Steel Fibre Reinforced Concrete Structures

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Universitat Politècnica de Catalunya | Universidad Politécnica de Madrid | Universidad Politécnica de Valencia

EUROCODES

EN 1992

Design
of concrete
structures

2nd generation of Eurocode 2 on concrete structures

Madrid, October 17th, 2023

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Contents

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Design of Steel Fibre Reinforced Concrete Structures According to the Annex L of the Eurocode-2 2023

Diseño de estructuras de hormigón reforzado con fibras de acero según el Anejo L del nuevo Eurocódigo-2 2023

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[c] *Institute of Concrete Science and Technology ICITECH Universitat Politècnica de València.*

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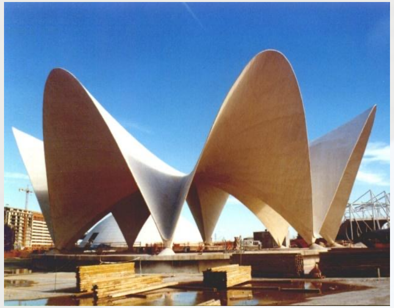
Introduction





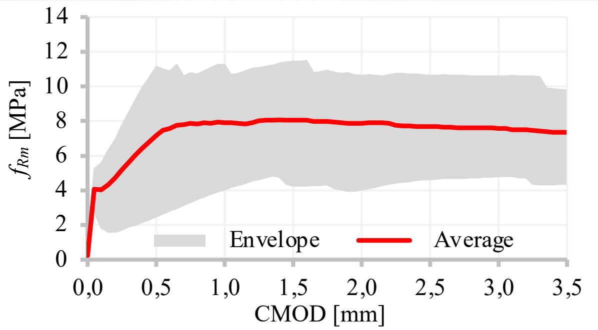

- FpEN 1992-1-1:2023 (Annex L) and 1992-1-2:2023 (Annex B)
- Annex L covers **steel fibre reinforced concrete** (EN 14889-1)
- **Informative** and each CEN member decides it status

Basis of design – Partial factors for materials

Annex L is fully aligned with the partial factor format of Eurocode 0

- **For compression** – neither f_c **nor its CoV are significantly affected by fibers**
- **For tension** – Although due to fibre distribution and orientation anisotropy **scatter in EN 14651 tests is 10–30%, combined use of $f_{R,k}$, κ_O, κ_G allows meeting target reliability levels**

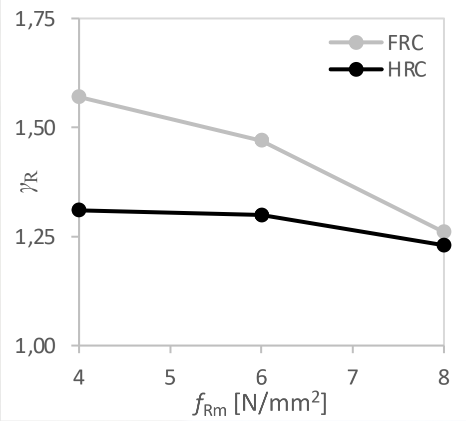
Design situations – Limit states	γ_{SF}
Persistent and transient design situations	1,50
Accidental design situations	1,20
Serviceability limit states	1,00



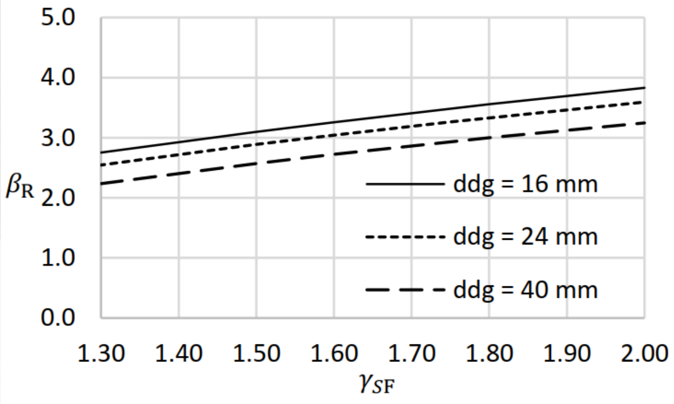
Basis of design – Partial factors for materials

