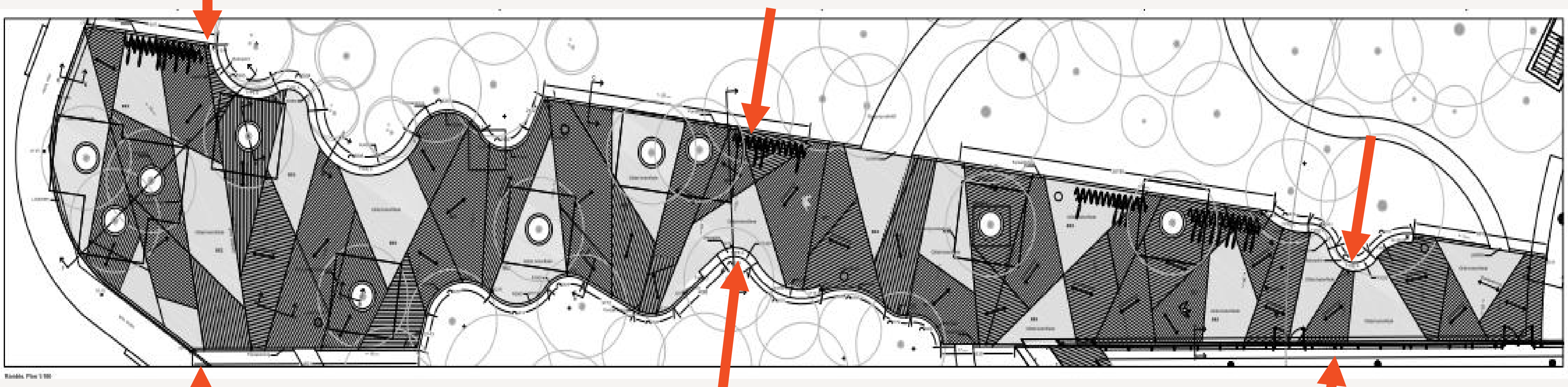
The landscape architect *Rasmus Astrup* from SLA expressed the following:

Approx. 100 m "Rambla"

- White concrete with organic shapes and holes for trees etc.
- Alternating surface texture
- Owner's concerns about dirt in joints
- Fire escape route – carry trucks

Outdoor pavement – odd shape

approx. 100 m



18.4 m

7 m

4,2 m

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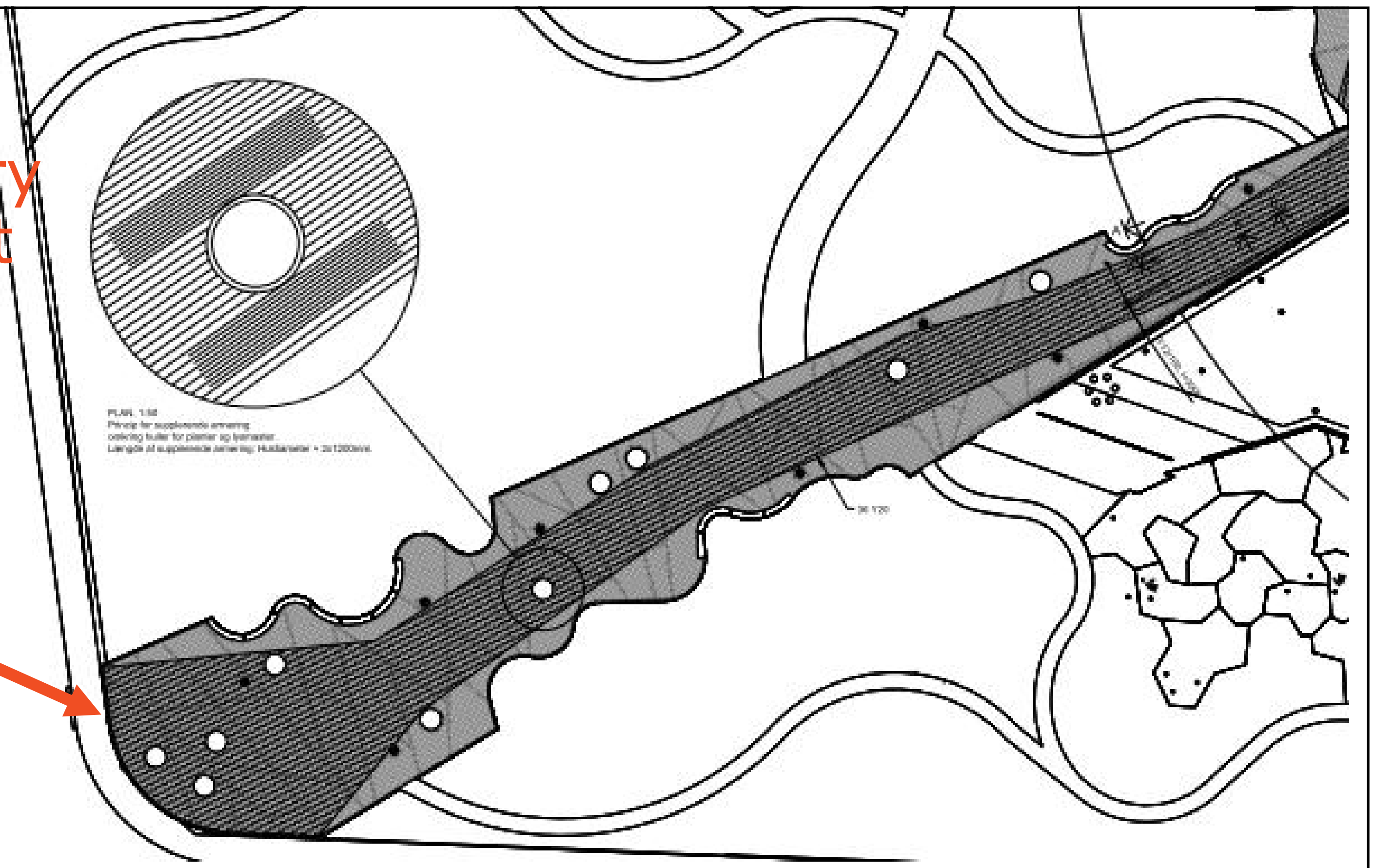
General and supplementary reinforcement

