Structural Design of Load-Bearing Fibre Concrete Structures

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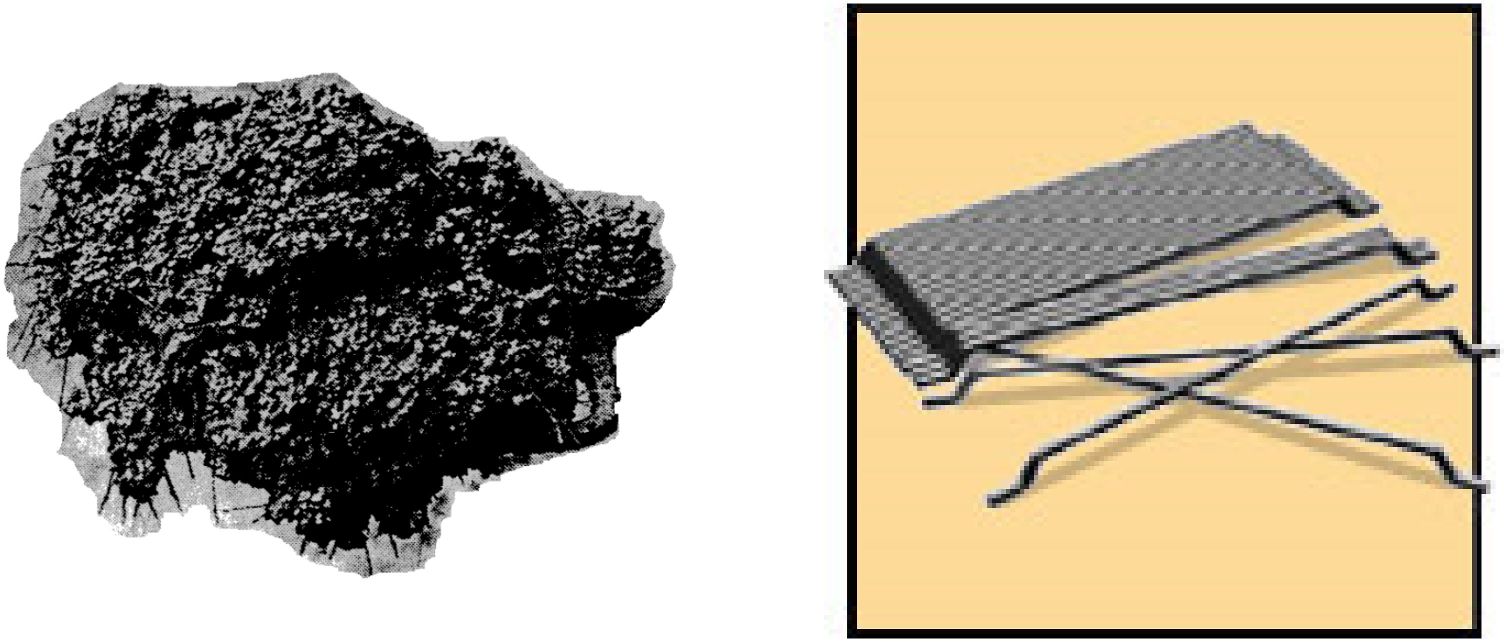
Fibre Concrete



Outline

- Historical background
- Swedish committee work
- Presentation of the new Swedish standard for designing fibre concrete structures
- Concluding remarks

Historical Background

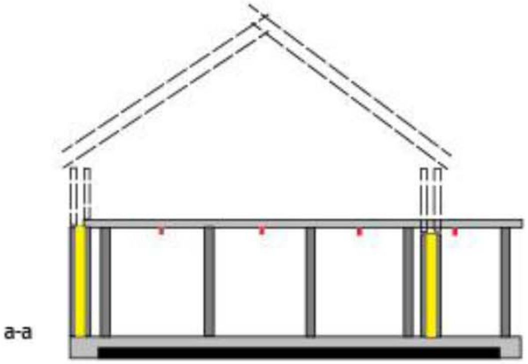
- Fibre concrete (FC) origins from the 19th century, there is an American patent from 1874.
- The modern development of FC started in USA in the mid 1950s.
- Swedish handbook on rock strengthening using shotcrete (Holmgren, 1992).
- Swedish report on steel fibre reinforced concrete (Svenska Betongföreningen, 1995).
- Swedish report on industrial concrete floors (including FC) (Svenska Betongföreningen, 2008).
- Swedish standard on design of FC structures (SIS, SS 812310:214, 2014).

