Technical seminar

Seminar

Design of reinforcement for RC elements under the combined effect of applied loads and restrained shrinkage

May 19th 2017

Ordem dos Engenheiros
Porto - Portugal

ORDEM DOS ENGENHEIROS
Universidade do Minho
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
GPBE Grupo Português de Betão Estrutural
FCT Fundação para a Ciência e a Tecnologia
COMPETE 2020
PORTUGAL 2020
União Europeia

Participants in the dimension challenge

A400 PROJETISTAS E CONSULTORES DE ENGENHARIA
newton CONSULTORES DE ENGENHARIA
TPF PLANEGE CENOR
MOTT MACDONALD
ADÃO DA FONSECA engenheiros consultores
STRENG
KHP LEIPZIG

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Design of reinforcement for RC elements under the combined effect of applied loads and restrained shrinkage

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http://civil.uminho.pt/integracrete/

Credits for photo of the background:

Preface

The design of reinforcement for RC elements under the combined effect of applied loads and restrained shrinkage is a complex topic, which is nowadays still under open discussion worldwide. Indeed, it is quite relevant to promote the discussion of good practices in this concern, mainly due to the lack of regulatory framework for design under the two combined effects. To address this need for discussion, the Seminar "Design of reinforced RC elements under the combined effect of applied loads and restrained shrinkage" took place in 19^{th} May 2017 at 'Ordem dos Engenheiros' in Porto (Portugal). It was a free seminar, open to the practising community (design and construction), as well as students and academics. It intended to present the most recent scientific advances in the subject, and specifically address interactive discussions among designers. This initiative was held in the scope of the FCT Project "IntegraCrete - A comprehensive multi-physics and multi-scale approach to the combined effects of applied loads and thermal/shrinkage deformations in reinforced concrete structures", under the combined initiative of the School of Engineering of the University of Minho (Department of Civil Engineering) and the Faculty of Engineering of the University of Porto (Department of Civil Engineering).

The event was preceded by a design challenge that had been proposed to several design offices in Portugal and abroad (A400, AdF, CENOR, KHP Leipzig, Mott Macdonald, Newton and Streng). The results of such design challenge were presented and discussed during the seminar, together with the presence of representatives from the participating teams. All participating teams are gratefully thanked for their voluntary participation.

Preface

The event also had the kind participation of Prof. Dirk Schlicke from Graz University of Technology (Austria), who has presented a new methodology for design based on strain compatibility, together with application examples. More than 90 people have enrolled to this event, showing its interest among all engineering community.

This e-book contains all the presentations shown during the event, with some adaptations for feasibility in this format. There has been partial update of some presentations with basis on discussions held during the event (particularly for the case of the presentation and discussion of the design challenge).

Acknowledgements

The IntegraCrete project (PTDC/ECM-EST/1056/2014; POCI-01-0145-FEDER-016841) is supported by FEDER funds through the Operational Program for Competitiveness Factors - COMPETE and National Funds through FCT - Portuguese Foundation for Science and Technology

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Content

Overview of difficulties in design associated to concrete shrinkage

Miguel Azenha - ISISE, University Minho, Portugal
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Rui Faria - CONSTRUCT, University of Porto, Portugal
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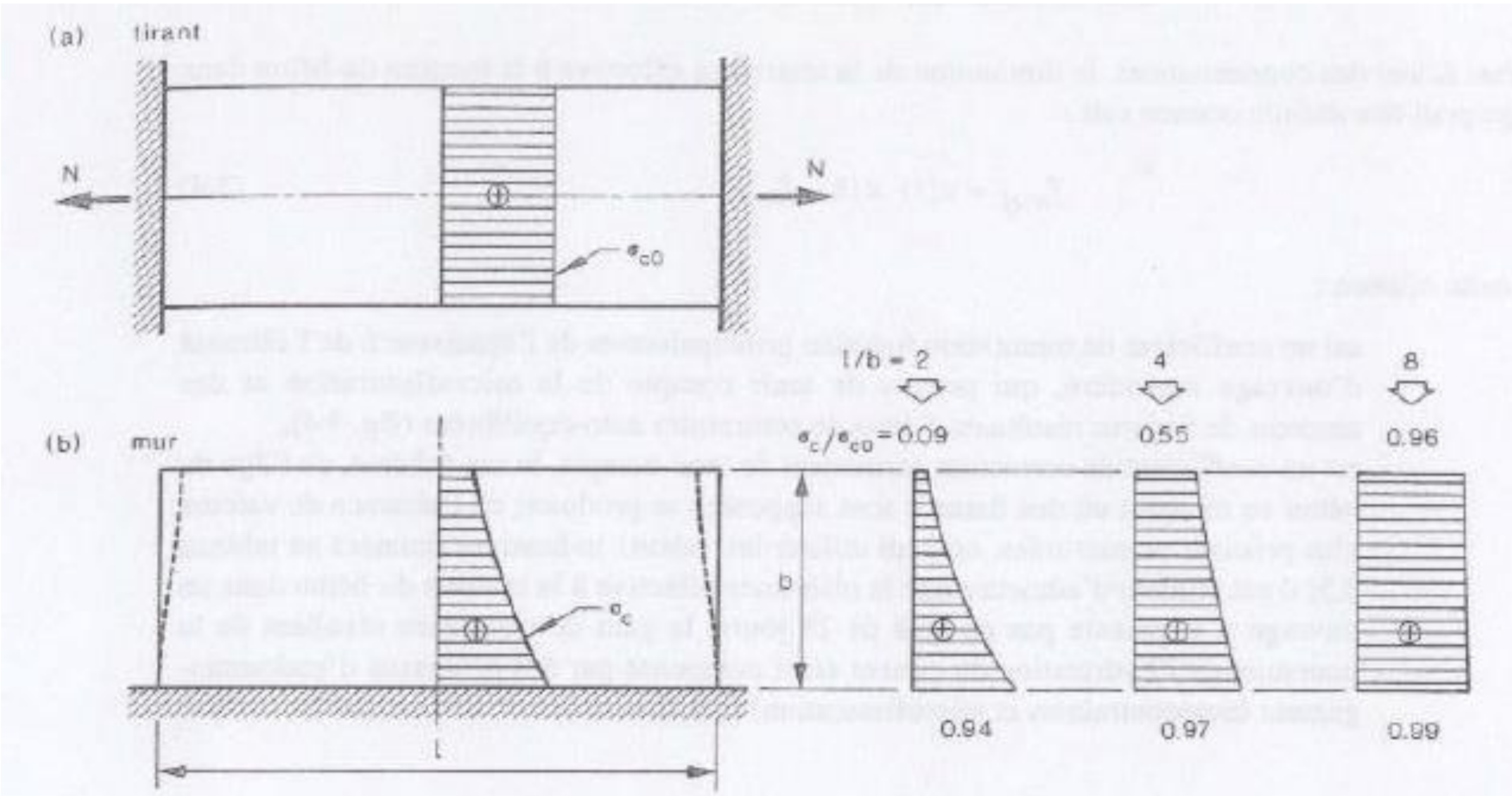
Pathologies and doubts in design for shrinkage

Surface cracks in slabs: often they are 'through cracks'

Pathologies and doubts in design for shrinkage

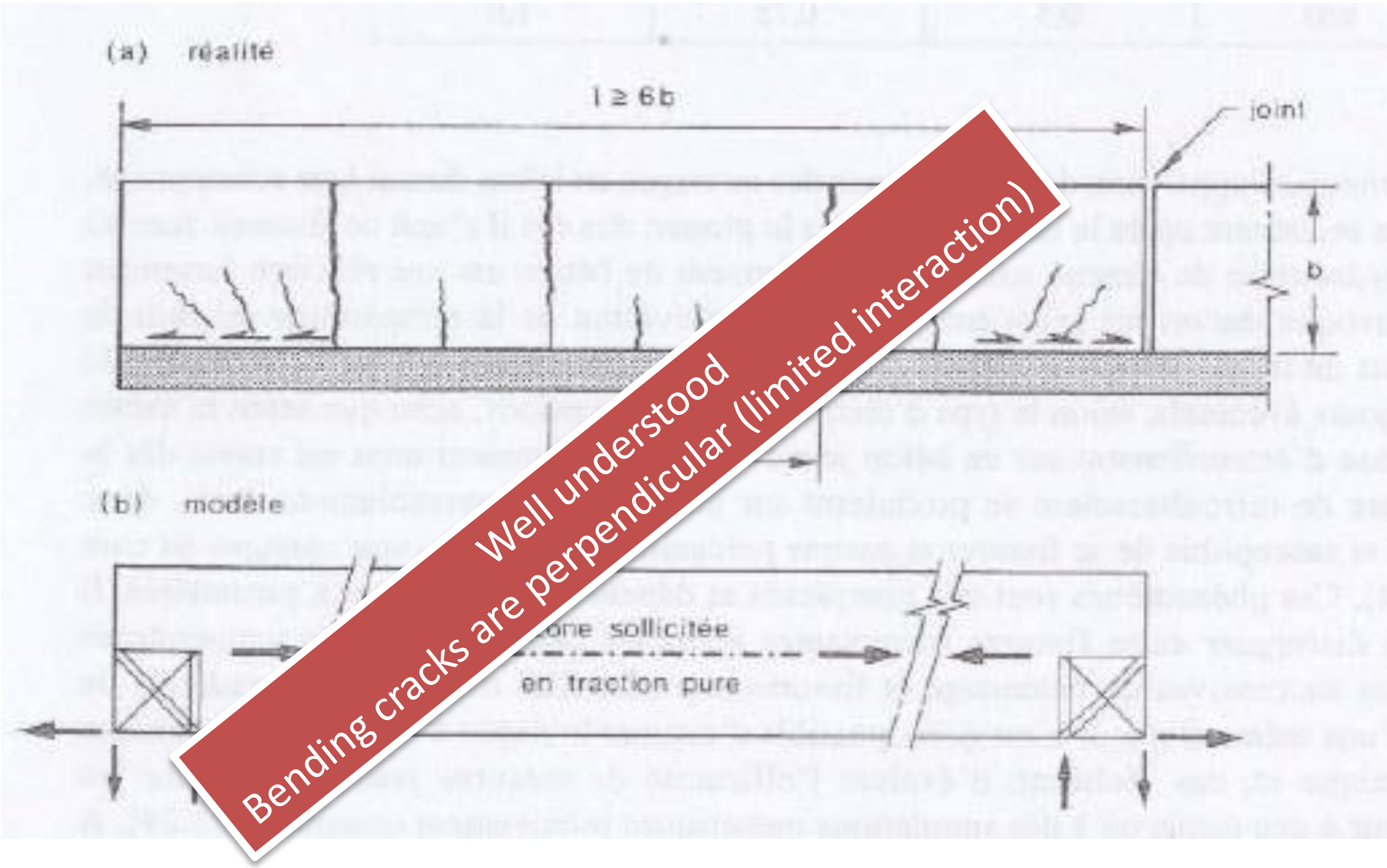
Retaining wall – thermal/shrinkage crack

Credit: Aveline Darquennes



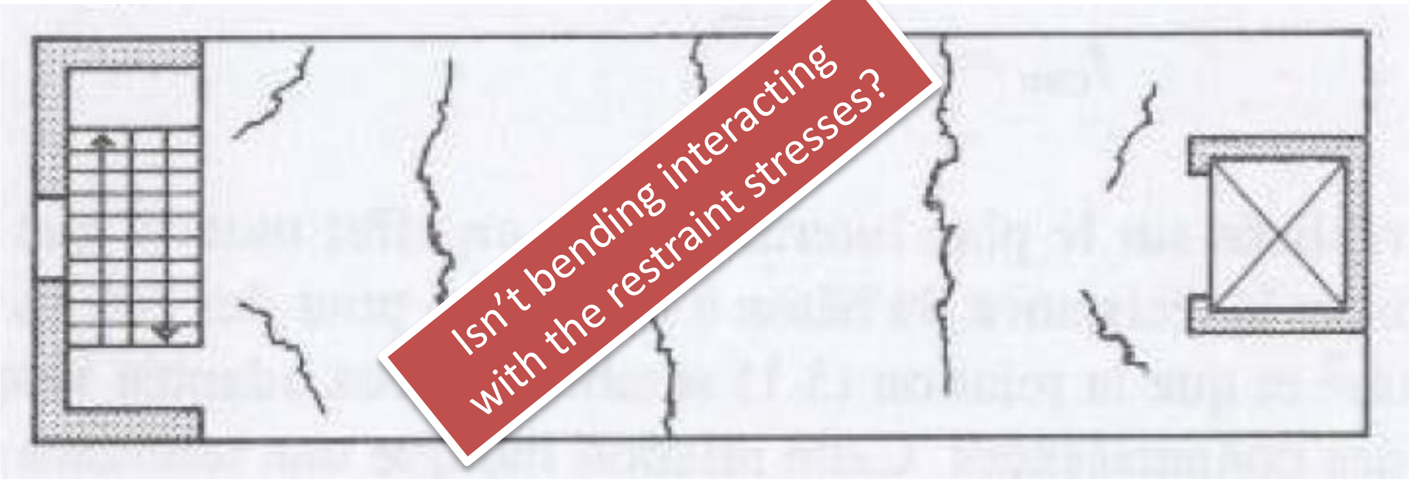
Credit: EPFL, Favre et al.

Restraint stresses are not constant!



Credit: EPFL, Favre et al.

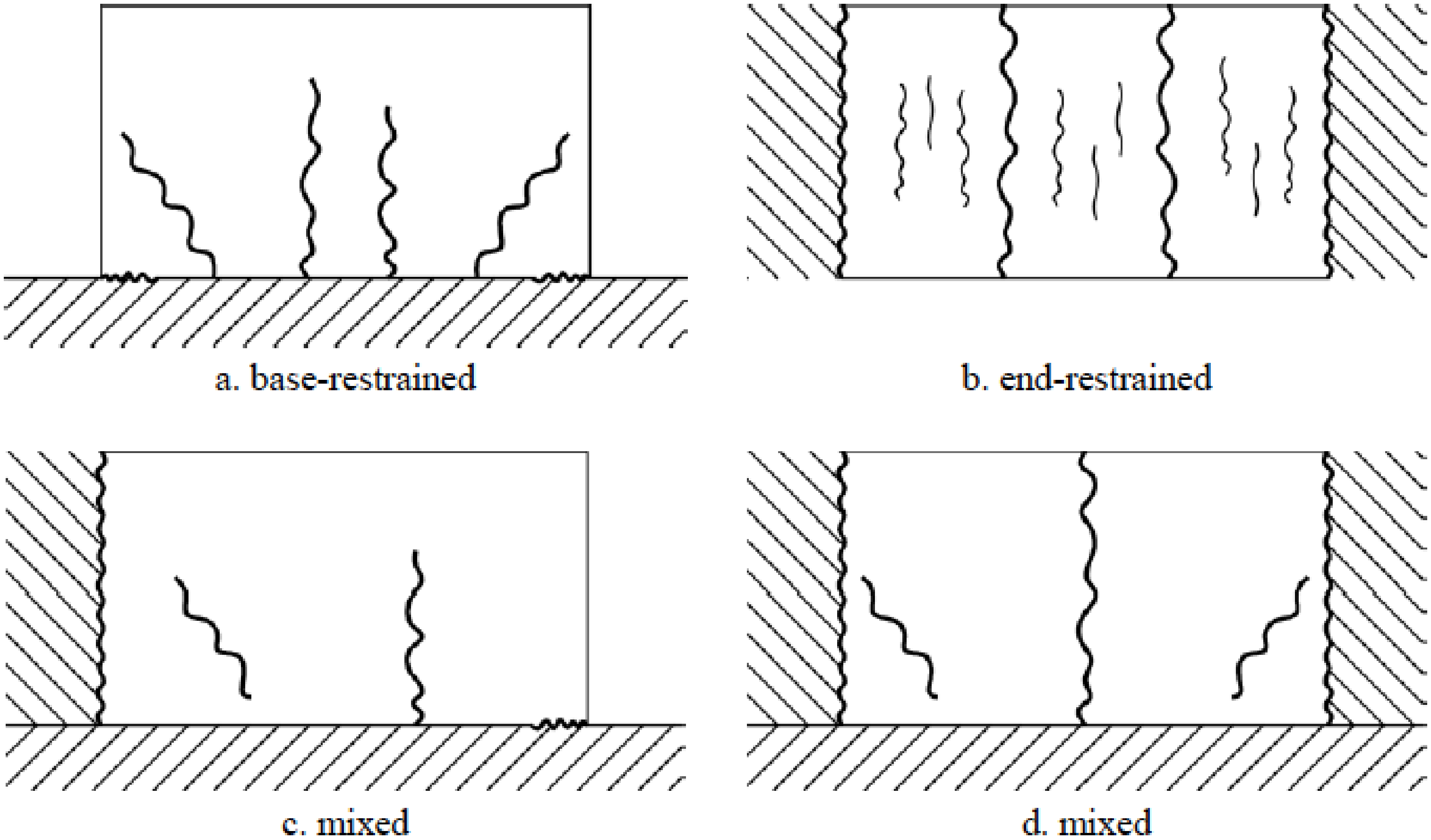
Typical restraints/cracking in walls



Isn't bending interacting with the restraint stresses?

Credit: EPFL, Favre et al.

Imposed deformation cracking



Cracking patterns according to restraint

Credit: Agnieszka Knopik et al.

Heavily reinforced slab

No excessive cracking -> *Was it 'overdesigned'?*

Concrete shrinks and regulations know about it!

EUROCODES
BUILDING THE FUTURE

Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings

2.3.3 Deformations of concrete

(1)P The consequences of deformation due to temperature, creep and shrinkage shall be considered in design.

(3) In building structures, temperature and shrinkage effects may be omitted in global analysis provided joints are incorporated at every distance d_{joint} to accommodate resulting deformations.

Note: The value of d_{joint} is subject to a National Annex. The recommended value is 30 m. For precast concrete structures the value may be larger than that for cast in-situ structures, since part of the creep and shrinkage takes place before erection.

Am I truly safe by neglecting shrinkage temperature effects in a 29m long structure?
Isn’t restraint to deformation a fundamental factor?

EUROCODES
BUILDING THE FUTURE

3.1.4 Creep and shrinkage

(3) The creep deformation of concrete $\varepsilon_{cc}(\infty,t_0)$ at time $t = \infty$ for a constant compressive stress σ_c applied at the concrete age t_0, is given by:

$$\varepsilon_{cc}(\infty,t_0) = \varphi(\infty,t_0).\ (\sigma_c / E_c) \qquad (3.6)$$

2.3.2.2 Shrinkage and creep

(1) Shrinkage and creep are time-dependent properties of concrete. Their effects should generally be taken into account for the verification of serviceability limit states.

5.4 Linear elastic analysis

(1) Linear analysis of elements based on the theory of elasticity may be used for both the serviceability and ultimate limit states.

(2) For the determination of the action effects, linear analysis may be carried out assuming:
i) uncracked cross sections,
ii) linear stress-strain relationships and
iii) mean value of the modulus of elasticity.

(3) For thermal deformation, settlement and shrinkage effects at the ultimate limit state (ULS), a reduced stiffness corresponding to the cracked sections, neglecting tension stiffening but including the effects of creep, may be assumed. For the serviceability limit state (SLS) a gradual evolution of cracking should be considered.

ANNEX B (Informative)

EUROCODES
BUILDING THE FUTURE

Creep and shrinkage strain

(...)

The mean coefficient of variation of the above predicted creep data, deduced from a computerised data bank of laboratory test results, is of the order of 20%.

Model Code 2010

fib Model Code for Concrete Structures 2010

Due to the inherent scatter of creep and shrinkage deformations, the errors of the model and the general uncertainty caused by randomness of material properties and environment, a prediction of the deformation may result in a considerable error. After short durations of loading or drying, the prediction error is higher than after long durations of loading and drying.

Based on a computerized database of laboratory test results a mean coefficient of variation for the predicted creep function $V_c = 25\ \%$ has been found.

Model Code 2010

fib Model Code for Concrete Structures 2010

7.6.4.4 Calculation of crack width in reinforced concrete members

7.6.4.4.1 General

For all stages of cracking, the design crack width w_d may be calculated by:

$$w_d = 2l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs}) \qquad (7.6\text{-}3)$$

where:

$l_{s,max}$ denotes the length over which slip between concrete and steel occurs. The steel and concrete strains, which occur within this length, contribute to the width of the crack; $l_{s,max}$ is calculated with Eq. (7.6-4);

ε_{sm} is the average steel strain over the length $l_{s,max}$;

ε_{cm} is the average concrete strain over the length $l_{s,max}$;

ε_{cs} is the strain of the concrete due to (free) shrinkage.

Reasonable when restraint to deformation is non-uniform?

Cracking relieves restraint!

Model Code 2010

fib Model Code for Concrete Structures 2010

Creep of powder type SCC is affected by its high paste content. In general, the creep deformation is approximately 10–20 % higher than that of conventional concrete of equal strength. However, the deformations are within the scatter band for ordinary structural concrete, which is defined to be ±30 %. If the structural response is sensitive to variations in creep behaviour tests are highly recommended.

The higher creep tendency of lightweight aggregate concrete due to the reduced stiffness of the aggregates is partially compensated by the lower creep capability of the stiffer cement paste matrix.

(...)

Eq. 5.1-73 was developed based on experimental results primarily with CEM I and CEM III cements. If other cement types are used or if large amounts of pozzolans are used in partial replacement of CEM I and the development of the creep deformations has high relevance for the design, this effect should be determined experimentally.

New mixing of concrete is definitely a challenge.
Shouldn't we be prescribing performance-based behaviour in design?

Model Code 2010

fib Model Code for Concrete Structures 2010

5.1.9.4.2 Range of applicability

The relations for creep and shrinkage given below predict the time-dependent mean cross-section behaviour of a concrete member moist cured at normal temperatures for not longer than 14 days.

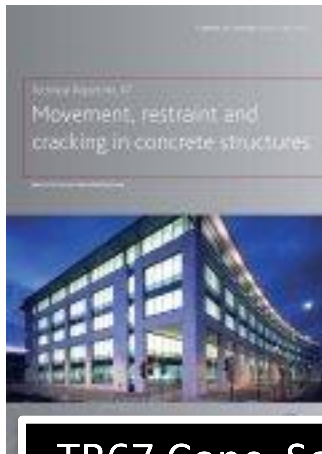
Unless special provisions are given, the relations are valid for ordinary structural concrete (20 MPa $\leq f_{cm} \leq$ 130 MPa) subjected to a compressive stress $|\sigma_c| \leq 0.4 f_{cm}(t_0)$ at an age at loading t_0 and exposed to a mean relative humidity in the range of 40 to 100% at a mean temperature in the range of 5°C to 30°C. The age at loading should be at least 1 day.

It is accepted that the relations apply as well to concrete in tension, though the relations given in the following are directed towards the prediction of creep of concrete subjected to compressive stresses.

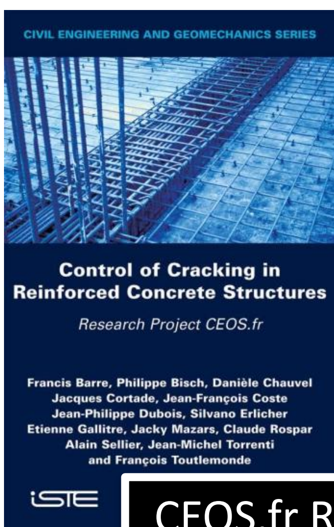
'Creep in tension' vs 'creep in compression'. Not really the same, but we are assuming it in our modelling.

Some design aids in the literature…

CIRIA C660



TR67 Conc. Soc.



CEOS.fr Report

IntegraCrete - A comprehensive multi-physics and multi-scale approach to the combined effects of applied loads and thermal/shrinkage deformations in reinforced concrete structures

The main purpose of this research is to close the research gap identified through a comprehensive program that incorporates **extensive experimental characterization**, **real scale testing with monitoring** of relevant data and their corresponding **simulation with multiscale and multiphysics approaches**.
(…)
The improved predictions of cracking and service life behaviour, and resulting design recommendations, are bound to cause significant impact on new structures and processes of strengthening with cement based materials that will have **improved cracking performance** and thus increased maintenance free lifespan.

Multiphysics | Multiscale | Experimental | Numerical | Applications

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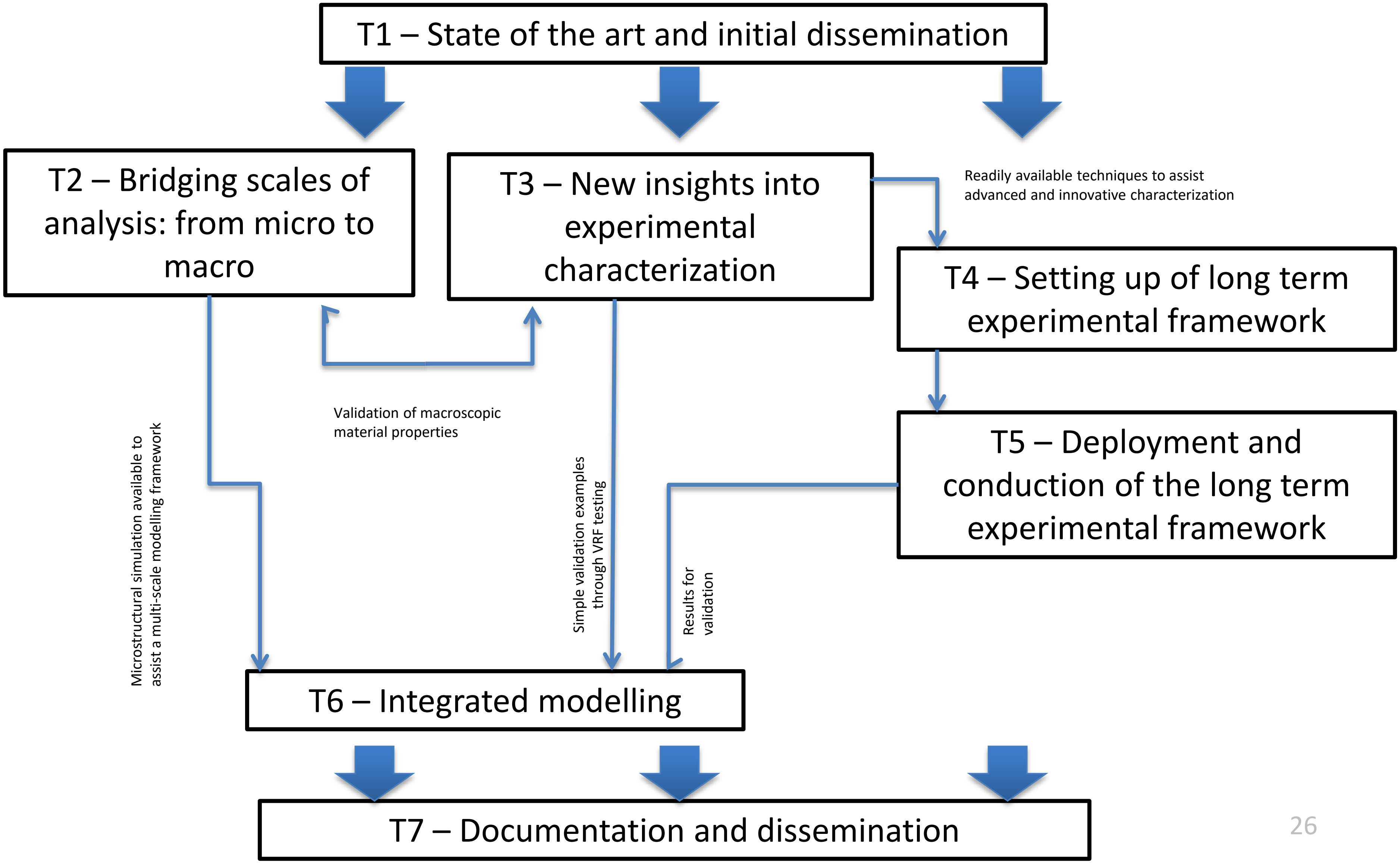
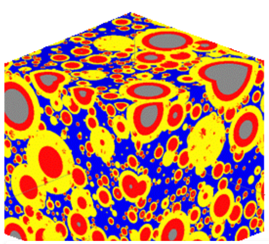

T1 – State of the art and initial dissemination
T2 – Bridging scales of analysis: from micro to macro
T3 – New insights into experimental characterization
Readily available techniques to assist advanced and innovative characterization
T4 – Setting up of long term experimental framework
Validation of macroscopic material properties
T5 – Deployment and conduction of the long term experimental framework
Microstructural simulation available to assist a multi-scale modelling framework
Simple validation examples through VRF testing
Results for validation
T6 – Integrated modelling
T7 – Documentation and dissemination

Task 2 - Bridging scales of analysis: from micro to macro

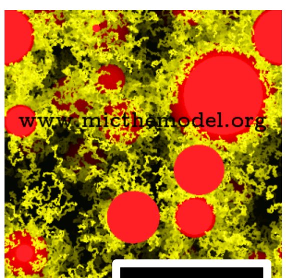
Overview

Attendance to course
<u>Multi-scale Modelling for Concrete MMC2</u>

Applying simulation models
μic and Hymostruc



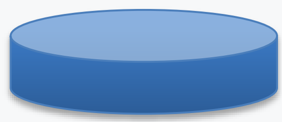
Hymostruc



μic

Cement paste characterization and testing

- Cement paste specimens
- Full characterization of cement through TGA, SEM/XRD



- Disc-shaped specimens, and more than 1 type of cement and w/c ratio
- Reference environment: 20ºC, sealed
- Alternative environments in terms of temperature and relative humidity
- Characterization of cement paste features along time:
    - Isothermal conduction calorimetry
    - TGA/XRD – degree of hydtation
    - Porosity testing (UPV; MIP)
    - Stiffness testing (EMM-ARM)
    - Strength
    - Shrinkage

Validation at cement paste level

Homogenization techniques

- Application of existing homogenization approaches to the cement paste behavior predictions
- Prediction of behaviour of concrete based on its composition and the results of micro-scale simulation

Interaction with experimental results obtained within Task 3

Validation at concrete scale level

Information output to Task 6

Task 3 - New insights into experimental characterization

Overview

Support on innovative experimental techniques proposed by the PI's

Innovative proposal of new advances for testing

- Provide robust and innovative characterization techniques that complement standard approaches for concrete characterization
- Boost the possibilities of simulation of the long term experimental program (T5) by combining unprecedented sets of data (see scheme below)
- Support to the establishment/validation of simulation of post-cracking behaviour of T6 with basis on VRF testing

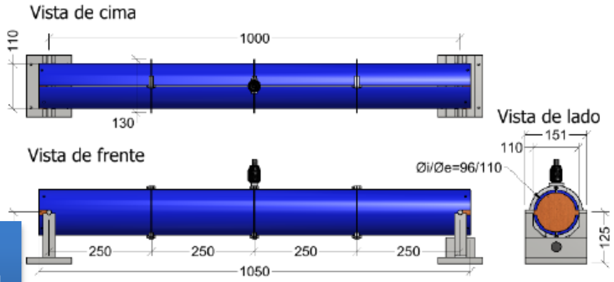
New variant to EMM-ARM

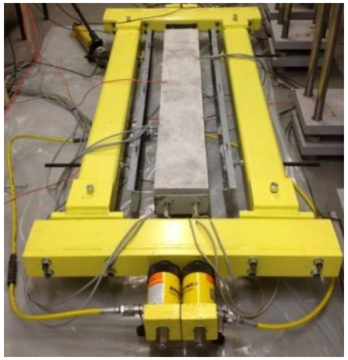
EMM-ARM

VRF

TDC

VisCoDyn+ creep





Information output to Tasks 4, 5, 6

Participation in the Round Robin Testing Series of COST Action TU1404

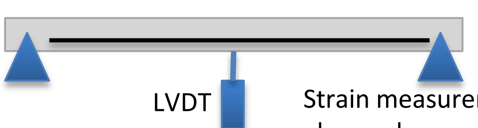
Task 4 – Setting up of long term experimental framework

Size the testing slabs

- Establish dimensions and load levels as to ensure representativeness of real situations, namely in terms of expectable crack width
- Some performance requirements:
  - Use of NSC (e.g. C25/30)
  - Relatively small span due to space limitation
  - Minimum slab thickness 15cm
  - Uneven reinforcement in top/bottom layers
  - Uniformly distributed load materialized by concrete blocks
  - Predictable crack width at 1yr ~0.2mm
- Preliminary size is: 2.6m×0.75m×0.15m, with 2.4m span (double supports in case of restraint)
- FEM simulations under the testing conditions envisaged in Task 5 to evaluate potential adaptations

Monitoring setup

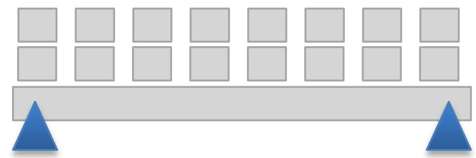
- Monitor mid-span deflections with permanently installed LVDT
- Check crack width with USB microscope
- Profile RH in companion specimen
- Measure internal temperatures
- Measure internal rebar strains with electric strain gages at several points
- Potential use of embedded concrete strain sensors (undesriable due to potential crack induction=



Create and build test setups

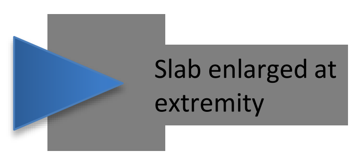
Load application

- Reach the desired load level with concrete blocks
- Possible piling of small spaced concrete blocks to avoid load carrying by contact between blocks



Restraint

- Restraint system that ensures realistic levels of restraint to deformation, namely enough to ensure cracking due to shrinkage -> robustness
- Issues regarding cracking of the slab in the region of support -> need to enlarge/strengthen
- Ensure no slack to the system, which would limit its capacity to restrain -> need to be under tension at the instant of casting



Temperature control

- Ensure relevant temperature gradients to the specimen, while not affecting the restraint system
- Use of thermostatic bath to enforce temperature, or merely apply XPS insulation

Test the setups

- The long term testing of T5 demands that nothing fails upon its start -> need to make a trial testing of all the test setups mentioned in T5: TY1 to TY4
- 1 month duration minimum
- Test with actual concrete and monitoring to assess feasibility
- Possibility of requiring adaptations and thus re-run the test.

Information output to Task 5

Task 5 – Deployment and conductions of the long term experimental framework

Overview

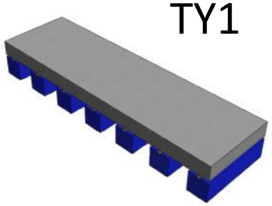
Information feed from Task 4

Long term testing based on 4 types of slabs

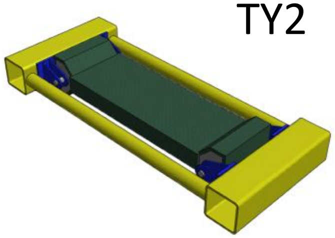
- 2 specimens per each type of slab
- Test takes place in sheltered conditions without any specific temperature or humidity control (lab environment)

	TY1	TY2	TY3	TY4
Thermal development	No	Yes	Yes	Yes
Restraint	No	Yes	Yes	No
Applied load	No	No	Yes	Yes

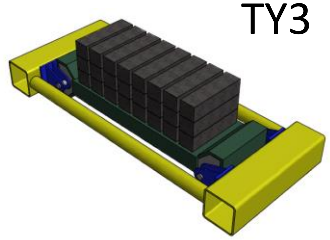
TY1



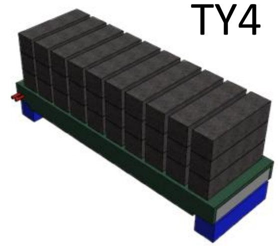
TY2



TY3



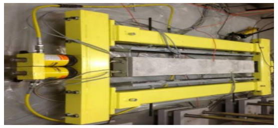
TY4



Calorimetry characterization, thermal dilation coefficent, specific heat and conductivity

Humidity profiling for diffusion equation coefficients; shrinkage coefficient

Parallel VRF testing

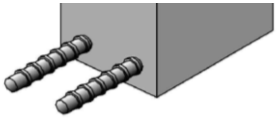


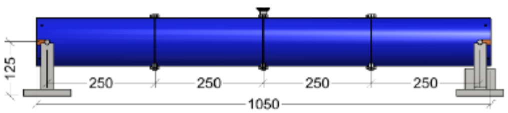
Complementary characterization and monitoring

Instrumentation for temperature, strain, deformation and crack width

Continuous datalogging

Stifness, strength and bond testing





Creep testing

Information output to Task 6

Task 6 – Integrated modelling

Information feed from Tasks 2,3,5

Multi-scale and multi-physics simulation

Overview of the modelling framework

Thermal field

- MATLAB custom code
- Energy balance including heat generation and thermally activated processes
- Thermal characterization obtained from T3,5
- Micro-scale properties will be inferred in parallel, and possible couplings T2-T6
- Equivalent age computation for evolution of properties

Moisture field

- MATLAB custom code
- Moisture diffusion equation based on RH as driving potential
- Diffusion properties obtained by back-analysis based on the RH profiling experiments of T3,5
- Possible multi-scale inference of properties from T2

Mechanical field

- DIANA FE software
- Reinforcement explicitly simulated, and cracking evaluated with smeared cracking models
- Creep evaluated through aging Kelvin chains
- Properties evolution based on micro scale models from T2
- Support of characterization from T3,5

Main features, novelties and challenges

- Intricate interaction between crack opening and creep/shrinkage phenomena still lacks research background and experimental evidence. VRF testing in the scope of T3 will support the development of such models, and their validation is expected in T6.
- Integration of the micro-scale prediction of material properties applied to the macro-scale -> multi-scale analysis
- Availability of the four types of slabs that differently combine complexities that interact with each other.(restraint, temperature, shrinkage, external load) allows easier tracing of imperfections in modelling approaches and better points towards more accurate predictions.
- As in previous works on behalf of the PI's, this research work is mostly recognizable by the wide participation of the same team in tasks that are normally performed separately by specific specialists: micro-scale modelling, material characterization, large scale experimental testing and monitoring, multi-physics numerical simulation.