- Thickness 150 mm
- Reinforced by Y12 per 100 both directions, cover 35±5 mm towards top face
- Supplementing stringers by 36 pcs. Y20 placed below the general reinforcement



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Outdoor pavement

The pavement is not crack free – a few minor and short cracks can be found w< 0.30 mm

"Owners of cracks"

THE DESIGNER (Owner/engineer/architect):

- Cracks due to drying shrinkage
- Cracks due to deformations
- Cracks due to changes of the cross section (thickness, width, box outs)
- Cracks due to restraints (columns, stairs)
- Cracks due to the construction system

THE CONTRACTOR:

- Cracks due to plastic shrinkage
- Cracks due to deformations of the form work
- Cracks due to non-confirming execution (layer and cover thickness)

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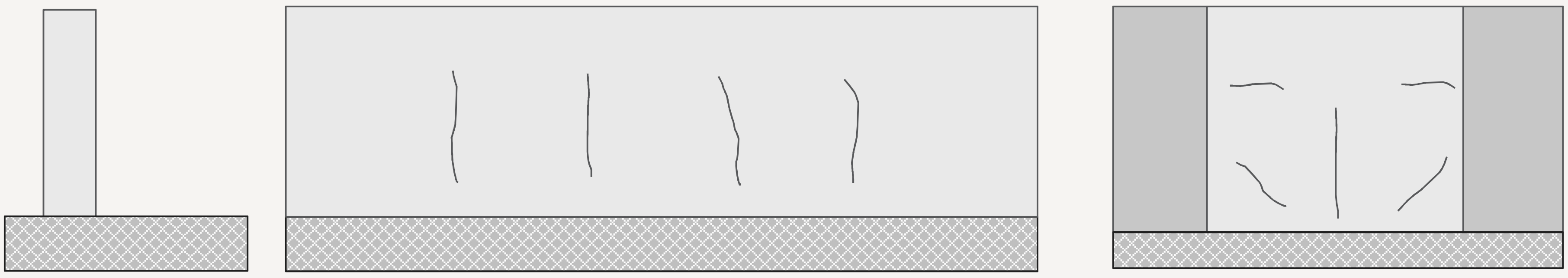
Early age thermal cracking – the Danish/Nordic way



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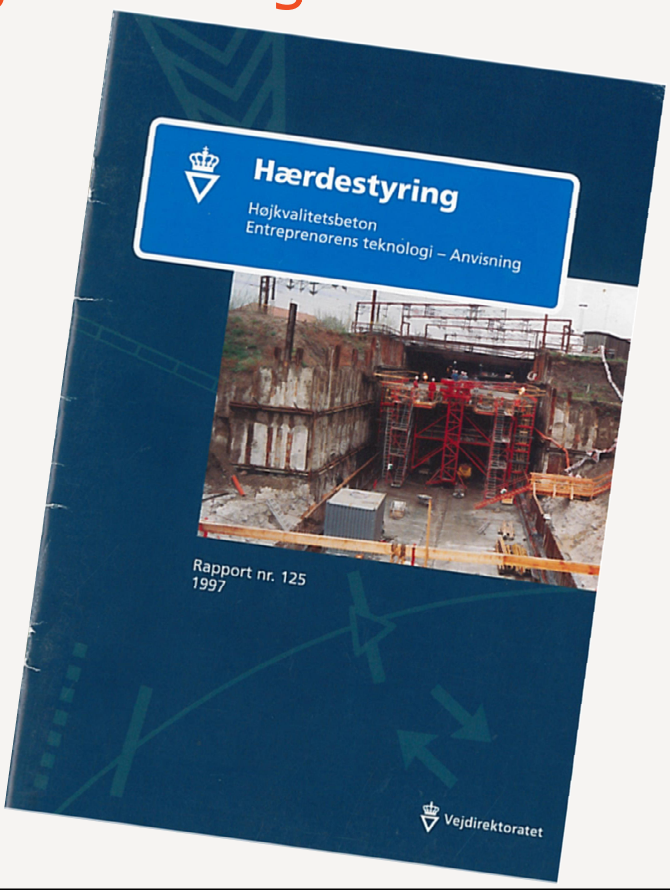
Early age thermal cracking – the right text and other guidance:

HETEK – report no. 125, 1997:



Early age thermal cracking – right and wrong texts:

DS 411, 3rd ed. 1984 – wrong interpretation of the problem:

~~Hvis væggen sammenstøbes med et tidligere udstøbt fundament, må det sikres, at forskellen mellem væggens middeltemperatur og fundamentets temperatur i nærheden af støbeskellet på intet tidspunkt overstiger ca 15 °C.~~

HETEK – report no. 125, 1997 – correct interpretation of the problem:

D_{ydre} Kravet til den ydre temperaturforskel, D_{ydre}, vedrører den maksimale forskel der må optræde i to sammenstøbte konstruktionsdeles respektive middeltemperaturer. Kravet stilles til konstruktionsdele, der støbes til forskellige tidspunkter. Hvis der optræder væsentlige forskelle i godstykkelse inden for

Early age thermal cracking – right and wrong texts:

DS/EN 13670:2010 – Anneks F (informativt):

(4) Overfladetemperaturen i støbeskel bør ikke være over 0 °C på støbetidspunktet.

What?

EN 13670:2009 (E) – Annex F (informative), F.8.2:

(4) The surface temperature at the construction joint should be above 0 °C at the time of concreting.

Luckily it was only a matter of wrong translation ☺

Therefore: Read multilingual standards carefully – and refer to the original

Early age thermal cracking – now the requirement only exists in the special specifications (Concrete Bridge - SWS-P) "Vejregler":

In connection with stitching, the difference between the mean temperature of concrete element .... and concrete element .... shall not exceed .... °C unless it is documented in the calculation that .... % of the current splitting tensile strength of the concrete is not exceeded.