Shotcrete for Rock Strengthening

Industrial Concrete Floors

Fraktarna, Stockholm, 2001. Foto J Hedebratt.

FC in Elevated Slabs



J Hedebratt, 2012

Swedish Committee Work

- Aim: Guidelines for designing load-carrying fibre concrete structures.
- Start: 2007.
- Original aim: Addition to the Swedish strucutral concrete handbook BBK 04.
- But Eurocode 2 was introduced in Sweden in 2009.
- New aim: Addition to Eurocode 2.
- Draft version: Summer 2013.
- Release of printed version: Spring 2014.

Introduction 1 (2)

- The aim of the standard is to provide Swedish national guidelines for designing load-carrying FC structures according to Eurocode 2.
- The standard uses the same headings and numbering as Eurocode 2.
- Repetitions have been avoided, why the standard has to be read parallel to Eurocode 2.
- The language of the standard is English.

Introduction 2 (2)

- On purpose, the committee selected the word *fibre concrete* instead of *steel fibre concrete* or *steel fibre reinforced concrete*.
- The idea is that the standard should be material-independent regarding fibre material.
- The standard authors are know that current synthetic fibres do provide rather modest performance if the fibre content is not enhanced substantially (which in turn may cause mixing & casting problems).

Aim

- The Standard applies to the design of buildings and other civil engineering works with steel or polymer fibres according to EN 14889-1 & EN 14889-2.
- The Standard does not cover glass, carbon, basalt or any other type of fibres.
- The Standard is intended to be used in conjunction with EN 1992-1-1 Eurocode 2 Design of concrete structures – Part 1-1 General rules & rules for buildings
- -1: Fibres for concrete - Part 1: Steel fibres – Definitions, specifications and conformity
- -2: Fibres for concrete - Part 2: Polymer fibres – Definitions, specifications and conformity

The Content is Connected to Eurocode 2

1 General

2 Bases of design

3 Materials

5 Structural analysis

6 Ultimate Limit State (ULS)

7 Serviceability Limit State (SLS)

8 Detailing of reinforcement and prestressing tendons – General

11 Lightweight aggregate concrete structures

Annexes

O. Calculations of strains & stresses in bending
P. Production & conformity control of fibre concrete
Q. Execution control of fibre concrete
R. Expected coefficient of variation for beam tests according to SS-EN 14651
S. Fibre concrete, statically indeterminate structures, and magnification factors

Definitions

English	Svenska	Kommentar
Fibre concrete	Fiberbetong	… the concrete matrix provides compressive strength & protection of the fibres whereas the fibres provide tensile strength …
Steel fibre	Stålfiber	SS-EN 14889-1
Polymer fibre	Polymerfiber	SS-EN 14889-2
Designed concrete	Betong med föreskrivna egenskaper	SS-EN 206
Prescribed concrete	Betong med föreskriven sammansättning	SS-EN 206

1.5.2

Basis of Design

- Structural components shall have structural system stability in ULS after a fully developed crack system though

1. Stress redistribution in statically indeterminate systems,
2. Combination of steel bar reinforcement or pre-tensioned steel reinforcement with fibre concrete.
3. External normal forces maintain equilibrium.

2.3.2.1

Shrinkage & Creep 1 (2)

- Shrinkage & creep shall be considered in ULS through

1. Stresses caused by restrained shrinkage & creep are superposed to mechanical stresses (theory of elasticity) or
2. Effects of shrinkage & creep are considered by increased ductility demand – in practice: design for $f_{R,3}$ instead of $f_{R,1}$ *or* for $f_{R,4}$ instead of $f_{R,2}$. (theory of plasticity).

2.3.2.2

Shrinkage & Creep 2 (2)

- In case of bending, distinguish between compressive creep & flexural creep.
- In case of *polymer fibre concrete*, long-term tests should be conducted (at elevated temperature if such temperature occurs in reality).