Validation of the simulation framework with the results of T5

Comparison with existing approaches

- Validated numerical framework is complex and impractical to apply in everyday scenario conditions.
- Application of the numerical simulation framework in parallel to regulatory or simplified approaches for crack prediction -> possible recommendations.
- Participation in the numerical benchmarking series to be held in the scope of COST Action TU1404.

Phenomenology of shrinkage and creep in reinforced concrete structures

Rui Faria - **CONSTRUCT, FEUP, Universidade do Porto, Portugal**

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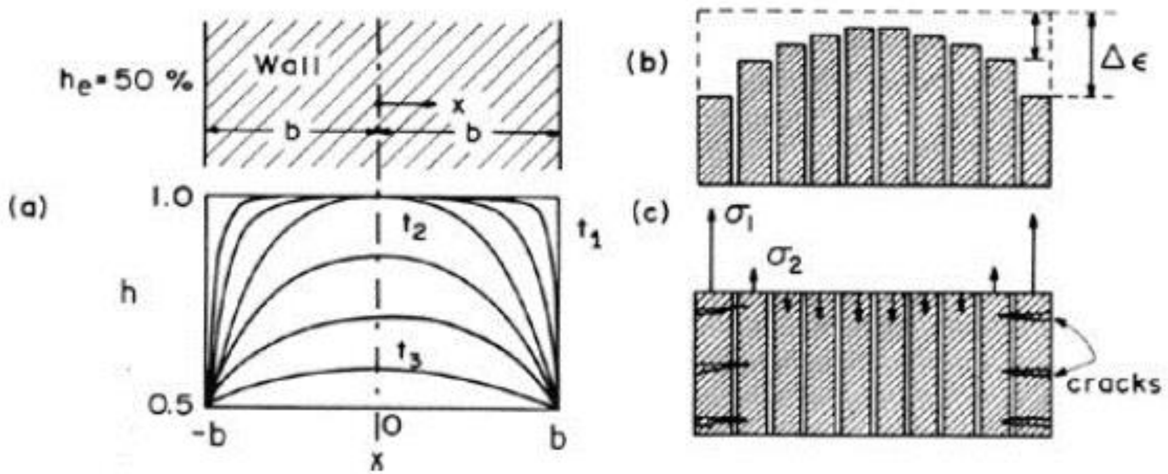
Concrete Shrinkage: Drying and Autogenous

- Shrinkage is a volume change, not related to external loading or mechanical phenomena. It is normally subdivided into **Drying Shrinkage** and **Autogenous Shrinkage** (see Eurocode 2).

- **Drying shrinkage** is due to loss of water to the environment, which is usually much drier than the concrete core. *'(…) drying is an extremely slow process. The outer layers reach hygral equilibrium with the relative humidity (RH) of the environment quickly, while the inner part may remain water saturated for decades'* (Wittmann, 2008):



Shrinkage measured in concrete samples is not a **real material property**:
- stresses, creep and cracking develop at the same time...

Autogenous shrinkage

- **Autogenous drying** is due to self-consumption of water by the cement hydration. Shrinkage can be also due to chemical and physical reactions of the solid skeleton with the pore solution (chemical shrinkage, etc.).

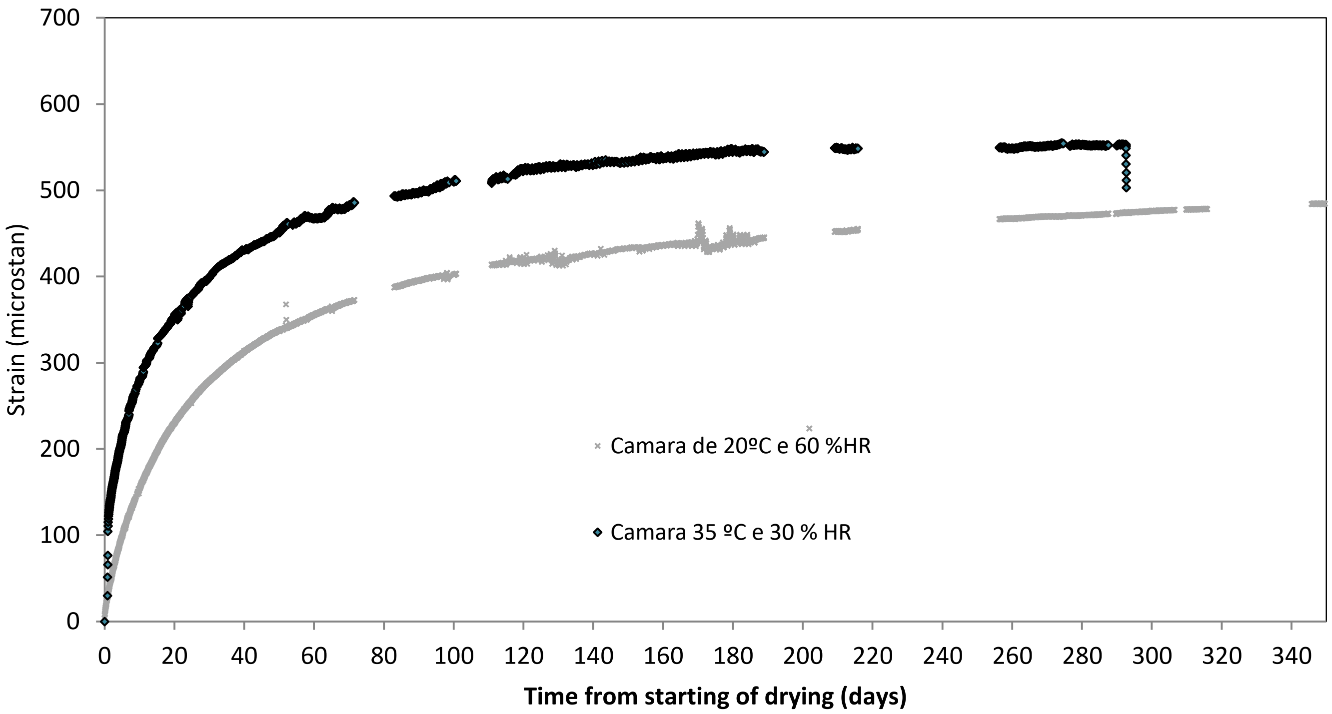
- In Normal Strength Concrete (NSC) **Drying Shrinkage** is the most relevant, due to the high w/c ratio and higher porosity of concrete. This facilitates drying of the core of the RC elements. *It normally lasts for **~30 years**, or even more!*

- High Strength Concrete (HSC) has low w/c ratio and dense concrete microstructure (low porosity). Thus, drying shrinkage is much less relevant than in NSC. Conversely, the low w/c ratio and the higher dosages of binders (cement, etc.) in HSC makes the self-consumption of water to be high. Thus **Autogenous Shrinkage** becomes relevant. It develops *during the **early ages**, after concrete casting*.

- These two forms of **Shrinkage** are already reflected on actual Design Codes, like EC2. They provide separated expressions for the autogenous and drying shrinkage, depending on the concrete class, environmental RH, element 'thickness', etc.

Experimental measurement of shrinkage

- Inside climatic chambers (FEUP and UM)



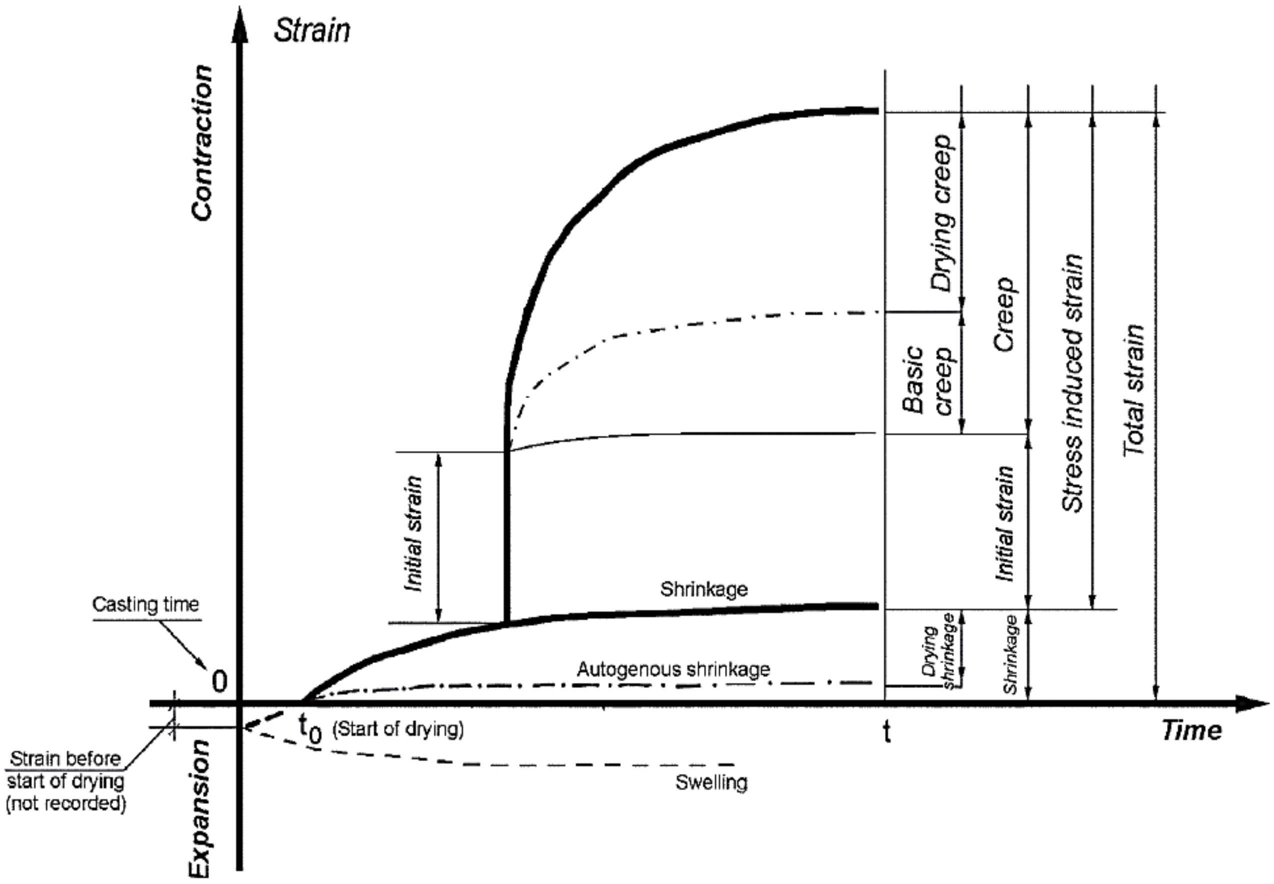
Concrete Creep

- **Concrete creep** is caused by complex mechanisms which are not yet fully understood. Neville *et al.* (1983) identified the following:
  - **Expulsion of the interlayer water** within the cement gel
  - **Sliding of the colloidal sheets in the cement gel** between the layers of absorbed water
  - Local fracture within the cement gel involving the breakdown (and formation) of physical bonds (micro-cracking)
  - Elastic deformation of the aggregate and the gel crystals as viscous flow and seepage occurring within the cement gel
  - (…)

Concrete creep

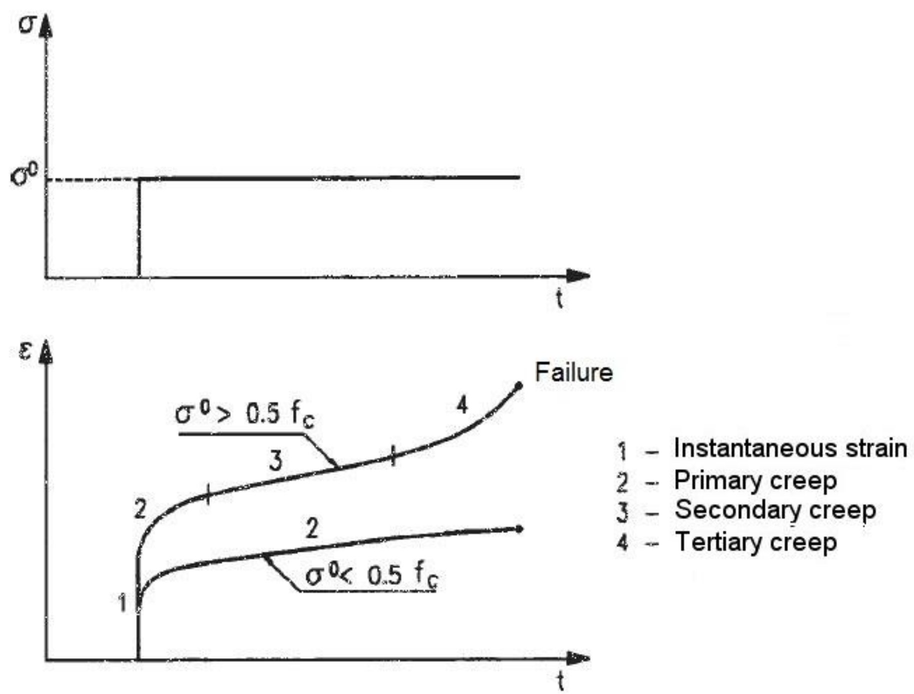
- Creep is influenced by:
  - Concrete composition
  - Environmental RH (creep increases as RH decreases)
  - Environmental T (as T increases drying accelerates, and the deformation of the cement paste increases)
  - Loading conditions (creep increases with the installed concrete stress)
  - Element geometry (creep is more significant in thin structural specimens)
- **Age of loading** has a very significant relevance in the magnitude of final creep: young concrete will thus have highest creep deformations.
- **Basic creep** is observed in sealed concrete specimens. It is a material property, as it depends of the composition of concrete mix.
- **Drying creep** occurs when the specimen is loaded on a dry environment. The drying creep depends on the RH content and gradient, and on the size and element geometry.

Basic creep, Drying creep and Total creep



Types of creep

- On a concrete element submitted to shrinkage, <u>but before the application of any external load</u>, **microcracks exist** in the interfacial zones between the matrix and the aggregates. They remain stable under stresses up to **~30%-50%** of **f_c**, and so creep strain is approximately proportional to the stress **(linear creep)** ⇒ EC2 states that concrete compressive stress should not exceed **$0.45f_{ck}$** (at the QPC of loading) for creep to remain <u>in the linear range</u>.



- Under higher concrete stresses creep strains increase very fast, which may lead to failure **(tertiary creep)**. <u>**It should be avoided !**</u>

Double Power Law (Bazant and Osman, 1976)

- The Double Power Law (DPL) is very much used to reproduce the instantaneous and the basic creep of concrete. In 1D conditions, and constant applied stress $\sigma(t_0)$ at age t_0, is reads:

$$\boxed{\varepsilon_c(t) = J(t,t_0)\,\sigma(t_0)}$$

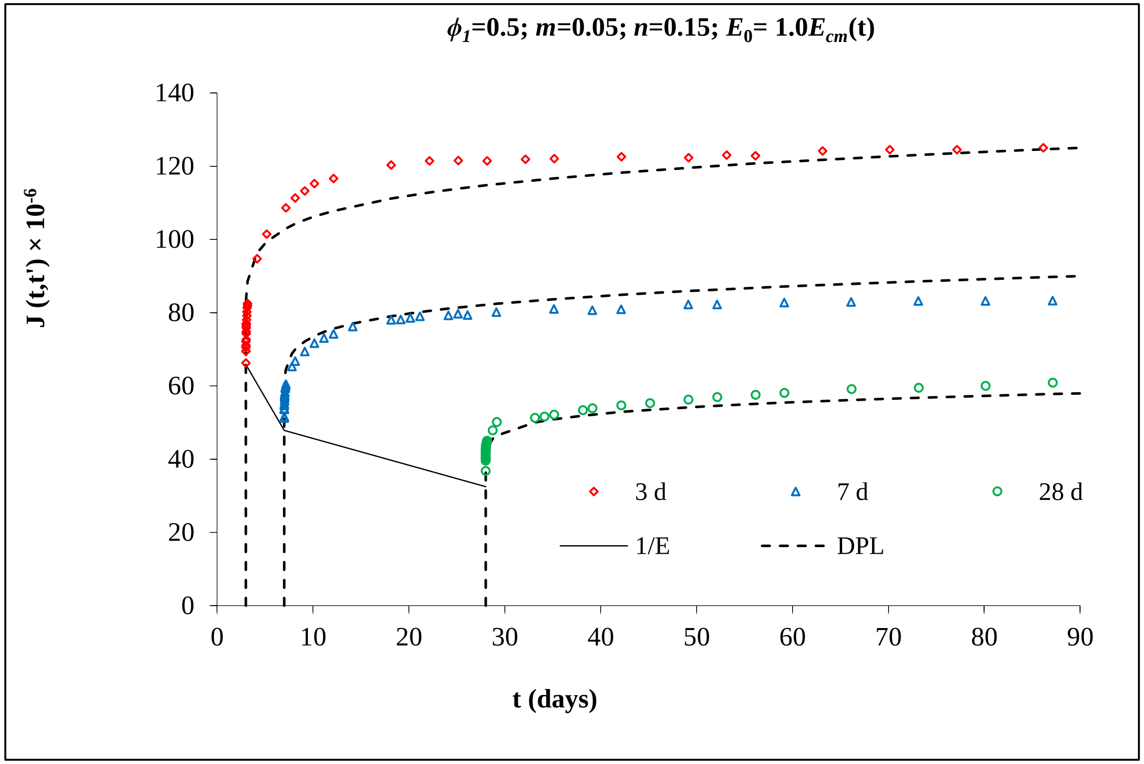
$$\boxed{J(t,t_0) = \frac{1}{E_0} + \frac{\phi_1}{E_0}\,t_0^{-m}\,(t-t_0)^n}$$

$$\boxed{\varepsilon_{cc}(t,t_0) = \sigma(t_0)\left[J(t,t_0) - \frac{1}{E_0}\right]}$$

- Relation with the creep coefficient $\varphi(t,t_0)$ stated in Design Codes:

$$\varepsilon_{cc}(t,t_0) = \frac{\sigma(t_0)}{E_0}\varphi(t,t_0) = \sigma(t_0)\left[J(t,t_0) - \frac{1}{E_0}\right] \Rightarrow \boxed{J(t,t_0) = \frac{\varphi(t,t_0)+1}{E_0}}$$

Experimental characterization of creep: $J(t,t_0)$

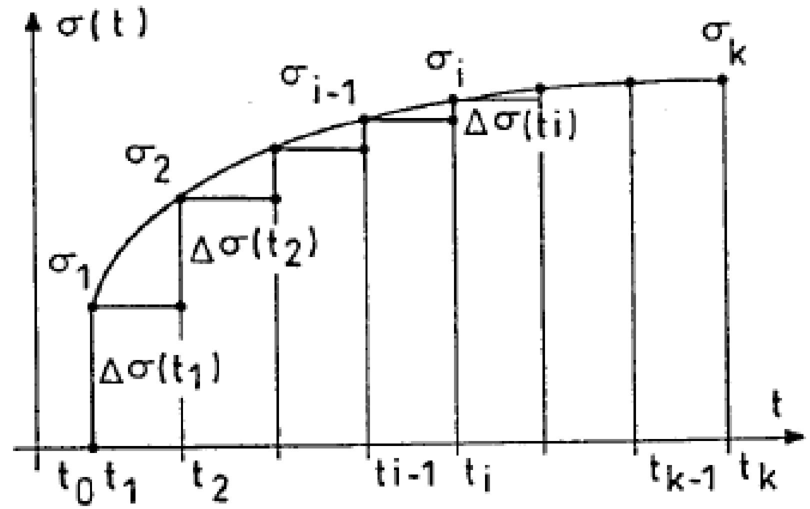


For a general stress state history…

- … the total concrete strain (instantaneous + creep) is defined as …

$$\boxed{\varepsilon_c(t) \;=\; \int_{t_0}^{t} J(t,\tau)\, d\sigma(\tau)}$$

… and computed in discrete form, for a generic instant t_n, using a time-stepping scheme with an interval Δt (…, t_{n-1}, $t_n = t_{n-1}+\Delta t$,…), and considering a sequence of concrete stress increments $\Delta\sigma(t_i)$:



$$\boxed{\varepsilon_c(t_n) \;=\; \sum_{t_0}^{t_n} J(t_n,t_i)\,\Delta\sigma(t_i)}$$

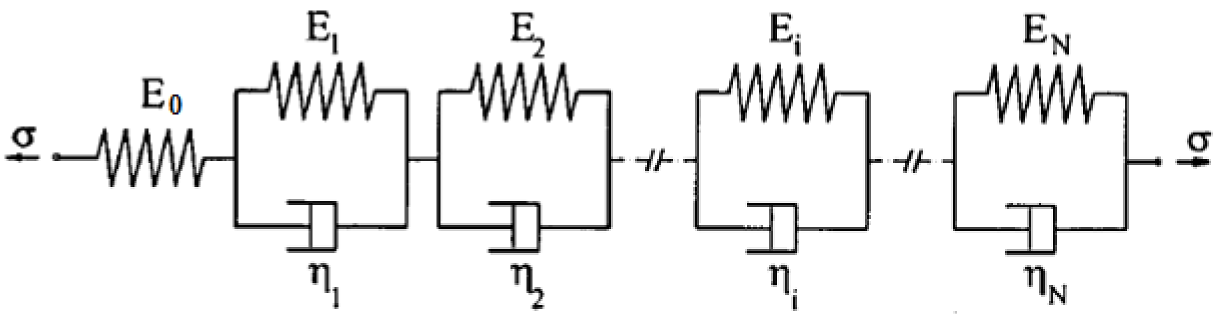
It is necessary to store all the stress history !

To avoid the need to store all the stress history…

- … the creep function $J(t,t_0)$ may be approximated as a Dirichlet series of N **real exponential functions**, in the form:

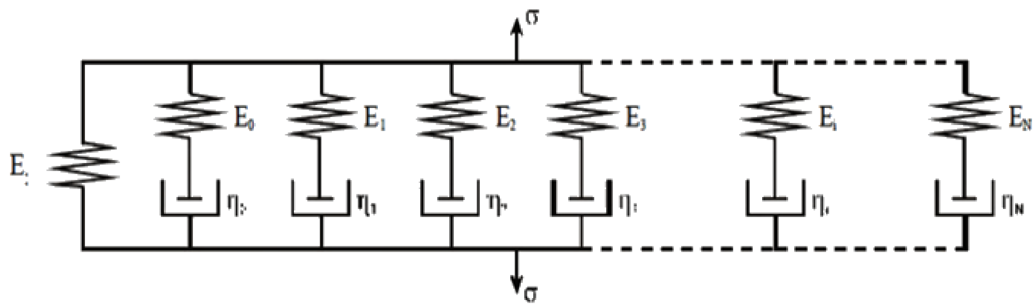
$$J(t,t_0) \approx \frac{1}{E_0} + \sum_{i=1}^{N} \frac{1}{E_i(t_0)} \left(1 - e^{-(t-t_0)/\tau_i} \right)$$

… which is equivalent to the use of the following **Kelvin chain**:



$$\tau_i = \frac{\eta_i}{E_i}$$

A Maxwell chain may also be used…



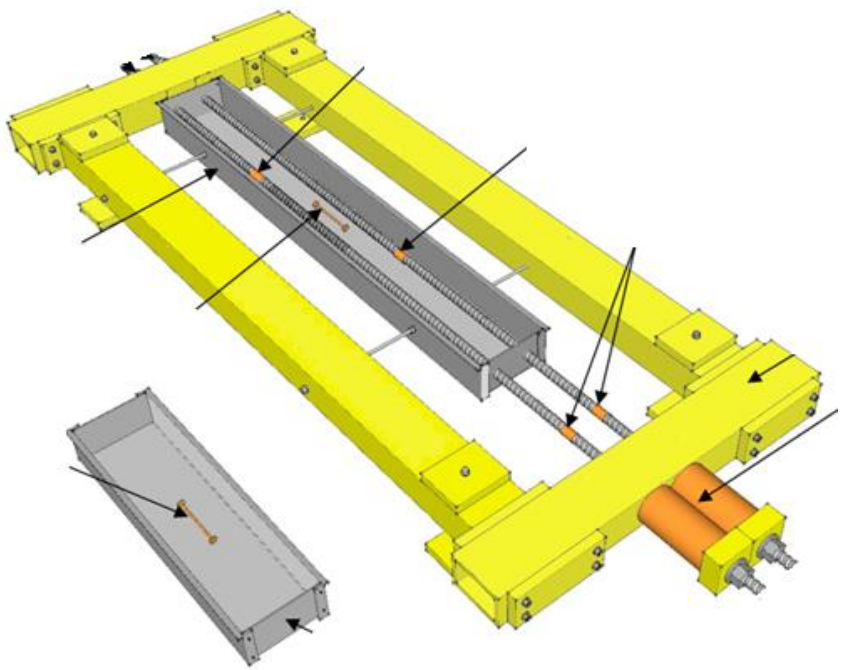
- The stress at time t_n, with the influence of creep, can then be obtained with recursive expressions of the form…

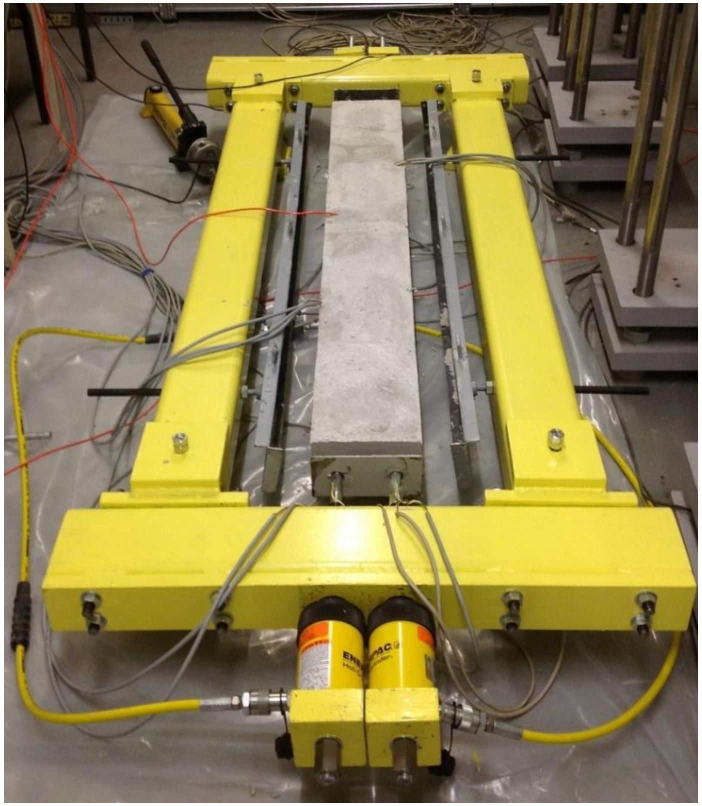
$$\boxed{\sigma_n = \sigma_{n-1} + \frac{1}{\bar{J}_n}\Delta\varepsilon_{\sigma,n} + \tilde{\sigma}_{n-1}}$$

average J in $[t_{n-1}, t_n]$

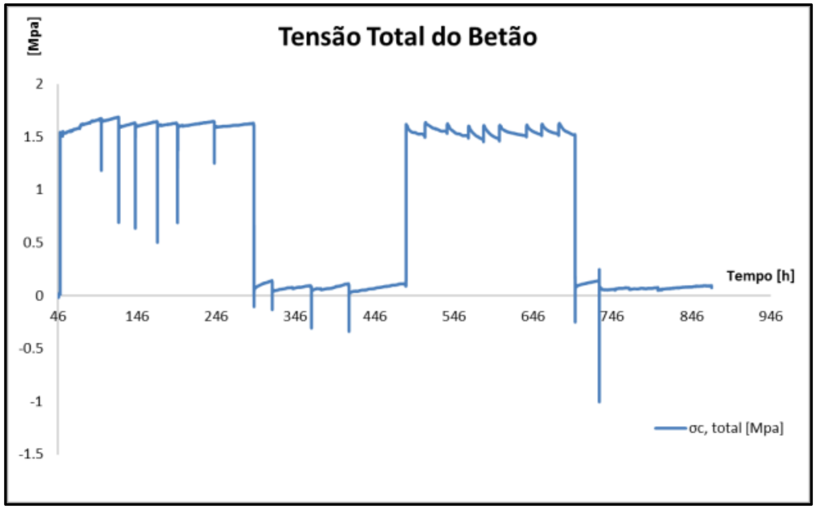
… where only the information from time t_{n-1} needs to be stored.

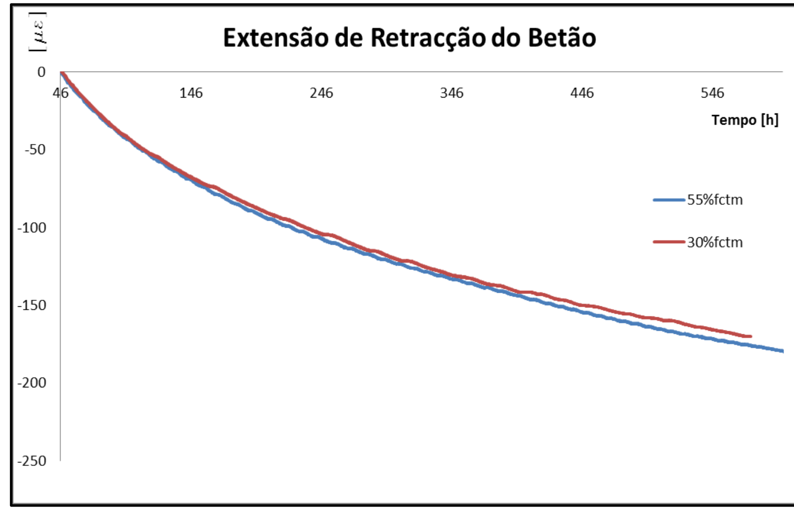
Experimental device at FEUP, developed with UM, where restrained shrinkage and tensile creep occur simultaneously (Faria *et al.* 2017)

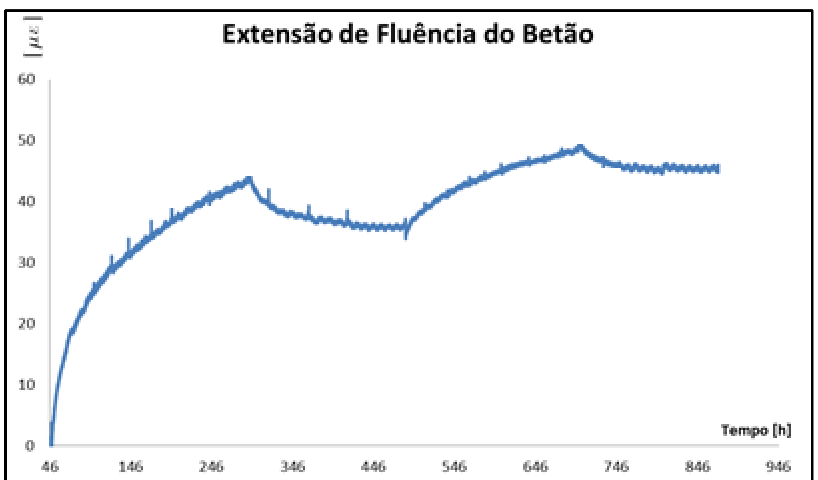


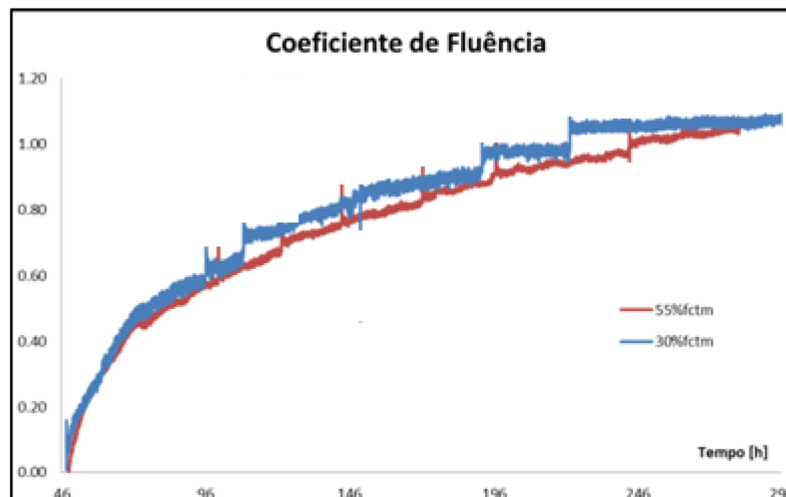


Typical results

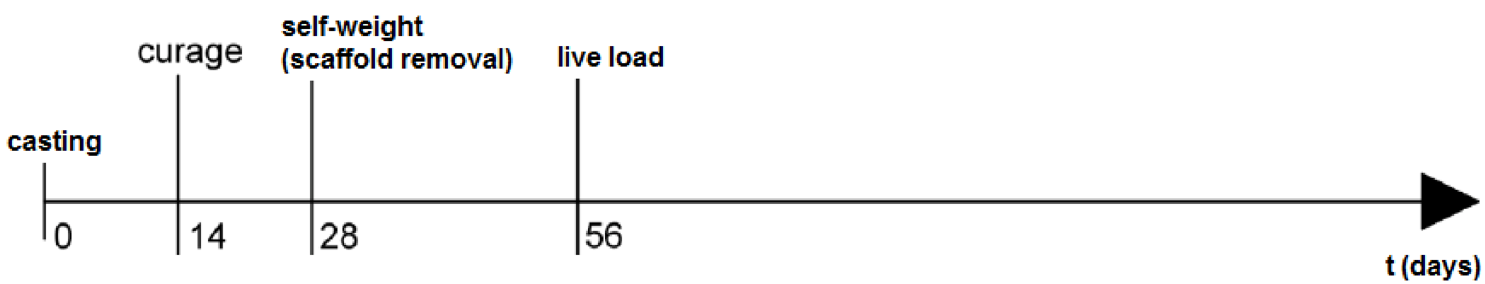


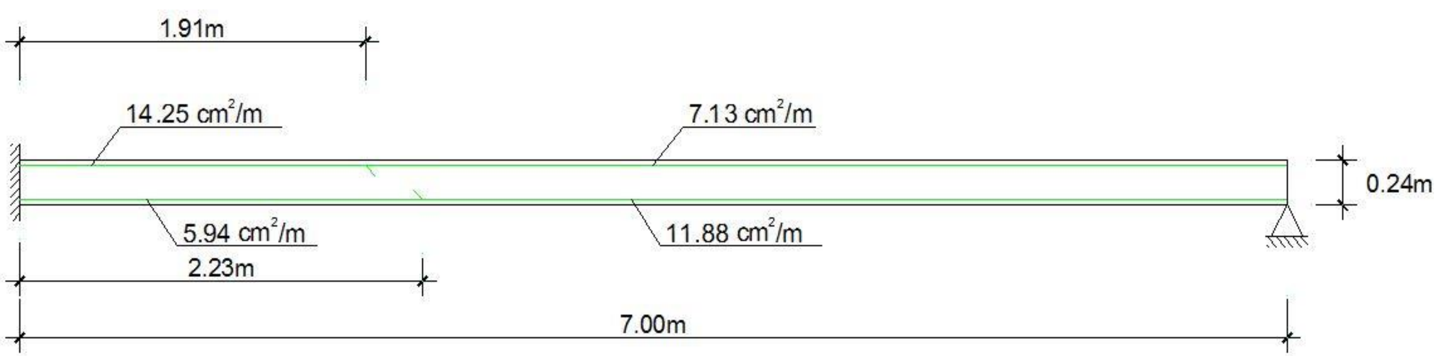




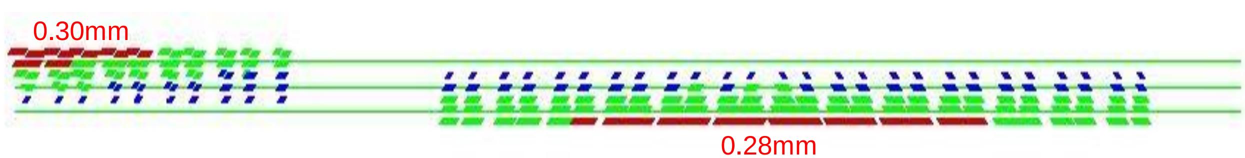


APPLICATION: w_k on a one-way slab under the QPC of loading, together with restrained drying shrinkage and creep ?

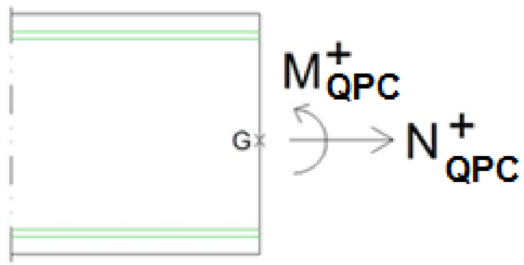




$\boxed{w_k}$



For design, what should be the axial force N^{+}_{QPC} (due to the restrained shrinkage), acting simultaneously with M^{+}_{QPC}, to guarantee e.g. w_k = 0.30mm ?



$$\boxed{N^{+}_{QPC} = f_{ctm} A_c = ?}$$

Too conservative: cracking (due to vertical loading + restrained shrinkage) significantly reduces N^{+}_{QPC} !