Specific cases may require partial factor calibration. Some examples include

- **Use of FORM for γ_{SF}** calibration of precast tunnel linings, elements without shear reinforcement
- **Calibration of a global resistance factor for non-linear analysis** (Annex F) for full-scale flat slabs



Aidarov et al. (2021)



Tošić et al. (2021)

$$\gamma_R = e^{(\alpha_R \cdot \beta \cdot V_R)}$$

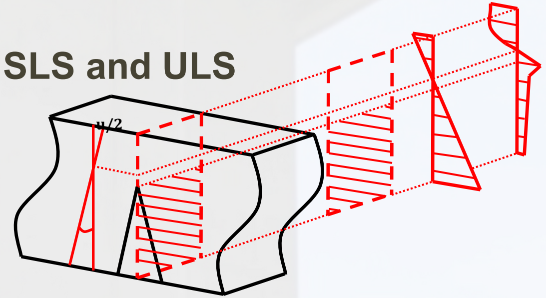
$$V_R = \frac{1}{1,65} ln\left(\frac{q_{Rm}}{q_{Rk}}\right)$$

ECOV (Cervenka 2013)

Material

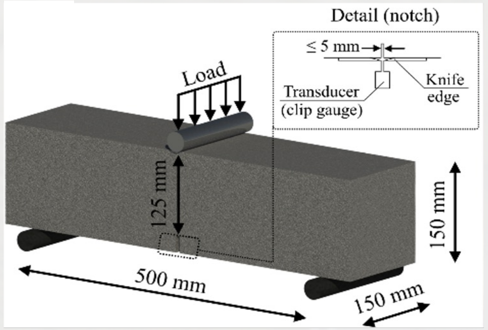
General aspects

- **Annex L refers to SF** meeting the EN 14889-1 as potential replacement of ordinary steel reinforcement
- **SF do not significantly modify the f_c, f_{ct}, E_c, ε_{cs}, φ_c (compression)**
- **SF provide residual tensile strength** (f_{Ft}) to cracked sections **in both SLS and ULS**

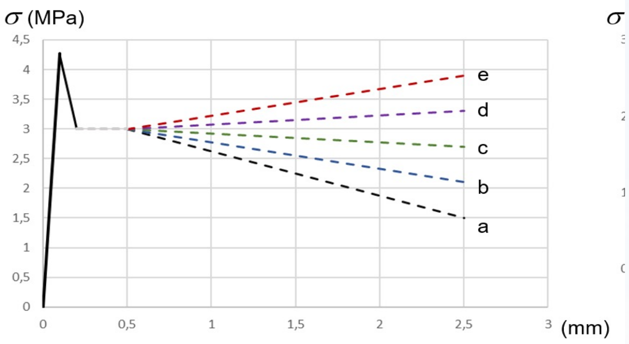


Stength and ductility classification

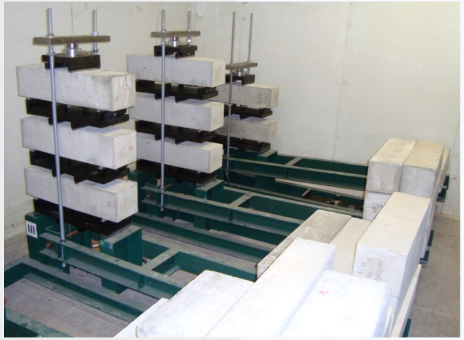
- **Strength Class (SC) based on $f_{R,1k}$ and ductility on $f_{R3,k}$/SC**



EN 14651:2005



Flexural stress vs CMOD (mm)



Llano-Torre et al. (2022)

Material

Design assumption for the material

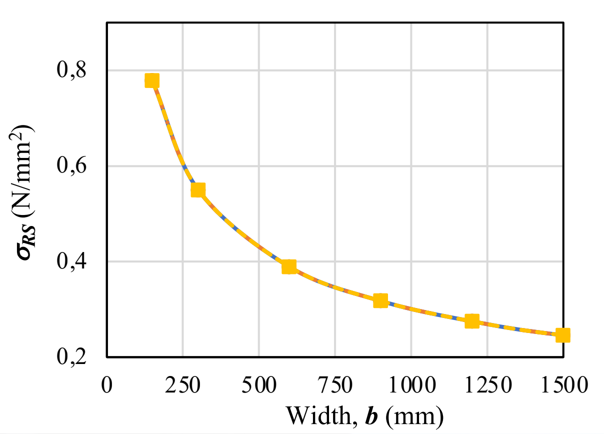
- $f_{R,1k}/f_{ctk;0.05} \geq 0.5$ (mínimum material ductility after cracking)
- Service (f_{Ftd}) and ultimate (f_{Ftud}) residual tensile strength of SFRC to be computed as:

$$f_{Ftsd} = \frac{f_{Fts,ef}}{\gamma_{SF}} = k_o \cdot k_G \cdot 0.37 \cdot \frac{f_{R1k}}{\gamma_{SF}} \qquad f_{Ftud} = \frac{f_{Ftu,ef}}{\gamma_{SF}} = k_o \cdot k_G \cdot 0.33 \cdot \frac{f_{R3k}}{\gamma_{SF}}$$

k_o: orientation factor ($f_{Ri,element}/f_{R,beam}$). k_o: = 0.5 unless verified by testing (< 1.7); k_o: = 1.0 for consistency classes S2-S5

k_G: factor to account for the member size (cracked area, A_{ct}); $k_G = 1.0 + 0.5A_{ct} \leq 1.5$

- Its is possible to consider up to 90% of f_{Rm}
- k_G = 1.0 for local mechanisms

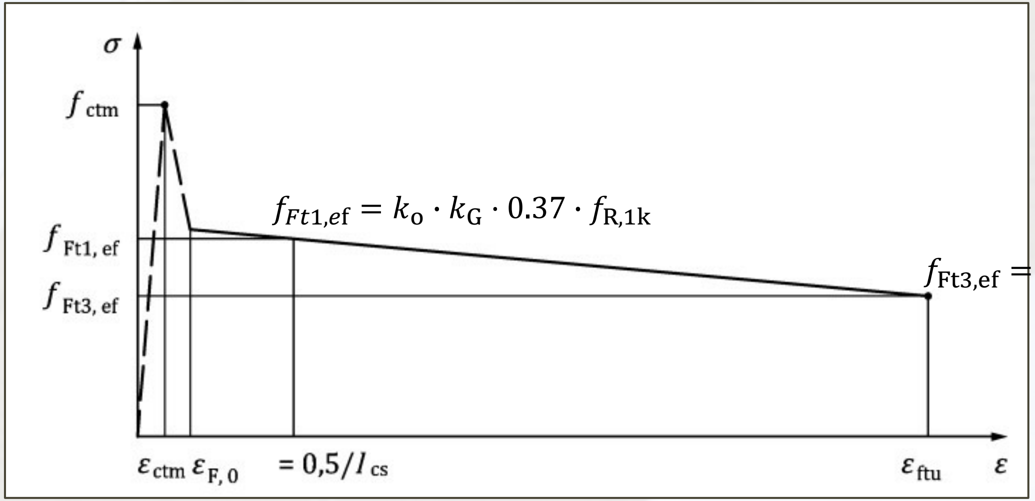


Material

Stress-strain relation for structural analysis

In tension

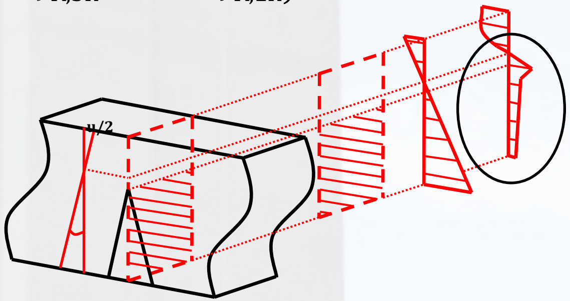
- a tri-linear constitutive law for the uniaxial stress-strain



$$f_{Ft1,ef} = k_o \cdot k_G \cdot 0.37 \cdot f_{R,1k}$$

$$f_{Ft3,ef} = k_o \cdot k_G \cdot (0.57 \cdot f_{R,3k} - 0.26 \cdot f_{R,1k})$$

l_{cs} structural characteristic length (it can be considered as a double factor considering size effect and synergy of the fibres and rebars contributions)



$$\varepsilon_{F,0} = 2 \cdot \varepsilon_{ctm} = 2 \cdot f_{ctm}/E_{cm}$$

$$\varepsilon_{Ftu} = \frac{w_u}{l_{cs}} \leq 2.5\frac{mm}{l_{cs}} < \varepsilon_{Ftud} = 0.02$$