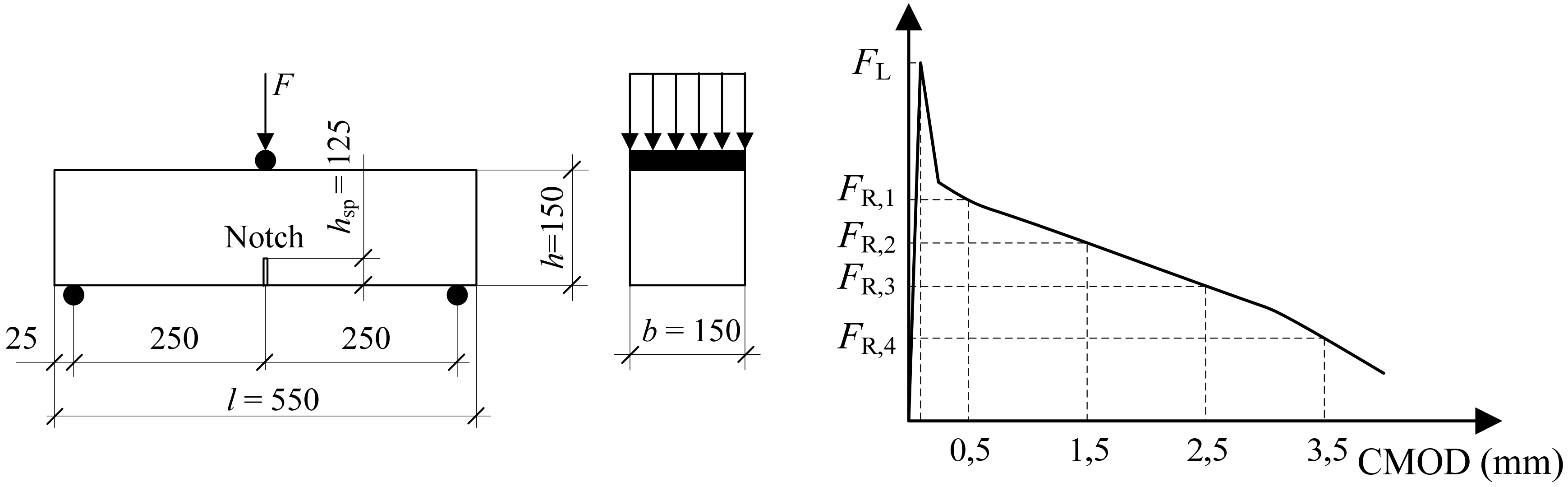
2.3.2.2

Partial Factors for Materials

Design situations	**γ_c for concrete**	**γ_s for reinforcing steel**	**γ_s for pre-stressing steel**	**γ_f for fibre concrete**
Persistent & transient	1,5	1,15	1,15	1,5
Exceptional	1,2	1,0	1,0	1,2
SLS	1,0	1,0	1,0	1,0