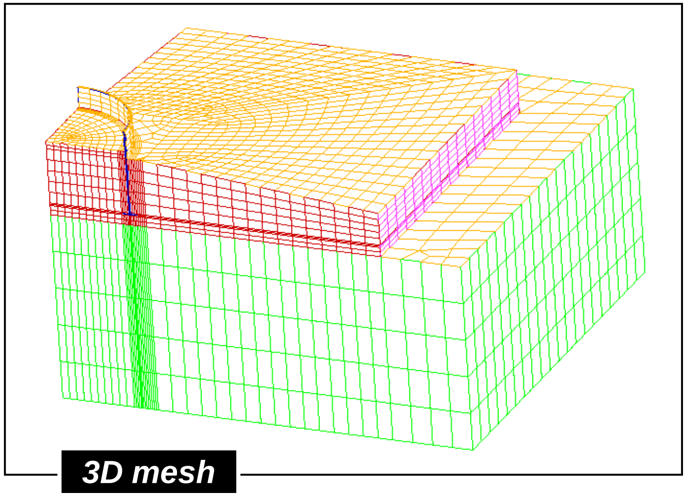
$$\boxed{N^{+}_{QPC} \approx [40\% - 45\%] \times f_{ctm} A_c}$$

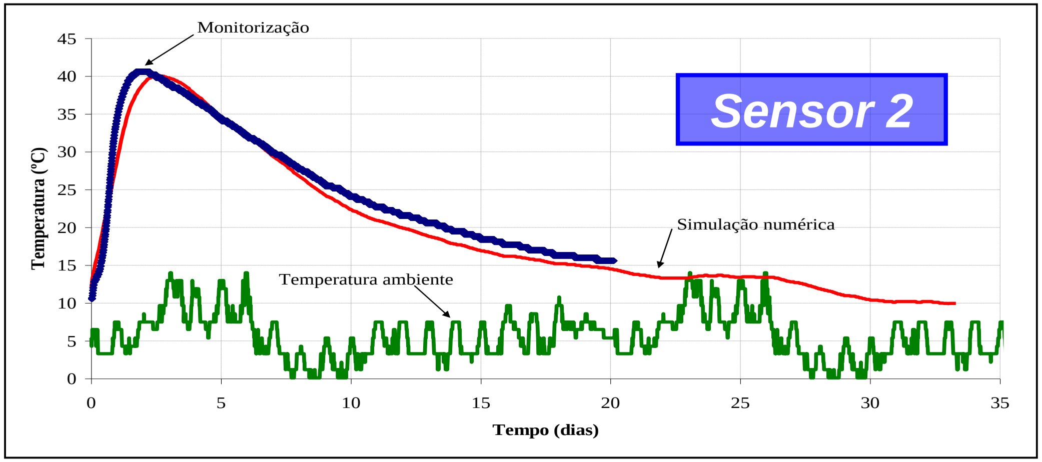
Obtained from the nonlinear time-stepping analysis, where drying shrinkage, creep and cracking where taken into account.

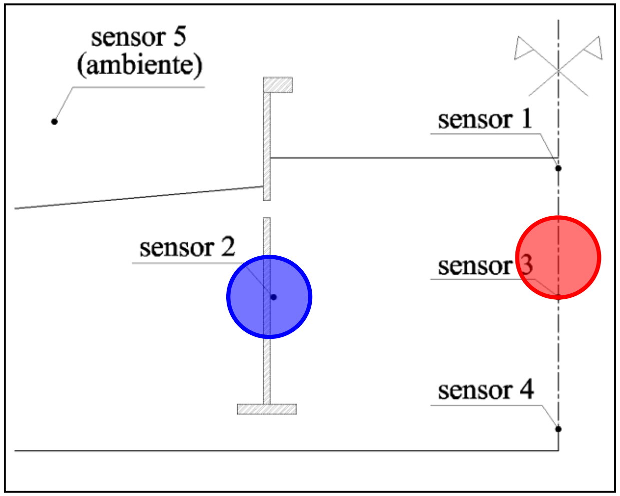
Thermal shrinkage and early-age creep during hydration are also of relevance in many cases

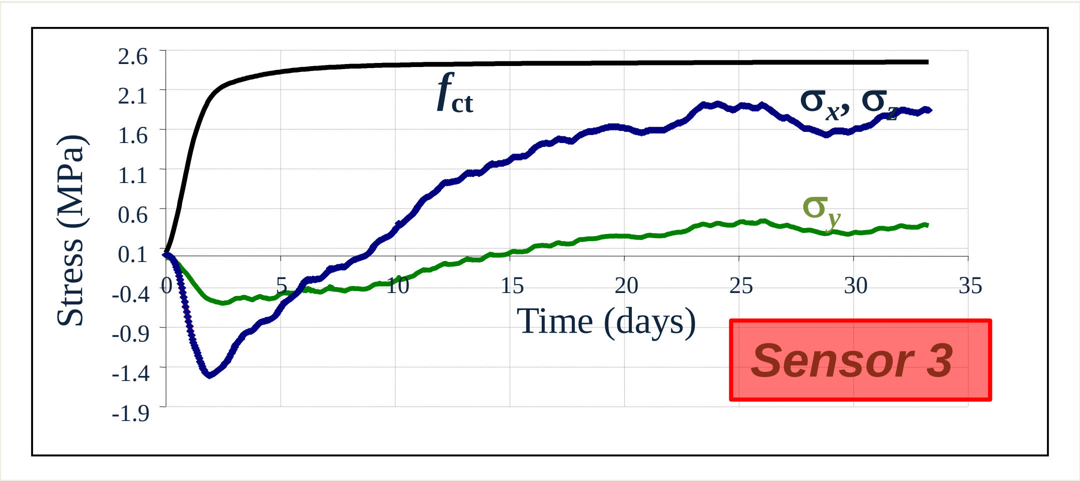
- Subject studied on a previous Research Project

Simulation and results









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Regulatory framework and recommendations for RC design considering the effects of shrinkage

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COMPETE 2020 PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

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ORDEM DOS ENGENHEIROS

Escola de Engenharia Universidade do Minho

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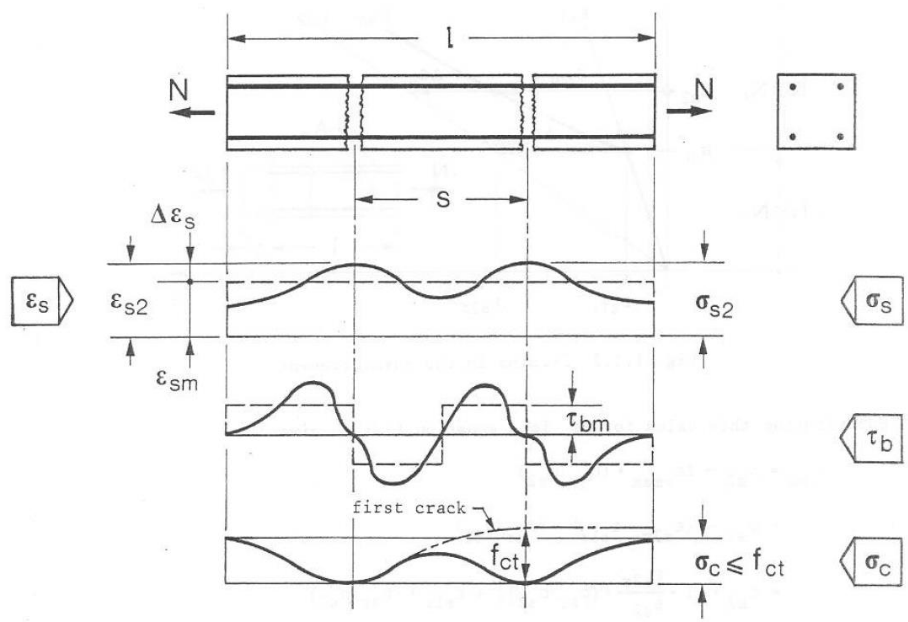
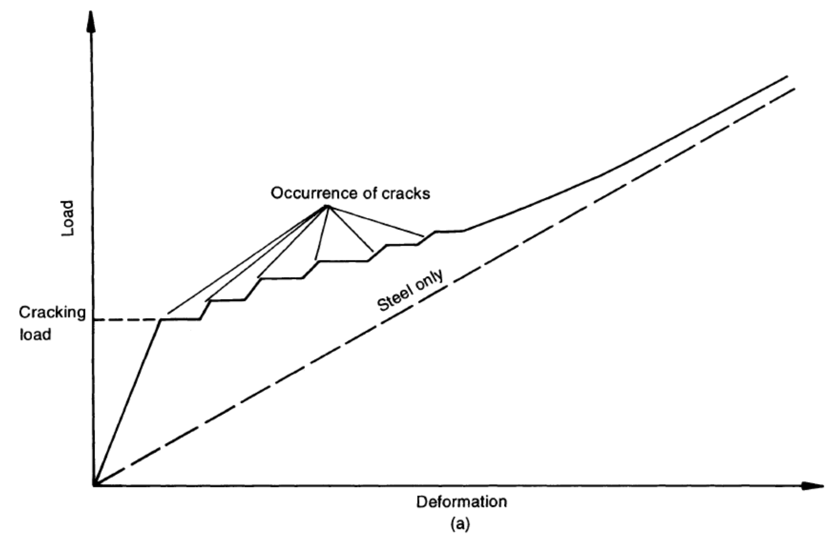
Cracking phenomena
Cracks due to applied loads

Cracks due to applied loads

- Cracks forms at about 90-110% of f_{ctm}





Average strain in reinforncement

$$\varepsilon_{sm} = \frac{\Delta l}{l} = \varepsilon_{s2} - \Delta\varepsilon_s$$

$\Delta\varepsilon_s$ – contribution of the concrete in tension between the cracks (tension stiffening).

Cracks due to applied loads

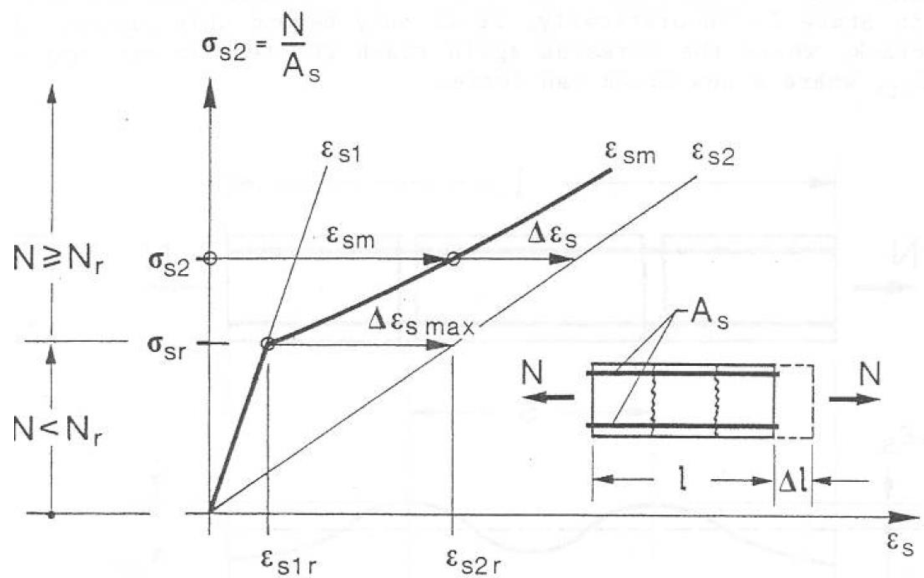
- Contribution of the concrete in tension between the cracks ($\Delta\varepsilon_s$)

$$\Delta\varepsilon_s = \Delta\varepsilon_{smax} \times (\sigma_{sr}/\sigma_{s2})$$

σ_{s2} – stress in the reinforcement at a cracked section under the combination of actions;
σ_{sr} – stress in the reinforcement, calculated on the basis of a cracked section, where the maximum stress in the concrete in tension is equal to f_{ct}.

$$\varepsilon_{sm} = (1-\tau) \times \varepsilon_{s1} + \tau \times \varepsilon_{s2}$$

ε_{s1} –strain in the reinforcement calculated for the uncracked section;
ε_{s2} – strain in the reinforcement calculated for the cracked section (neglecting the contribution of concrete in tension);
τ – distribution coefficient.



Cracks due to applied loads

- distribution coefficient (τ)

$$\begin{cases} \tau = 1 - \beta_1 \times \beta_2 \times \left(\dfrac{\sigma_{sr}}{\sigma_{s2}}\right)^2 \\ \tau = 0 \qquad for\ \sigma_{s2} < \sigma_{sr} \end{cases}$$

σ_{s2} – stress in the reinforcement at a cracked section under the combination of actions;
σ_{sr} – stress in the reinforcement, calculated on the basis of a cracked section, where the maximum stress in the concrete in tension is equal to f_{ct}.

$\beta_1 = \frac{1}{2.5K_1}$ – Coefficient take account bond quality of the reinforcement

$K_1 = 0.4$ for high bar bons
$K_1 = 0.8$ for smooth bars

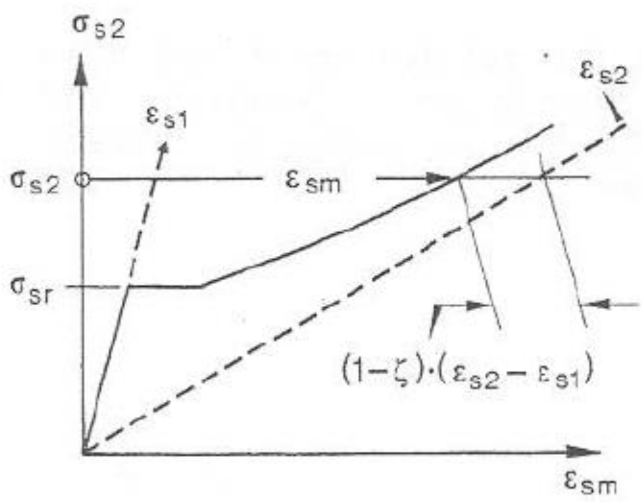
β_2 – coefficient representing the influence of the duration of application or of repetition of loading

$\beta_2 = 1.0$ for first loading
$\beta_2 = 0.5$ for long term loads or for a large number of cycles of load

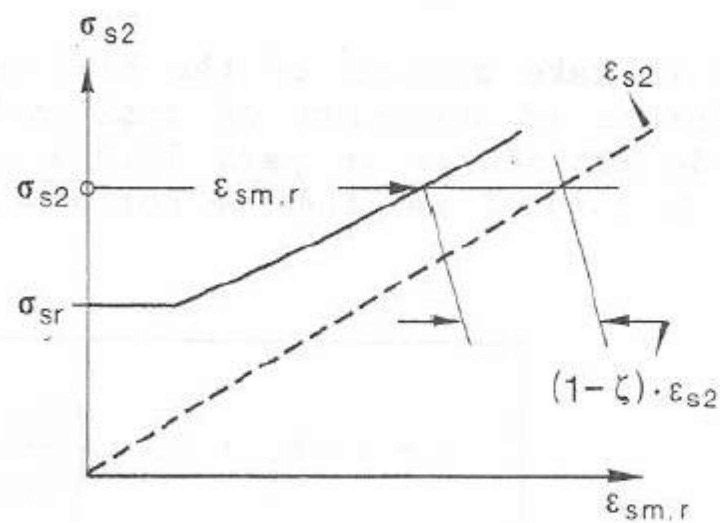
Cracks due to applied loads

- In the calculation of crack widths only the average strain in the reinforcement relative to that in the adjacent concrete is considered:

$$\varepsilon_{sm,r} = \tau \times \varepsilon_{s2} \geq 0.4\,\frac{\sigma_{s2}}{E_s}$$



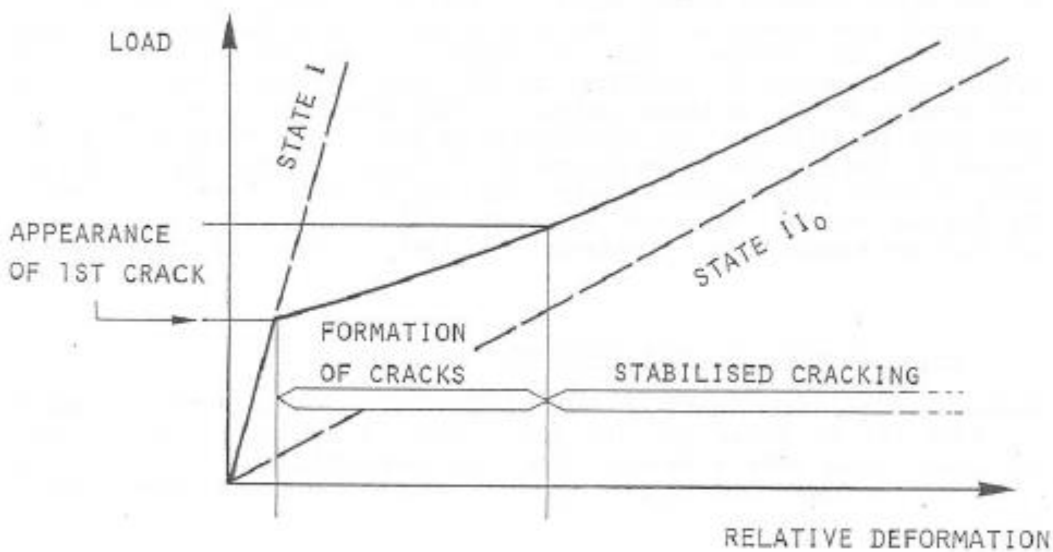
Average strain in the reinforcement



Average strain in the reinforcement relative to that in the adjacent concrete

Cracks due to applied loads

- There is two limiting state of behaviour of a reinforced concrete member subjected to tension or bending include of uncracked section (state I) and cracked section (state II)



Cracks due to applied loads

- When cracking is due to applied loads, the loading is independent of the stiffness of the member and stabilized cracking state will occur.
- In the stabilized state, the average crack width (w_m) can be determined according to:

$$w_m = S_{rm} \times \varepsilon_{sm,r}$$

S_{rm} – average crack spacing;
$\varepsilon_{sm,r}$ – average increase in strain in the reinforcement relative to surrounding concrete.

Cracks due to applied loads

❑ Crack spacing

Depends on the rate of stress transferred from the reinforcement (stress due to carrying all forces at the cracked section) to the concrete.

$$\tau \pi \emptyset S_0 = A_c f_{ct}$$

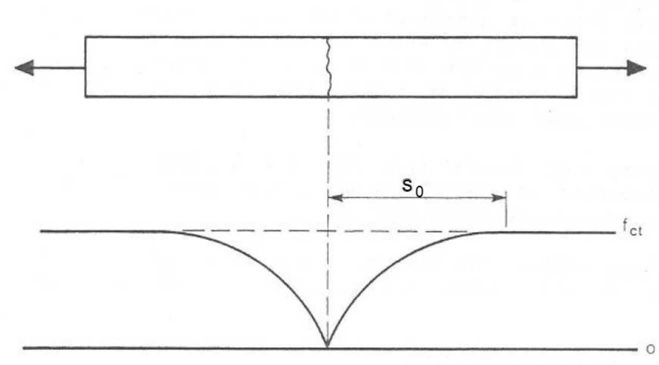
τ – bond stress;
A_c – area of concrete;
f_{ct} – tensile strength of concrete.

reinforcement ratio

$$\rho = \pi \emptyset^2 / 4 A_c$$

$$S_0 = \frac{1}{4} \times \frac{f_{ctm}}{\tau} \times \frac{\emptyset}{\rho}$$

Extensive studies (CEB Group, 1985; Beeby and Narayanan, 2009; Balazs, 2013) show that the concrete cover has a significant influence on the crack spacing.



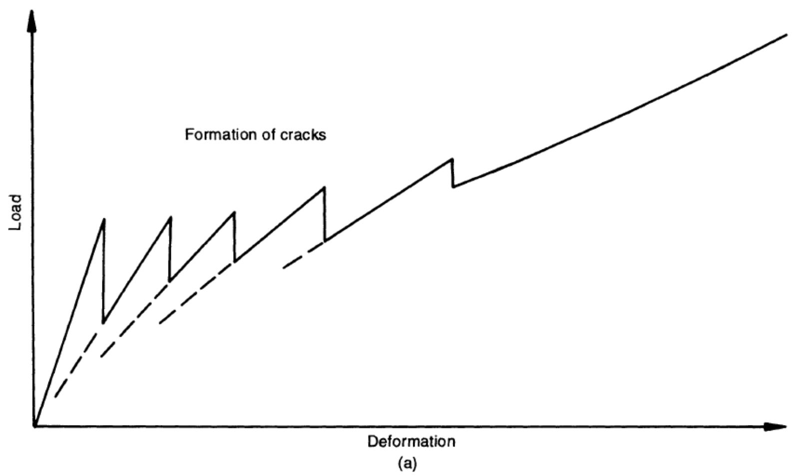
$$S_0 = kc + \frac{1}{4} \times \frac{f_{ctm}}{\tau} \times \frac{\emptyset}{\rho}$$

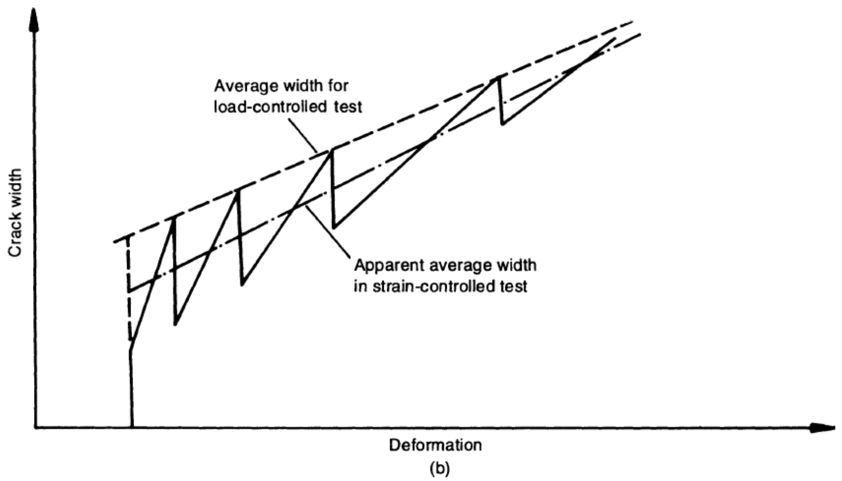
c – reinforcement cover;
k – empirical parameter to take the influence of the concrete cover into consideration (k=1.0)

Cracking phenomena
Cracks due to imposed deformations

Cracks due to imposed deformations

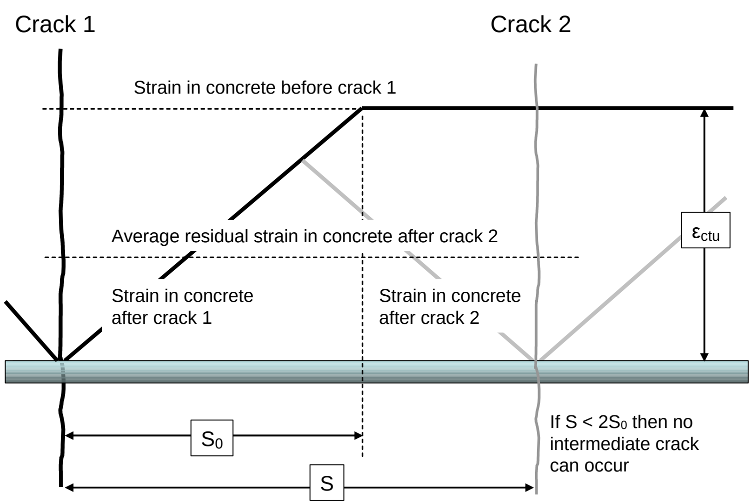
- When the formation of cracks is due to increasing of strain and not increasing of loads, the reduction of stiffness resulting from the crack formation leads to a reduction in the tensile force supported by the member.

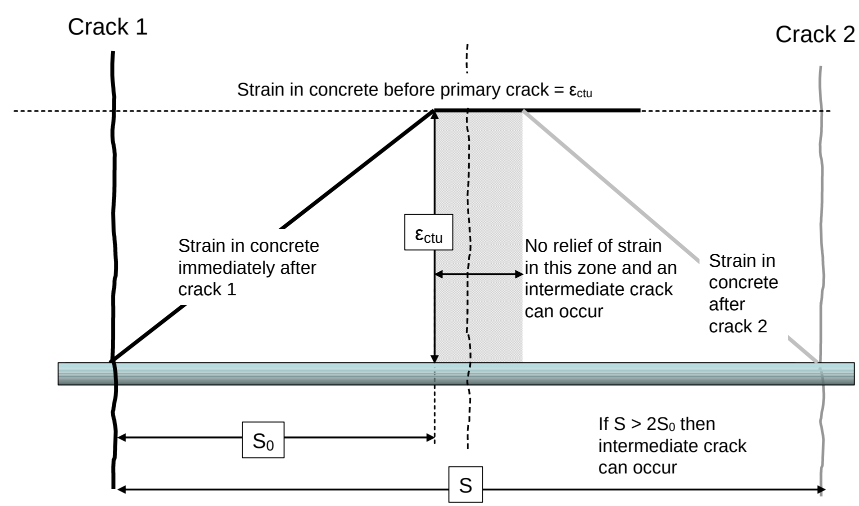




Cracks due to imposed deformations

- The first crack will occur in the highest restraint area and at the location of lowest strain capacity of concrete.

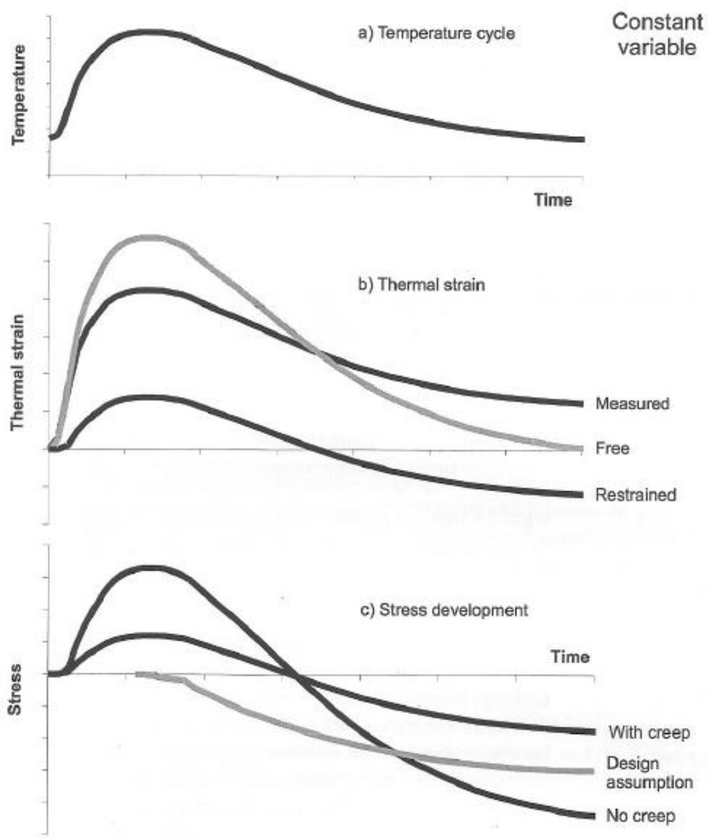




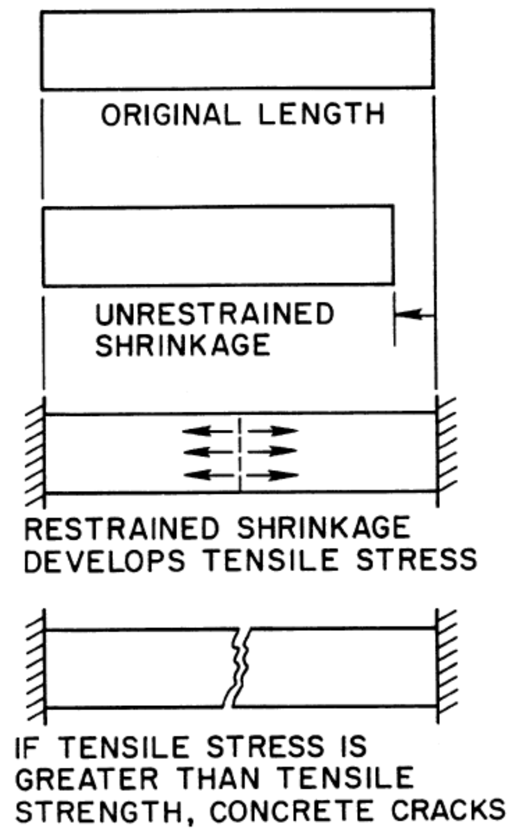
Cracks due to imposed deformations

- Causes:

Temperature variations

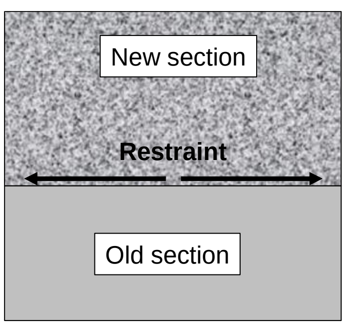


Shrinkage

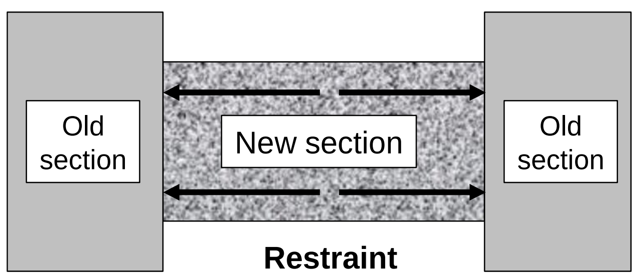


Cracks due to imposed deformations

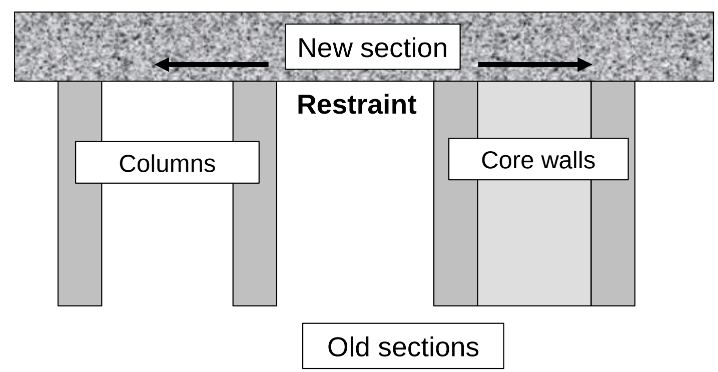
- Restraint factors
  - Wrong calculation of the level of restraint may result in wasteful over design or under design leading to unacceptable cracking. For example, a difference in restraint factor of 0.1 from, say, 0.5 to 0.6, will result in a 20 percent increase in the estimated restrained strain and this could make the difference between no cracking and cracking, or acceptable and unacceptable crack widths.



Edge restraint



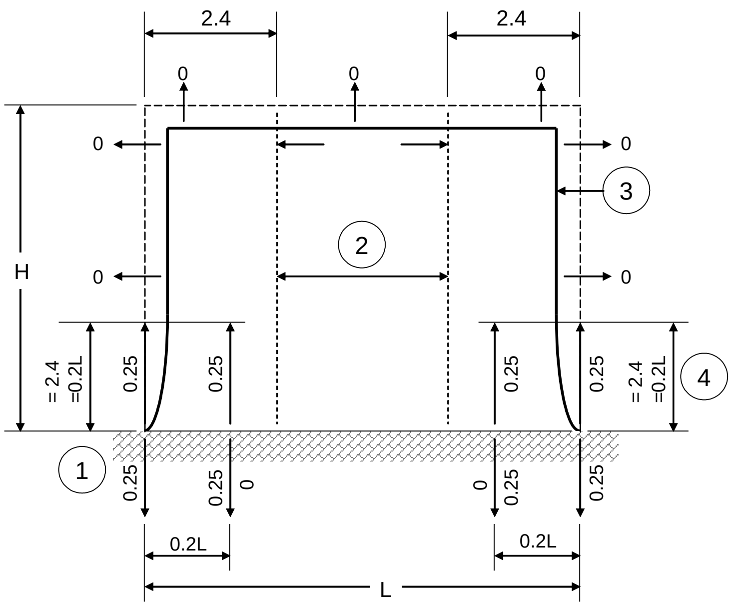
End restraint

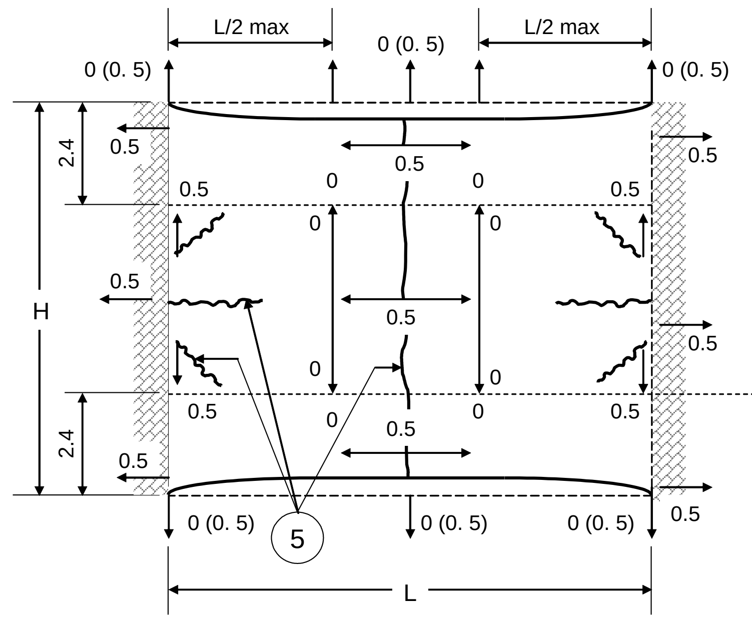


Intermittent restraint

Cracks due to imposed deformations

- Restraint factors (EN 1992-3)





Edge restraint

End restraint

Restraint factors for central zone of walls		
Ratio L/H	R at base	R at top
1	0.5	0
2	0.5	0
3	0.5	0.05
4	0.5	0.5
>8	0.5	0.5

KEY

1 Vertical restraint factors

2 Horizontal restraint factor

3 Expansion or free contraction joints

4 Whichever value is greater

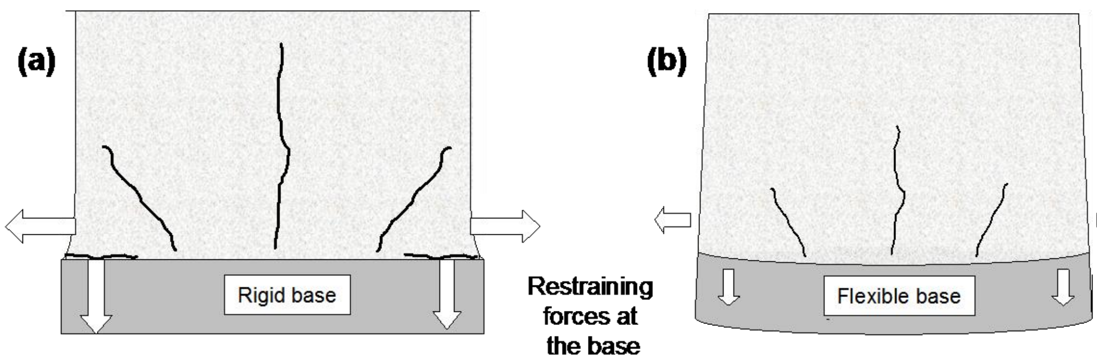
5 Potential primary cracks

Cracks due to imposed deformations

- Restraint factors


ACI 207.2R-95

Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete

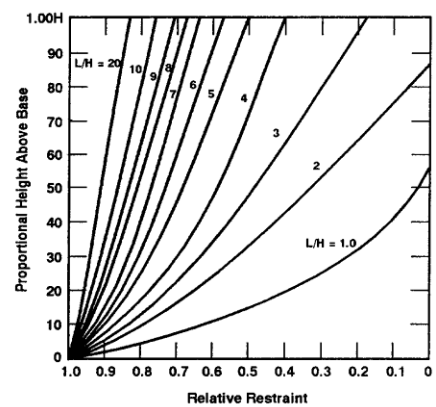


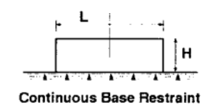
ACI 207.2R-95

The restraint at the base can be computed from:

$$R_j = \frac{1}{1 + \frac{A_n}{A_o}\,\frac{E_n}{E_0}}$$

A_n – cross sectional area of the new (restrained) concrete
A_o – cross sectional area of the old (restraining) concrete
E_n – modulus of elasticity of the new concrete
E_o – modulus of elasticity of the old concrete





Cracks due to imposed deformations

- Restraint factors (CIRIA C660)

restraint at the base

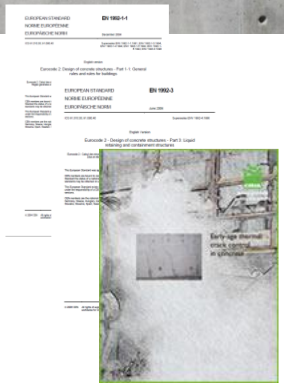
$$R_j = \frac{1}{1 + \frac{A_n}{A_o}\frac{E_n}{E_0}}$$

restraint at an height *h*

$$R = R_j \times \left[1.372\left(\frac{h}{L}\right)^2 - 2.543\left(\frac{h}{L}\right) + 1\right] + 0.044\left[\left(\frac{L}{H}\right) - 1.969\right]\left(\frac{h}{H}\right)^{1.349}$$

Limitations of maximum allowable crack width

Limitations of maximum allowable crack width



- EN 1992-1-1, EN 1992-3 and CIRIA C660

Exposure Class	Reinforced members and prestressed members with unbonded tendons	Prestressed members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0,4[1]	0,2
XC2, XC3, XC4	0,3	0,2[2]
XD1, XD2, XS1, XS2, XS3		Decompression

Note 1: For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.
Note 2: For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

For retaining water structures w_{max} is defined as a function of the hydrostatic pressure to the wall thickness (h_D/h).