...continues...

Early age thermal cracking – now the requirement only exists in the special specifications (Concrete Bridge - SWS-P) "Vejregler":

…continued…

The Contractor's documentation for ensuring compliance with the hardening requirements shall be available in the form of calculations of expected temperature and tension conditions.

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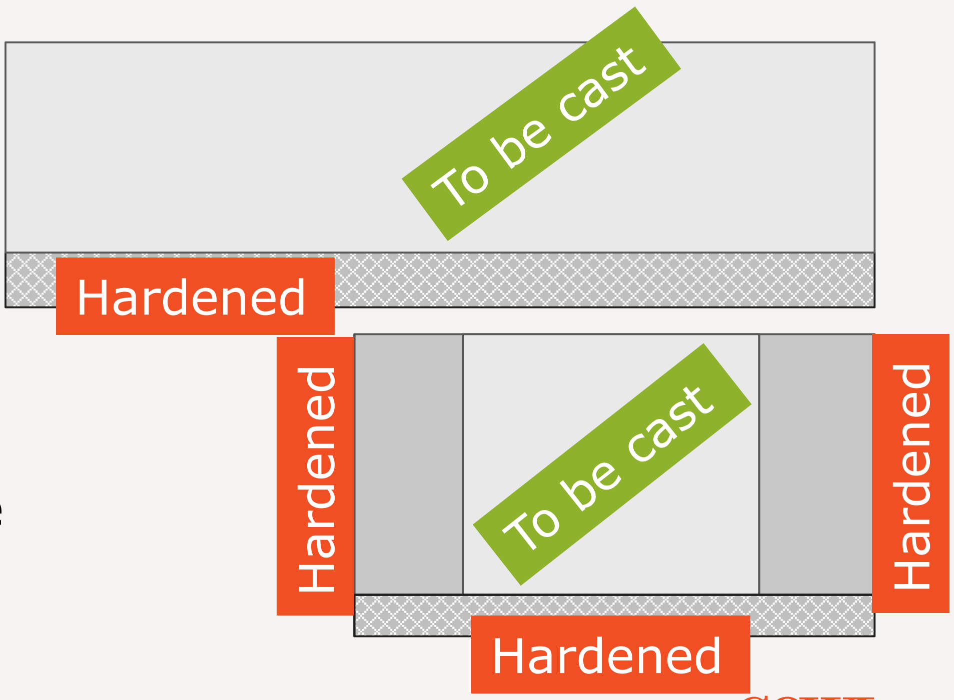
Early age thermal cracking

- The difference between the already cast structure's mean temperature and the new casting's mean temperature "$\Delta_{mean,max}$" shall be limited to 15 °C
- This requirement is **only relevant** when the length of the structure exceeds 4-6 m along the casting joint.



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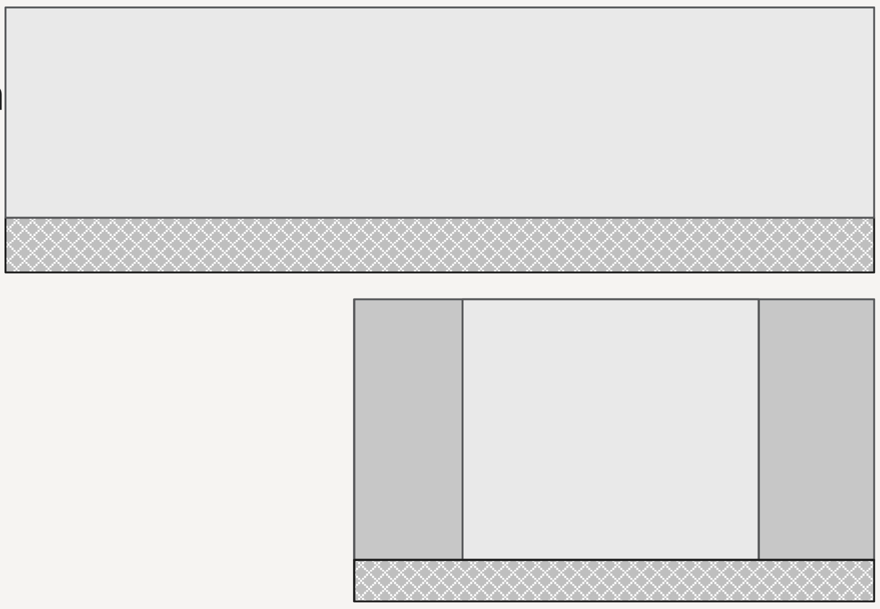
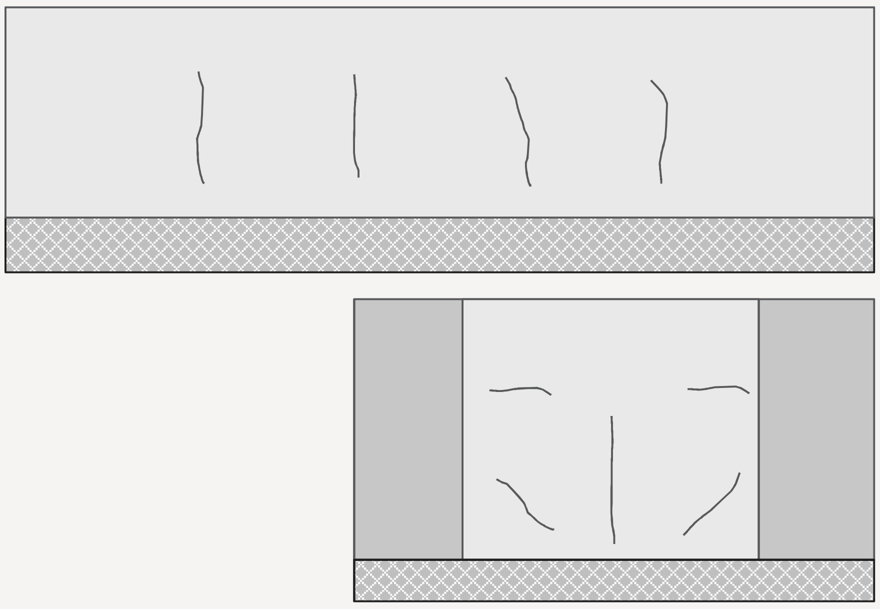
Early age thermal cracking