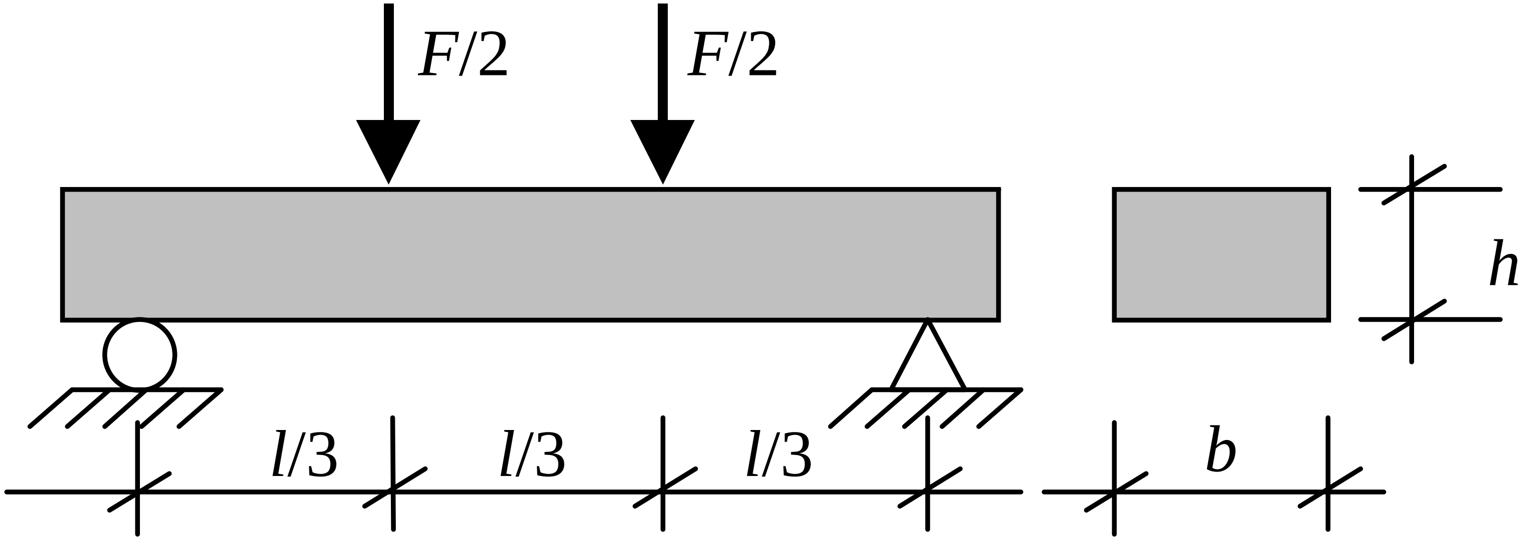
2.4.2.4

Testing Fibre Concrete



- 3 point bending tests on notched FC beams according to SS-EN 14651
- $f_{R,i} = (3/2)\cdot(F_{R,i}\cdot l)/(b_w\cdot h_{sp})$; $i = 1, 2, 3, 4$