For $h_D/h \leq 5$, $w_{max} = 0.2$ mm

For $h_D/h \geq 35$, $w_{max} = 0.05$ mm

- fib-model code 2010 – w_{max} =0.3 mm for general cases

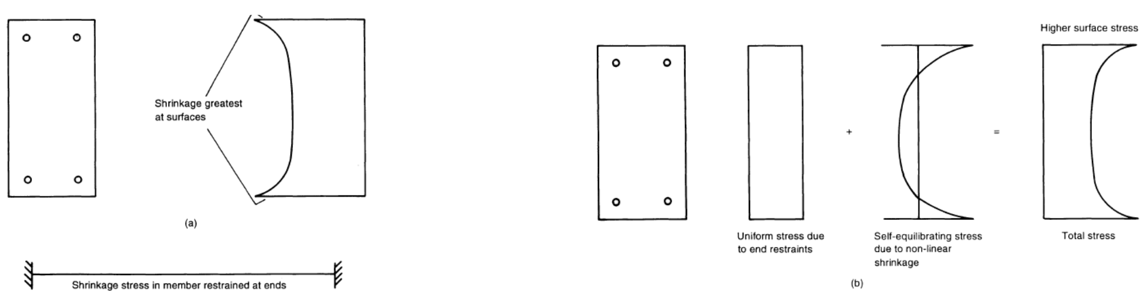
Minimum reinforcement for controlling cracks

Minimum reinforcement for controlling cracks

- For prevention of bars yielding the minimum area of reinforcement must be prepared to allow the bars remain elastic during the cracking of concrete;
- However, using of $A_{s,min}$, is not a guarantee for occurrence of small cracks or achieving the maximum acceptable crack width in a reinforced concrete section;
- For prevention of reinforcement yielding at the first crack:

$$A_s f_y > A_c f_{ct}$$

- Furthermore, where deformations of the concrete resulting from shrinkage or temperature change in the member itself are restrained, the internal self-equilibrating stresses will occur. These stresses occur more rapidly near the member surface and so we should use the factor *k* in the above formula to consider the non-uniformly influence of them in the cross section of a member.



Minimum reinforcement for controlling cracks

- EN 1992-1-1

$$A_{s,min}\sigma_s = k_c k f_{ct,eff} A_{ct}$$

A_{ct} – area of concrete within tensile zone. The tensile zone is that part of the section which is calculated to be in tension just before formation of the first crack;

σ_s – absolute value of the maximum stress permitted in the reinforcement immediately after formation of the crack;

$f_{ct,eff}$ – mean value of the tensile strength of the concrete effective at the time when the cracks may first be expected to occur;

k – coefficient which allows for the effect of non-uniform self-equilibrating stresses, which lead to a reduction of restraint forces (k=1.0 for webs with h ≤ 300 mm or flanges with widths less than 300 mm and k=0.65 for webs with h ≥ 800 mm or flanges with widths greater than 800 mm);

k_c – coefficient which takes account of the stress distribution within the section immediately prior to cracking and of the change of lever arm.

Minimum reinforcement for controlling cracks

- CIRIA C660 and Australian Standards

$$A_{s,min} = 3k_s\, A_{ct}/f_s$$

Assumes f_{ctm}=3.0 MPa

A_{ct} – area of concrete within tensile zone. The tensile zone is that part of the section which is calculated to be in tension just before formation of the first crack;

f_s – absolute value of the maximum stress permitted in the reinforcement immediately after formation of the crack;

k_s – coefficient which allows for the effect of non-uniform self-equilibrating stresses and the stress distribution within the section immediately prior to cracking and of the change of lever arm.

Crack width and crack spacing
Approaches for applied loads

EN 1992-1-1

- Maximum crack width (w_k)

$$w_k = S_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm})$$

$S_{r,max}$ – maximum crack spacing;

ε_{sm} – mean strain in the reinforcement including the effect of imposed deformations and tension stiffening;

ε_{cm} – mean strain in the concrete between cracks.

- Average strain ($\varepsilon_{sm} - \varepsilon_{cm}$)

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \dfrac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \geq 0.6\,\frac{\sigma_s}{E_s}$$

σ_s – stress in the tension reinforcement assuming a cracked section;

$\alpha_a = E_s/E_{cm}$;

$f_{ct,eff}$ – mean value of the tensile strength of the concrete effective at the time when the cracks may first be expected to occur ($f_{ct,eff} = f_{ctm}$)

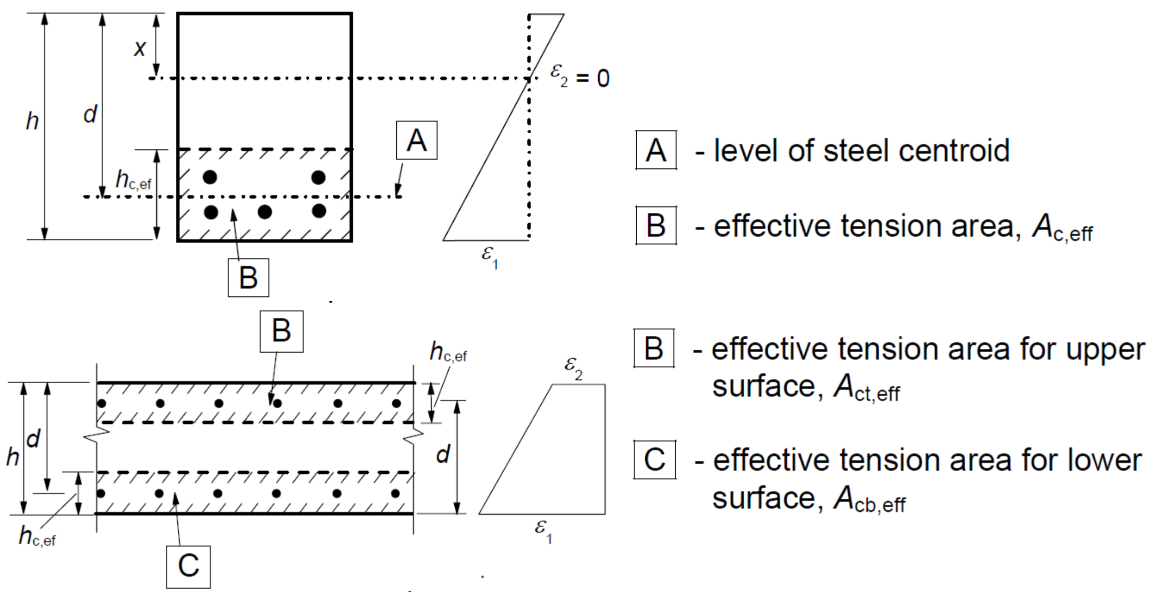
k_t – factor dependent on the duration of the load (0.6 for short term loading and 0.4 for long term loading)

EN 1992-1-1

- Reinforcement ratio ($\rho_{p,eff}$)

$$\rho_{p,eff} = A_s / A_{c,eff}$$

A_s – area of reinforcement in tension;
$A_{c,eff}$ – effective area of concrete in tension surrounding the reinforcement of depth, $h_{c,eff}$, where $h_{c,eff}$ is the lesser of 2.5(h-d), (h-x)/3 or h/2

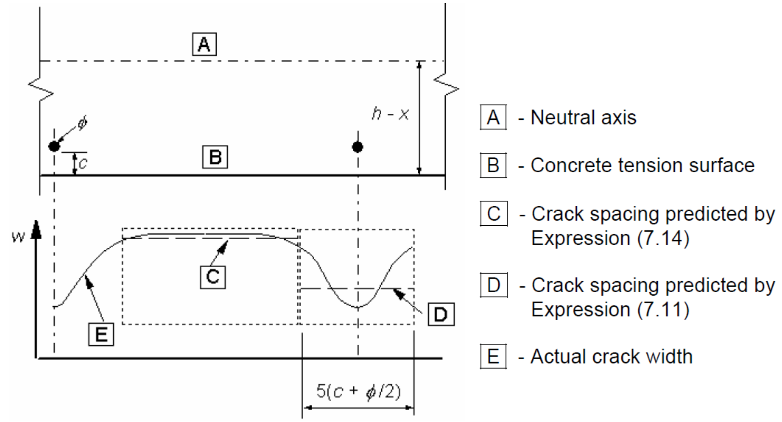


EN 1992-1-1

❑ Maximum crack spacing ($S_{r,max}$)

- If spacing of the bonded reinforcement ≤ 5(c + Ø/2)

$$S_{r,max} = k_3 c + k_1 k_2 k_4 Ø/\rho_{p,eff}$$



k_1 – coefficient which takes account of the bond properties of the bonded reinforcement (0.8 for high bond bars and 1.6 for bars with an effectively plain surface)
k_2 – coefficient which takes account of the distribution of strain (0.5 for bending and 1.0 for pure tension)

For cases of eccentric tension or for local areas

$$k_2 = (\varepsilon_1 + \varepsilon_2)/2\,\varepsilon_1$$

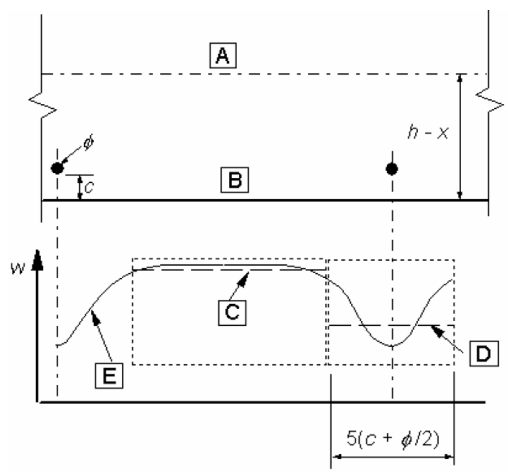
Where ε_1 is the greater and ε_2 is the lesser tensile strain at the boundaries of the section considered, assessed on the basis of a cracked section

EN 1992-1-1

- Maximum crack spacing ($S_{r,max}$)

- If spacing of the bonded reinforcement > 5(c + Ø/2)

$$S_{r,max} = 1.3\,(h - x)$$



A - Neutral axis

B - Concrete tension surface

C - Crack spacing predicted by Expression (7.14)

D - Crack spacing predicted by Expression (7.11)

E - Actual crack width

EN 1992-1-1

❑ Control of cracking without direct calculation

- Maximum bar diameters $\varnothing^*_s$

Steel stress[2] [MPa]	Maximum bar size [mm] w_k= 0,4 mm	w_k= 0,3 mm	w_k= 0,2 mm
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6
360	10	8	5
400	8	6	4
450	6	5	-

Table 7.2N

- Maximum bar spacing

Steel stress[2] [MPa]	Maximum bar spacing [mm] w_k=0,4 mm	w_k=0,3 mm	w_k=0,2 mm
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

Table 7.3N

Assumptions:

- c = 25mm;
- $f_{ct,eff}$ = 2,9MPa;
- h_{cr} = 0,5;
- $(h\text{-}d) = 0{,}1h$;
- k_1 = 0,8;
- k_2 = 0,5;
- k_c = 0,4;
- k = 1,0;
- k_t = 0,4
- k’ = 1,0

EN 1992-1-1

- Control of cracking without direct calculation

• The maximum bar diameter should be modified as follows

For Bending
(at least part of section in compression)

$$\emptyset_s = \emptyset_s^* \left(f_{ct,eff}/2.9\right)\frac{k_c h_{cr}}{2(h-d)}$$

For tension
(uniform axial tension)

$$\emptyset_s = \emptyset_s^* \left(f_{ct,eff}/2.9\right)\frac{h_{cr}}{8(h-d)}$$

$\emptyset_s$ – adjusted maximum bar diameter
$\emptyset^*_s$ – maximum bar size given in the Table 5.1
h – overall depth of the section
h_{cr} – depth of the tensile zone immediately prior to cracking, considering the characteristic values of axial forces under the quasi-permanent combination of actions
d – effective depth to the centroid of the outer layer of reinforcement

fib-Model Code 2010

fib **Model Code for Concrete Structures 2010**

- Design crack width (w_d)

$$w_d = 2l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs})$$

$l_{s,max}$ – length over which slip between concrete and steel occurs. The steel and concrete strains, which occur within this length, contribute to the width of crack

ε_{sm} – average steel strain over the length $l_{s,max}$

ε_{cm} – average concrete strain over the length $l_{s,max}$

ε_{cs} – strain of the concrete due to (free) shrinkage

fib-Model Code 2010

fib Model Code for Concrete Structures 2010

- length $l_{s,max}$

$$l_{s,max} = kc + \frac{1}{4} \times \frac{f_{ctm}}{\tau_{bms}} \times \frac{\emptyset_s}{\rho_{s,eff}}$$

k – empirical parameter to take the influence of the concrete cover into consideration; as a simplification, *k*=1.0 can be assumed
c – concrete cover (c ≤ 75 mm)
τ_{bm} – mean bond strength between steel and concrete (determined according to the table)

	Crack formation stage	*Stabilized cracking stage*
Short term, instantaneous loading	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$
Long term, repeated loading	$\tau_{bms} = 1.35 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.4$ $\eta_r = 1$

Table 7.6-2

fib-Model Code 2010

fib **Model Code for Concrete Structures 2010**

- Relative mean strain $(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs})$

$$\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs} = \frac{\sigma_s - \beta \times \sigma_{sr}}{E_s} - \eta_r \times \varepsilon_{sh}$$

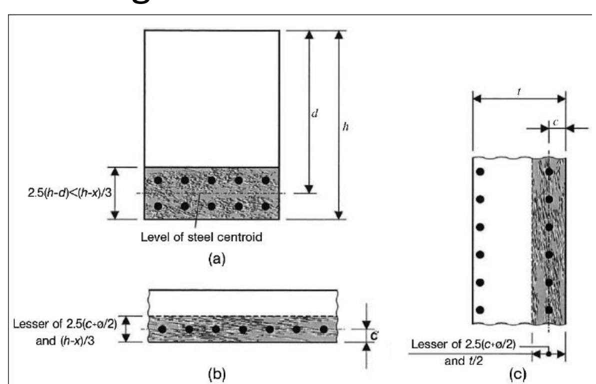
σ_s – steel stress in a crack
σ_{sr} – maximum steel stress in a crack in the crack formation stage, which, for pure tension, is:

$$\sigma_{sr} = \frac{f_{ctm}}{\rho_{s,ef}}(1 + \alpha_e \rho_{s,ef})$$

β – empirical coefficient to assess the mean strain over $l_{s,max}$ depending on the type of loading (table 7.6-2)
η_r – coefficient for considering the shrinkage contribution
ε_{sh} – shrinkage strain

$$\alpha_e = \frac{E_s}{E_c}$$

$$\rho_{s,ef} = \frac{A_s}{A_{c,ef}}$$



fib-Model Code 2010

fib Model Code
for Concrete Structures
2010

- These equations are valid for determining the surface crack width of members under the pure tension.

- For members subjected to bending, the values of crack width are obtained at the level of the reinforcement.

- In bending, crack spacing and crack width will be larger at the extreme tensile fiber.

- Therefore, in this situation the value of crack width at the extreme tensile fiber should be multiplied by a factor of (h-x)/(d-x)

ACI 224.1R

- ❑ Maximum crack width (w)

- For elements in bending:

$$w = 0.046\beta f_s \sqrt[3]{d_c A} \times 10^{-6}$$

β – ratio of distance between neutral axis and tension face to distance between neutral axis and centroid of reinforcing steel (taken as approximately 1.20 for typical beams in buildings);

f_s – reinforcing steel stress;

d_c – thickness of cover from tension fiber to center of the closest bar;

A – area of concrete symmetric with reinforcing steel divided by number of bars.

ACI 224.2R

- Maximum crack width (w)

- For elements in direct tension:

$$w = 4\varepsilon_s t_e$$

ε_s – tensile strain in reinforcing bar assuming no tension in concrete;
t_e – effective concrete cover:

$$t_e = d_c\sqrt{1 + \left(\frac{s}{4d_c}\right)^2}$$

However, ACI ignores the contribution of concrete between cracks!

JSCE Guidelines N 15

- Maximum crack width (*w*) for elements in bending

$$w = 1.1 k_1 k_2 k_3 \{4c + 0.7(c_s - \emptyset)\} \left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd} \right]$$

k_1 – constant to take into account the effect of surface geometry of reinforcement on crack width (1.0 for deformed bars and 1.3 for plain bars)

k_2 – constant to take into account the effect of concrete quality on crack width (it represents the effect of changes in bonding characteristics between the reinforcement and the concrete due to changes of concrete quality on crack width):

$$k_2 = \frac{15}{f'_c + 20} + 0.7$$

k_3 – constant to take into account the effect of multiple layers of tensile reinforcement on crack width:

$$k_3 = \frac{5(n+2)}{7n+8}$$

n – number of the layers of tensile reinforcement

JSCE Guidelines N 15

- Maximum crack width (w) for elements in bending

$$w = 1.1 k_1 k_2 k_3 \{4c + 0.7(c_s - \emptyset)\} \left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd} \right]$$

c – concrete cover

c_s – center-to-center distance of tensile reinforcements

Φ – diameter of tensile reinforcement

ε'_{csd} – compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete (it should be determined with the consideration of shape of cross section of the member, environmental condition, magnitude of stress and etc.)

σ_{se} – increment of stress of reinforcement from the state in which concrete stress at the portion of reinforcement is zero

Indian Standards IS 3370-2

- Maximum crack width (w)

- For elements in bending

$$w = \frac{3a_{cr}\varepsilon_m}{1 + \frac{2(a_{cr} - C_{min})}{D - x}}$$

a_{cr} – distance from the point considered to the surface of the nearest longitudinal bar (for points close to the bars, a_{cr} is equal to the cover);

ε_m – average strain at the level where the cracking is being considered;

C_{min} – minimum cover to the tension steel;

D – overall depth of the member;

x – depth of neutral axis.

Indian Standards IS 3370-2

- Average strain (ε_m)

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2$$

ε_1 – strain at the level considered
ε_2 – strain due to stiffening effect of concrete between cracks

$$\varepsilon_2 = \frac{b_t(D-x)(a'-x)}{3E_sA_s(d-x)}$$ crack width of 0.2 mm

$$\varepsilon_2 = \frac{1.5b_t(D-x)(a'-x)}{3E_sA_s(d-x)}$$ crack width of 0.1 mm

b_t – width of section the centroid of the tension steel
E_s – modulus of elasticity of reinforcement
A_s – area of tension reinforcement
d – effective depth
a' – distance from the compression face to the point at which the crack width is being calculated

Indian Standards IS 3370-2

- ❑ Maximum crack width (w)

- For elements in direct tension

$$w = 3a_{cr}\varepsilon_m$$

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2$$

$$\varepsilon_2 = \frac{2b_t D}{3E_s A_s}$$ crack width of 0.2 mm

$$\varepsilon_2 = \frac{b_t D}{3E_s A_s}$$ crack width of 0.1 mm

Crack width and crack spacing
Approaches for imposed deformations

EN 1992-1-1

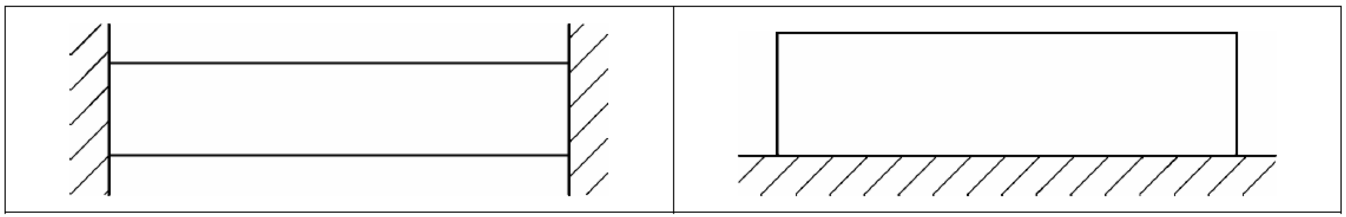
- “For cracking caused dominantly by restraint, the bar sizes given in Table 7.2N are not exceeded where the steel stress is the value obtained immediately after cracking (i.e. σ_s in Expression (7.1)).”

Expression (7.1): $$A_{s,min}\sigma_s = k_c k f_{ct,eff} A_{ct}$$

EN 1992-3

- Maximum crack width (w_k)

$$w_k = S_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm})$$



(a) restraint of a member at its ends (b) restraint along one edge

- End restraint

$$(\varepsilon_{sm} - \varepsilon_{cm}) = 0.5\alpha_e k_c k f_{ct,eff}\,(1 + 1/(\alpha_e \rho))/E_s$$

$\rho = A_s/A_{ct}$

k – coefficient which allows for the effect of non-uniform self-equilibrating stresses, which lead to a reduction of restraint forces;

k_c – coefficient which takes account of the stress distribution within the section immediately prior to cracking and of the change of lever arm.

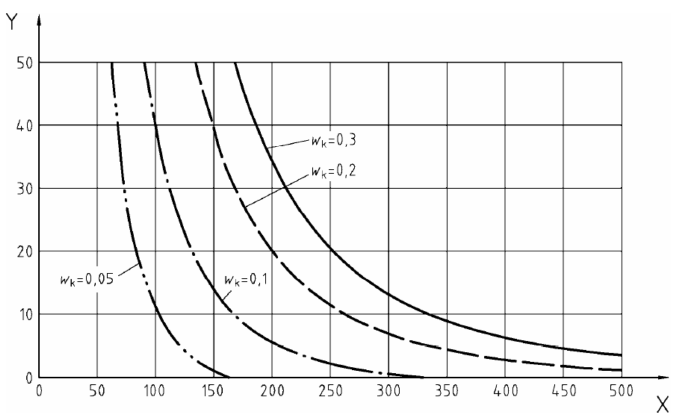
EN 1992-3

- End restraint

- For checking the cracking without direct calculation

$$\sigma_s = k_c k\, f_{ct,eff}/\rho$$

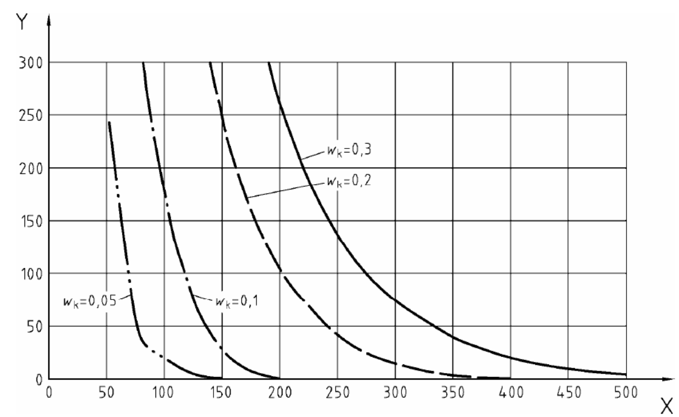
Maximum bar diameter



Key

X reinforcement stress, σ_s (N/mm²)
Y maximum bar diameter (mm)

Maximum bar spacing



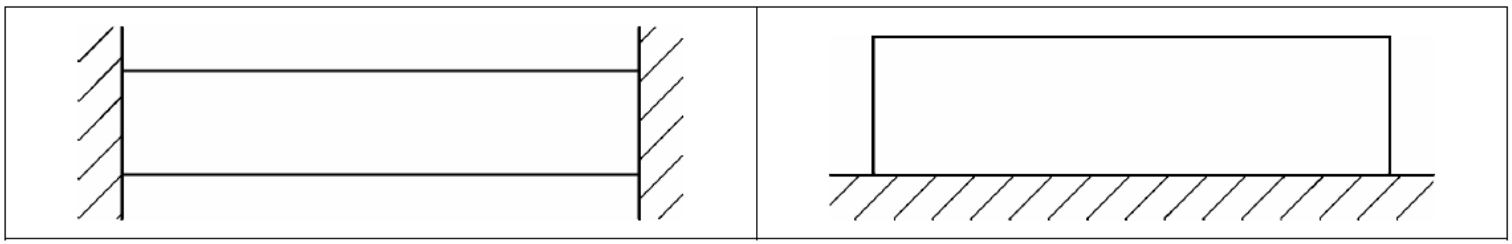
Key

X reinforcement stress, σ_s (N/mm²)
Y maximum bar spacing (mm)

EN 1992-3

- Maximum crack width (w_k)

$$w_k = S_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm})$$



(a) restraint of a member at its ends

(b) restraint along one edge

- One edge restraint

"Unlike the end restrained situation, the formation of a crack in this case only influences the distribution of stresses locally and the crack width is a function of the restrained strain rather than the tensile strain capacity of the concrete."

$$(\varepsilon_{sm} - \varepsilon_{cm}) = R_{ax}\varepsilon_{free}$$

R_{ax} – restraint factor;

ε_{free} – strain which would occur if the member was completely unrestrained

CIRIA C660

❑ Ends restraint

- The method of CIRIA C660 for condition of ends restraint is similar to EN 1992-3

$$w_k = S_{r,max} 0.5 \alpha_e k_c k f_{ct,eff} \left(1 + 1/(\alpha_e \rho)\right)/E_s$$

❑ One edge restraint

$$w_k = S_{r,max}\, \varepsilon_{cr}$$

ε_{cr} – crack-inducing strain

CIRIA C660

- Crack-inducing strain

$$\varepsilon_{cr} = \varepsilon_r - 0.5\,\varepsilon_{ctu}$$

Where:

$$\varepsilon_r = K_1\{[\alpha_c T_1 + \varepsilon_{ca}]R_1 + \alpha_c T_2 R_2 + \varepsilon_{cd} R_3\}$$

$$\varepsilon_{ctu} = 1.01(f_{ctm}/E_{cm}) \times 10^6 + 8.4\,microstrain$$

K_1 – coefficient for the effect of stress relaxation due to creep under sustained loading;
α_c – coefficient of thermal expansion of concrete;
T_1 – difference between the peak temperature, T_p, and the mean ambient temperature T_a;
T_2 – long term fall in temperature which takes into account the time of year at which the concrete was cast;
ε_{ca} – autogenous shrinkage;
ε_{cd} – drying shrinkage;
R_1 – restraint factor that applies during the early thermal cycle;
R_2 R_3 – restraint factors applying to long-term thermal movement and drying shrinkage respectively.

fib-Model Code 2010

fib **Model Code for Concrete Structures 2010**

- For imposed deformation, the crack formation stage applies when the mean strain satisfies the following condition:

$$\varepsilon = \frac{\Delta L}{L} \leq \frac{\sigma_{sr}(1-\beta)}{E_s}$$

- If the mean strain is larger than this value, the stabilized cracking stage applies. However, *"under imposed deformation the stabilized cracking stage is usually not reached"*.
- fib recommend the same equation for calculation of crack width in all stages of cracking:

$$w_d = 2l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs})$$ =0 if in crack formation stage

	Crack formation stage	*Stabilized cracking stage*
Short term, instantaneous loading	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$
Long term, repeated loading	$\tau_{bms} = 1.35 \cdot f_{ctm}(t)$ $\beta = 0.6$ $\eta_r = 0$	$\tau_{bms} = 1.8 \cdot f_{ctm}(t)$ $\beta = 0.4$ $\eta_r = 1$

Do not consider the restraint factor!!

Discussion

Examples

Example 1: RC Tie under external tension

Assumptions:

- RC Tie with one bar at the center and under tensile applied load
- cross section: 10 cm x 10 cm
- Reinforcement: 1 ϕ16 mm
- Concrete class: C20/25, f_{ctm} = 2.2 MPa
- Steel class: S400, f_{yk} = 400 MPa
- External load: F = 35 kN

Example 2: Reinforced concrete slab restrained at ends only without applied loads

Assumptions:

- Slab geometry dimensions: 0.15 m x 1.0 m x 10 m
- Reinforcement: 5 ϕ12 mm (top) & 5 ϕ12 mm (bottom)
- Concrete cover: c=30 mm
- Concrete class: C20/25, f_{ctm}= 2.2 MPa
- Steel class: S400, f_{yk} = 400 MPa
- Relative humidity: 50%
- $h_0 = \frac{2A_c}{u}$ = 150 mm
- Drying shrinkage started after 28 days
- Ignoring the self-weight of concrete
- Ignoring the autogenous shrinkage

Examples

Example 3: Reinforced concrete wall restrained at base on the foundation

Assumptions:

- Wall geometry dimensions (condition 1): 0.15 m x 3.0 m x 12 m
- Wall geometry dimensions (condition 2): 0.15 m x 3.0 m x 24 m
- Wall geometry dimensions (condition 3): 0.15 m x 3.0 m x 48 m
- Foundation geometry dimensions: height=1.5 m & width=2.5 m
- Horizontal wall reinforcement: $\phi 12 \| 20$ cm
- Vertical wall reinforcement: $\phi 12 \| 20$ cm
- Foundation reinforcement: $\phi 16 \| 20$ cm
- Concrete cover to the outer surface of vertical reinforcement: c=30mm
- Other properties are similar to example 2.

Illustrated of the result of different approaches in calculation of crack width and crack spacing

	Including methods		Including factors		Example 1		Example 2		Example 3	
					RC Tie under external tension		Slab with ends restrained		Wall restrained at base	
	Applied load cracking	Imposed deformation cracking	Restrained factors	Shrinkage strain	$S_{r,max}$ (mm)	w_k (mm)	$S_{r,max}$ (mm)	w_k (mm)	$S_{r,max}$ (mm)	w_k (mm)
Approaches										
EN 1992-1-1	✓	✘	✘	✘	415	0.26	-	-	-	-
EN 1992-3	✘	✓	✓	✓	-	-	195	0.15	697.5	0.19
CIRIA C660	✘	✓	✓	✓	-	-	195	0.15	697.5	0.15*
fib-Model Code 2010	✓	✓	✘	✓	322.22	0.4	368.3	0.3	693.44	0.4
ACI	✓	✘	✘	✘	168	0.14	-	-	-	-
JSCE guideline	✓	✘	✘	✓	-	-	-	-	-	-
Indian standard	✓	✘	✘	✘	126	0.18	-	-	-	-
Canadian standard	✘	✘	✘	✘	-	-	-	-	-	-
Australian standard	✘	✘	✘	✘	-	-	-	-	-	-

Notes:
dash sign (-) in each block shows that related approaches did not recommended any method for calculation of crack spacing and crack width in that situation

* the value of crack width for wall restrained at base calculated with ignoring the influence of early-age and long-term thermal cracking and autogenous shrinkage to be comparable with method of EN 1992-3

Numerical analyses of the combined effects of external actions and restrained shrinkage deformations in slabs

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CONSTRUCT, University of Porto, Portugal

Motivation and objectives

- Cracking control in restrained RC building slabs

- Determination of minimum required reinforcement ($w \leq w_{\text{limit}}$)

- Important parameter to be determined: axial force due to restrained shrinkage
  (slab restrained by rigid walls)

- Usual assumption for this parameter: $N_{cr} \cong A_c \times f_{ctm}$
  (in general, is very conservative; in special cases is not on the safe side)

- Analysis procedure: nonlinear FE analysis

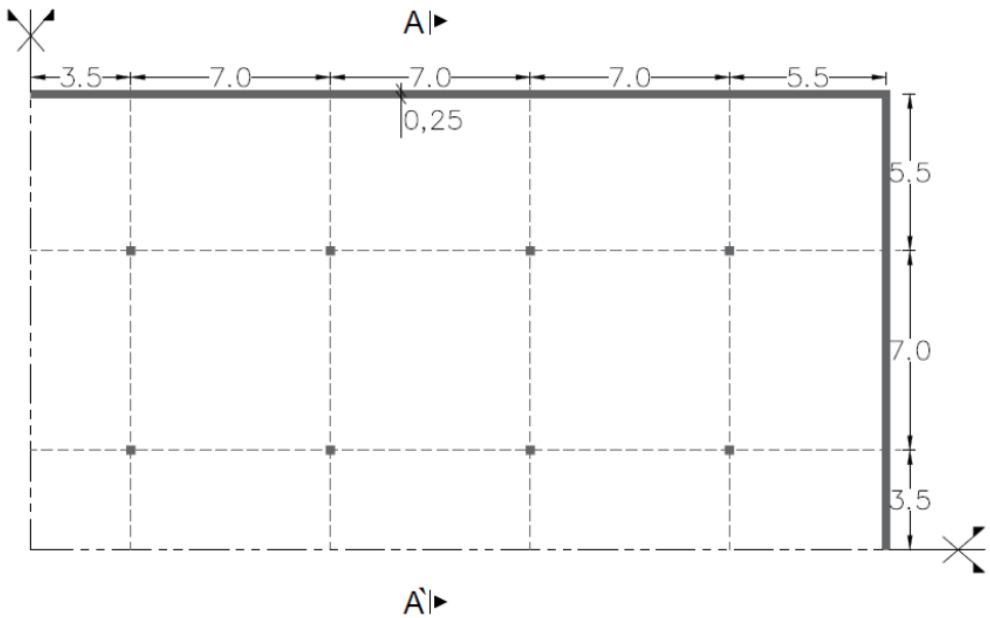
- Soil structure interaction is considered, with two scenarios:
  - granite residual soil
  - rock mass

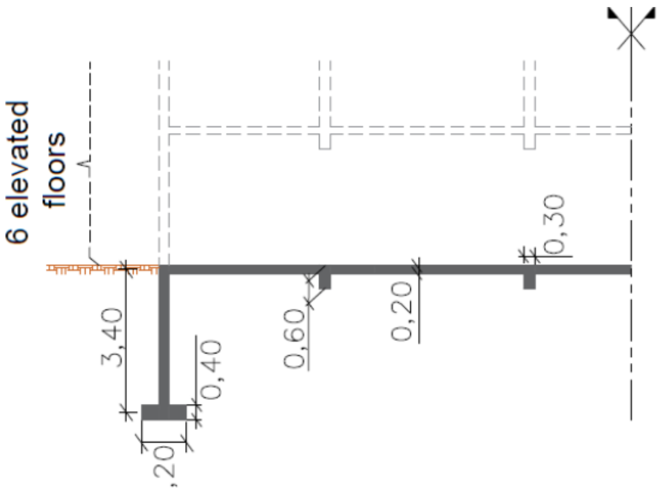
Outline of the presentation

- ❑ Motivation and objectives
- ❑ Case study
- ❑ FE modelling approach
- ❑ Analysis results
- ❑ Concluding remarks

Case study

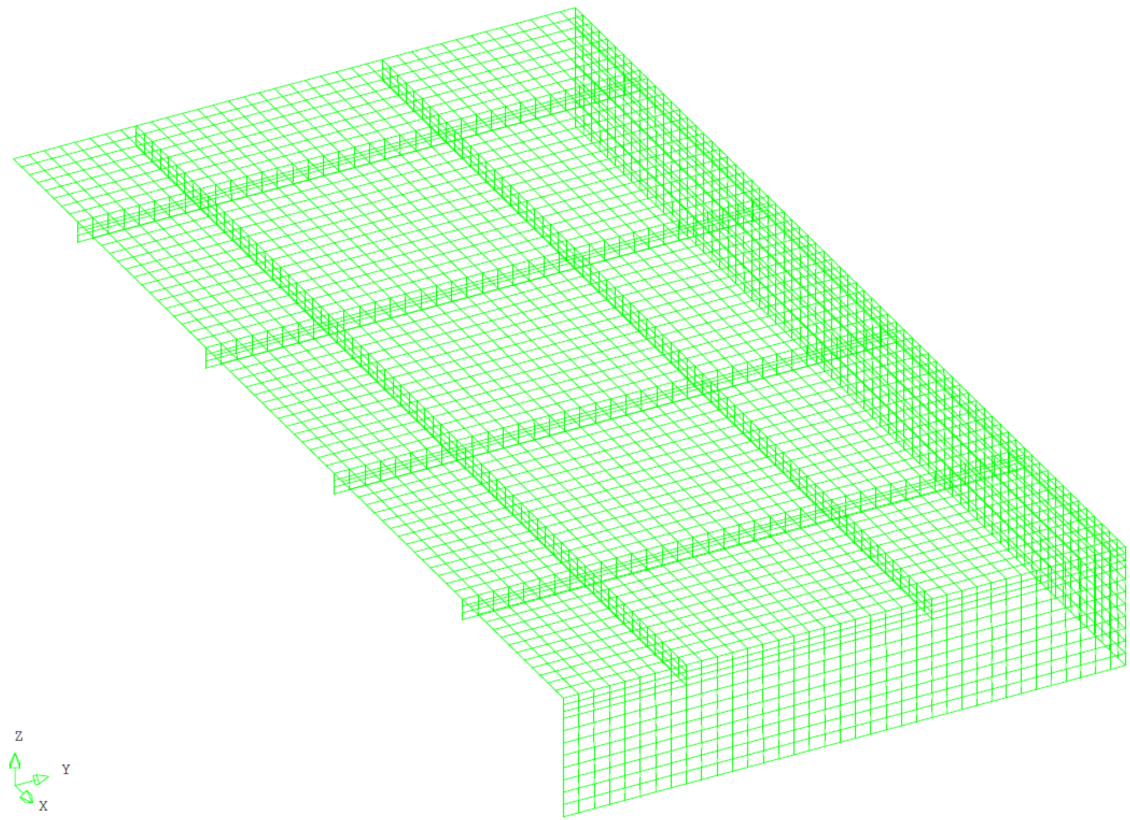
- RC building with dimensions in plan of $60 \times 32 m^2$
- 0,20m thick solid slab; RC beams
- Direct foundation on rock or granite residual soil
- Analysis of first floor above foundation
- C25
- $RH_{average}$ = 60%; $T_{average}$ = 20ºC
- Shoring removed 28 days after casting
- Quasi-permanent load: 3kN/m2 + self-weight