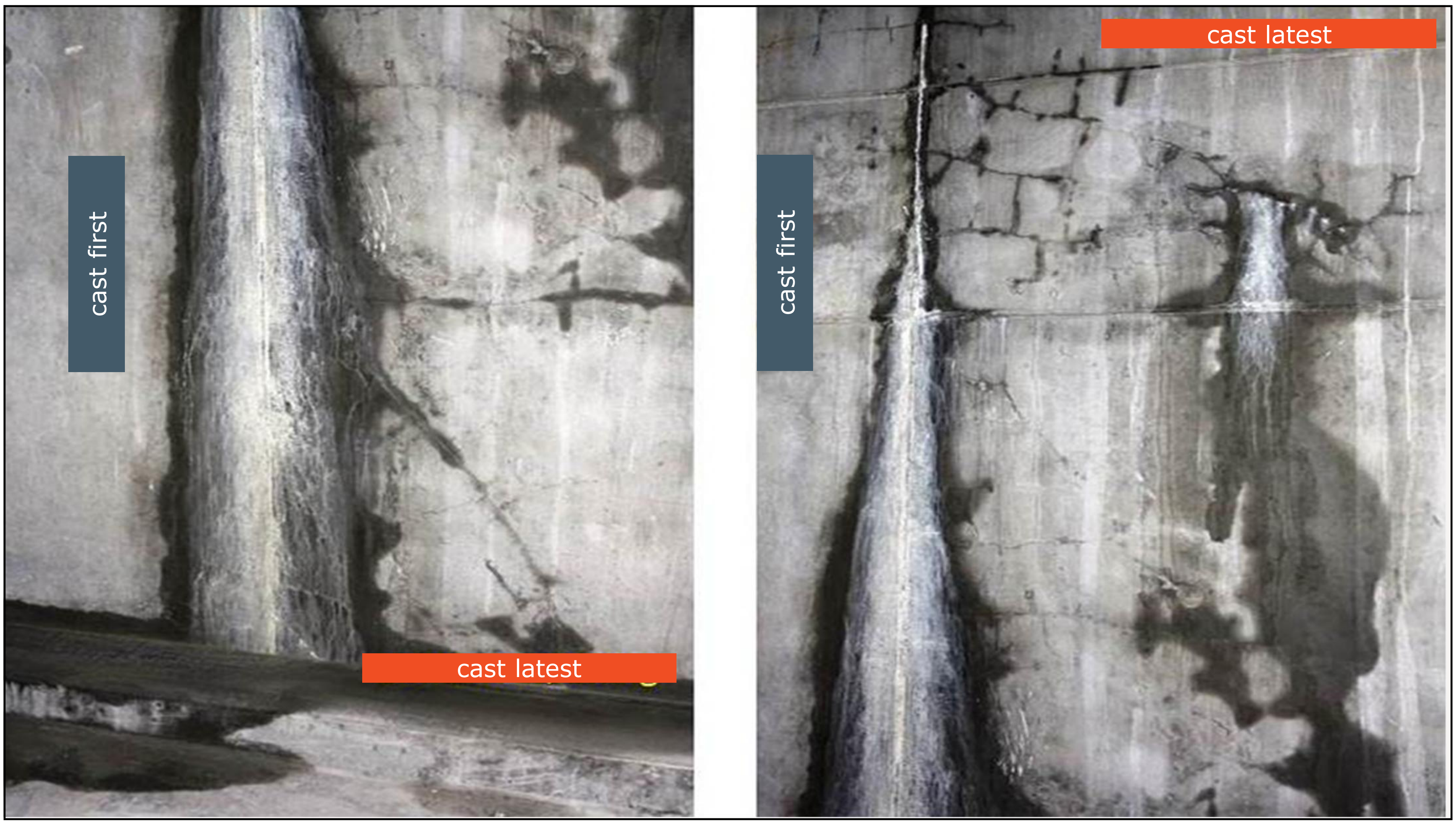
- If $\Delta_{mean,\ max}$ is **NOT EXCEEDED**, cracks passing through the structural member will most likely not form at an early stage.
- A sufficient reinforcement to control cracks due to shrinkage is still needed and must be able to distribute the cracking even at a late stage.
- The concrete strength is fully developed at this time, and therefore the reinforcement shall correspond to the design strength, f_{ck}.