Testing FC According to *Svenska Betongföreningen*

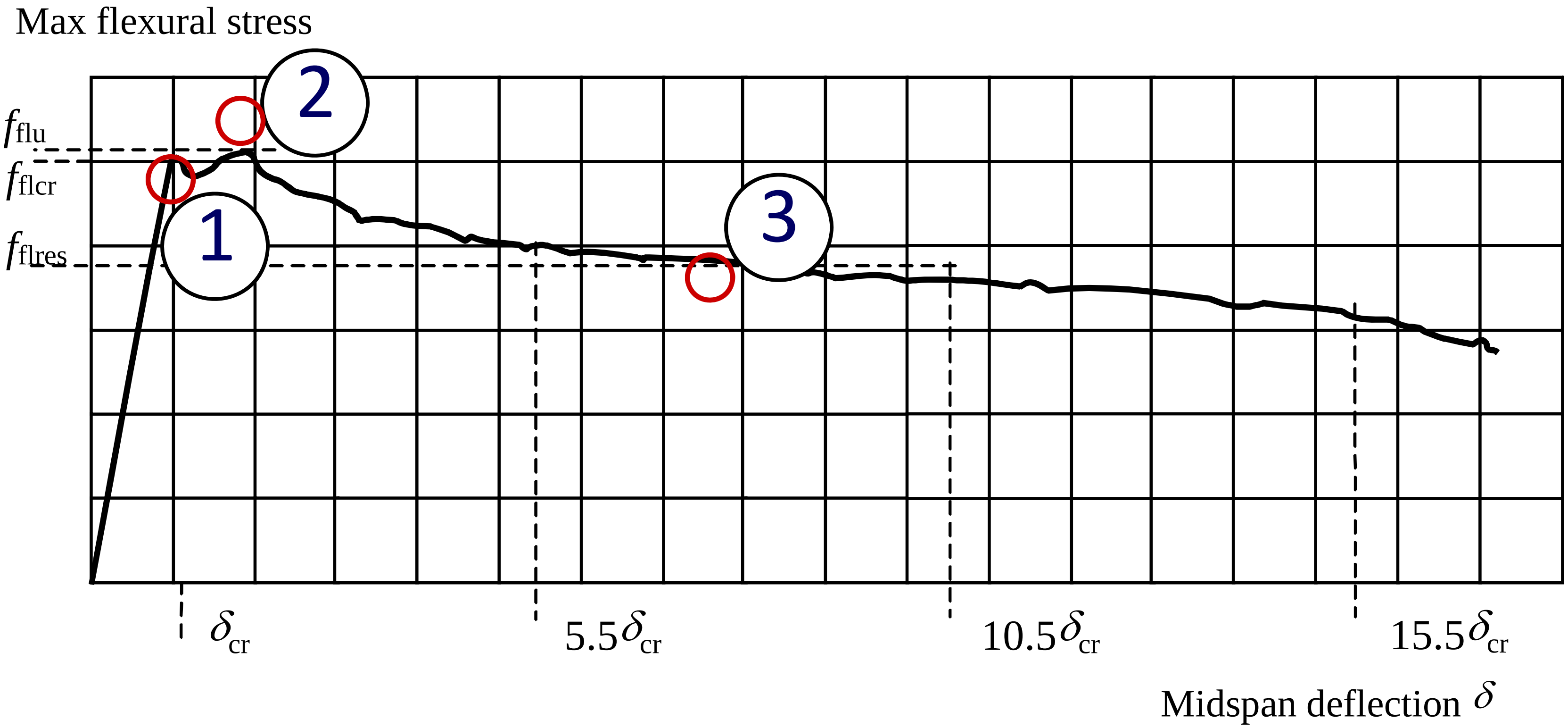


l = 450 mm, b = 125 mm, h = 75 mm

Flexural Tensile Strength According to *Svenska Betongföreningen*

(1) Cracking strength (3) Residual strength

(2) Ultimate strength



Residual Flexural Tensile Strength

- *Characteristic residual flexural tensile strength of fibre concrete* = characteristic value of the flexural tensile strength after cracking
- $f_{\mathrm{fl,res}} = R_{10,X} \cdot f_{\mathrm{fl,cr}}/100$; $X = 20, 30, 40, \ldots$

- Comparison between the international EN 14651 & the Swedish SBF test method:

- $f_{\mathrm{R,1}} \approx R_{10,20} \cdot f_{\mathrm{fl,cr}}/100$
- $f_{\mathrm{R,2}} \approx R_{10,30} \cdot f_{\mathrm{fl,cr}}/100$

Classifying Residual Flexural Tensile Strength 1 (3)

- Classes defined for all four levels of the residual flexural tensile strength $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ & $f_{R,4}$
- For everyone, six steps with the interval = 1,0 MPa.
- In total: 4×6 = 24 classes.
- Residual flexural tensile strength are determined thrugh beam testing according to SS-EN 14651 after 28 days.
- The classes are based on the characteristic value (lower 5 % fractile).

3.5.1

Classifying Residual Flexural Tensile Strength 2 (3)

Class R_1	**$f_{R,1}$**	**Class R_2**	**$f_{R,2}$**	**Class R_3**	**$f_{R,3}$**	**Class R_4**	**$f_{R,4}$**
	MPa		MPa		MPa		MPa
$R_1 1$	1.0	$R_2 1$	1.0	$R_3 1$	1.0	$R_4 1$	1.0
$R_1 2$	2.0	$R_2 2$	2.0	$R_3 2$	2.0	$R_4 2$	2.0
$R_1 3$	3.0	$R_2 3$	3.0	$R_3 3$	3.0	$R_4 3$	3.0
$R_1 4$	4.0	$R_2 4$	4.0	$R_3 4$	4.0	$R_4 4$	4.0
$R_1 5$	5.0	$R_2 5$	5.0	$R_3 5$	5.0	$R_4 5$	5.0
$R_1 6$	6.0	$R_2 6$	6.0	$R_3 6$	6.0	$R_4 6$	6.0

3.5.1

Classifying Residual Flexural Tensile Strength 3 (3)

Example of classifying:

- C30/37 – $R_1 3/R_3 2 \Rightarrow$
- Compressive strength = 30 MPa (cylinder)
- 37 MPa (cube)
- Residual flexural tensile strength = 3 MPa in class R_1
- Residual flexural tensile strength = 2 MPa in class R_3
- All values = characteristic values