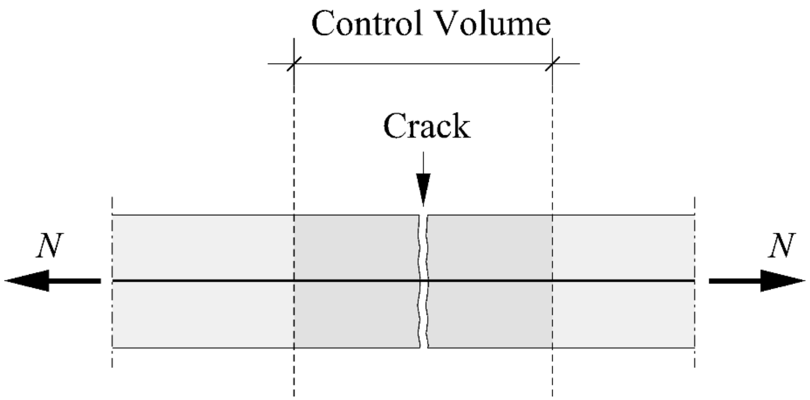
Case study

- 8-node shell finite elements (FEs)
- Numerical integration along the FE thickness
- Software DIANA
- Phased analysis
- Concrete elements activated 1 day after casting
- Analysis ends at 30 years



FE modelling approach

Smeared crack model with strain decomposition (and multiple fixed cracks):



Average concrete strain = $\varepsilon_{\text{crack}} + \varepsilon_{\text{elastic}} + \varepsilon_{\text{creep}} + \varepsilon_{\text{shrinkage}} + \varepsilon_{\text{temperature}}$

=

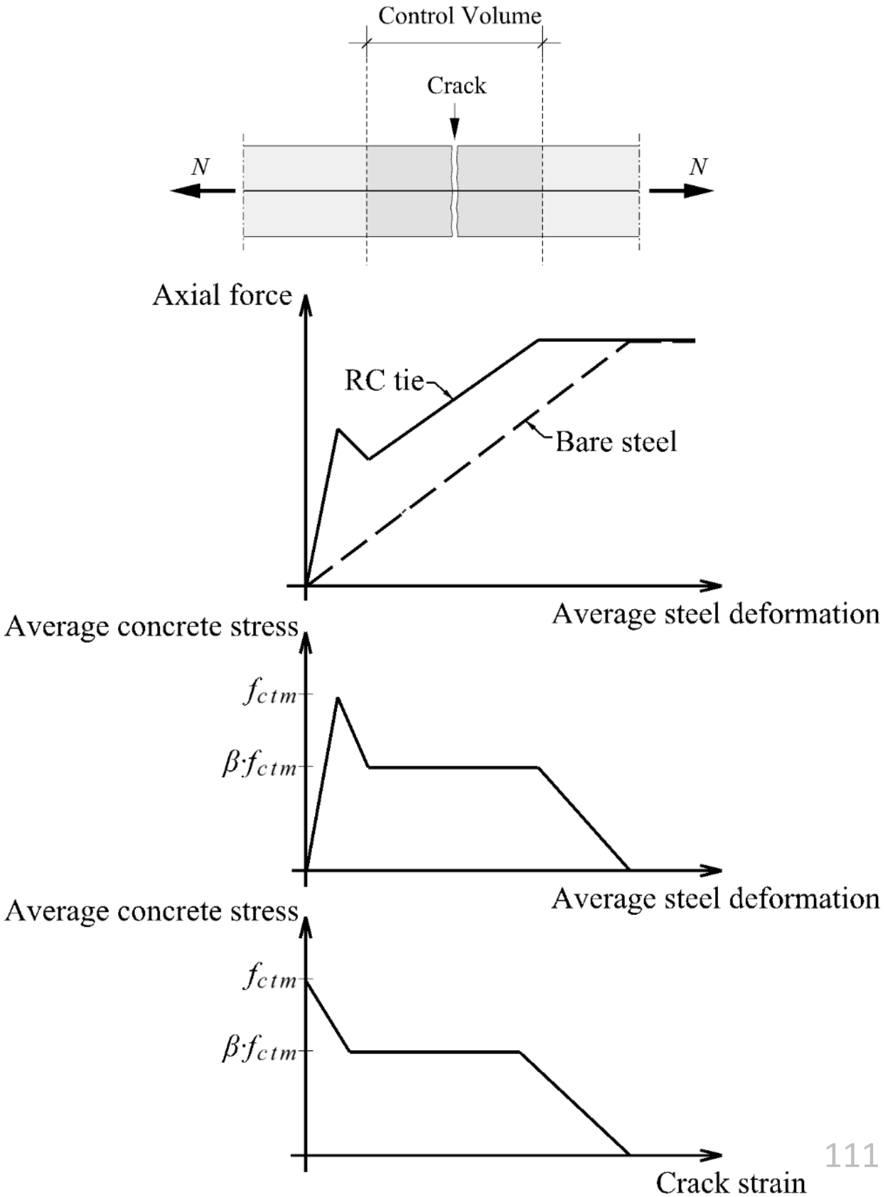
Average steel strain

fib Model Code

Kelvin Chain Model
(adjusted to *fib* Model Code)

FE modelling approach

Tension stiffening diagram:



- ❑ Large FEs (large control volume)

  ⇓

  suitable for real scale structures

- ❑ Tension stiffening approach is consistent with Eurocode 2 and fib Model Code

FE modelling approach

Properties of the foundation materials:

	Residual granite soil (W5)	Rock mass (W3)
Modulus of elasticity, E	80 MPa	6000 MPa
Coefficient of Poisson	0,35	0,20
Friction angle	38°	52°
Cohesion	10 kPa	300 kPa
Dilation angle	5º	5º

Mohr-Coulomb model

Simulation of the foundation deformability:

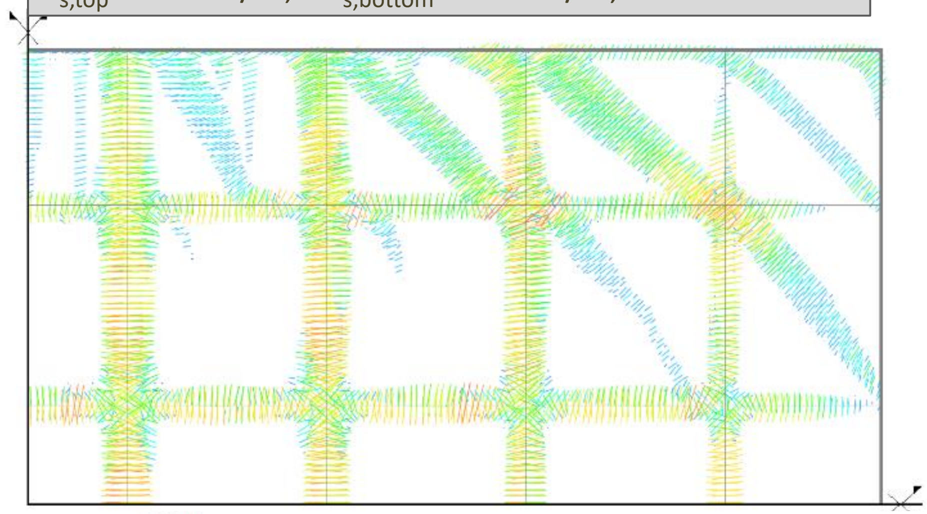
	Solo	Rocha
Vertical stiffness	$3{,}38 \times 10^4$ kN/m^3	$2{,}31 \times 10^6$ kN/m^3
Horizontal stiffness (tangential)	$2{,}95 \times 10^4$ kN/m^3	$2{,}17 \times 10^6$ kN/m^3
Rotational Stiffness	$7{,}13 \times 10^3$ kNm/m/rad	$4{,}89 \times 10^5$ kNm/m/rad

Analysis results

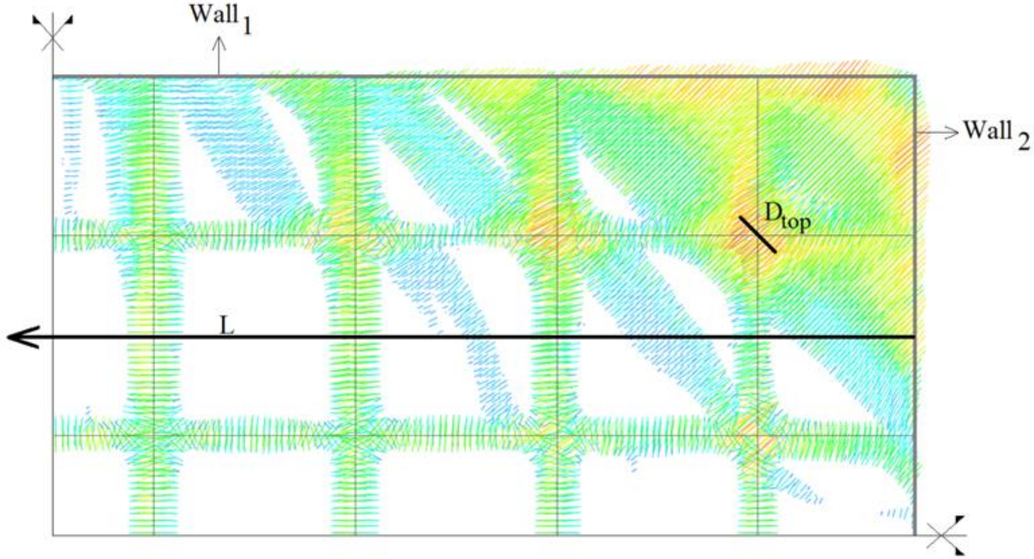
Crack pattern, at 30 years, at the top slab surface:

$a_{s,top}$ = 12cm²/m; $a_{s,bottom}$ = 10cm²/m; cover ~ 30mm

Foundation in soil (W3):



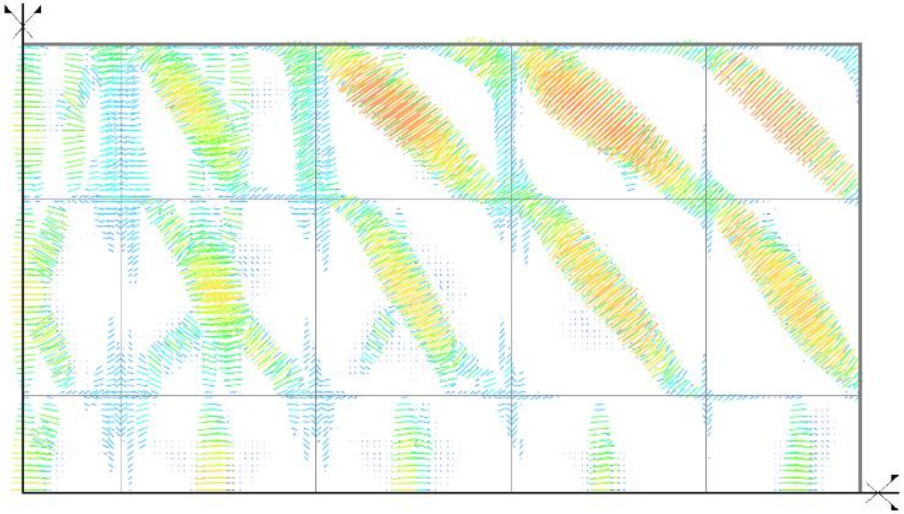
Rigid supports at the base of the wall:



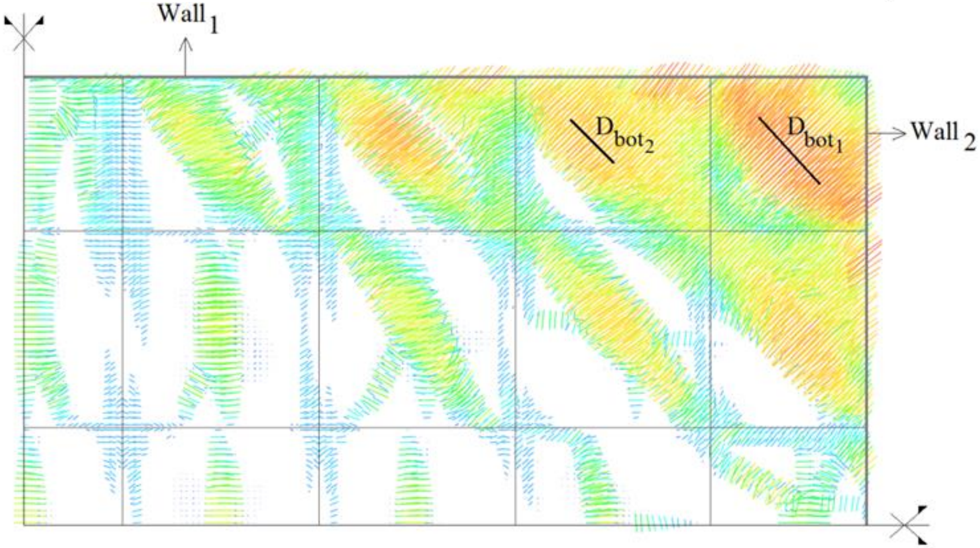
Analysis results

Crack pattern, at 30 years, at the bottom slab surface:

Foundation in soil (W3):

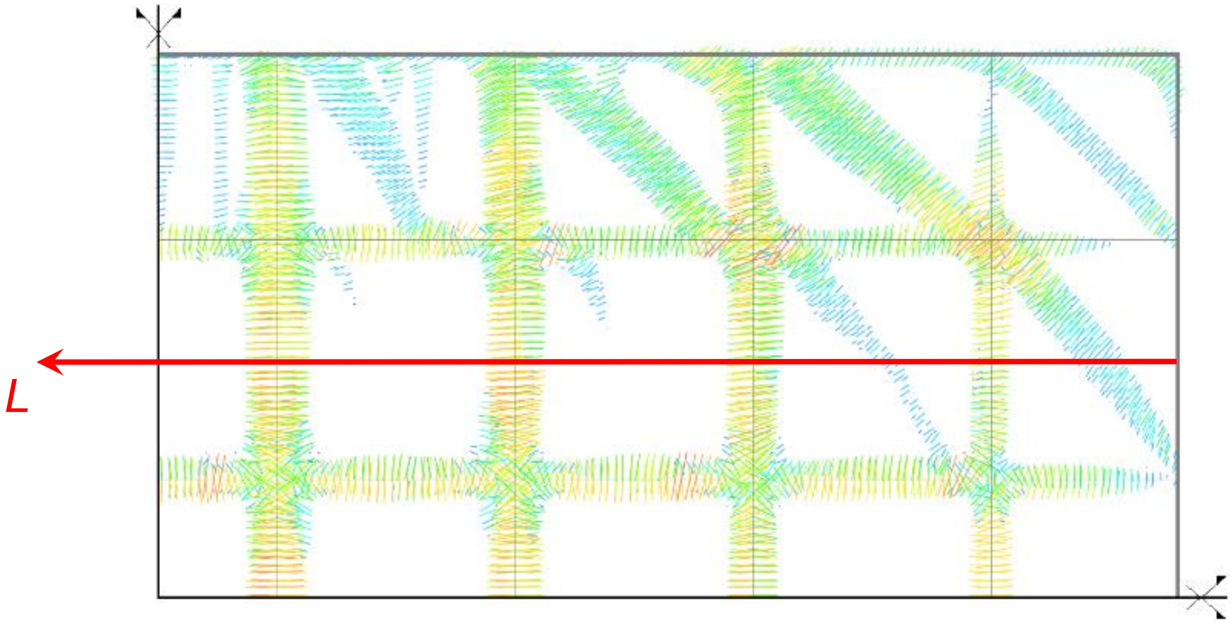


Rigid supports at the base of the wall:



Analysis results

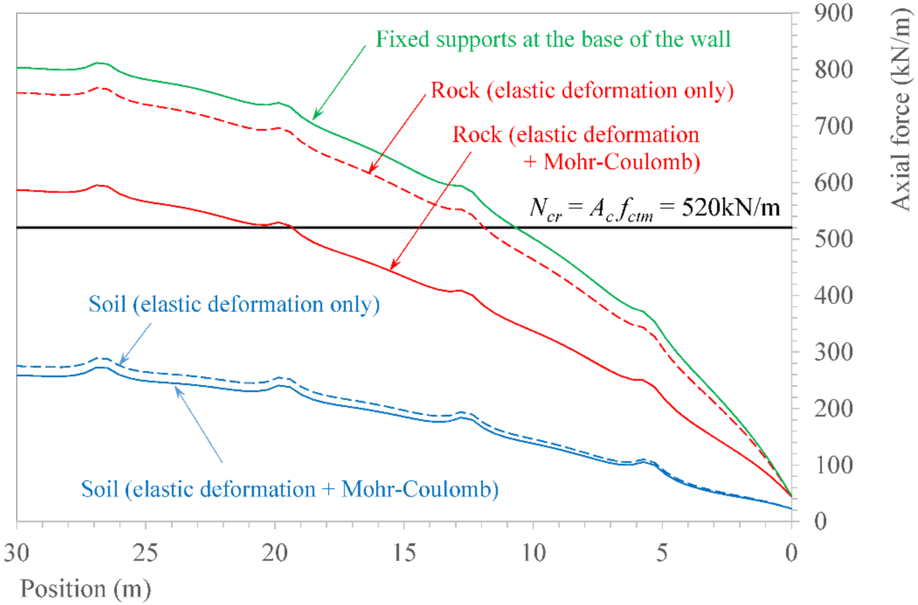
Axial force along line L:



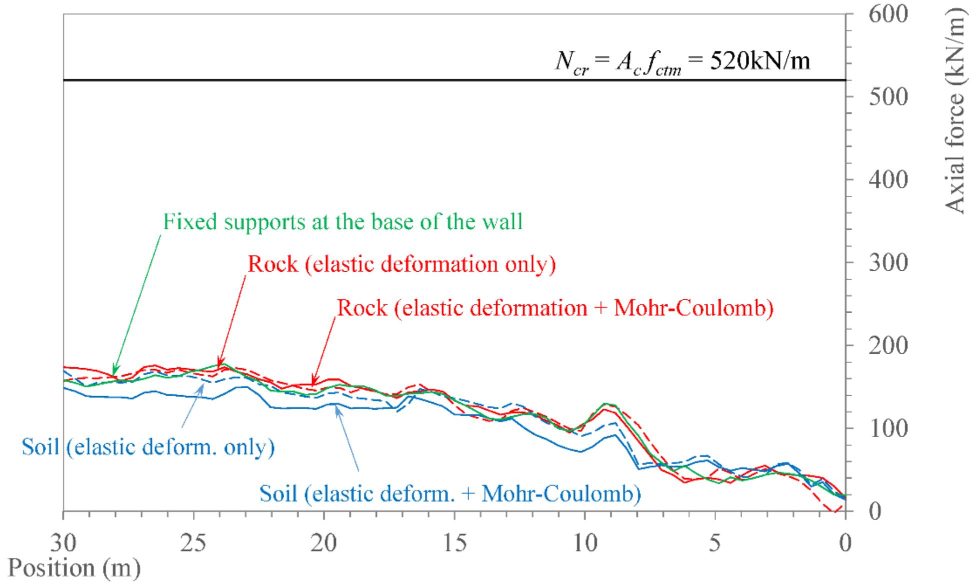
Analysis results

Axial force along line L:

Analysis without cracking effects:



Analysis with cracking effects:



Concluding remarks

Calculation of $a_{s,req}$ for cracking control ($w \leq w_{limit}$):

- Non-linear analysis (NLA) considering a feasible amount of reinforcement in the slab and in the walls;
- Estimation of $a_{s,req}$ considering the efforts determined in the previous NLA;
- New NLA, with the new amount of reinforcement, to confirm that the modification of the applied efforts is negligible

Conclusions

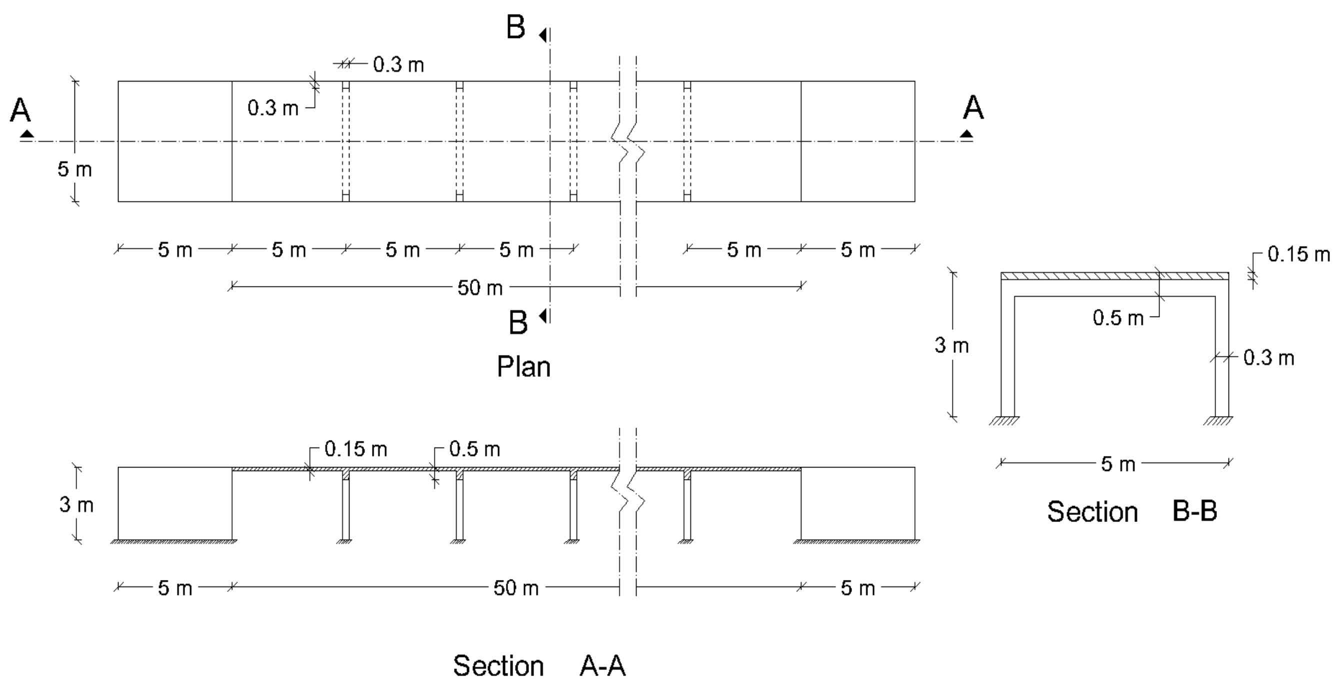
- Cracking in restrained RC slabs is strongly affected by foundation characteristics.
- In the analyzed structures, the axial force in the slab is significantly lower than $N_{cr} \cong A_c \times f_{ctm}$
- Critical positions: close to the corners of the slab (cracks at ~45° with respect to the wall directions).
- The Mohr-Coulomb Model had a minor influence on the analysis results, in the structure supported by granite residual soil.
- The analysis procedure adopted in this work has potentialities to be used in the design of large restrained slabs.

Design challenge for reinforcement in a highly restrained slab

Miguel Azenha - ISISE, University Minho, Portugal
Carlos Sousa - CONSTRUCT, University of Porto, Portugal
José Granja - ISISE, University of Minho, Portugal
Rui Faria - CONSTRUCT, University of Porto, Portugal
Behzad ZahabiZadeh - ISISE, University Minho, Portugal

COMPETE 2020 PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO
PORTUGAL 2020
UNIÃO EUROPEIA Fundos Europeus Estruturais e de Investimento
ORDEM DOS ENGENHEIROS
Escola de Engenharia Universidade do Minho
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

- **Challenge 1:** Quantify the reinforcement necessary for an adequate control of crack widths (w_k<0.3mm) due to restrained shrinkage/temperature. In this part of the challenge, ignore the existence of applied loads and therefore disregard any bending reinforcement in the slab.
- **Challenge 2:** Considering the combined effect of applied loads and restrained shrinkage/temperature, quantify the necessary reinforcement and present the corresponding construction drawings for the slab.



Assumptions:

- Concrete class C20/25; Steel class S400C; Concrete cover 30mm
- Environment: constant temperature T=20ºC and constant humidity RH=50%
- Slab is 15cm deep, with plan dimensions of 5m × 50m
- Slab is supported in 30 × 50cm beams of the same type of concrete/steel
- The beams are supported at their extremities by 30 × 30cm columns (3m tall), which are in turn rigidly fixed at their base.
- Disregard autogenous shrinkage and consider that drying and loading both start at t=28 days.
- At the extremities, the slab is rigidly connected to two massive concrete elements of 5×5×3m. Assume that the massive elements are hardened concrete with more than 1 year old, in thermal equilibrium with the surrounding environment. The massive elements are rigidly connected to an infinitely stiff foundation.
- Apart from self-weight, the slab has additional permanent loads g_k=2 kN/m^2 and a live load q_k=2kN/m^2 (ψ_2=0.3) - Residential building - Category A according to EC1

Participation

A400
PROJETISTAS E CONSULTORES DE ENGENHARIA

TPF
PLANEGE CENOR

STRENG

newton
CONSULTORES DE ENGENHARIA. LDA.

MOTT MACDONALD

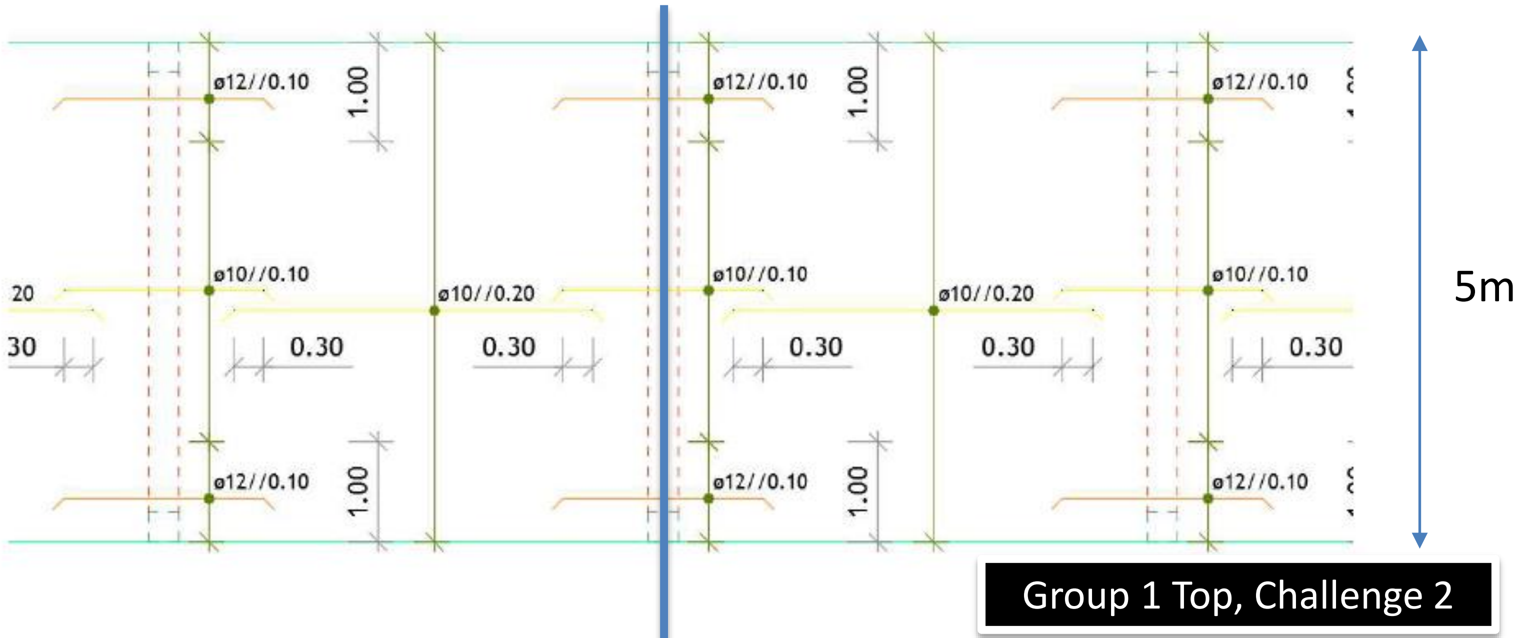
ADÃO DA FONSECA
engenheiros consultores

KHP LEIPZIG

Comparison of results made on anonymous base: Group 1 to Group 7

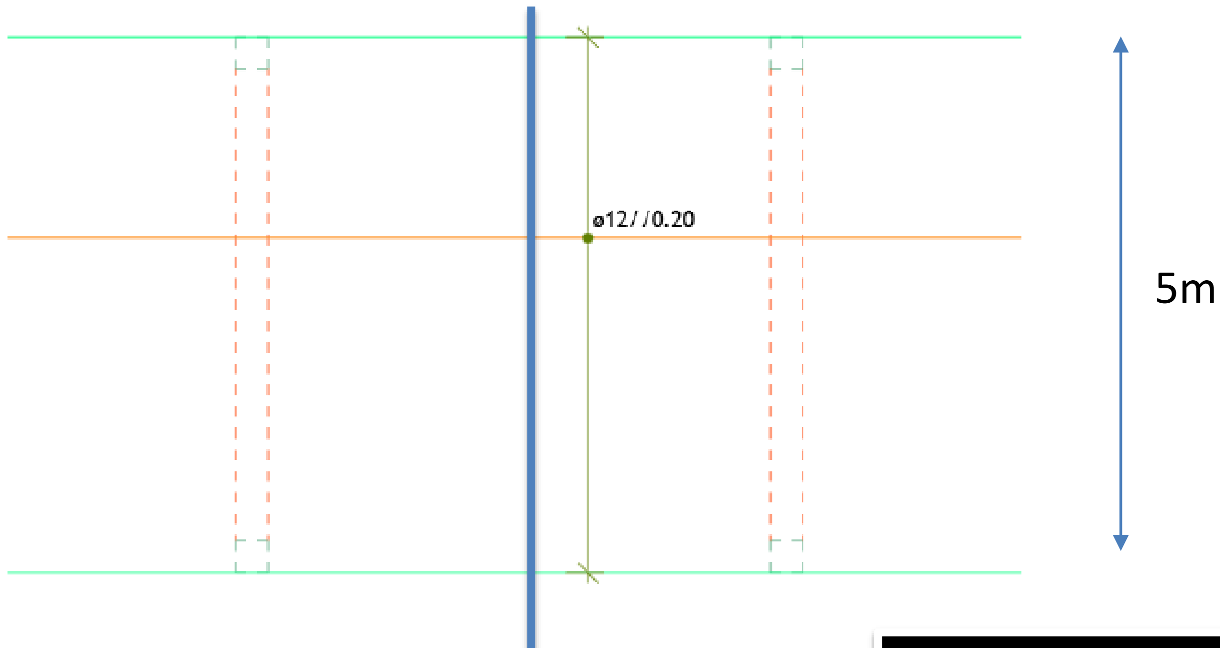
Comparison of results – Criteria for quantitative comparison

- Discussion partially based on the global reinforcement area at the top surface (cross section over the support beam) and bottom surface (cross section through the midspan). Example below for assessment of reinforcement area for group 1 on Top surface (support).



In the signaled cross-section (support), Group 1 has ϕ10/10 along 3m and ϕ12//0.10 along 2.0m (challenge 2). This corresponds to a total TOP reinforcement area at the cross-section of $7.9cm^2/m \times 3.0m + 11.3cm^2/m \times 2.0m = 46.5cm^2$ (challenge 2)

Comparison of results – Criteria for quantitative comparison

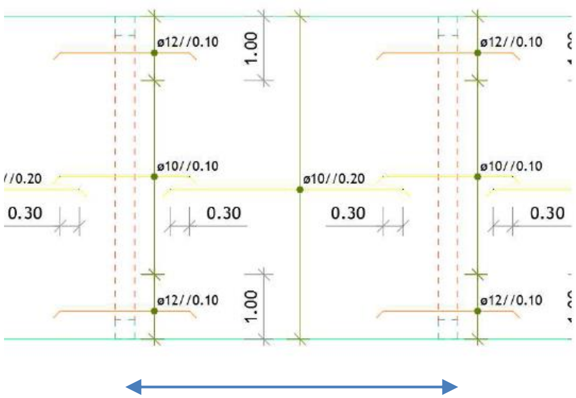


Group 1 Bottom, Challenge 2

In the signaled cross-section (mid-span), Group 1 has ϕ12/20 along 5m (challenge 2). This corresponds to a total BOTTOM reinforcement area at the cross-section of 5.65cm^2/m x 5.0m = 28.25cm^2 (challenge 2)

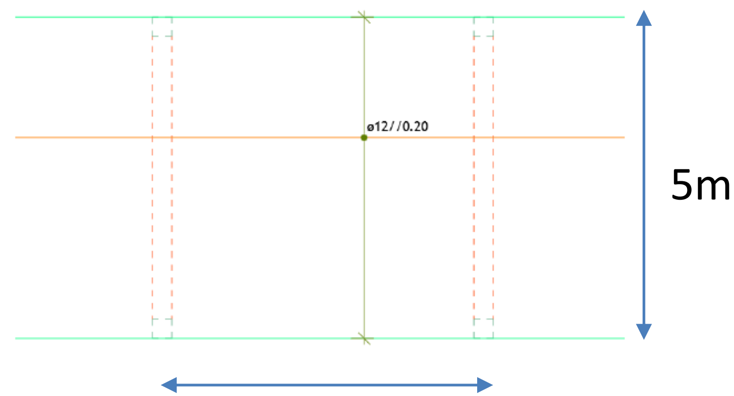
Global reinforcement in a single bay (only compared in Chal. 2)

Top



5m

Bottom



5m

Single bay reinforcement calculated only for longitudinal reinforcement, and disregarding splices due to long reinforcements for all participants.

Global reinforcement calculated in Kg, considering ϕ8 with 0.39kg/m, ϕ10 with 0.62kg/m and ϕ12 with 0.89kg/m.

Example for calculation of the global reinforcement for Group 1

Top reinforcement: ϕ10//10 (3.6m length and 5m width) + ϕ10//10 (2m length and 3m width) + ϕ10//10 (2m length and 3m width)

Bottom reinforcement: ϕ12//20 (5m length and 5m width)

Total weight of reinforcement: ~297 kg

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 1

- Following the approach proposed by Luís, R (2005) “Análise e dimensionamento de estruturas de betão com sobreposição de efeitos de deformações impostas” (MSc thesis in Portuguese)

- Evaluate the cracking force of the slab and ensure reinforcement to avoid yielding (f_{yk}) upon first crack opening.

- Assume a reduction factor (shown in the table below) for the tensile force acting on the slab, according to Luis, R (2005).

- Check if the reinforcement designed above is enough to attain adequate crack width control according EN1992-1-1:2004. Evaluate stress in reinforcement using expression 7.1 of EN1992 and infer the crack width with basis on Tables 7.2/7.3 of EN1992-1-1:2004.

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ12//20, with w_k=0.2mm.

		$\Delta\varepsilon_{cs}$ - Extensão de Retracção				
		0,10‰	0,20‰	0,30‰	0,40‰	0,50‰
p % de Armadura da secção em análise	0,50%	0,30	0,40	0,45	0,475	0,50
	0,80%	0,27	0,35	0,40	0,425	0,45
	1,00%	0,25	0,35	0.35	0.40	0.40

Group 1, Table of reduction factors

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 2

- Calculate the minimum reinforcement according to EN1992-1-1:2004 expression 7.1, and assuming a non-yielding criterion (f_{yk}).

$$A_{s,min}\sigma_s = k_c\, k\, f_{ct,eff}\, A_{ct}$$

- Explicit calculation of crack width, using the approach of EN1992-1-1:

$$w_k = s_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm})$$

With consideration that

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \varepsilon_{cs}$$

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ8//10, with w_k=0.26mm.

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 3

- Approach similar approach to that of Group 1, through application of a reduction of a reduction factor (45%) to the post-cracking tensile force acting on the slab. This allows the calculation of the stress in longitudinal reinforcement at post-cracked stage with expression (7.1) of EN1992-1-1:2004.

- Explicit calculation of crack width, based on expression (7.9) of EN1992-1-1 (no indication of any adaptations due to shrinkage strain effects).

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ10//15, with w_k=0.298mm.

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 4

- Not discussed here. See the deformation based method explained in the last chapter of this publication.

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ8//10, with w_k<0.30mm.

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 5

- No response given to design challenge 1

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 6

- Initial simplified calculation of minimum reinforcement area according to EN1992-1-1, equation 9.1:

$$A_{s,min} = 0{,}26 \frac{f_{ctm}}{f_{yk}} b_t d$$

- Correction of the attained reinforcement by successive application of crack width calculations, under the assumption that (similar to Group 2)

$$w_k = s_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm})$$

with $(\varepsilon_{sm} - \varepsilon_{cm}) = \varepsilon_{cs}$

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ8//10, with w_k=0.256mm.