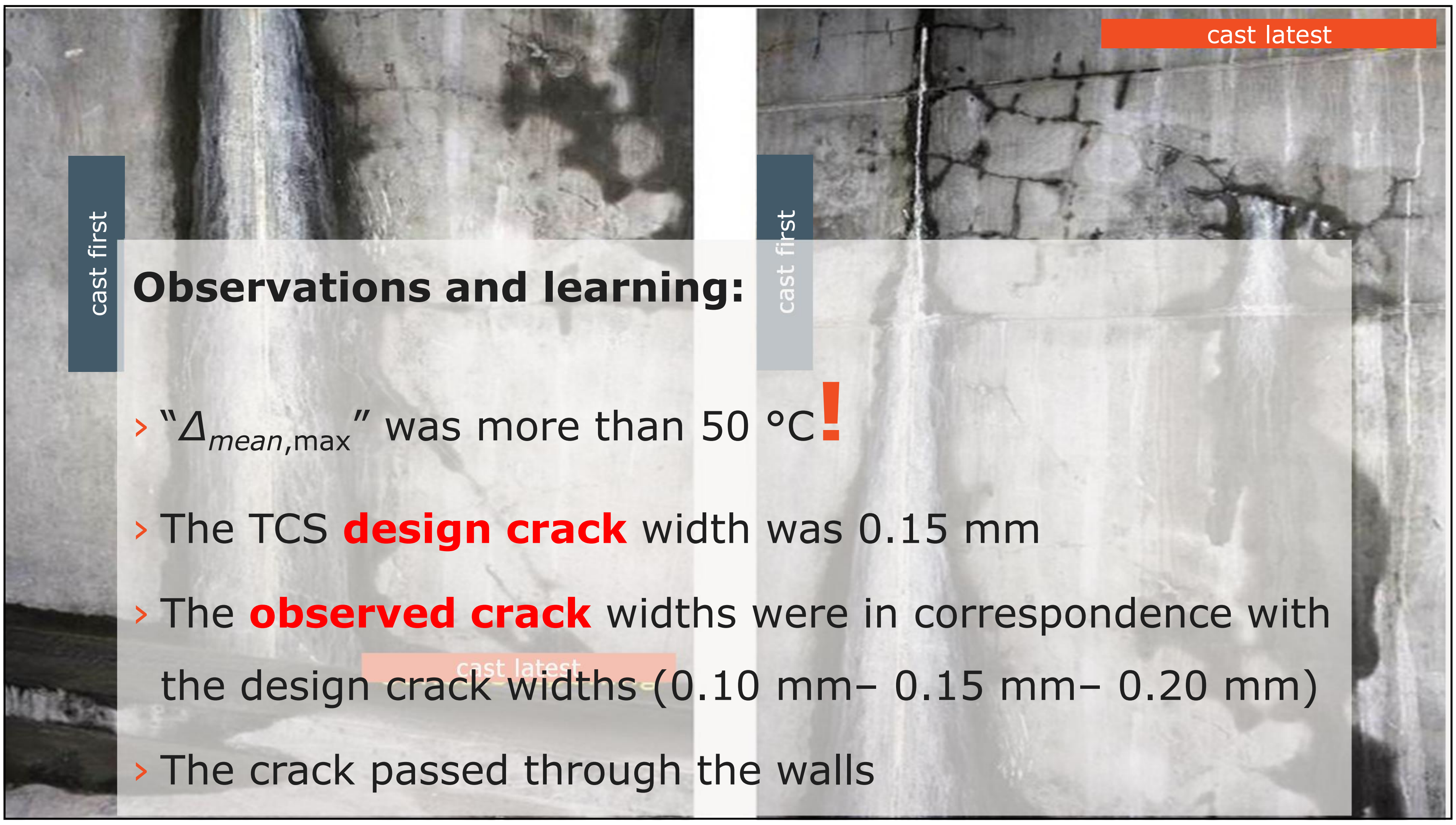


Early age thermal cracking

- If $\Delta_{mean,\ max}$ is **EXCEEDED**, cracks passing through the structural member will most likely form early.
- A sufficient reinforcement for control of TCS cracks will act and will control and distribute the cracking.
- The concrete strength is not fully developed at this time, and therefore the reinforcement is strong compared to the concrete's tensile capacity







Observations and learning:

- “$\Delta_{mean,\mathrm{max}}$” was more than 50 °C**!**
- The TCS **design crack** width was 0.15 mm
- The **observed crack** widths were in correspondence with the design crack widths (0.10 mm– 0.15 mm– 0.20 mm)
- The crack passed through the walls

Is temperature control always needed?

- Sufficient reinforcement is needed to control for late cracking due to TCS
- The maximum crack width is the same – but it appears at an early stage
- The crack development is independent of the stress/strain

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Questions

- What is the strength of concrete when early age cracks appear?
- Does the reinforcement work at this stage?
- How can this be tested?
- Will such a design rule be cost-effective for society?

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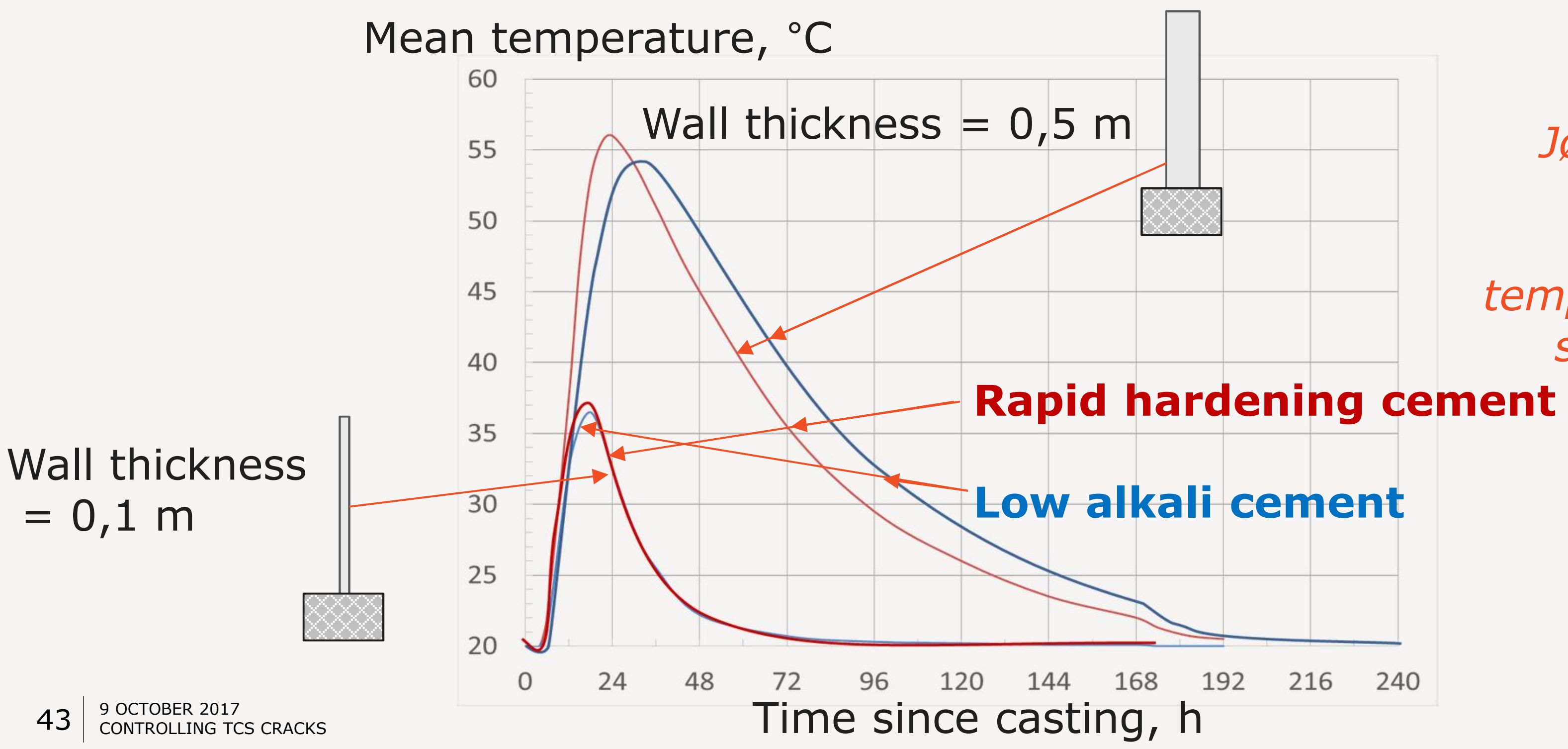
Simulation of early age temperatures, “wall on base”