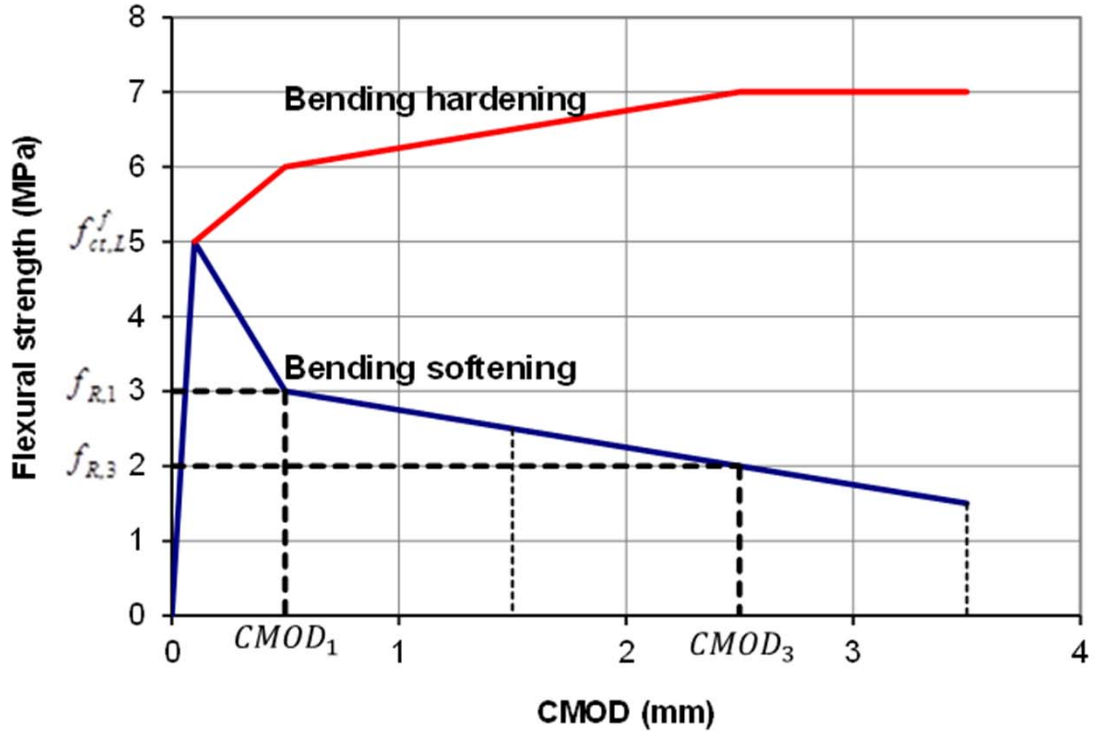
3.5.1

Prerequisite on Fibre Concrete

- $C_1 = 100 \times f_{R,1}/f_{ctk,0,05} \geq 50$ %
- $100 \times f_{R,3}/f_{R,1} \geq 50$ %
- The intention is to ensure a certain ductility of the fibre concrete.

3.5.1

Bending Hardening or Bending Softening?



3.5.1

Characteristic Residual Tensile Strength

$$f_{\mathrm{ft,R1}} = 0{,}45 \cdot f_{\mathrm{R,1}}$$

$$f_{\mathrm{ft,R3}} = 0{,}37 \cdot f_{\mathrm{R,3}}$$

3.5.1

Design Residual Tensile Strength

- Ultimate Limit State (ULS):

$$f_{\mathrm{ftd,R1}} = \eta_{\mathrm{f}} \cdot \eta_{\mathrm{det}} \cdot \frac{f_{\mathrm{ft,R1}}}{\gamma_{\mathrm{f}}} \qquad f_{\mathrm{ftd,R3}} = \eta_{\mathrm{f}} \cdot \eta_{\mathrm{det}} \cdot \frac{f_{\mathrm{ft,R3}}}{\gamma_{\mathrm{f}}}$$

- Serviceability Limit State (SLS):

$$f_{\mathrm{ftd,R1}} = \eta_{\mathrm{f}} \cdot \frac{f_{\mathrm{ft,R1}}}{\gamma_{\mathrm{f}}}$$

3.5.2

Fibre Orientation Factor η_f

- Factor considering the fibre orientation in the concrete.
- $\eta_f \geq 0,5$
- For horizontally cast concrete members, set η_f = 1,0 (width > 5×thickness).
- For other members, select $0,5 < \eta_f \leq 1,0$ dependent on member dimensions, fibre length, & casting procedure.
- For SLS, η_f = 1,0.

3.5.2

Factor Considering Degree of Statically Determination η_{det}

- Statically indeterminate structures provides possible stress redistribution. There are several cross sections to consider.
- The probability that several cross section have low strength is less than the probability for just one single low strength cross section (= the case for statically determinate structures).
- Slabs have considerably larger possibilities to stress redistribution than beams.
- Annex S is a background document for the tabled values.

3.5.2

Values of the Factor η_{det} 1 (3)

Case No	**Type of structural member**	η_{det}
1	Statically determinate beams	1
2	Statically indeterminate beams	1,4
3	Rectangular slabs with 2 opposite edges simply supported (others free)	1
4 a	Simply supported circular slabs	1,4

3.5.2

Values of the Factor η_{det} 2 (3)

Case No	Type of structural member	η_{det}
4 b	Rectangular slabs with ≥ 3 edges simply supported	1,4
5 a	Circular slabs with clamped edges	2
5 b	Rectangular slabs with ≥ 1 edge clamped (others simply supported)	2
5 c	Slabs-on-grade	2