Material

Stress-strain relation for structural analysis

In compression

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Disponible en www.hormigonyacero.com

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Compressive Behaviour of Steel-Fibre Reinforced Concrete in Annex L of New Eurocode 2

Comportamiento en compresión del hormigón reforzado con fibras de acero según el Anejo L del nuevo Eurocódigo 2

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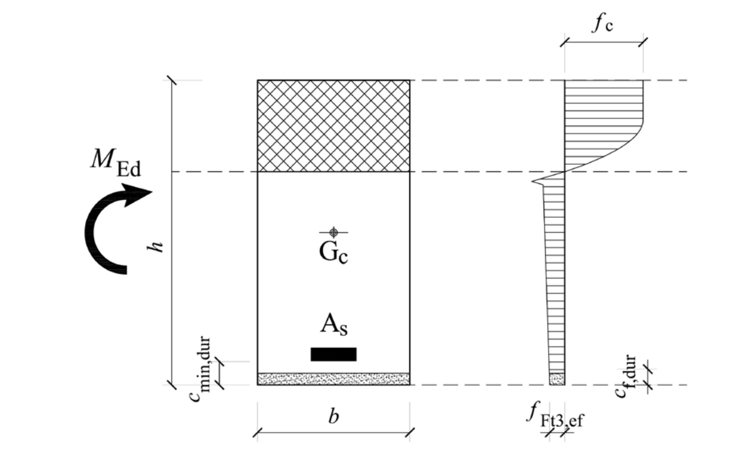
Durability – Minimum cover

Annex L approach is valid both for EC2 section 6 (XRC) or Annex P (current EC-2)

- Minimum cover due to durability requirements $c_{min,dur}$ **is only valid for embedded reinforcement**
- **Cover unaffected by fibers**, except to prevent fibre accumulation => c_{min} **= 20 mm**
- **Spalling due to corroded fibres is unlikely** – small stresses are generated due to small fibre size

SFRC elements considered as equivalent RC elements in terms of durability



1. SFRC under XC2–XC4, XD1–XD3, XS1–XS3 designed to be *uncracked* at SLS

In ULS, disregard tensile strength in a "sacrificial layer" of $c_{f,dur}$ = 10 mm from the exposed surface

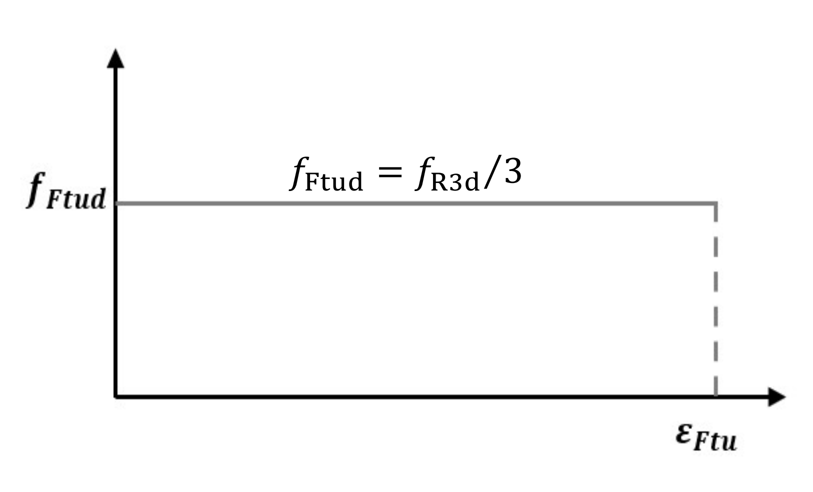
2. SFRC under XC2–XC4, XD1–XD3, XS1–XS3 designed to be *cracked* at SLS