Thanks to Jørgen Schou, UNICON for providing temperature and strength data

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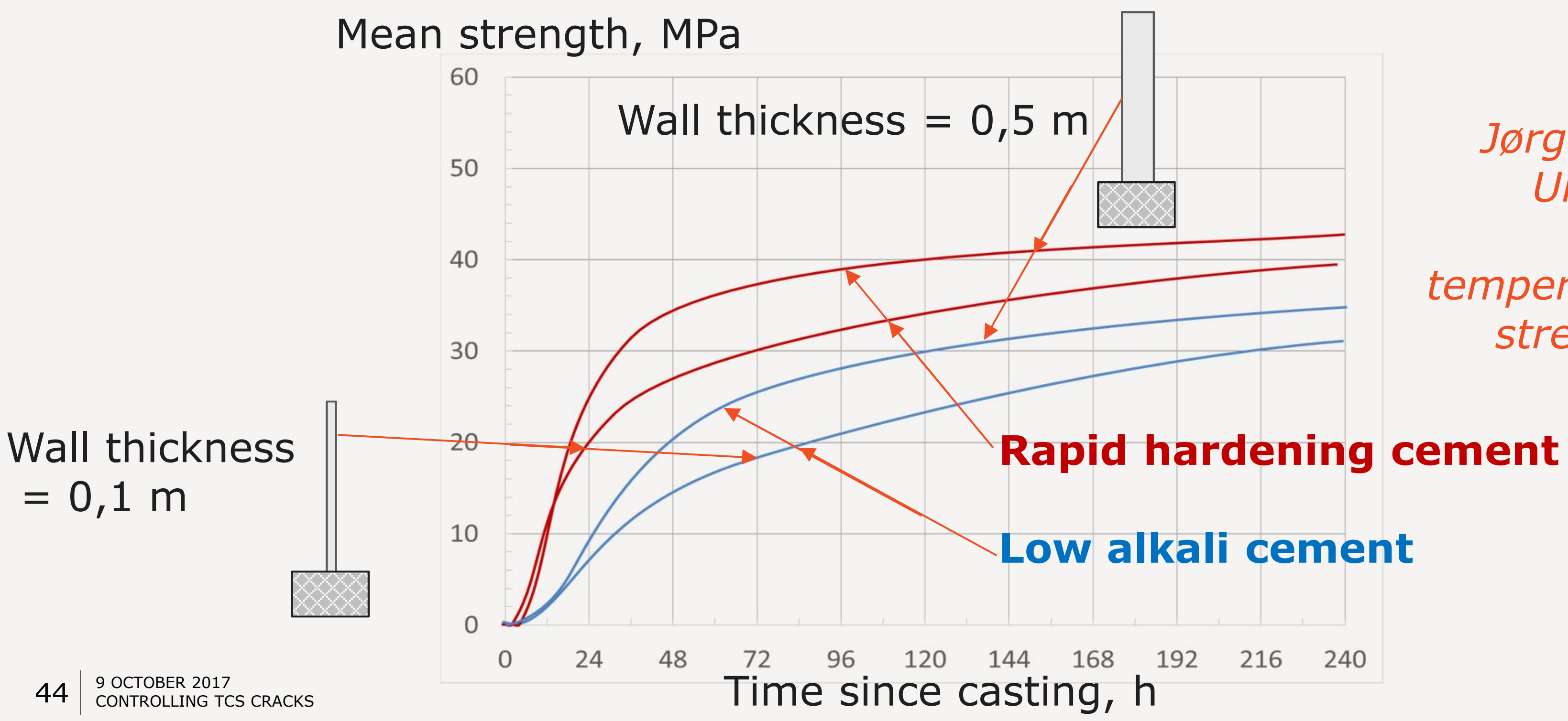
Simulation of strength development