Challenge1: Restrained shrinkage/temperature

Methodological aspects and results

Group 7

- Consideration of the direct crack width calculation expressions of EN1992-3 (Annex M) and CIRIA 600

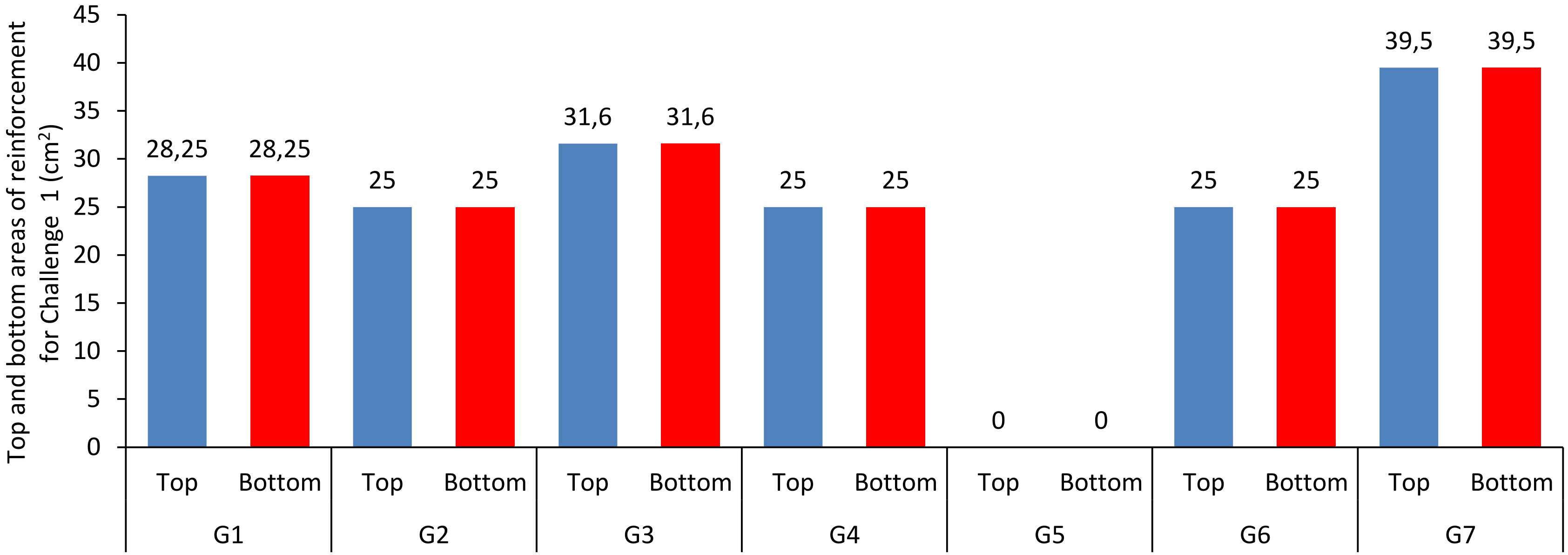
$$w_k = \frac{0.5\alpha_E k_c k f_{ct,eff}}{E_s}\left(1 + \frac{1}{\alpha_E \rho}\right) s_{r,máx}$$

$$s_{r.máx} = 3.4c + 0.425\frac{k_1 \emptyset}{\rho_{eff}}$$

- Reduction of the cracking force for the purpose of crack width calculations, according to the reccomendations of “Crack control for imposed deformations” by J. Câmara and R. Luís (2007). A coefficient of 0.8 was used.

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ10//10, with w_k=0.34mm.

Challenge1: Restrained shrinkage/temperature
Summary of results for top/bottom area



Three main approaches:

- Reduction factor on cracking force, according to Luís, R. on G1, G3, G7. Higher reinforcement in G7 due to choice of a higher reduction factor than G1, G3.
- Considering shrinkage strain as the single strain parameter in crack width calculation on G2 and G6.
- Deformation-based approach by G4 (see last presentation)

Global scatter of results is relatively small (G7 excluded)

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 1

- Same methodology as shown for Challenge 1: reduction factor of tensile force in service, according to the recommendations of Luís, R (2005).

- Evaluate reinforcement and crack widths in SLS and ULS according to EN1992-1-1:2004. The axial restraint force considers the same reduction factor as shown in challenge 1 (consideration of bending together with axial force). Calculation of crack width with expression 7.9 of EN1992-1-1:2004.

- Final solution:
  - Top surface (support): ϕ10//10 (central zone – 3m) + ϕ12//10 (lateral region – 2m) ,
  - Bottom surface (mid-span) ϕ12//20,
  - Crack width w_k=0.19mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 2

- Initial design of reinforcement for simple bending according to EN1992 in ULS. Redistribution coefficient for negative bending moments: 0.85.

- SLS evaluated for the quasi-permanent combination in simple bending.

- Verification of crack width using an expression that includes shrinkage:

$$w_k = s_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm} + \varepsilon_{cs})$$

- **Relatively to the minimum reinforcement computed throughout the entire slab in challenge 1, some areas have been relieved because of the compressive stresses induced by bending moments (e.g. top surface at mid-span; bottom surface at supports). Quantitative criterion not explained, though.**

- Final solution:
  - Top surface (support): ϕ8//10, with reduction for ϕ8//20 in the span region
  - Bottom surface (mid-span): ϕ8//10, with reduction for ϕ8//20 in the support region
  - Crack width w_k=0.19mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 3

- Design for ULS was disregarded, as simplification for this design challenge. Focus on SLS.

- SLS evaluated for the quasi-permanent combination, under bending together with axial force, including the longitudinal force resulting from reduction of the cracking force by 45%. Calculation of crack width with expression 7.9 of EN1992-1-1.

- Final solution:
  - Top surface (support): ϕ10//15 + ϕ8//15, with reduction for ϕ10//15 in the span region
  - Bottom surface (mid-span): ϕ10//15 + ϕ8//30 , with reduction for ϕ10//15 in the support region
  - Crack width w_k=0.268mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 4

- Not discussed here. See the deformation based method explained in the last chapter of this publication.
- **As compared to Challenge 1, there has been a relief of reinforcement in the areas where bending brings compression (similar situation as the response of Group 2). Top region in the span is actually unreinforced.**
- Final solution:
  - Top surface (support): ϕ8//10 , with reduction for 'no reinforcement' in the span region
  - Bottom surface (mid-span): ϕ8//10
  - Crack width w_k<0.30mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 5

- Following CIRIA C660 guidelines in regard to crack control for both short and long term predictions. EN1992-1-1:2004 and EN1992-3:2006 used for concrete properties and reinforcement design.

- Explicit consideration of construction sequence (with FE method) to obtain restraint stresses for distinct scenarios (staged construction of slab bays)

- Using CIRIA C660 temperature spreadsheets to estimate adiabatic temperature rise and differentials at early age

- Calculation of early age strains and long term strains in the slab, considering the combined effects of temperature/shrinkage and creep in FEM MIDAS.

- Computation of “early age crack inducing strain” and ”long term crack inducing strain” according to CIRIA C660. Same for tensile strain capacity

- Final solution: Top and bottom surfaces of the slab reinforced with ϕ12//20, with w_k<0.30mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 6

- Initial application of a base reinforcement of ϕ8//15 throughout all regions of both top and bottom surfaces of the slab in satisfaction of minimum reinforcement area of equation 9.1 of EN1992-1-1:2004 (note that this is lower than the reinforcement of challenge 1, which was ϕ8//15).

- Calculation of additional reinforcement based on bending moments (calculation in simple bending with no explicit consideration of restraint stresses).

- Crack width calculation with REBAP, MC90 and EN1992 (method to consider the restrained shrinkage not disclosed)

- Final solution:
  - Top surface (support): ϕ8//15 + ϕ8//15 , with reduction for ϕ8//15 in the span region
  - Bottom surface (mid-span): ϕ8//15 + ϕ8//15 , with reduction for ϕ8//15 in the support region
  - Crack width w_k=0.30mm.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Methodological aspects and results

Group 7

- Consideration of both ULS and SLS states.

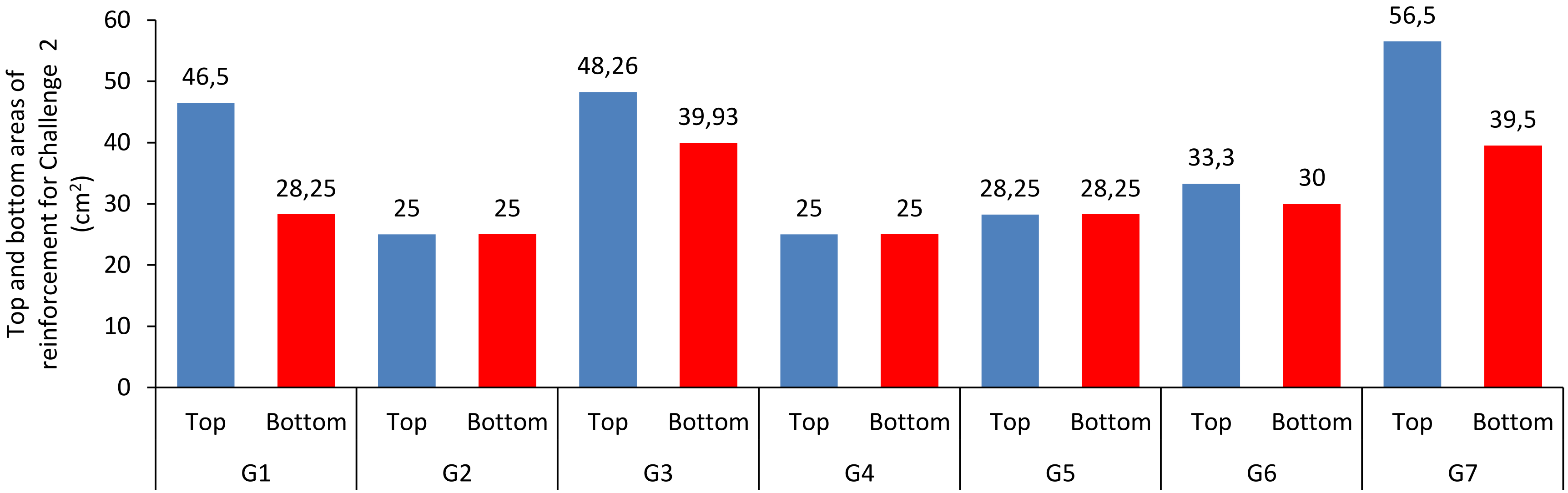
- Crack width calculation done for bending combined with axial force, with explicit consideration of the tensile force due to restrained shrinkage. The reduction coefficient was 0.5 (smaller than the one considered by the same team in design challenge 1, which had the value of 0.8).

- Crack width calculation according to standard expressions of EN1992-1-1:2004 (no adaptation of the crack width expression due to shrinkage)

- Final solution:
  - Top surface (support): ϕ12//10, with reduction for ϕ10//10 in the span region
  - Bottom surface (mid-span): ϕ10//10
  - Crack width w_k=0.263mm.

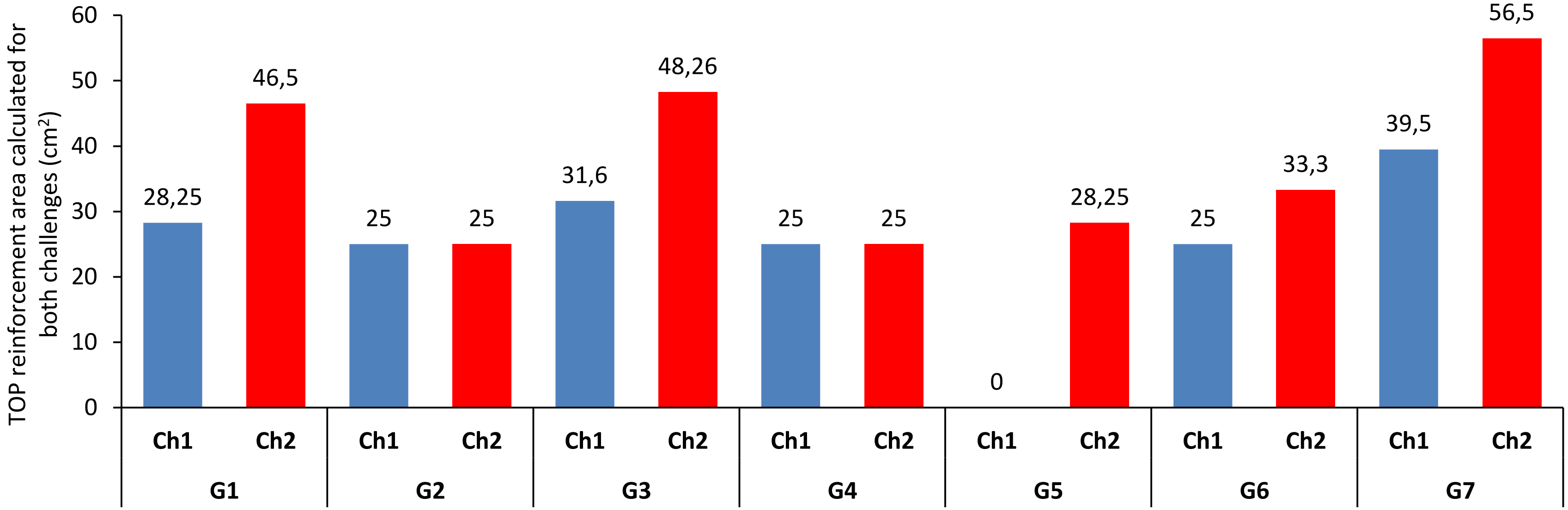
Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

Summary of results for top/bottom area



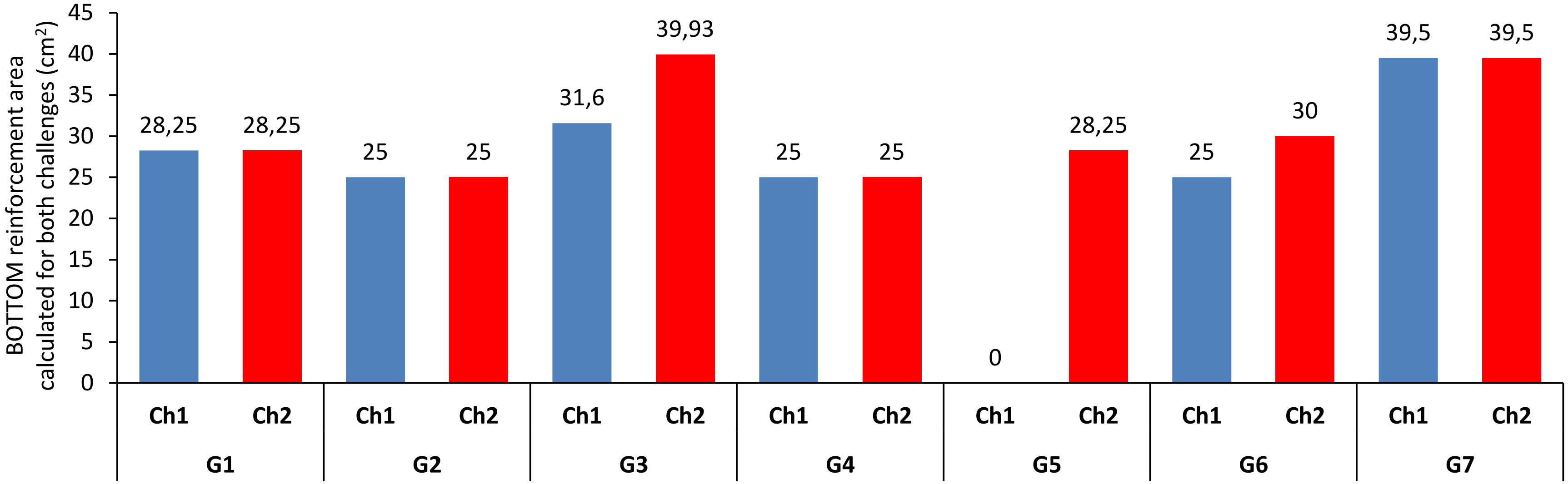
- The groups that used approaches of bending with axial force based on the reduction coefficient proposed by Luís, R (G1, G3, G7) had the largest differences between top and bottom reinforcement area.
- The approaches with crack width estimation based in simple bending of G2, G6 led to rather similar top and bottom reinforcement areas.
- G4 used a deformation based approach (see last presentation) and has the same top and bottom reinforcement
- G5 used a strain based approach mostly based on CIRIA C660. Final conclusion led to equal top and bottom reinforcement.

Comparison of results of Challenge 1 and Challenge 2 -> TOP Reinforcement



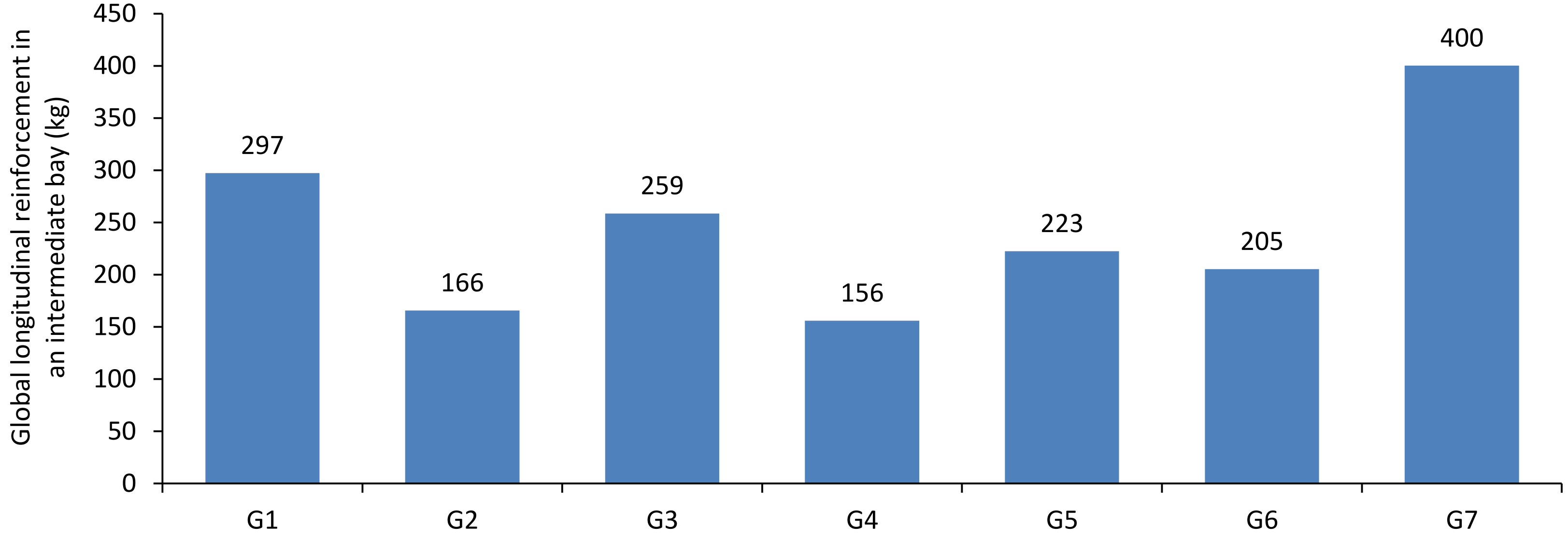
- The region of interest in the graphs above is the cross-section right at the support region (maximum tensile stresses due to bending).
- All groups have either the same reinforcement as shown in challenge 1, or a surplus to such reinforcement. The degree of increase is variable. Larger increases in G1, G3, G7, which are commonly using bending + axial force verification, as opposed to G2, G4, G6.
- Noteworthy to mention that the top reinforcement at mid-span (not shown in the graph above) was relieved as compared to Challenge 1, by both G2 and G4!

Comparison of results of Challenge 1 and Challenge 2 -> BOTTOM Reinforcement



- Bottom reinforcement was kept quite similar between Challenge 1 and Challenge 2 for most groups (exception for G3).

Challenge 2 – Global longitudinal reinforcement in a single bay (all regions of the bay)



- There is a very wide dispersion of final results
- Approaches based on bending combined with axial force (adopted by G1, G3, G7) have consistently led to higher areas of reinforcement.
- The approach based on CIRIA C660 of G5 is exactly matching the average of all results.
- Lowest reinforcement needs are attained with the simple bending approaches of G2, G6.
- The lowest reinforcement quantity attained is shown by the deformation based approach (see last presentation).

Final notes

- The wide dispersion of results reached by different designers is not surprising at all. In fact, different design codes include different assumptions which have very important implications on the final result. Such differences can be found even in codes which follow, globally, the same approach for direct calculation of the crack width, for example the Eurocode 2 [EN 1992-1-1 (2004)] and the fib Model Code 2010.

- Naturally, design codes do not provide calculation procedures to determine the actual crack opening which will be observed in the real structure. Instead, the codes are reference documents which define minimum requirements and give guidelines to minimize the dispersion of the results reached by different practitioners. Design codes evolve over time, as the knowledge about each engineering problem also evolve, and new experiences are consolidated.

- Obviously one cannot say that there is an exact answer to the Challenges 1 and 2. This is especially true if the codes and guidelines to be followed in the design are not fixed beforehand. Having all these caveats in mind, the following slides disclose the values reached by the IntegraCrete team. The reference method for assessing the nonlinear, time-dependent, behavior of the structure is the one shown in the 4th presentation, by C. Sousa et al. Two different design codes are considered: the Eurocode 2 and the fib Model Code 2010.

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

- The required reinforcement can be estimated based on:

  1) The axial force in the restrained RC tie. This should be taken as the cracking force. The cracking force decreases along time, due to the effects of shrinkage restrained by the reinforcement. We adopt, in these calculations, the cracking force at long term, herein denoted by $N_{cr,\infty}$. Some comments regarding this assumption can be found in the next slides.

  2) A numerical procedure for calculation of the crack width, for a given steel stress at the crack (this steel stress is given by $N_{cr,\infty}/A_s$). Alternative procedures for calculation of the crack width are considered here, the ones proposed by the Eurocode 2 and the *fib* Model Code 2010 (MC2010). The addition of a free shrinkage deformation term, $|\varepsilon_{sh}|$ in these calculations is also discussed.

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

- For Step 1), the calculation of the cracking force at long term, $N_{cr,\infty}$, can be made as follows:

Firstly, the concrete stress, in uncracked sections, due to the restraint induced by the reinforcement has to be calculated:

$$\sigma_{ci} = \frac{\varepsilon_{sh}\, E_s\, \rho_{eff}}{1 + \dfrac{E_s}{E_{c,adj}}\, \rho_{eff}}$$

Then, the cracking force is given by:

$$N_{cr,\infty} = (f_{ctm} - \sigma_{ci})\, A_c \left(1 + \frac{E_s}{E_{c,adj}}\, \rho_{eff}\right)$$

The non-linear analyses, following the procedure shown in the 4th presentation (by C. Sousa et al.), confirm the validity of these formulas.

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

- As regards the procedure for calculation of the crack width , for a given steel stress at the crack [Step 2)], two different design guidelines are considered here: the Eurocode 2 and the MC2010.

  It is important to note that none of these guidelines considers a free shrinkage deformation term in this calculation. That is, these guidelines state that the crack opening should be calculated as[1]:

$$w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})$$

  However, that is not coherent with the actual structural behavior of a reinforced concrete member. Locally, around a crack, the shrinkage strains contribute to the increase of the relative deformations between the concrete and the steel and, consequently, to the increase of the crack opening. Therefore, in this discussion, we also show the results of calculations in which such free shrinkage deformations are taken into account. Those are denoted by “adaptations” of the Eurocode 2 and MC2010 procedures, and consist of calculating the crack opening as:

$$w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm} + |\varepsilon_{sh}|)$$

Note [1]: The MC2010 denotes the total transfer length by 2 $l_{s,max}$ but that means the same as $s_{r,max}$

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

By using the latter equation, the analysis procedure is coherent with the use (in Step 1) of the cracking force at long term. The crack opening increases along time, and the maximum value is reached at long term, but only if the approach represented by the latter equation is followed. Non-linear analyses confirm that. That is also acknowledged in the paper of Câmara and Luís[1], cited by some of the participants in the Design Challenge.

The following table summarizes the calculation results. The area of reinforcement shown ($a_{s,bot}$ = $a_{s,top}$) is the value needed to meet the condition $w \leq 0.30$mm. The cracking force and the $s_{r,max}$ value are also shown. Note that the cracking force depends on the amount of steel reinforcement. For $a_{s,top} = a_{s,bot} \approx$ 6 cm^2/m, the cracking force $N_{cr,\infty}$ is approximately 80% of $A_c\ f_{ctm}$.

Note [1]: Câmara J., Luís, R. *Crack Control for Imposed Deformations.* http://jsj.pt/main/wp-content/uploads/2015/02/JCamara-Crack-Control-for-Imposed-Deformations-Helsinquia.pdf

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

Procedure for calculation of w	$a_{s,bot}$ = $a_{s,top}$ = (cm²/m)	$N_{cr,\infty}$ (kN/m)	$s_{r,max}$ or 2 $l_{s,max}$ (m)
Eurocode 2 [1] $w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})$	5.9	269	0.447
MC2010 [1] $w = 2\, l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm})$	4.1	285	0.608
Adaptation of Eurocode 2 [2] $w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm} + \lvert\varepsilon_{sh}\rvert)$	9.0	230	0.385
Adaptation of MC2010 [2] $w = 2\, l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm} + \lvert\varepsilon_{sh}\rvert)$ $(\eta_r = 1; \tau_{bms} = 1.8\, f_{ctm}; \beta = 0.6)$	7.2	251	0.448

Note [1]: In the calculation of the transfer length, the steel bar diameter was taken as 8mm
Note [2]: In the calculation of the transfer length, the steel bar diameter was taken as 10mm

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

- It is important to realize that the amount of reinforcement provided in the structure shall not be smaller than the minimum area to avoid yielding upon the formation of the first crack. Such area is determined by the condition:

$$A_s = \frac{1}{f_{yk}} A_c f_{ctm} \left(1 + \frac{E_s}{E_c} \frac{A_s}{A_c}\right)$$

The result is $a_{s,top} = a_{s,bot}$ = 4.3 cm^2/m

- Looking at the results in the previous table, one can see that the inclusion of the term $|\varepsilon_{sh}|$ leads to a notable increase in the required area of reinforcement. Given the enormous implications of this term, a question needs to be placed:

If the inclusion of this term is coherent with the actual structural behavior, why isn't it recommended by the present design codes?

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

If the inclusion of this term is coherent with the actual structural behavior, why isn't it recommended by the present design codes?

The absence of that term is even more questionable in the case of the MC2010. This code recommends the consideration of $|\varepsilon_{sh}|$ in long term analyses of structures in stabilized cracking stage (like the case of the Design Challenge 2), but recommends not considering it in the analysis of structures in crack formation stage. That doesn't make sense from a theoretical point of view. In the explanatory paper of this part of the MC2010[1], nothing is written about this important issue, which marks an evolution with respect to the previous version of the MC2010.

The answer to the previous question might be quite simple. The code formulae for calculation of crack openings need to be calibrated against experimental data. An expression of the type $w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm} + |\varepsilon_{sh}|)$ will only provide accurate results after the parameters needed for calculation of $s_{r,max}$ and $\varepsilon_{sm} - \varepsilon_{cm}$ are correctly calibrated. Such a calibration is really needed in a near future.

NOTE[1]: Balázs G.L. et al. (2013) Design for SLS according to fib Model Code 2010. Structural Concrete, vol. 14
http://www.fib-international.org/fib-model-code-2010

Challenge1: Restrained shrinkage/temperature

IntegraCrete Team results

Meanwhile, before such a calibration is available, the use of expressions of the type $w = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})$ should be made cautiously. The steel stress at the crack should be calculated, in that case, considering the cracking force for short term loading:

$$N_{cr} = f_{ctm}\, A_c \left(1 + \frac{E_s}{E_c}\, \rho_{eff}\right)$$

Besides that, special attention should be paid to the determination of the minimum steel area to avoid yielding upon the formation of the first crack. The f_{ctm} value provided by the Eurocode 2 for the concrete class specified in the project might not be a realistic estimate of the actual tensile strength *in situ*. Interaction between the structure designer and the material characterization is certainly beneficial in this regard.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

IntegraCrete Team results

- The required reinforcement can be estimated based on:

  1) The internal efforts (axial force and bending moment), at long term. For the study shown in this presentation, these internal efforts are determined through the nonlinear analysis approach shown in the presentation of C. Sousa et al.

  2) A numerical procedure for calculation of the crack width, for a given steel stress at the crack. Two alternative procedures are considered, the ones proposed by the Eurocode 2 and the fib Model Code 2010 (MC2010). Unlike the approach followed in the discussion of the Challenge 1, now no adaptation is made to the provisions of the Eurocode 2 and the MC2010.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

IntegraCrete Team results

- From Step 1), the most important result to be calculated is the axial force. In fact, the bending moments, at long term, are almost independent from the amount of reinforcement in the slab (as long as it is kept within reasonable limits) and are almost equal to the results of linear analyses. The following table shows the axial force, at long term, calculated in three different analyses (considering three different amounts of reinforcement). Note that these amounts are not necessarily the values required to keep the crack opening smaller than 0.3mm.

Analysis	$a_{s,bot}$ (cm²/m)	$a_{s,top}$ (cm²/m)	N (kN/m)	$\frac{N}{A_c\, f_{ctm}}$
#1	5	6	138	42%
#2	8	10	149	45%
#3	10	12	159	48%

- These results confirm that the axial force is not very sensitive to the amount of reinforcement in the slab.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

IntegraCrete Team results

- As regards Step 2), to assess the implications of different crack width calculation procedures, the following table shows the required area of reinforcement to keep the crack opening smaller than 0.30mm, using the Eurocode 2 and MC2010 approaches. The MC2010 estimate for the crack opening at the level of the reinforcement is also shown. In these calculations, the axial force at long term was taken as 149kN/m, so that the only variant is the procedure for crack width calculation.

	Area required by the condition $w \leq 0.3$mm	
Procedure for calculation of w	$a_{s,bot}$ (cm^2/m)	$a_{s,top}$ (cm^2/m)
Eurocode 2	4.2	5.7
MC2010 (w at level of reinforcement)	8.2	9.9
MC2010 (w at the surface)	10.5	12.9

The differences are enormous! The result based on the MC2010 procedure (bottom line of the table) is more than twice the result based on the Eurocode 2.

Challenge 2: Combined effect of applied loads and restrained shrinkage/temperature

IntegraCrete Team results

- The main differences between the Eurocode 2 and MC2010 methods are:
  - The Eurocode 2 does not consider, in the direct calculation of the crack opening, the effect of free shrinkage deformation in the cracked concrete ($|\varepsilon_{sh}|$ term). On the contrary, the MC2010 considers this effect in the stabilized cracking stage. Note that, even though the entire structure does not reach the stabilized cracking stage, this stage is reached in the regions of support and mid-span (the internal efforts are higher than the ones needed to induce cracking).
  - According to the MC2010 the crack opening to be compared with the limit value (limit of 0.30mm in this case) is the one at the concrete surface. The corresponding results are shown in the bottom line of the previous table. The table also shows the results which would be reached if the objective was getting a crack opening of 0.3mm at the level of the reinforcement (middle line of the table).

- Bearing mind that the *fib* Model Code 2010 (released in 2013) was calibrated against new experimental results, the previous table shows the reason why cracks larger than 0.3mm can be found in structures designed strictly following the provisions of Eurocode 2.

A new methodology for design of large and highly restrained RC elements

- Background and examples of practical application -

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PORTUGAL 2020
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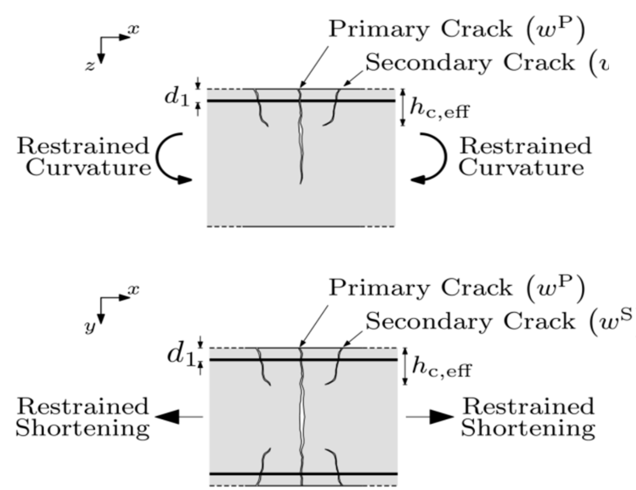
ORDEM DOS ENGENHEIROS
Escola de Engenharia Universidade do Minho
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

iBB Research group “Crack width control in restrained concrete”

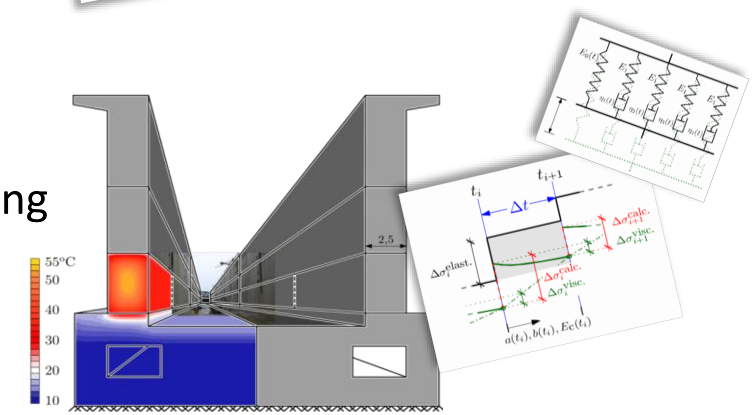
experimental testing

on-site monitorings

deformation-based reinforcement design



modelling



iBB Research group "Crack width control in restrained concrete"

- objectives
  - efficient crack width control
  - reasonable reinforcement amounts
  - avoidance of dilation joints
- design strategy
  - deformation compatibility
  - superposition of loads and restraints
  - soil-structure-interaction
- practical application
  - jointless watertight constructions
  - unreinforced mass concrete
  - jointless building constructions

Outline

- ❑ general behaviour of reinforced concrete
- ❑ EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
  - crack width control for combined action of restraints and loads
    - illustration example: FCT design challenge
- ❑ design on basis of deformation compatibility
  - basic principle
  - design of members which are primarily restrained
  - design of members under combined effect of loads and restraints
    - illustration example: FCT design challenge
- ❑ practical references
- ❑ conclusion

Part 1

- ❑ general behaviour of reinforced concrete
- ❑ EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
  - crack width control for combined action of restraints and loads
    - illustration example: FCT design challenge
- ❑ design on basis of deformation compatibility
  - basic principle
  - design of members which are primarily restrained
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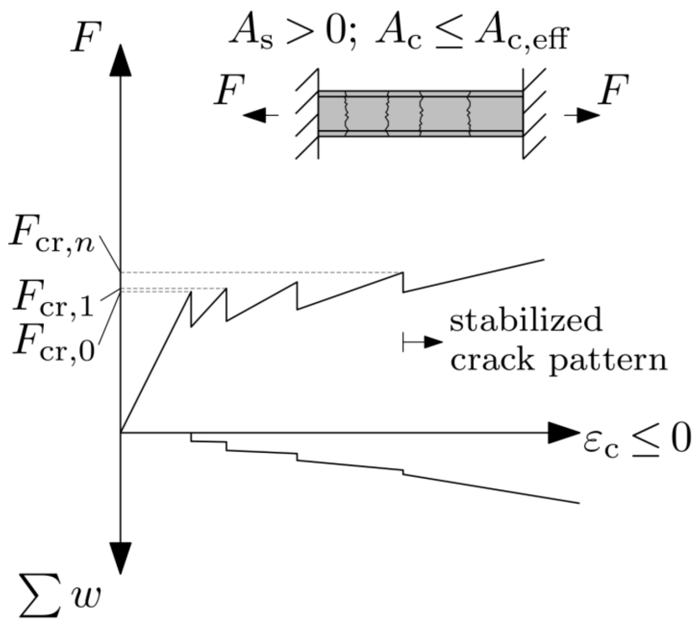
    - illustration example: FCT design challenge
- ❑ practical references
- ❑ conclusion

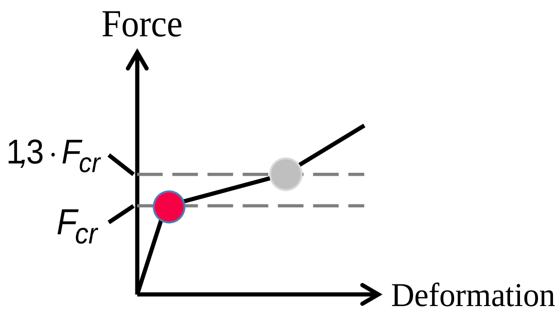
General behaviour of reinforced concrete

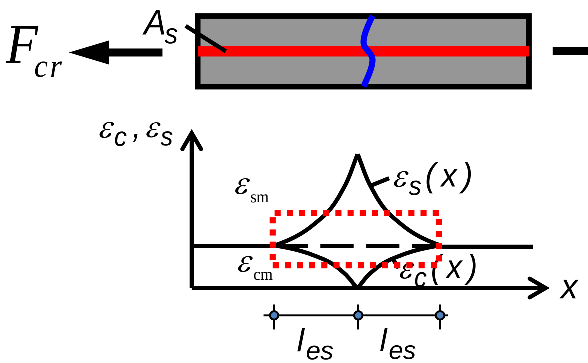
- cracking occurs when cracking forces are reached
- if reinforcement is not yielding, a so called successive cracking on the level of cracking forces takes places until stabilized crack pattern is reached