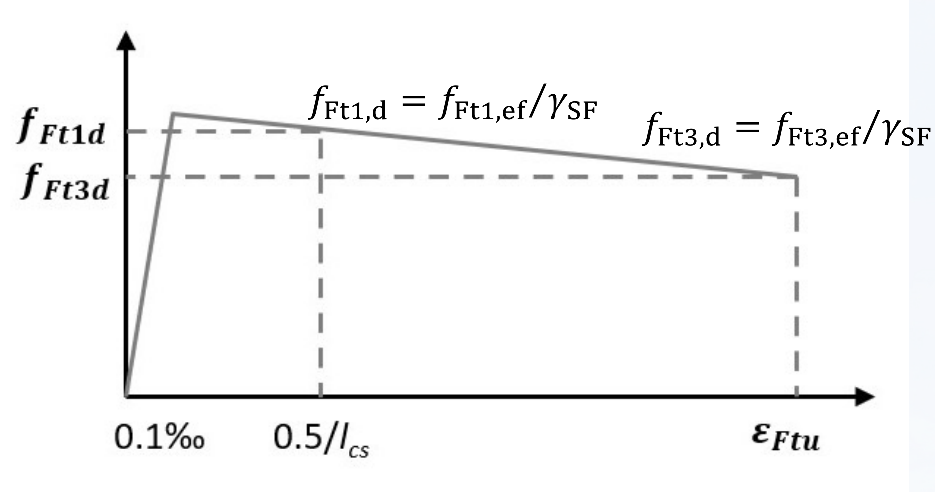
In ULS, disregard tensile strength in a "sacrificial layer" of $c_{f,dur} = k_{dur} \cdot c_{min,dur}$ mm from the exposed surface

A reduction of $c_{f,dur}$ is possible due to reduced crack widths in SFRC: $c_{f,dur} = k_{dur} \cdot c_{min,dur} \cdot \frac{w_{k,cal}}{w_{lim,cal}} \leq 10\ \text{mm}$

ELU: Bending with or without axial force

Two simplified stress–strain constitutive models: (1) rigid-plastic and (2) bi-linear

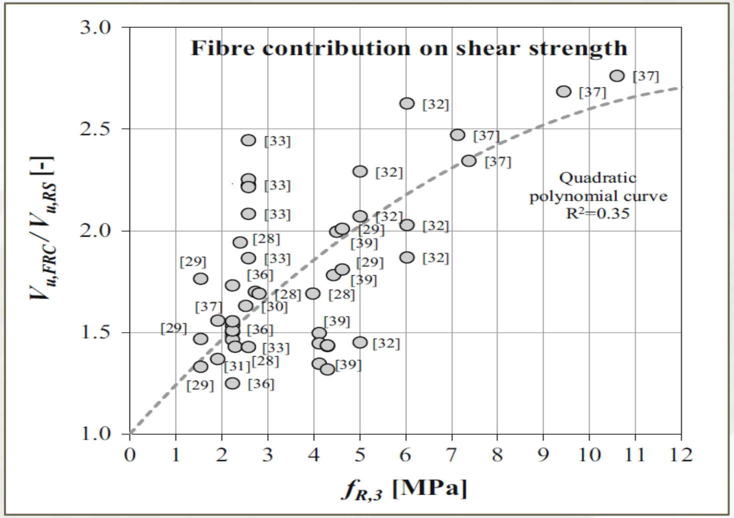




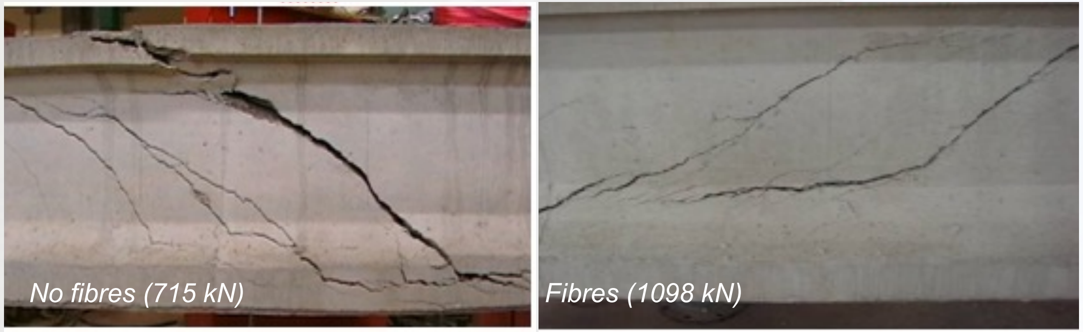
- The rigid-plastic has been proven to be reliable on large datasets (μ = 1.011; CoV = 8%)
- The rigid-plastic model should be used for ductility classes **a, b, c**; for **d, e** only to determine ULS capacity at ε_{FTud}.