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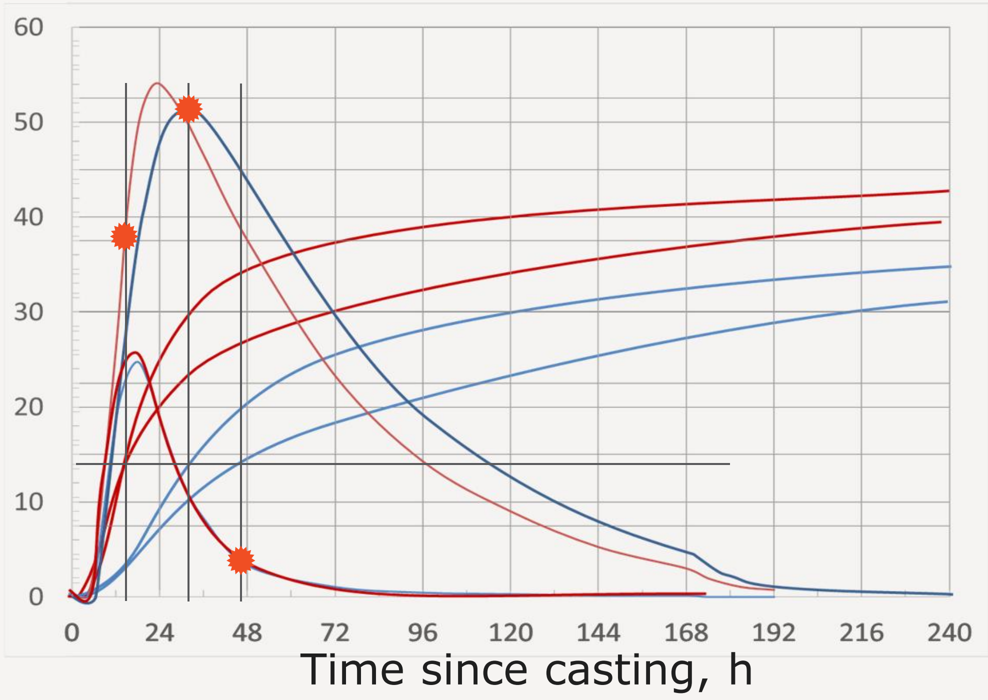
Simulation of early age temperatures, “wall on base”

14 MPa, i.e. reinforcement is anchored



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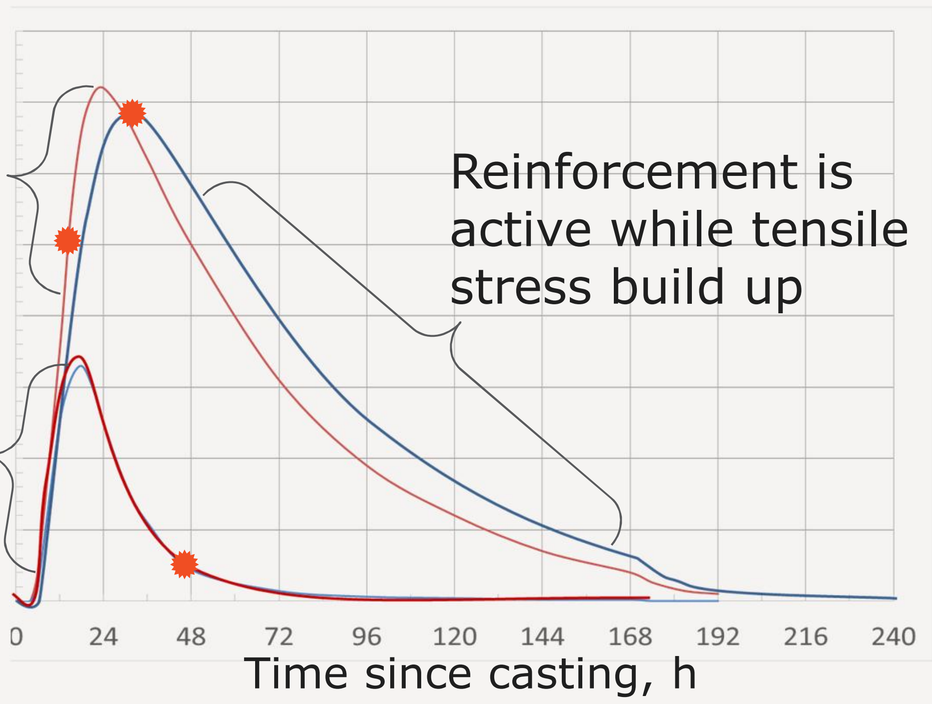
Simulation of early age temperatures, “wall on base”

Compressive stress build up

Reinforcement is active while tensile stress build up

Barely no stress and low risk of cracking



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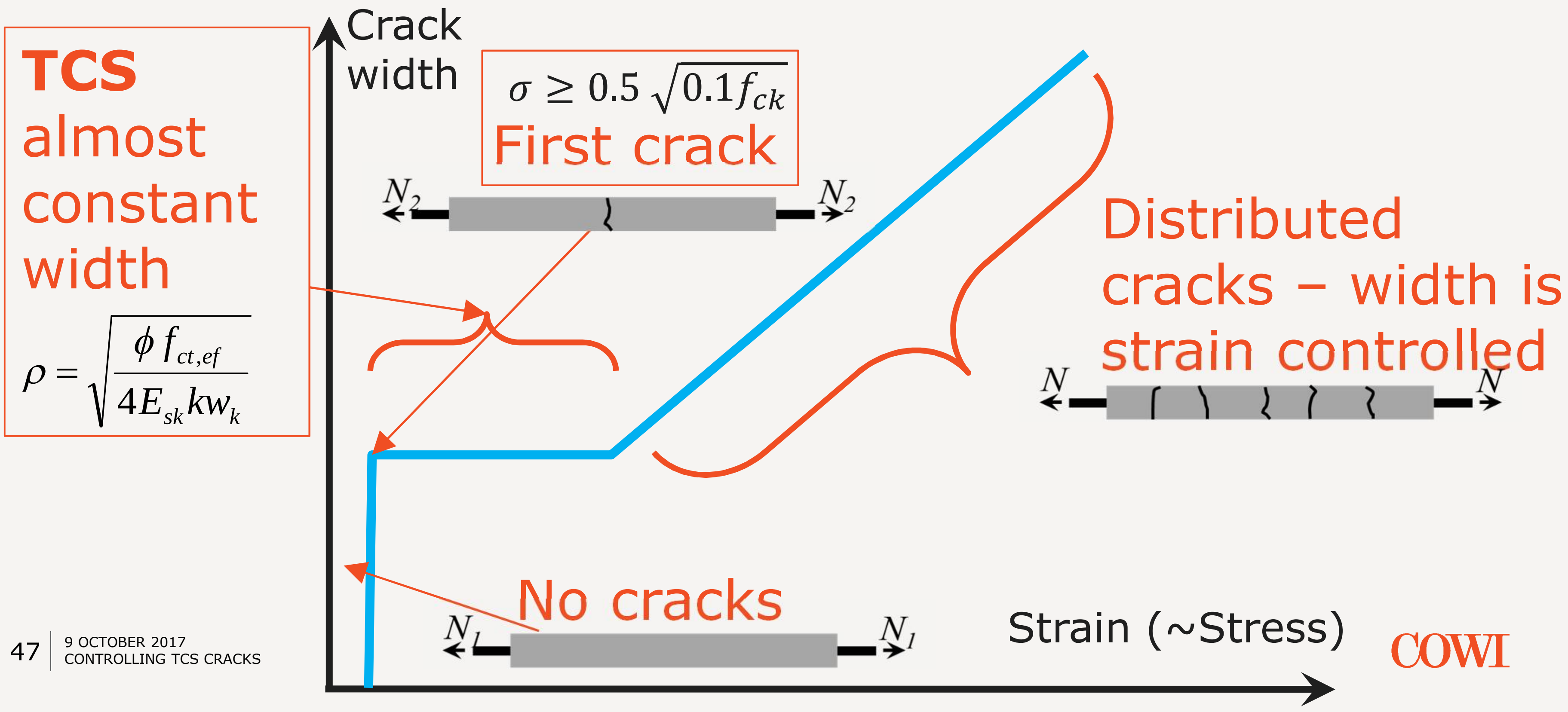
Development of cracks in reinforced concrete