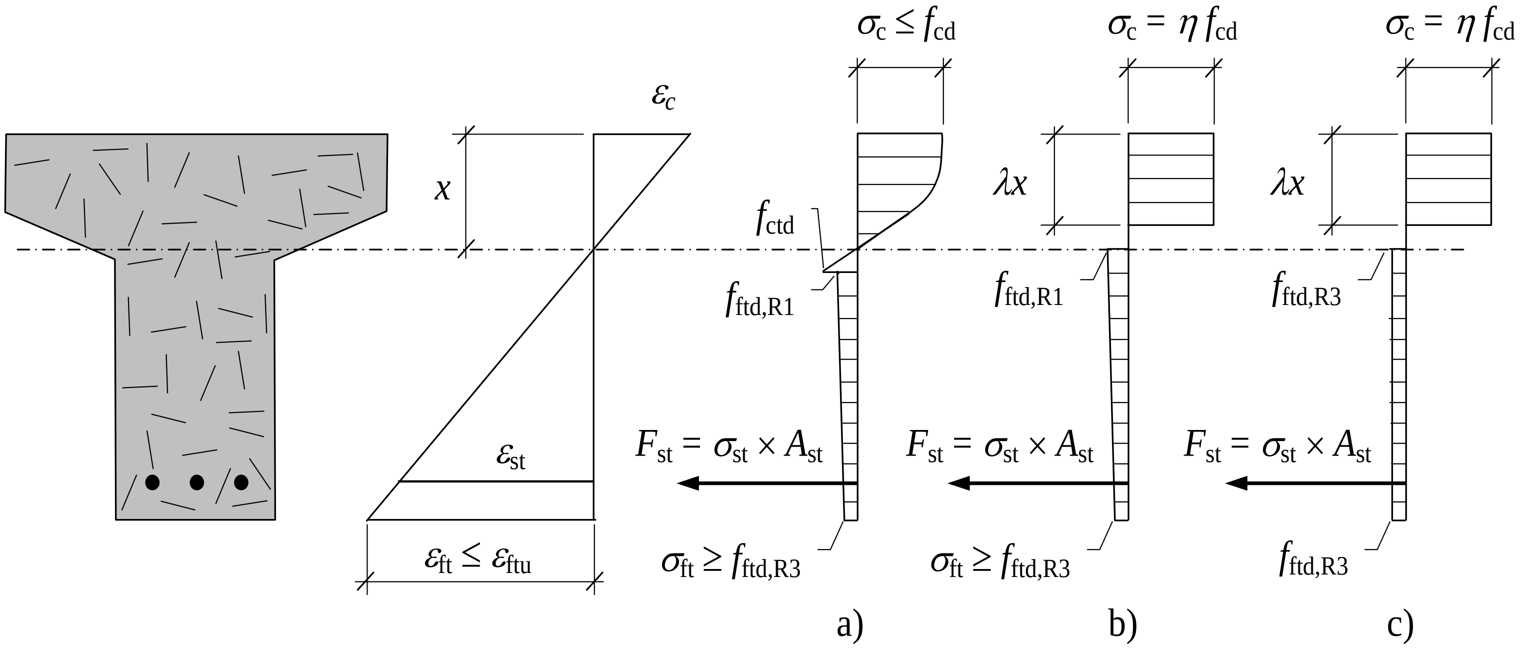
3.5.1

Values of the Factor η_{det} 3 (3)

Case No	Type of structural member	η_{det}
5 d	Interior spans of pile-supported slabs	2
5 e	Interior spans of column-supported slabs	2
5 f	Interior spans of simply supported continuous slabs	2

3.5.1

ULS – Bending Moment



a) General stress distribution

b) 1st simplified distribution

c) 2nd simplified distribution

$$\sigma_{ft} = f_{ftd,R1} - \frac{\varepsilon_{ft}}{\varepsilon_{ftud}}\left(f_{ftd,R1} - f_{ftd,R3}\right)$$

6.1

ULS – Shear

- In cases without shear reinforcement:

$$V_{\mathrm{Rd,cf}} = \left\{ \frac{0.18}{\gamma_{\mathrm{C}}} \cdot k \cdot \left[100 \cdot \rho \left(1 + \underbrace{7.5 \cdot \frac{f_{\mathrm{ct,R3}}}{f_{\mathrm{ctk}}}}_{\text{Fibre contribution}} \right) \cdot f_{\mathrm{ck}} \right]^{1/3} + 0.15 \cdot \sigma_{\mathrm{cp}} \right\} \cdot b_{\mathrm{w}} \cdot d$$

- Conventional reinforcement ρ is needed.
- Consciously choice of the committee (safe side).
- The equation is based on an Italian proposal that has been found to represent test data from the literature best (Mondo, 2011).