ELU: Shear and Punching

- **The presence of SFs enhance the shear strength** due to:
  - ✓ **control the opening of inclined cracks** induced by shear stresses;
  - ✓ allow a **multiple and stable shear crack progression** delaying the formation of the critical shear crack
  - ✓ **improve the shear transfer across cracks** an the aggregate interlock capacity



Increase in shear strength due to the effect of fibres (Cuenca et al. (2018)).



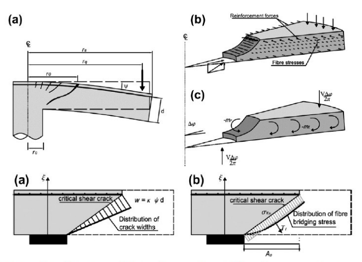
Cuenca and Serna (2013).

ELU: Shear and Punching

- Annex L approach for Shear
  - concrete contribution based on the formulation of **the Critical Shear Crack Theory** (CSCT)
  - **effect of fibres** described by an additional strength term $\boldsymbol{f_{Ftud}}$
  - **parameter $\boldsymbol{\eta_F}$ to express that the effect is not fully additive** to the concrete contribution

without stirrups: $\tau_{\mathrm{Rd,cF}} = \eta_{\mathrm{cF}} \cdot \tau_{\mathrm{Rd,c}} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}} \geq \eta_{\mathrm{cF}} \cdot \tau_{\mathrm{Rdc,min}} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}}$

with stirrups: $\tau_{\mathrm{Rd,sF}} = \left(\eta_{\mathrm{sw}} \cdot \rho_{\mathrm{w}} \cdot f_{\mathrm{ywd}} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}}\right) \cdot \cot\theta \ \geq \rho_{\mathrm{w}} \cdot f_{\mathrm{ywd}} \cdot \cot\theta$



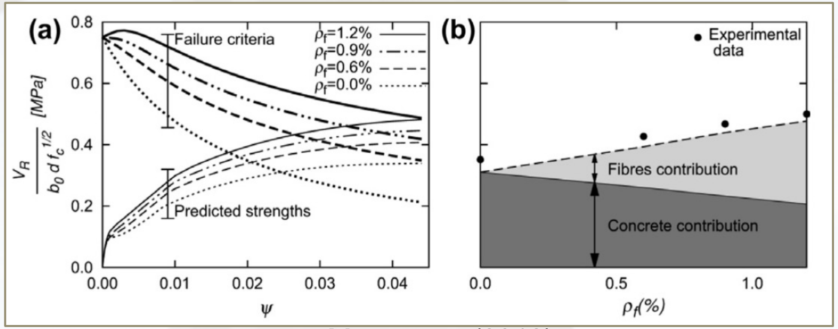
- Annex L for Punching (similar to Shear)
  - η_{F} = 0.4

without stirrups

$$\tau_{\mathrm{Rd,cF}} = \eta_c \cdot \tau_{\mathrm{Rd,c}} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}} \geq \eta_c \cdot \tau_{\mathrm{Rdc,min}} + \boldsymbol{f_{Ftud}}$$

with stirrups

$$\tau_{\mathrm{Rd,csF}} = \eta_c \cdot \tau_{\mathrm{Rd,c}} + \eta_s \cdot \rho_w \cdot f_{ywd} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}} \geq \rho_w \cdot f_{ywd} + \boldsymbol{\eta_{\mathrm{F}}} \cdot \boldsymbol{f_{\mathrm{Ftud}}}$$



Maya et al. (2012)

ELU: Torsion

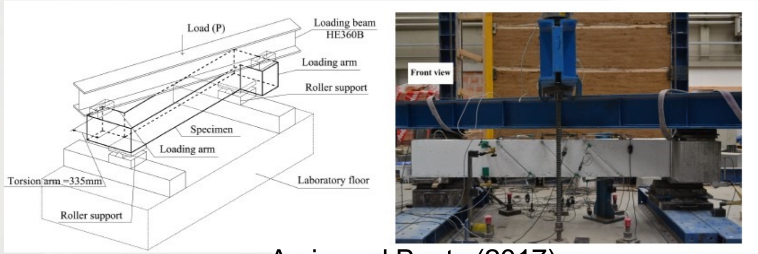
Torsion provisions follow the philosophy adopted for shear:

- **Fibres are considered as a smeared reinforcement**
- Reduction of the RC contribution (no full addition with the fibre contribution)
- Torsional capacities governed by yielding of either transverse or longitudinal reinforcement

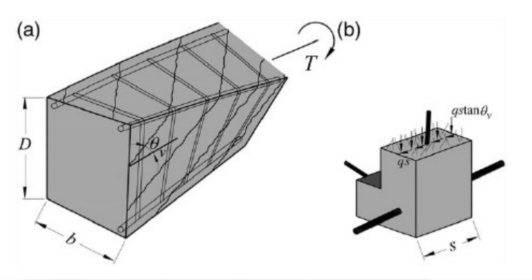
$$\tau_{\mathrm{t,Rd,swF}} = \eta_{\mathrm{sw}}\tau_{\mathrm{t,Rd,sw}} + \boldsymbol{\eta_{\mathrm{F}} f_{\mathrm{Ftud}}} \geq \tau_{\mathrm{t,Rd,sw}}$$

$$\tau_{\mathrm{t,Rd,slF}} = \eta_{\mathrm{sl}}\tau_{\mathrm{t,Rd,slF}} + \boldsymbol{\eta_{\mathrm{F}} f_{\mathrm{Ftud}}} \geq \tau_{\mathrm{t,Rd,}sl}$$

- For combinations of torsion + shear and/or bending, one of the following should be adopted:
  - the fibre contribution is used to resist only torsional effects
  - the fibre contribution is used to resist only shear and/or bending effects (disregarding the fibre contribution to resisting torsional effects)



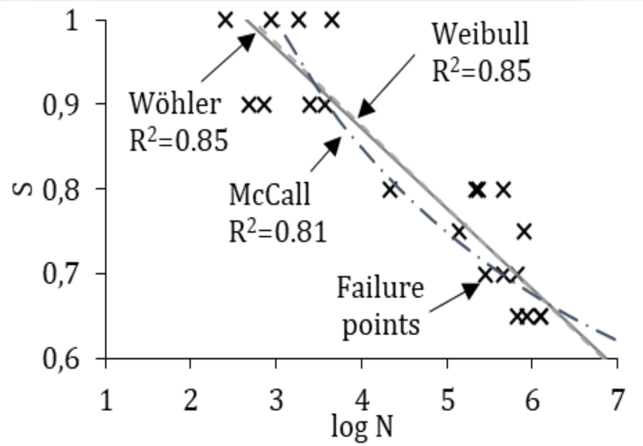
Amin and Bentz (2017)



Facconi et al. (2019)

ELU: FATIGUE

Contribution of FRC in fatigue resistance disregarded (due to divergences in literature)



- Tarifa *et al*., 2015 – Rail track slabs
- Domingo *et al*., 2023 – Segmental bridges
- Plizzari *et al*., 1997 – Uniaxial tension
- Saucedo *et al*., 2013 – Uniaxial compression
- ….

Carlesso *et al*. (2012)

Serviceability Limit States (SLS) – Crack control

Crack control is one of the most well-known and proven benefits of SFRC

- Same approach as for RC – $w_k = k_w \cdot \mathbf{S}_{\mathbf{r,m,cal}} \cdot (\boldsymbol{\varepsilon}_{\mathbf{sm}} - \varepsilon_{cm})$

Two cases are considered for SFRC

1. A multi-crack pattern associated to a presence of conventional reinforcement at a spacing ≤10Ø
2. A single-crack pattern when the spacing of conventional reinforcement is larger than 10Ø