General behaviour of reinforced concrete

- occurring crack width
  - single cracks:





$$w_k = \int_0^{s_r} \left(\varepsilon_s(x) - \varepsilon_c(x)\right) dx$$

$$w_k = 2 \cdot l_{es} \cdot \left(\varepsilon_{sm} - \varepsilon_{cm}\right)$$

$$\varepsilon_{sm} = \varepsilon_{c,\max} + k_t \cdot \left(\frac{\sigma_s}{E_s} - \varepsilon_{c,\max}\right)$$

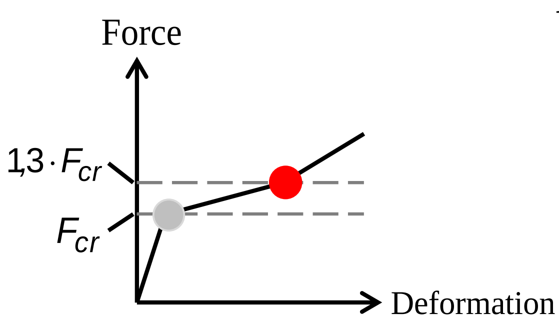
$$\varepsilon_{cm} = \left(1 - k_t\right) \cdot \varepsilon_{c,\max}$$

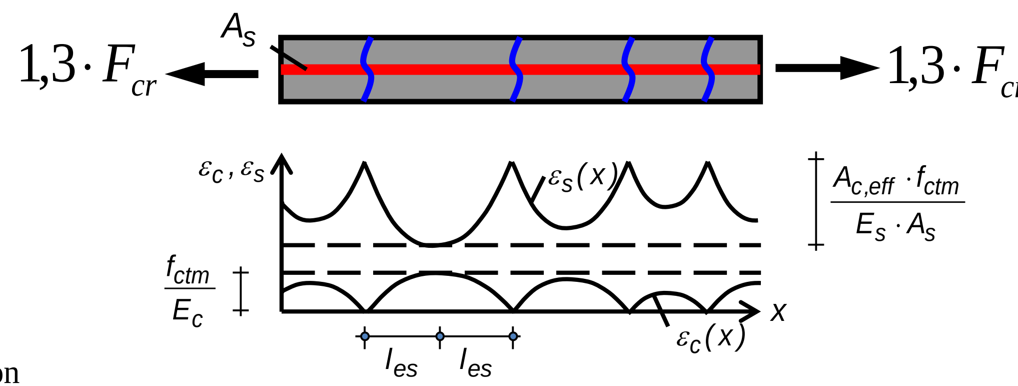
$$l_{es} = \frac{F_s}{\tau_{sm} \cdot U_S} = \frac{\sigma_s \cdot d_s}{\tau_{sm} \cdot 4}$$

$$w_k = \frac{\sigma_s \cdot d_s}{2 \cdot \tau_{sm}} \cdot k_t \cdot \frac{\sigma_s}{E_s}$$

General behaviour of reinforced concrete

- correlation of steel stress and occurring crack width
  - stabilized crack pattern:





  - ○ crack spacing requires statistical considerations
    - – safe side assumption on basis of $A_{c,\text{eff}}$:

$$l_{\text{e}} = \frac{A_{\text{c,eff}} \cdot f_{\text{ctm}}}{\tau_{\text{sm}} \cdot \pi \cdot d_{\text{s}}}$$

$$w_{\text{k}} = 2 \cdot \frac{A_{\text{c,eff}} \cdot f_{\text{ctm}}}{\tau_{\text{sm}} \cdot \pi \cdot d_{\text{s}}} \cdot (\varepsilon_{sm} - \varepsilon_{cm})$$

with:

$$\varepsilon_{sm} = \frac{\sigma_{\text{s}}}{E_{\text{s}}} - \frac{A_{\text{c,eff}} \cdot f_{\text{ctm}}}{E_{\text{s}} \cdot A_{\text{s}}} \cdot (1 - k_{\text{t}})$$

$$\varepsilon_{cm} = \frac{f_{\text{ctm}}}{E_{\text{c}}}(1 - k_{\text{t}})$$

General behaviour of reinforced concrete

- correlation between steel strain and crack width
  - conservatively taken from the single crack pattern:

$$w_\mathrm{k} = \frac{\sigma_\mathrm{s} \cdot d_\mathrm{s}}{2 \cdot \tau_\mathrm{sm}} \cdot k_\mathrm{t} \cdot \frac{\sigma_\mathrm{s}}{E_\mathrm{s}} \quad \rightarrow \quad \sigma_\mathrm{s}(w_\mathrm{k}) = \sqrt{\frac{2}{k_\mathrm{t}} \cdot \frac{w_\mathrm{k} \cdot \tau_\mathrm{sm} \cdot E_\mathrm{s}}{d_\mathrm{s}}}$$

- required reinforcement for crack width control
  - derived from stabilized crack pattern, but also applicable for single cracks:

$$A_\mathrm{s} = \sqrt{\frac{F_\mathrm{cr} \cdot (F_\mathrm{s} - F_\mathrm{cr} \cdot (1 - k_\mathrm{t})) \cdot d_s}{2 \cdot \tau_\mathrm{sm} \cdot E_s \cdot w_\mathrm{k}}}$$

with: F_cr .... force to produce a new crack in the effective concrete zone
F_s ... force to be taken by the reinforcement after cracking

for: $F_\mathrm{cr} \leq F_\mathrm{s}$ ... only single cracks are to be expected and F_s is to set as F_cr
$F_\mathrm{s} > F_\mathrm{cr}$ ... stabilized crack pattern to be expected

Part 2

- general behaviour of reinforced concrete
- EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
  - crack width control for combined action of restraints and loads
    - illustration example: FCT design challenge
- design on basis of deformation compatibility
  - basic principle
  - design of members which are primarily restrained
  - design of members under combined effect of loads and restraints
    - illustration example: FCT design challenge
- practical references
- conclusion

EC2-1 regulations regarding restraint / minimum reinforcement

- minimum reinforcement for crack width control according to cracking forces
  - enabling successive cracking with respect to occurring steel stress

$$A_{\mathrm{s,min}} \cdot \sigma_{\mathrm{s}}\left(w_{\mathrm{k}}\right) \geq F_{\mathrm{cr}}$$

$$A_{\mathrm{s,min}} \cdot \sigma_{\mathrm{s}}\left(w_{\mathrm{k}}\right) \geq k \cdot k_{\mathrm{c}} \cdot A_{\mathrm{ct}} \cdot f_{\mathrm{ct,eff}} \rightarrow A_{\mathrm{s,min}} = k \cdot k_{\mathrm{c}} \cdot A_{\mathrm{ct}} \cdot \frac{f_{\mathrm{ct,eff}}}{\sigma_{\mathrm{s}}\left(w_{\mathrm{k}}\right)}$$

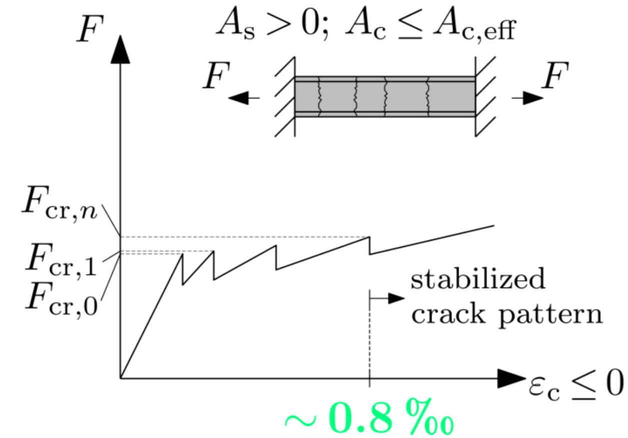
k → factor for consideration of pre-damage due to Eigenstresses

k_c → factor for consideration of stress distribution
(k = 1.0 for centric restraint, k = 0.4 for bending restraint)

$f_{ct,eff}$ → modification of f_{ctm} to consider early age cracking as well as differences of tensile strength between laboratory and on-site conditions

EC2-1 regulations regarding restraint / superposition with loads

- consideration of combined effect of applied loads and restraints
  - observations
    - restraint decreases by crack opening during successive cracking
    - in common cases the stabilized crack pattern is not reached until ca. 0.8 ‰ deformation was imposed to the member



  - conclusions for design (German Annex)
    - in common cases the superposition of loads and restraints can be neglected as long as deformation impact exceeds not 0.8 ‰
    - minimum reinforcement is usually fully utilized for statically required reinforcement

FCT design challenge according to EC2-1

- details and task

Concrete: C30/37

f_{cd} = 17 N/mm²
f_{ctm} = 2.9 N/mm²
γ_c = 0.025 kN/m³
ε_{cu3} = 3.50 ‰
E_{cm} = 33000 N/mm²
h = 0.150 m
L = 5.00 m

Reinforcement: S400C

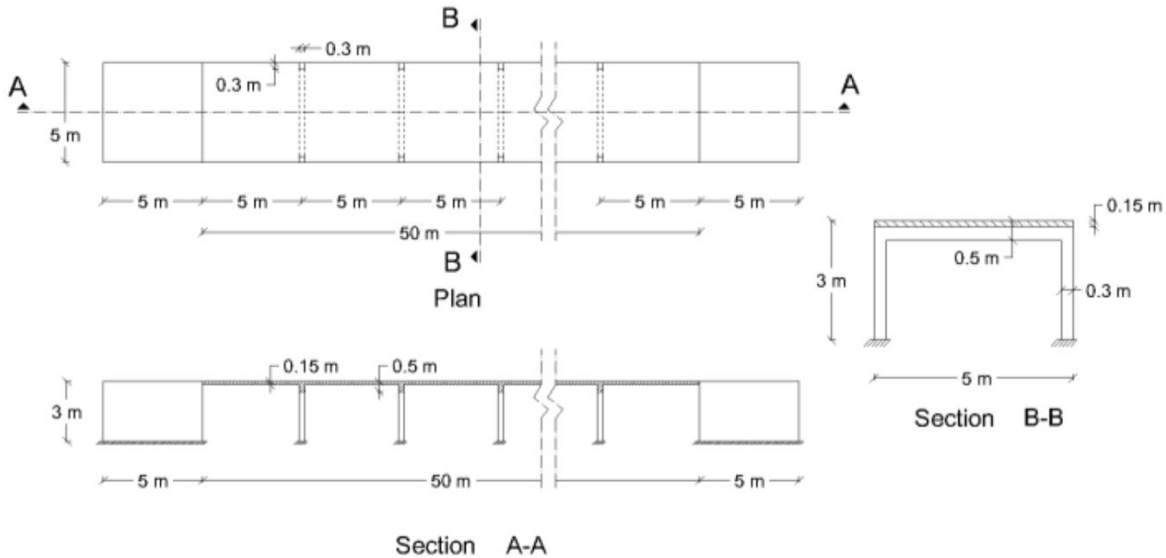
f_{yk} = 400 N/mm²
f_{yd} = 348 N/mm²
c = 30 mm

Loading: residential building Cat A

$g_{k,1}$ = 2.0 kN/m²
q_k = 2.0 kN/m²
ψ_2 = 0.3 [-]

Envirnonmental conditions

RH = 50 %
$t_{0,drying}$ = 28 d



case 1: minimum reinforcement for crack width control of w_k = 0.3 mm (only restraints)

case 2: reinforcement for crack width control of w_k = 0.3 mm considering combined effect of restraint and loading

FCT design challenge according to EC2-1

- case 1: minimum reinforcement for crack width control
  - centric restraint for service life with $f_{ct,eff} = 0.8 \times f_{ctm}$

$$F_{cr} \leq F_s \rightarrow F_{cr} = F_s : \qquad A_s = \sqrt{\frac{F_s^2 \cdot k_t \cdot d_s}{2 \cdot \tau_{sm} \cdot E_s \cdot w_k}}$$

$$F_s = \frac{A_c}{2} \cdot f_{ct,eff} = \frac{0.15}{2} \cdot 0.8 \cdot 2.9 = 0.174\,\mathrm{MN/m}$$

$$k_t = 0.6$$

$$\tau_{sm} = 1.8 \cdot f_{ctm} = 1.8 \cdot 2.9 = 5.22\,\mathrm{M/m^2}$$

$$E_s = 200\,000\,\mathrm{M/m^2}$$

$$w_k = 0.3\,\mathrm{mm}$$

$$A_s = \sqrt{\frac{0.174^2 \cdot 0.6 \cdot 8}{2 \cdot 5.22 \cdot 200\,000 \cdot 0.3}} = 4.8\,\mathrm{cm^2/m}$$

$\longrightarrow$ rebar d_s=8 mm

rebar spacing s=10 cm

FCT design challenge according to EC2-1

- case 2: combined effect of loads and restraints
  - statically required reinforcement and crack width control under load

	column	field	
M_{Ed}	11.9	5.9	kNm/m
d_s	8	8	mm
d	0.116	0.116	m
$M_{Ed} = N_c \cdot z$: 0 =	**5.440 x²**	**5.440 x²**	
	+1.578 x	**+1.578 x**	
	-0.012	**-0.006**	
→ $x_{1,1}$ =	0.007	0.004	m
$x_{1,2}$ =	~~**-0.297**~~	~~**-0.294**~~	m
z =	0.113	0.115	m
ε_{s1} =	51.75	105.66	‰
$A_{s,min}$ =	2.19	2.19	cm²/m
	1.51	1.51	
$A_{s,max}$ =	60.00	60.00	cm²/m
$A_{S1,req}$ =	3.02	2.19	cm²/m
required rebar spacing *s*=	14	20	cm

	column	field	
M_g	4.17	2.09	kNm/m
M_{perm}	5.42	2.71	kNm/m
M_{rare}	8.34	4.17	kNm/m
M_{cr}	8.70	8.70	kNm/m
cracking:	not without restraint	not without restraint	

↳ explicit crack width control for load is not required

→ minimum reinforcement decisive for crack width control

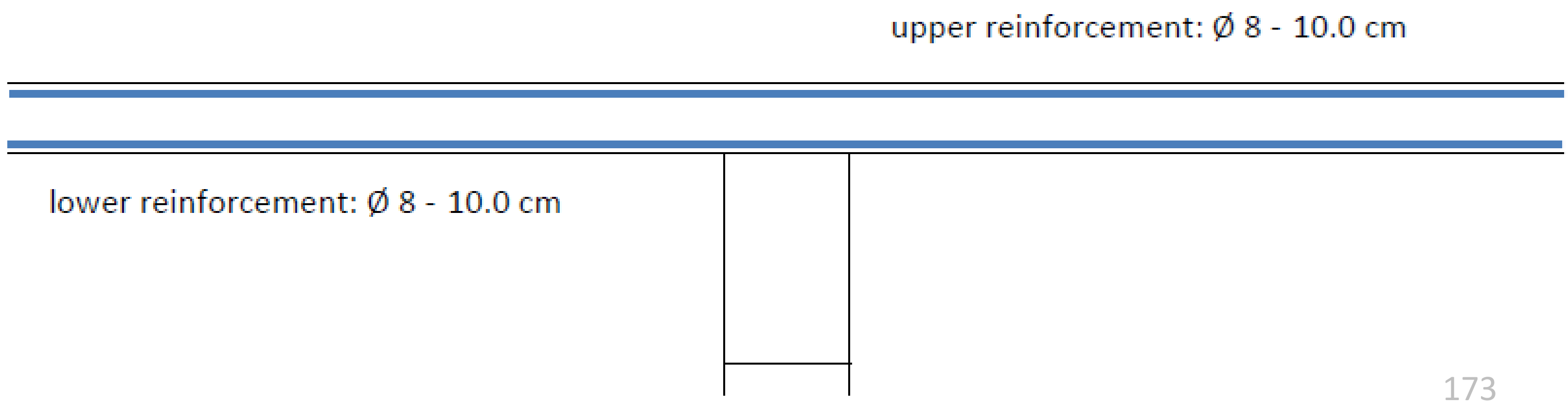
FCT design challenge according to EC2-1

- case 2: combined effect of loads and restraints
  - minimum reinforcement as lower limit without superposition of loads and restraints as long as $\varepsilon_{c,eff} \leq 0.8$ ‰ (acc. to German Annex)

deformation impact:

$$\left.\begin{aligned} \varepsilon_{cds}(t=\infty, t_{0,drying} = 28\text{ d}) &= 0.57\text{ ‰} \\ \varphi(t=\infty, t_{0,drying} = 28\text{ d}) &= 2.5\ [-] \\ \rho &= 0.8\ [-] \end{aligned}\right\} \quad \varepsilon_{eff} = \frac{\varepsilon_{cds}}{1+\rho\cdot\varphi} = 0.19\text{ ‰} \leq 0.8\text{ ‰}$$

  - required longitudinal reinforcement according to EC2-1

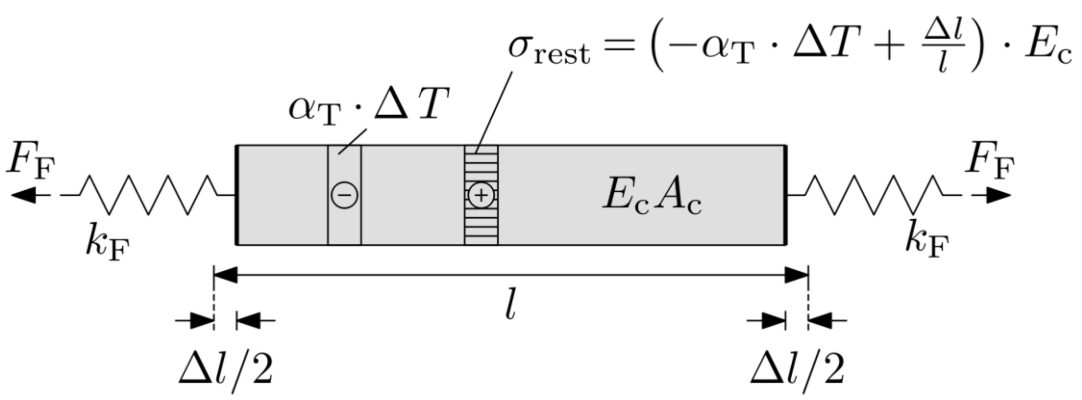


Part 3

- general behaviour of reinforced concrete
- EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
  - crack width control for combined action of restraints and loads
    - illustration example: FCT design challenge
- design on basis of deformation compatibility
  - basic principle
  - design of members which are primarily restrained
  - design of members under combined effect of loads and restraints
    - illustration example: FCT design challenge
- practical references
- conclusion

Design on basis of deformation compatibility

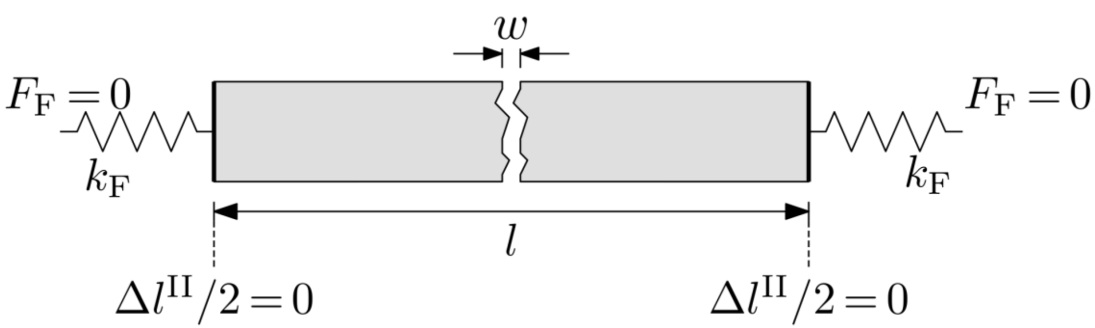
- basic principle
  - restraint stresses with respect to realistic restraining situation



Design on basis of deformation compatibility

- basic principle
  - deformation compatibility after cracking
    - without reinforcement

$\alpha_\mathrm{T} \cdot \Delta T;\ E_\mathrm{c} A_\mathrm{c}$

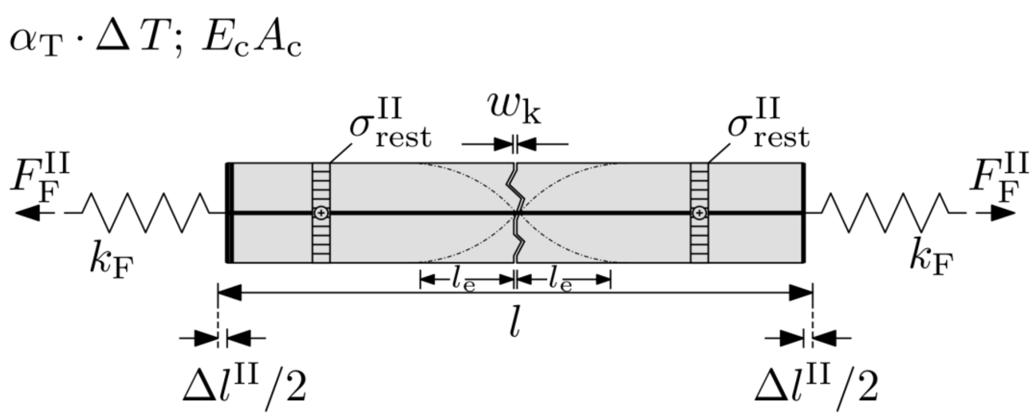


whereby: $\sigma_\mathrm{rest}^\mathrm{II} = 0$

$$w = -\alpha_\mathrm{T} \cdot \Delta T \cdot l$$

Design on basis of deformation compatibility

- basic principle
  - deformation compatibility after cracking
    - with reinforcement



whereby: $-\alpha_{\mathrm{T}} \cdot \Delta T \cdot l = w_{\mathrm{k}} + \frac{\sigma_{\mathrm{rest}}^{\mathrm{II}}}{E_{\mathrm{c}}} \cdot \left(l - 2 \cdot l_{\mathrm{e}} \cdot (1 - k_{\mathrm{t}})\right) + \Delta l^{\mathrm{II}}$ and

$$\sigma_{\mathrm{s}} \cdot A_{\mathrm{s}} \approx \sigma_{\mathrm{rest}}^{\mathrm{II}} \cdot A_{\mathrm{c}}$$

Design on basis of deformation compatibility

- Practical application
  - minimum reinforcement for members which are predominantly restrained
    - design task: required reinforcement for crack width control

$$A_{s,min} = \frac{-\alpha_T \cdot \Delta T \cdot a^{II} \cdot l - w_k}{\left(l - 2 \cdot l_e \cdot (1 - k_t)\right)} \cdot \frac{E_c A_c}{\sigma_s(w_k)}$$

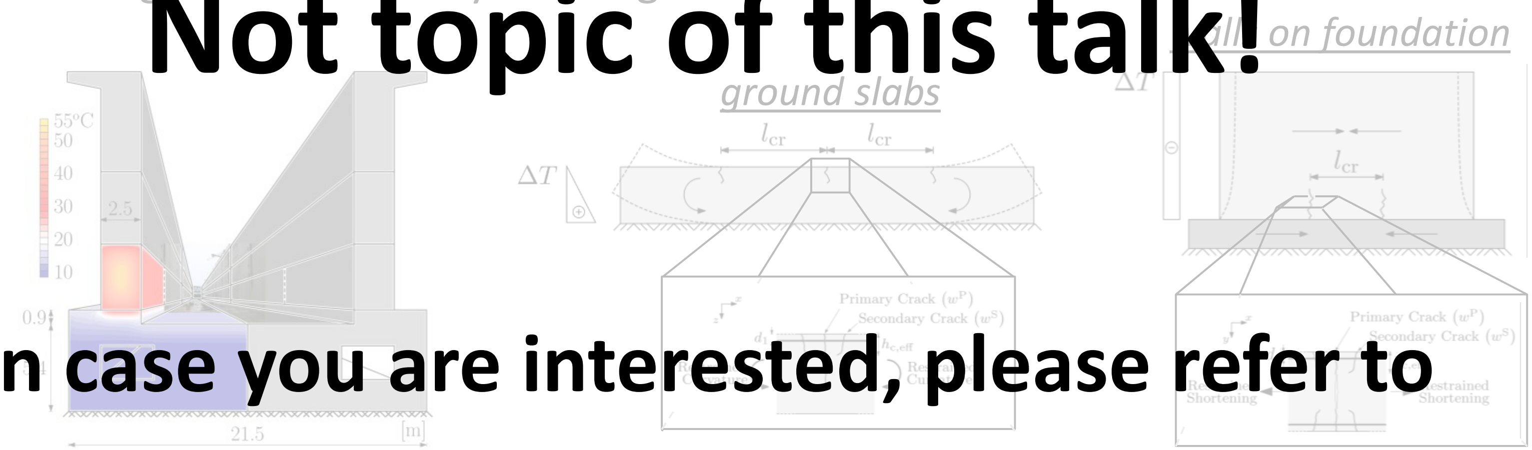
  - design of members under combined effect of loads and restraints
    - design task: verification of crack width criteria with respect to occurring restraint forces in the overall structure

$$N_{rest} = \frac{-\alpha_T \cdot \Delta T \cdot a^{II} \cdot l - w_k}{\left(l - 2 \cdot l_e \cdot (1 - k_t)\right)} \cdot E_c A_c$$

Design on basis of deformation compatibility

- minimum reinforcement for members which are predominantly restrained
  - quantification of restrained deformation
  - determination of gemetrically set primary crack pattern
  - practice-oriented verification of deformation compatibility with regard to secondary cracking

Not topic of this talk!

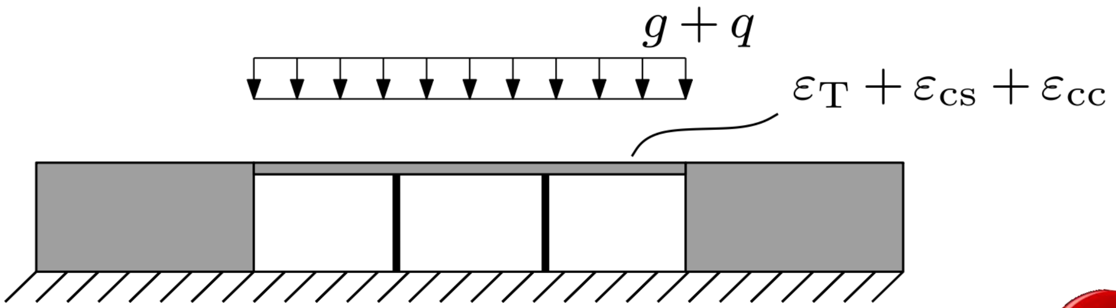


In case you are interested, please refer to

Schlicke, D. and Tue, N. V. (2015), *Minimum reinforcement for crack width control in restrained concrete members considering the deformation compatibility.* Structural Concrete, 16: 221 - 232. doi: 10.1002/suco.201400058

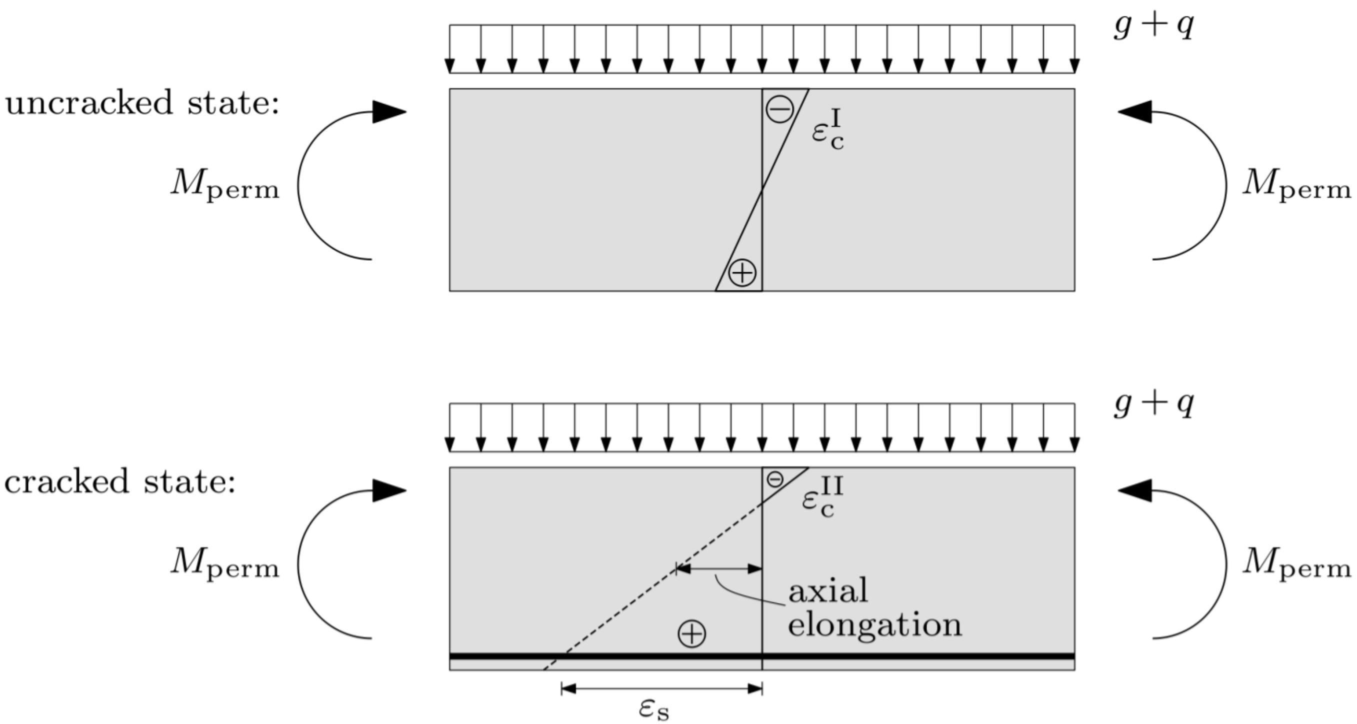
Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints



Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints
  - bending cracks under permanent loads cause axial elongation of the member



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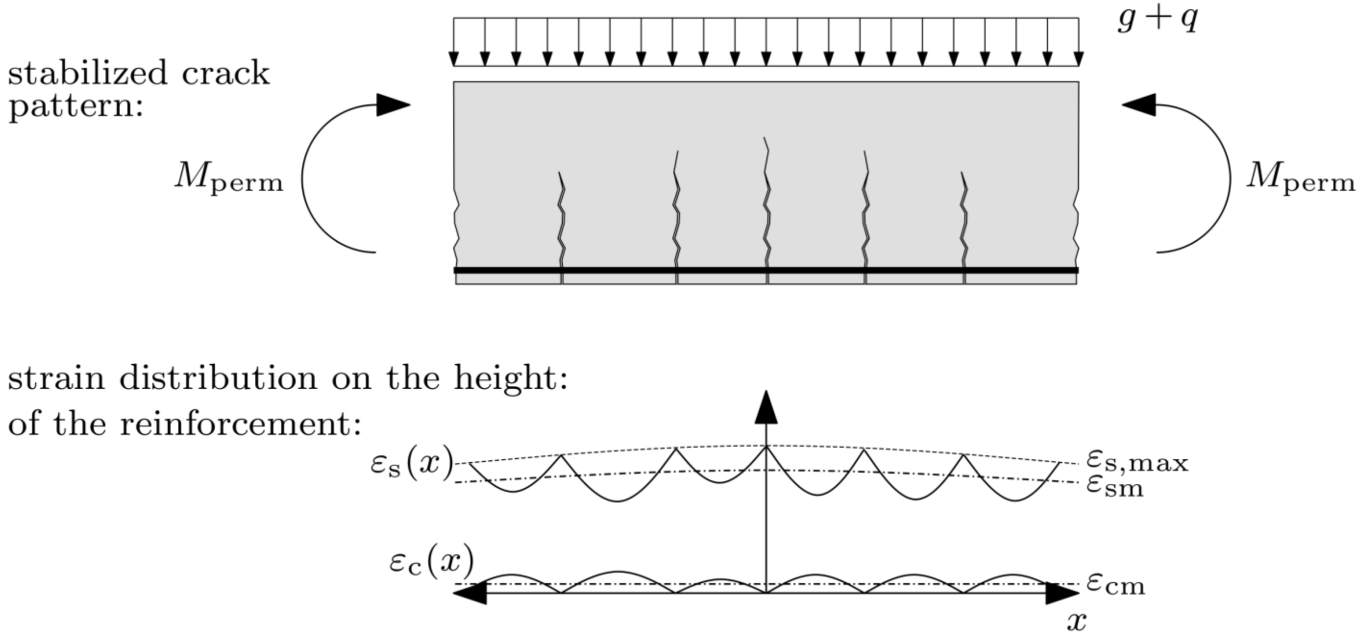
Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints
  - in case of cracking due to loading a stabilized crack pattern can be assumed



Design on basis of deformation compatibility

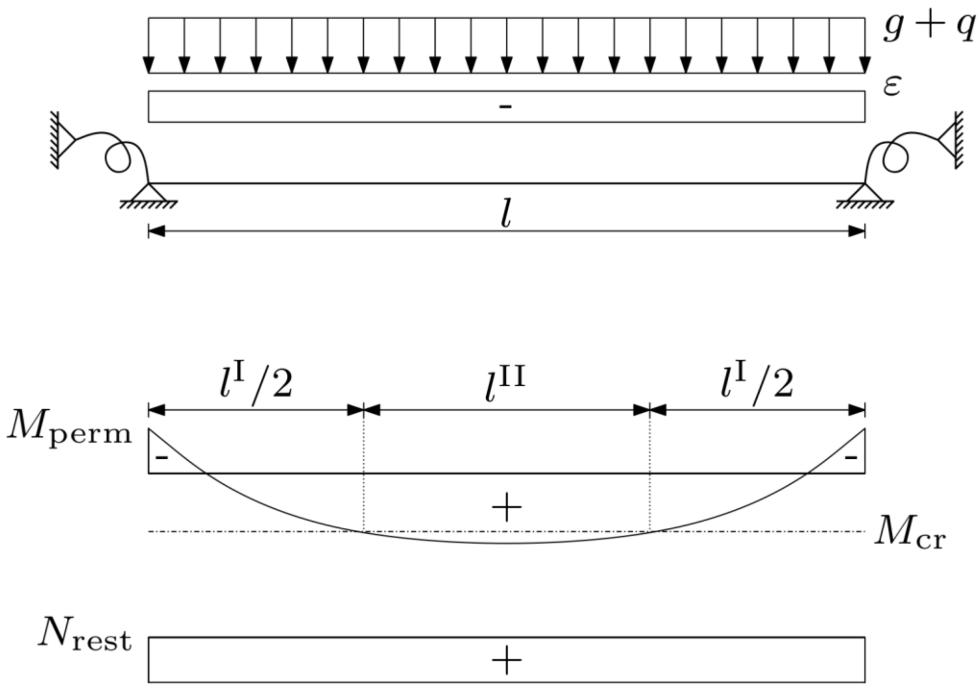
- design of members under combined effect of loads and restraints
  - axial strain in the stabilized crack pattern:
    - correct solution
      - integration of strains along the gravity axis of the member
      - consideration of real crack opening over the member height (no plane cross section)
    - practice-oriented engineering solution
      - assumption of plane cross section but disregard of strains in the compression zone:

$$\Delta\varepsilon_{\mathrm{free}}^{\mathrm{II}} = 0.5 \cdot \varepsilon_{\mathrm{sm}}$$

for stabilized crack pattern: $$\Delta\varepsilon_{\mathrm{free}}^{\mathrm{II}} = 0.5 \cdot \left(\frac{\sigma_{\mathrm{s}}}{E_{\mathrm{s}}} - (1-k_{\mathrm{t}}) \cdot \frac{A_{\mathrm{c,eff}} \cdot f_{\mathrm{ctm}}}{A_{\mathrm{s}} \cdot E_{\mathrm{s}}}\right)$$

Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints
  - axial strain of the whole member with respect to cracked and uncracked areas



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Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints
  - axial strain of the whole member with respect to cracked and uncracked areas

$$\Delta\varepsilon_{\mathrm{free}} = \left[\Delta\varepsilon_{\mathrm{free}}^{\mathrm{II}} \cdot l^{\mathrm{II}} + \Delta\varepsilon_{\mathrm{free}}^{\mathrm{I}} \cdot (l - l^{\mathrm{II}})\right]/l$$

  - in the uncracked part only elastic strains due to possible restraint force:

$$\Delta\varepsilon_{\mathrm{free}}^{\mathrm{I}} = \frac{N_{\mathrm{rest}}}{A_{\mathrm{c}} \cdot E_{\mathrm{c}}}$$

  - in the cracked part only axial strain due to bending

$$\Delta\varepsilon_{\mathrm{free}}^{\mathrm{II}} = 0.5 \cdot \left(\frac{\sigma_{\mathrm{s}}}{E_{\mathrm{s}}} - (1 - k_{\mathrm{t}}) \cdot \frac{A_{\mathrm{c,eff}} \cdot f_{\mathrm{ctm}}}{A_{\mathrm{s}} \cdot E_{\mathrm{s}}}\right)$$

Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints
  - balance between deformation impact and releasable deformation in the system:

$$|\Delta\varepsilon_{\text{eff}}| \leq |\Delta\varepsilon_{\text{free}}|$$

    - either fulfilled due to cracking under permanent loads or
    - to be achieved with additional cracking due to increasing restraint force
      - iterative solution consisting of determination of required length to be cracked $\left(l_{\text{req}}^{\text{II}}\right)$ and occurring restraint force until it can be shown that:

$$|\Delta\varepsilon_{\text{eff}}| \leq \left|\left[\Delta\varepsilon_{\text{free}}^{\text{II}} \cdot l^{\text{II}} + \Delta\varepsilon_{\text{free}}^{\text{I}} \cdot (l - l^{\text{II}})\right]/l\right|$$

Design on basis of deformation compatibility

- design of members under combined effect of loads and restraints / recipe
  1. quantification of deformation impact
  2. determination of permanent stressing due to loads
  3. identification of cracked areas under permanent loads
  4. comparison of the deformation impact with the released axial deformation in the cracked areas under permanent loads:
     a. if deformation impact is absorbed: crack width control under load is decisive, whereas additional restraint forces can be excluded
     b. if deformation impact is NOT yet absorbed: determination of restraint forces to achieve the required size of cracked areas
        i. if sufficiently large areas with cracks can be created, crack width control under load is decisive; occurring restraint forces are to be considered in regard to their interaction within the structure
        ii. if not possible, minimum reinforcement for centric restraint is to be provided and cracking forces are to be considered for structural analysis

FCT design challenge solved with deformation-based concept

1. quantification of deformation impact

deformation impact:

$\varepsilon_{cds}(t = \infty, t_{0,drying} = 28\text{ d}) = 0.57$ ‰
$\varphi(t = \infty, t_{0,drying} = 28\text{ d}) = 2.5$ [-]
$\rho = 0.8$ [-]

$$\varepsilon_{eff} = \frac{\varepsilon_{cds}}{1+\rho\cdot\varphi} = 0.19\text{ ‰} \leq 0.8\text{ ‰}$$

2. determination of permanent stressing due to loads

	column	field	
M_g	4.17	2.09	kNm/m
M_{perm}	5.42	2.71	kNm/m
M_{rare}	8.34	4.17	kNm/m
M_{cr}	8.70	8.70	kNm/m
cracking:	not without restraint	not without restraint	

FCT design challenge solved with deformation-based concept

3. identification of cracked areas under permanent loads

	column	field	
M_g	4.17	2.09	kNm/m
M_{perm}	5.42	2.71	kNm/m
M_{rare}	8.34	4.17	kNm/m
M_{cr}	8.70	8.70	kNm/m
cracking:	not without restraint	not without restraint	

4. comparison of the deformation impact with the released axial deformation in the cracked areas under permanent loads:
   a. if deformation impact is absorbed: crack width control under load is decisive, whereas additional restraint forces can be excluded

NOT APPLICABLE
in the present case!