6.2.2

ULS – Punching

- In cases without shear reinforcement:

$$v_{\mathrm{Rd,cf}} = \frac{0{,}18}{\gamma_{\mathrm{C}}} \cdot k \cdot \left[100 \cdot \rho \left(1 + \underbrace{7{,}5 \cdot \frac{f_{\mathrm{ct,R3}}}{f_{\mathrm{ctk}}}}_{\text{Fibre contribution}} \right) \cdot f_{\mathrm{ck}} \right]^{1/3} + 0{,}15 \cdot \sigma_{\mathrm{cp}}$$

- For FC ground-supported slabs & column bases without conventional reinforcement:
- $v_{\mathrm{Rd,cf}} = v_{\mathrm{Rd,f}} = (k/2) \cdot C \cdot f_{\mathrm{R,3}} / \gamma_{\mathrm{f}}$
- k = thickness dependent factor in EC 2, 6.2.2
- C = constant = 0,45

6.4.4

Recommended Values of Max Crack Width w_{max} (mm)

Exposure class	L50	L100	Note
X0, XC1	-	-	Crack width does not influence durability.
XC2, XC3	0,5	0,4	
XC4	0,4	0,3	
XS1, XS2, XD1, XD2	0,3	0,2	
XS3, XD3	0,2	0,1	Combination with reinf. necessary.

The values deal with the case ”fibres only” considering durability.

7.3.1

Minimum Reinforcement

$$A_{\mathrm{s,min}} \cdot \sigma_{\mathrm{s}} = k_{\mathrm{c}} \cdot k \cdot (1 - k_{\mathrm{f}}) \cdot f_{\mathrm{ct,eff}} \cdot A_{\mathrm{ct}}$$

$$k_{\mathrm{f}} = \frac{f_{\mathrm{ftd,R1}}}{f_{\mathrm{ct\,m}}} \leq 1.0$$

7.3.2

Control of Cracking without Direct Calculation

$$\phi_{\mathrm{s,f}} = \phi_{\mathrm{s}} \cdot \frac{\sigma_{\mathrm{s}} \cdot A_{\mathrm{s}}/b}{4 \cdot (h-d) \cdot f_{\mathrm{ct,0}}} \cdot \frac{1}{(1-k_{\mathrm{f}})^2} \leq \phi_{\mathrm{s}} \frac{f_{\mathrm{ct,eff}}}{f_{\mathrm{ct,0}}} \cdot \frac{1}{(1-k_{\mathrm{f}})^2}$$

- $\phi_{\mathrm{s,f}}$ = modified bar reinforcement size for FC
- σ_{s} = steel stress according to EC 2, Table 7.2N
- A_{s} = tensile reinforcement area
- h = section height
- d = internal level arm for the bar reinforcement
- b = width of the tensile zone
- $f_{\mathrm{ct,0}}$ = 2,9 MPa

7.3.3

Computation of Crack Widths

- The calculation is based on the same principle as used for RC in EC 2.
- Calculate characteristic crack width w_k.
- Calculate strain difference (ε_{sm}-ε_{cm}) using one of two alternatives.
- Calculate max crack spacing $s_{r,max}$.
- Calculate max crack width at bending w_{max}.
- Calculate max crack width for restraint stresses w_{max}.

7.3.4

Minimum Reinforcement in Beams

- Minimum reinforcement:
- $A_{s,min} = A_c \cdot (k_c \cdot f_{ctm} - \eta_f \cdot \eta_{det} \cdot f_{ct,R3}) / f_{yk}$
- Condition for ”fibre only” cases:
- $\eta_f \cdot \eta_{det} \cdot f_{ct,R3} > k_c \cdot f_{ctm}$
- A_c = tensile concrete area (in bending), $h_{ct} = h/2$
- k_c = stress distribution coefficient (in bending)

9.2.1.1

Concluding Remarks

- Finally, there is a standard for designing load-bearing FC structures!
- The expectation is that this standard shall provide the structural engineers with an additional alternative.
- It is essential that the guidelines are solid and solidly supported by the society. New fibres are welcome but new fibre concretes have still to fulfil the requirement and the spirit of the guidelines.
- Do not put fibres against conventional reinforcement – combination is in many cases the optimal solution.