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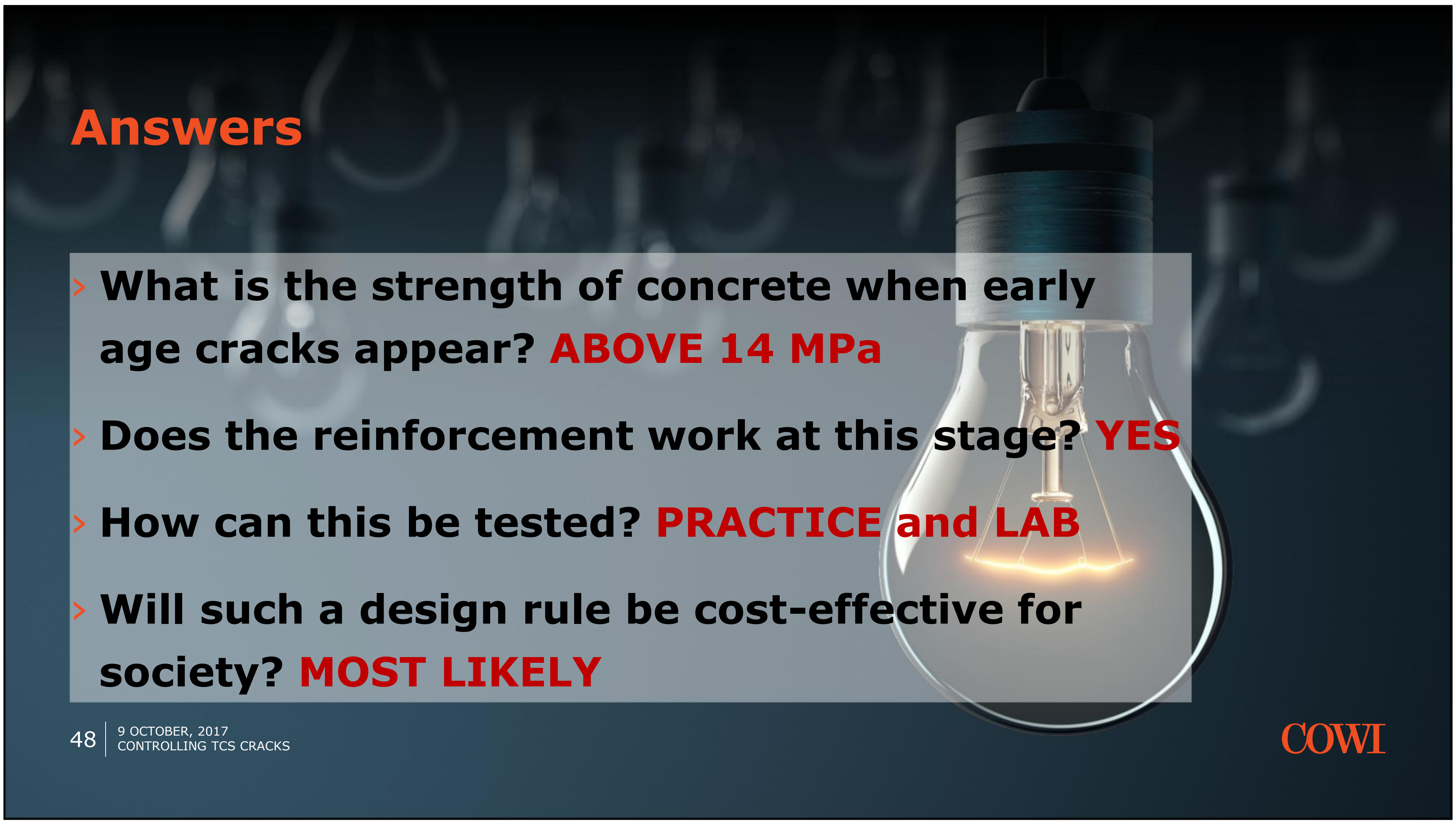
Answers



- What is the strength of concrete when early age cracks appear? **ABOVE 14 MPa**
- Does the reinforcement work at this stage? **YES**
- How can this be tested? **PRACTICE and LAB**
- Will such a design rule be cost-effective for society? **MOST LIKELY**

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Summary and closure

- Cracks in concrete structures can be controlled but not completely avoided
- ADVANTAGES:
  - Walls in tunnels, pools, containers etc. can be made water tight (to Class 1) without the use of membranes
  - Floors, pavements, walls etc. where the visual appearance and the function is in focus can be made without joints for dilation
- But controlling cracks can be noticed in the bill of quantities for reinforcement!
- It is likely that the minimum reinforcement designed to control TCS cracking ((late) thermal actions, shrinkage and creep) also controls early age cracks due to the heat of hydration

THANKS FOR YOUR ATTENTION!