FCT design challenge solved with deformation-based concept

4. comparison of the deformation impact with the released axial deformation in the cracked areas under permanent loads:
   b. if deformation impact is NOT yet absorbed: determination of required size of cracked area:

$$l_{\mathrm{req}}^{\mathrm{II}} = \frac{\Delta\varepsilon_{\mathrm{eff}} - \dfrac{N_{\mathrm{rest}}}{A_{\mathrm{c}} \cdot E_{\mathrm{c}}}}{0.5 \cdot \left(\dfrac{\sigma_{\mathrm{s}}(w_{\mathrm{k}})}{E_{\mathrm{s}}} - (1-k_{\mathrm{t}}) \cdot \dfrac{A_{\mathrm{c,eff}} \cdot f_{\mathrm{ctm}}}{E_{\mathrm{s}} \cdot A_{\mathrm{s}}} \right) - \dfrac{N_{\mathrm{rest}}}{A_{\mathrm{c}} \cdot E_{\mathrm{c}}}} \cdot l$$

→ with: $\Delta\varepsilon_{\mathrm{eff}} = 0.19\,‰$

$$\sigma_{\mathrm{s}}(w_{\mathrm{k}}) = \sqrt{\frac{2}{k_{\mathrm{t}}} \cdot \frac{w_{\mathrm{k}} \cdot \tau_{\mathrm{sm}} \cdot E_{\mathrm{s}}}{d_{\mathrm{s}}}} = 361\ \mathrm{N/mm^2}$$

$$A_{\mathrm{c,eff}} = \min \begin{cases} 2.5 \cdot d_1 \cdot b & = 2.5 \cdot \left(3.0 + \dfrac{0.8}{2}\right) \cdot 100 & = 850\,\mathrm{cm^2/m} \\ \dfrac{h}{2} \cdot b & = \dfrac{15}{2} \cdot 100 & = 750\,\mathrm{cm^2/m} \\ \dfrac{h-x}{3} \cdot b & = \dfrac{15-x}{3} \cdot 100 & = \max.500\,\mathrm{cm^2/m} \end{cases}$$

FCT design challenge solved with deformation-based concept

- determination of required size of cracked area

$$l_{\mathrm{req}}^{\mathrm{II}} = \frac{0.19 \cdot 10^{-3} - \dfrac{N_{\mathrm{rest}}[\mathrm{MN}]}{0.15 \cdot 30\,000}}{\dfrac{0.5}{200\,000} \cdot \left(361 - (1-0.6) \cdot \dfrac{500 \cdot 2.9}{A_{\mathrm{s,prov}}[\mathrm{cm}^2/\mathrm{m}]}\right) - \dfrac{N_{\mathrm{rest}}[\mathrm{MN}]}{0.15 \cdot 30\,000}} \cdot 5.0$$

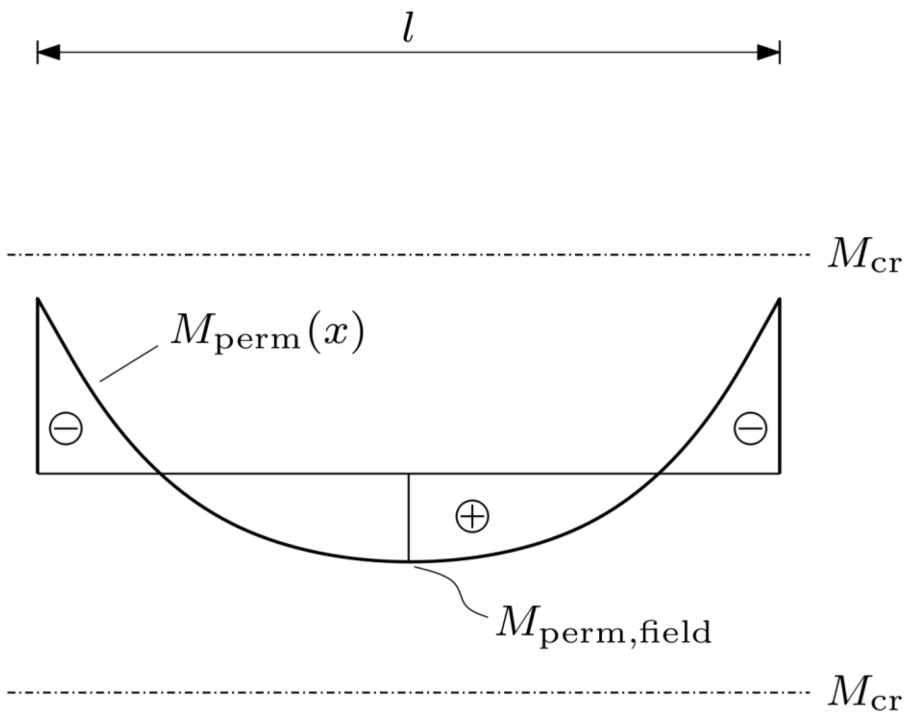
→ iterative solution:

- N_{rest} and $l_{\mathrm{req}}^{\mathrm{II}}$ are connected over the distribution of M_{perm}
- $A_{\mathrm{s,prov}}$ results from the reinforcement design for bending under consideration of N_{rest}

FCT design challenge solved with deformation-based concept

→ determination of N_{rest} according to an assumed $l_{\text{req}}^{\text{II}}$:

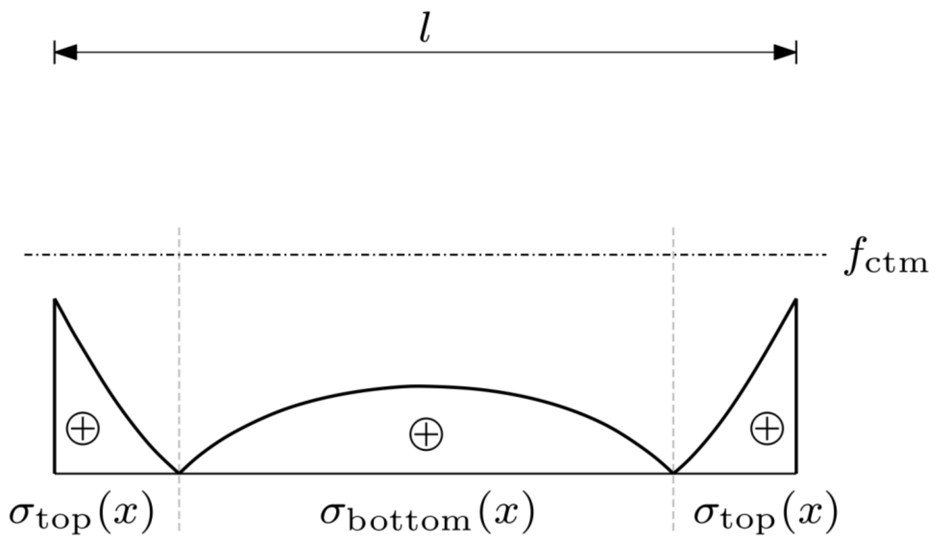
step 1: distrubution of permanent moment in one field vs. cracking moment



FCT design challenge solved with deformation-based concept

→ determination of N_{rest} according to an assumed $l_{\text{req}}^{\text{II}}$:

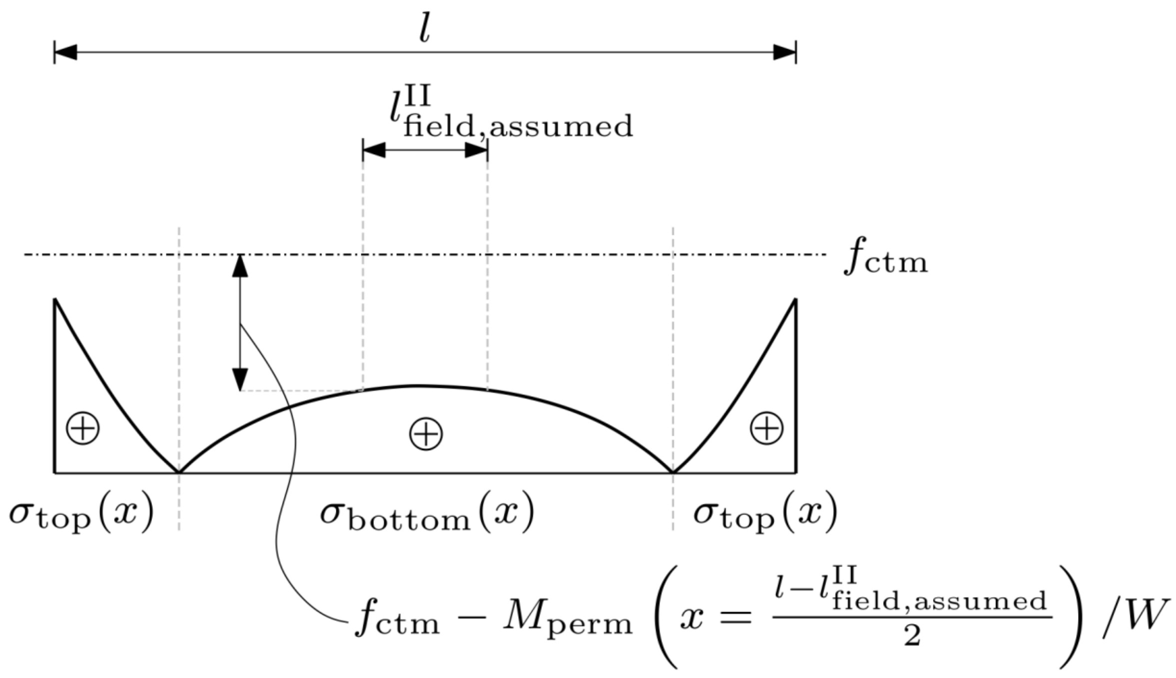
step 2: according max. tensile stresses in one field vs. tensile strength



FCT design challenge solved with deformation-based concept

→ determination of N_{rest} according to an assumed $l^{\text{II}}_{\text{req}}$:

step 3: determination of „required“ tensile stress to cause cracking within $l^{\text{II}}_{\text{req}}$



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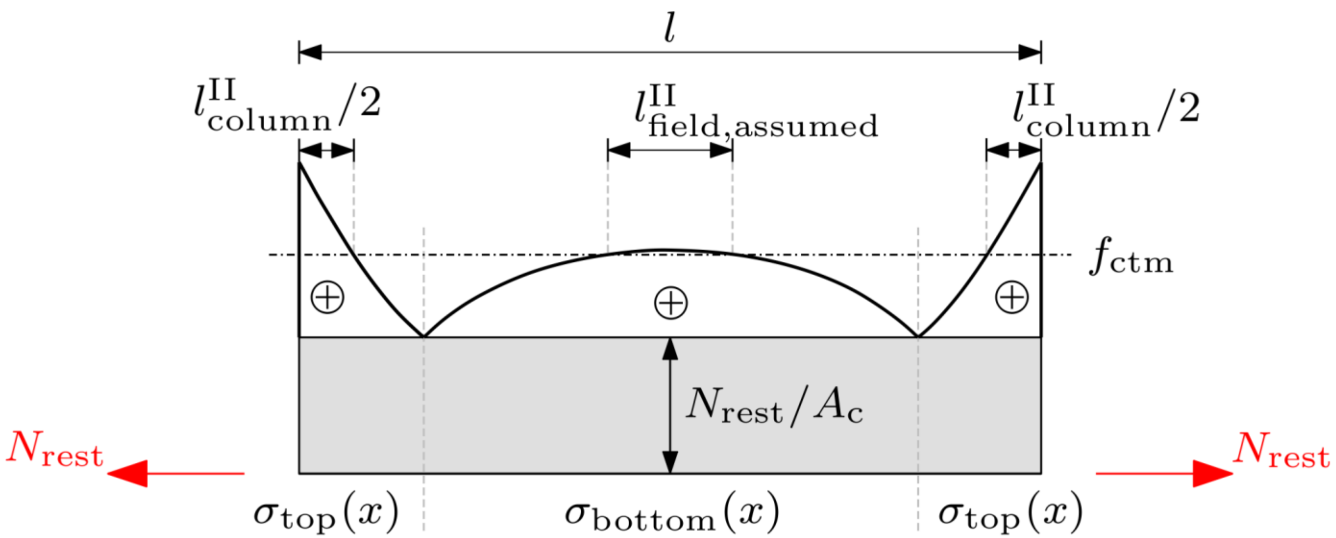
→ determination of N_{rest} according to an assumed $l^{\text{II}}_{\text{req}}$:

step 4: derivation of N_{rest} from the stress difference



FCT design challenge solved with deformation-based concept

→ determination of N_{rest} according to an assumed $l_{\mathrm{req}}^{\mathrm{II}}$:

$$M_{\mathrm{perm}}\left(x=\frac{l-l_{\mathrm{field,assumed}}^{\mathrm{II}}}{2}\right)=M_{\mathrm{perm,field}}\cdot\left(\frac{12\cdot x}{l}-\frac{12\cdot x^{2}}{l^{2}}-2\right)=2.68\,\mathrm{kNm/m}$$

$$N_{\mathrm{rest}}=A_{\mathrm{c}}\cdot\max\left\{0;\,f_{\mathrm{ctm}}-\frac{M_{\mathrm{perm}}(x)}{W}\right\}=327.9\,\mathrm{kN/m}$$

→ according input data:

$l^{\mathrm{II}}_{\mathrm{field,assumed}}$ = 0.33 m
$l^{\mathrm{II}}_{\mathrm{tot,assumed}}$ = 1.26 m

$l^{\mathrm{II}}_{\mathrm{req}}$ = 1.26 m --> OK
$A_{\mathrm{s1,prov}}$ = 4.2 cm²/m

FCT design challenge solved with deformation-based concept

$$N_{\text{rest}} = 327.9 >> F_{\text{cr,eff}} = 500\,\text{cm}^2/\text{m} \cdot 2.9\ \text{N/mm}^2 = 145\,\text{kN/m}$$

in the present case, cracking in the field area is not likely!

→ cracking starts in the point of max. bending stresses over the column with

$$N_{\text{rest}} = A_{\text{c}} \cdot \left(0.8 \cdot f_{\text{ctm}} - \frac{M_{\text{perm}}}{W}\right) = 0.15 \cdot \left(0.8 \cdot 2.9 - \frac{0.0054}{0.15^2 \cdot 1.0} \cdot 6\right) = 132\,\text{kN/m}$$

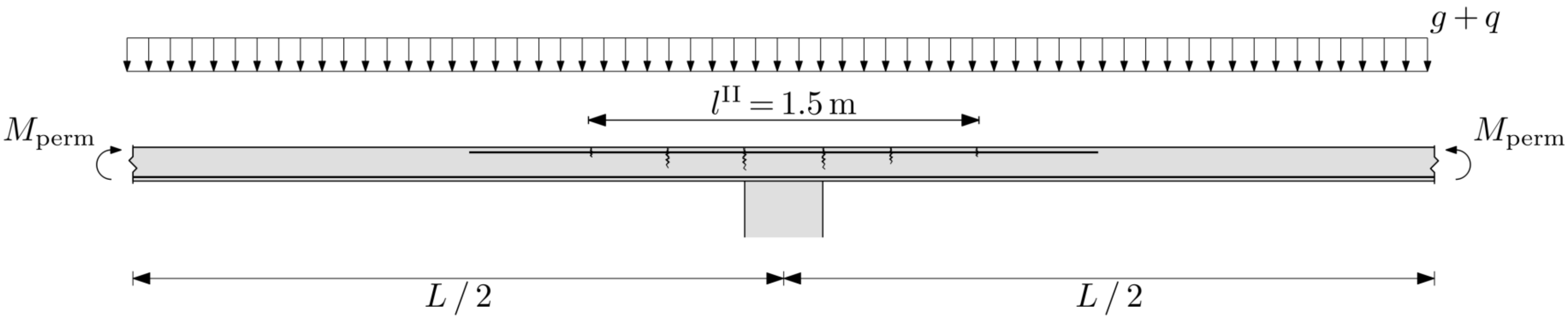
→ after initial cracking over the column, new cracks can only be produced next to the prior crack whereby the Force is limited to $F_{\text{cr,eff}}$

FCT design challenge solved with deformation-based concept

...and with respect to ongoing cracking on the level of $F_{\text{cr,eff}}$ the required length to be cracked increases to:

$$l_{\text{req}}^{\text{II}} = \frac{0.19 \cdot 10^{-3} - \dfrac{0.145}{0.15 \cdot 30\,000}}{\dfrac{0.5}{200\,000} \cdot \left(361 - (1 - 0.6) \cdot \dfrac{500 \cdot 2.9}{4.21}\right) - \dfrac{0.145}{0.15 \cdot 30\,000}} \cdot 5.0 = 1.5\,\text{m}$$

...whereby cracks can solely occur from the column onwards. Equilibrium is achieved after 0.75 m to each side (still in the area with negative moment)

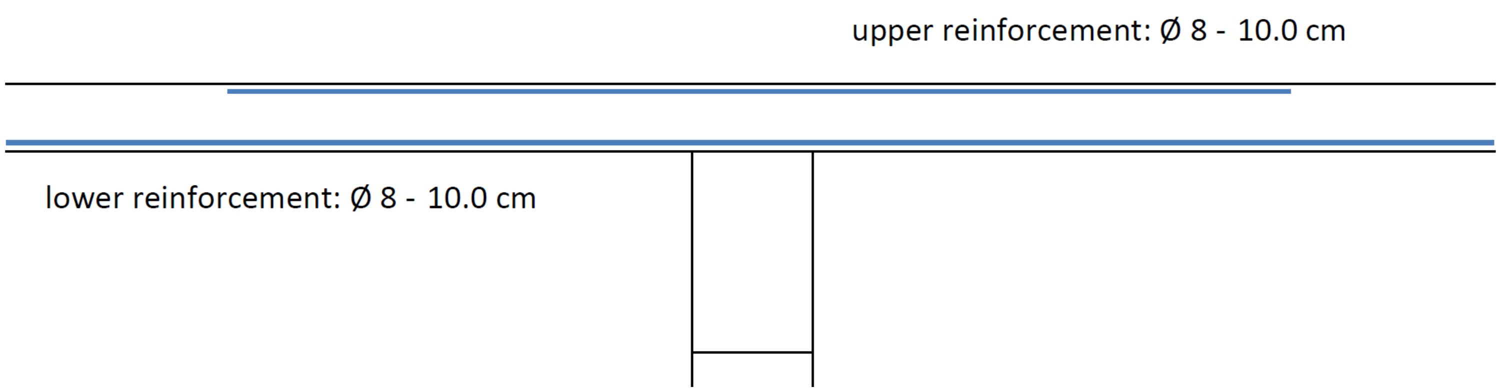


FCT design challenge solved with deformation-based concept

- verification of crack width criteria (over the column):

$$A_s = \sqrt{\frac{F_s^2 \cdot k_t \cdot d_s}{2 \cdot \tau_{sm} \cdot E_s \cdot w_k}} \qquad A_s = \sqrt{\frac{0.145^2 \cdot 0.6 \cdot 8}{2 \cdot 5.22 \cdot 200\,000 \cdot 0.3}} = 4.01\,\mathrm{cm^2/m}$$

$$F_s = F_{cr,eff} = 145\,\mathrm{kN/m}$$



FCT design challenge solved with deformation-based concept

- Conclusion deformation-based solution of FCT design challenge:
  - deformation-based concept is applicable
  - transparent superposition of loads and restraints on the safe side
    - restraint force available for ULS design of structure (must not be considered in ULS design of slab since significant decrease of restraint force can be expected when reinforcement yields)
  - consistent results regarding reinforcement arrangement
    - reinforcement always in the tension zone
    - verification of the compression zone in the field (no cracking due to restraint)
  - altogether, only moderate reinforcement savings compared to EC2 in the present case (only due to savings of top reinforcement in the field)
    - main reason is the low utilisation of the slab due to loads
  - critical view on simplified approach according to EC2
    - overestimation of restraint force by ~50% (N_{cr} = 348 kN/m, $N_{cr,eff}$ = 145 kN/m)

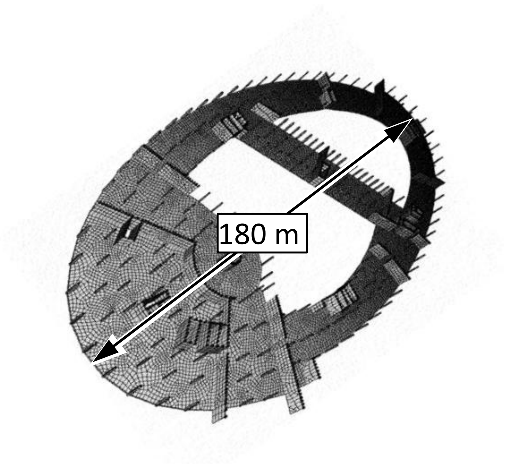
Part 4

- ❑ general behaviour of reinforced concrete
- ❑ EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
  - crack width control for combined action of restraints and loads
    - illustration example: FCT design challenge
- ❑ design on basis of deformation compatibility
  - basic principle
  - design of members which are primarily restrained
  - design of members under combined effect of loads and restraints
    - illustration example: FCT design challenge
- ❑ **practical references**
- ❑ conclusion

Practical references

- jointless building construction : Sky Headquarter Munich, Germany
  - large slab, highly restrained

View of finished construction (L = 180 m)



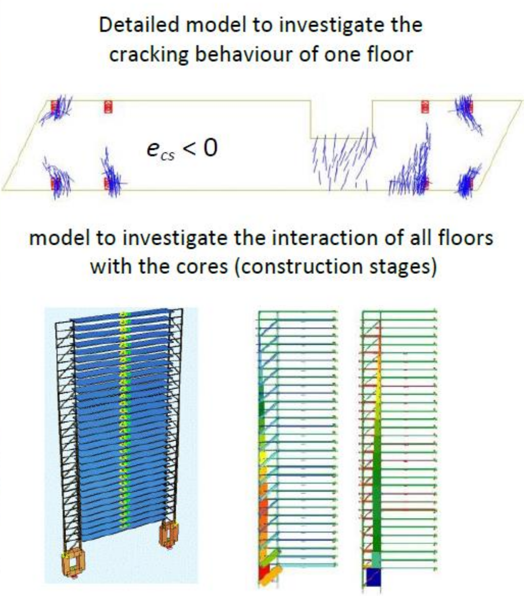
Calculation model "floor above ground level"

Sky Headquarter, München-Unterföhring

Practical references

- jointless building construction : Highlight Towers Munich, Germany
  - high number of small slabs, strong interaction with the cores

View of finished construction (H = 106 and 126 m)

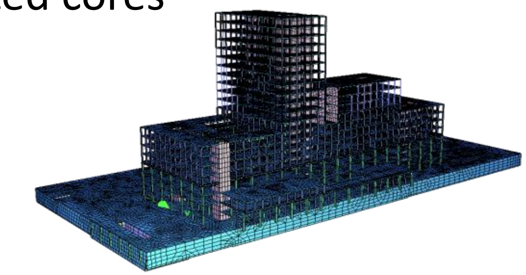


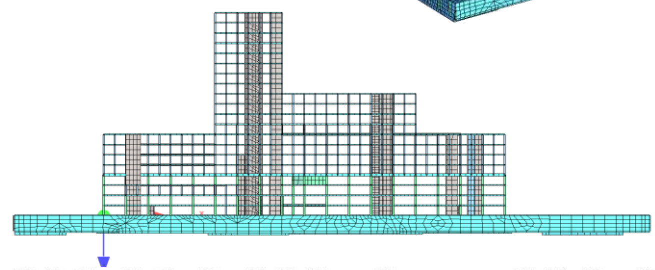
Calculation models

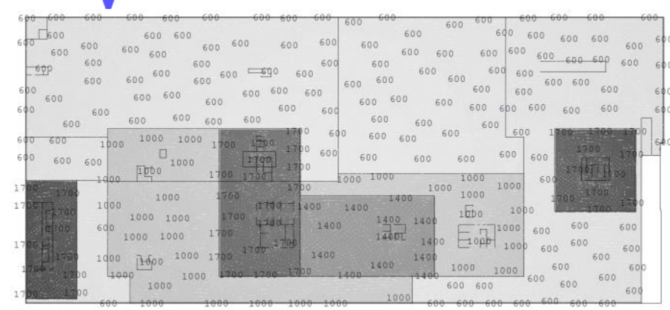
Highlight Towers Parkstadt Schwabing

Practical references

- jointless building construction : Hospital ZNA, Belgium
  - large slabs with strong interaction with irregularly situated cores



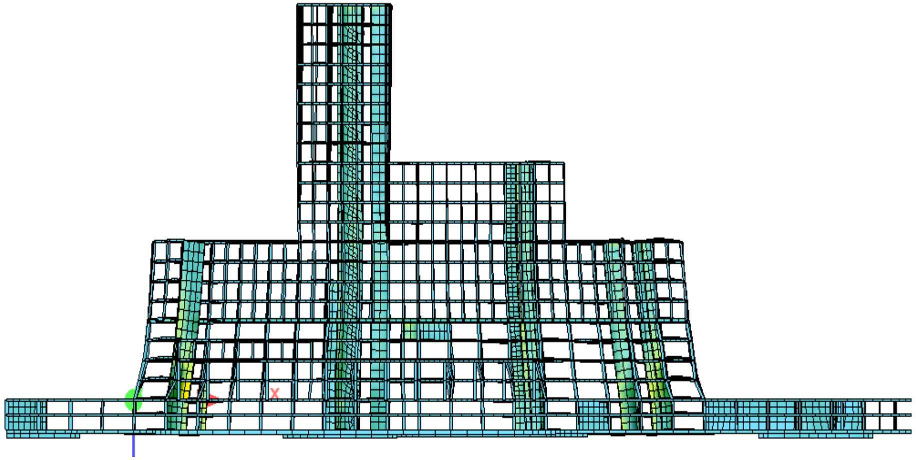


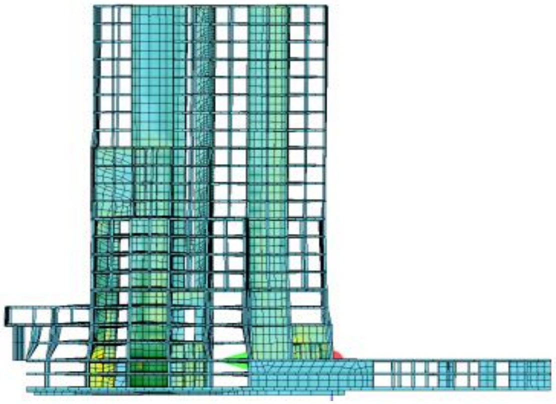


Hospital with 22 storeys
- ground slab ca. 225 m x 105 m with varying thickness
- retaining walls 8 m high in ground water
- 2 basement floors with areal dimensions as ground slab
- 20 floors above ground with decreasing size
- 13 irregularly penetrating building cores

Practical references

- jointless building construction : Hospital ZNA, Belgium
  - large slabs with strong interaction with irregularly situated cores

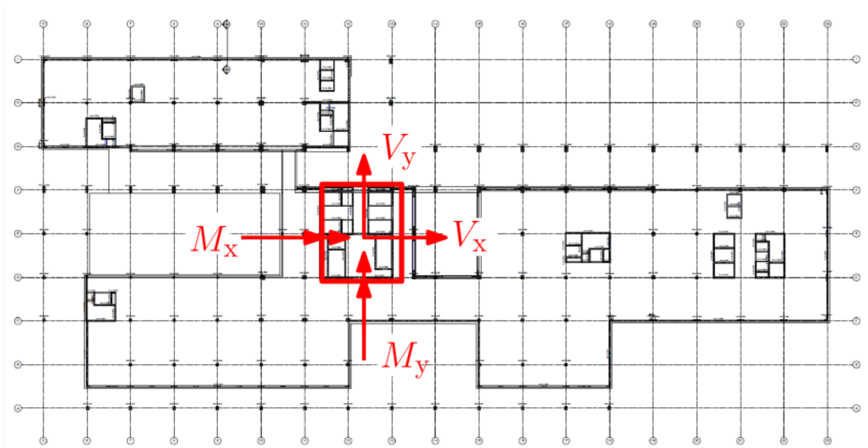


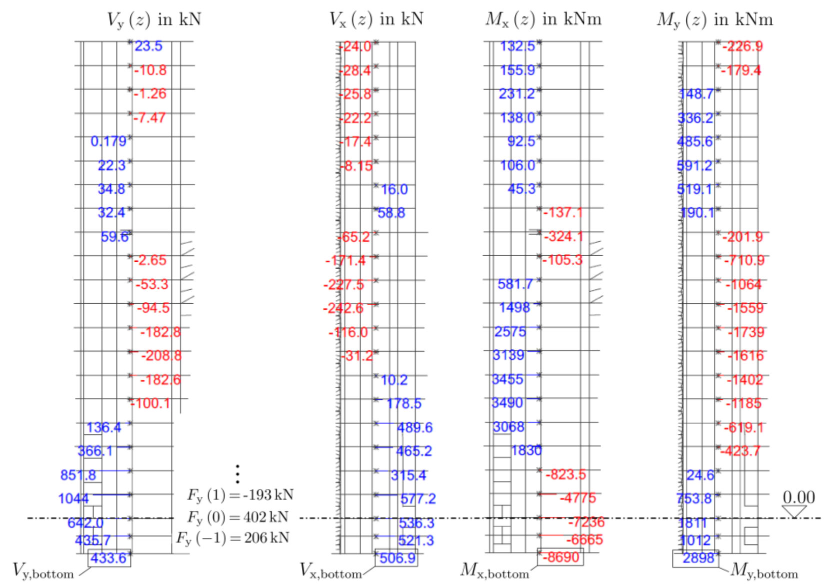


→ stressing of the cores to be determined with a 3D model taking into account axial as well as bending stiffness of the slabs after cracking

Practical references

- jointless building construction : Hospital ZNA, Belgium
  - large slabs with strong interaction with irregularly situated cores

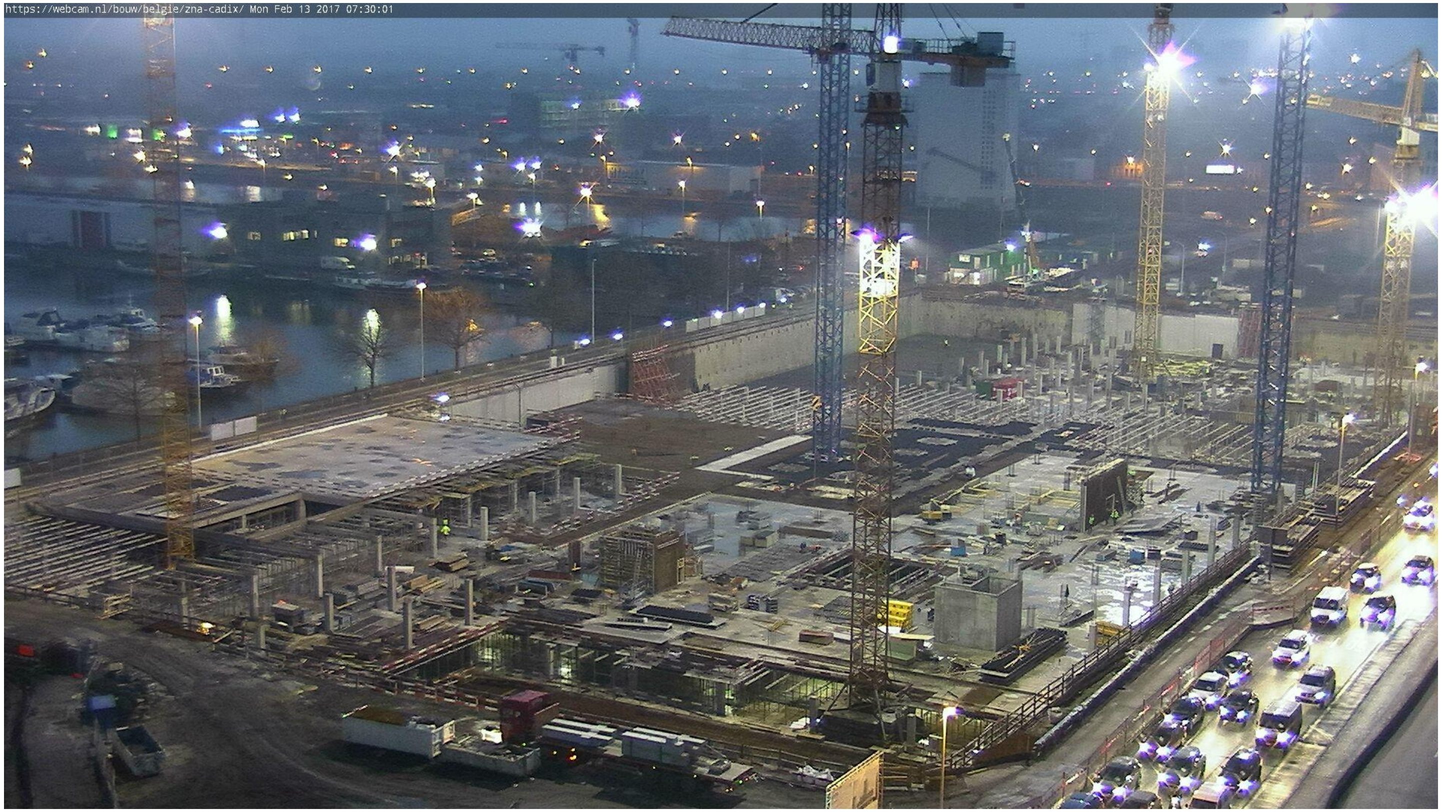




→ determination of final cutting forces for design of the cores by integration of stresses

Practical references

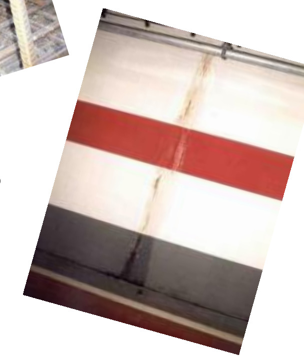
- jointless building construction : Hospital ZNA, Belgium
  - jointless ground slab and retaining walls



Conclusion

- EC2-1 regulations regarding restraint
  - minimum reinforcement according to cracking forces
    is a practicable safe side approach but included empiricism is either inefficient or in case of empiric modifications a risk for serviceability

vs.



- design on basis of deformation compatibility
  - basic principle **is mechanically consistent**
  - deformation-based design of members which are primarily restrained **enables cooperation between concrete technology, structural design and construction site leading to efficient reinforcement amounts AND jointless structures.**
  - deformation-based design of members under combined effect of loads and restraints **is possible and enables jointless constructions.**

- practical references: **very good feedback due to clarity of the procedure and possibility to proof it!**

References

- Schlicke, D. (2014), *Minimum reinforcement for restrained concrete members, PhD thesis*, Graz University of Technology, ISBN: 978-3-85125-473-0. (in German)

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- Schlicke, D., Tue, N. V., Klausen, A., Kanstad, T. and Bjøntegaard, Ø. (2014), *Structural analysis and crack assessment of restrained concrete walls – 3D FEM-simulation and crack assessment*, Proceedings of the 1st Concrete Innovation Conference, Oslo, Norway

- Turner, K. (2017), *An integrated approach to determination of minimum reinforcement for jointless hydraulic structures*, PhD thesis, Graz University of Technology

Closing remark

Please do not hesitate to contact us in case of any question or if you wish us to apply the presented approach to your project!

iBB Research group “Crack width control in restrained concrete”

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