- *In the first case*

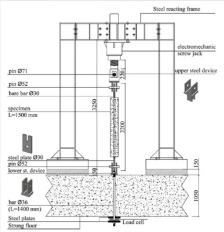
k_w = 1.7

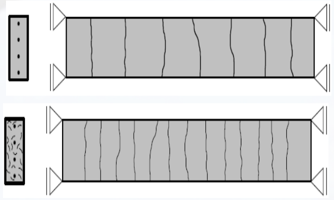
$$s_{\mathrm{r,m,cal,F}} = 1{,}5 \cdot c + \frac{k_{\mathrm{fl}} \cdot k_{\mathrm{b}}}{7{,}2} \cdot \frac{\emptyset}{\rho_{\mathrm{p,eff}}} \cdot (1 - \alpha_{\mathrm{f}}); \quad \alpha_{\mathrm{f}} = \frac{f_{\mathrm{Ft1,ef}}}{f_{\mathrm{ctm}}} \leq 1{,}0$$

- *In the second case*

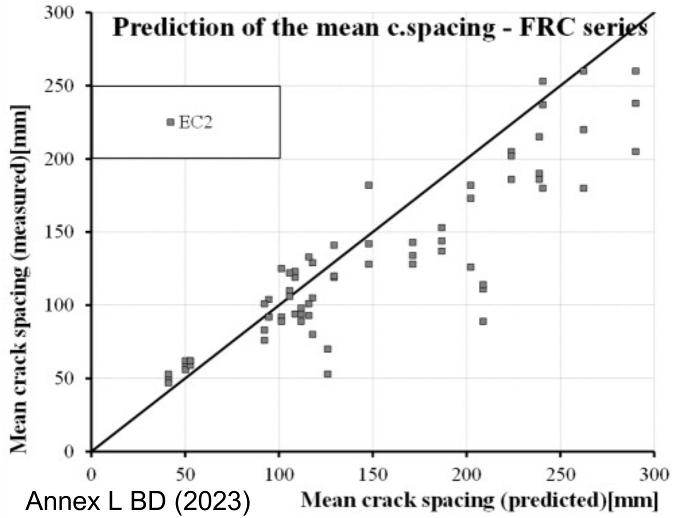
$\boldsymbol{k_w}$ = 1.3

$$s_{\mathrm{r,m,cal,F}} = h - x$$





Tiberti *et al.*, 2023

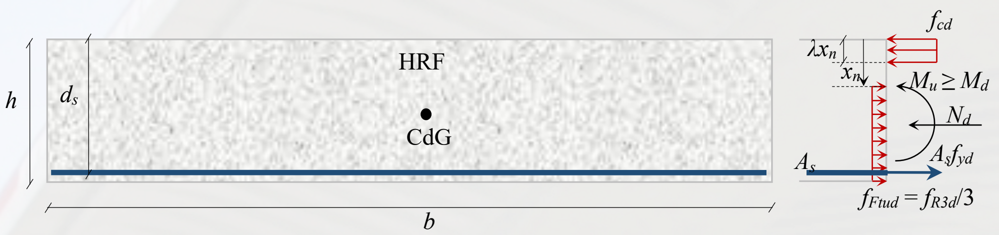


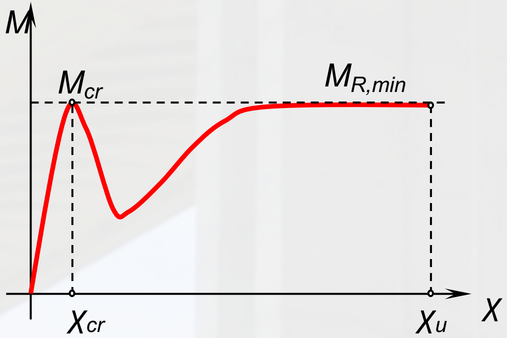
Annex L BD (2023)

Detailing of members and particular rules

Rules for mínimum reinforcement

- In ULS with M_{Ed} and N_{Ed} then $A_{s,min}$ from imposing $M_{R,min}(N_{Ed}) \geq M_{cr}(N_{Ed})$
- In ULS with M_{Ed} = 0 and N_{Ed} (pure tensión) then $A_{s,min}$ from imposing $N_{R,min} \geq N_{cr}$
- **BEAMS –per ductility – require $A_s \geq A_{s,min}$**





- In **ULS of Shear** $\rho_{Fw,min} \geq \rho_{w,min} - \dfrac{f_{Ftu,ef}}{f_{yk}} \geq 0$

$$M_{R,min}(\boldsymbol{f_{Ftud}}, \boldsymbol{A_{s,min}}) - M_{cr} = 0$$

- In **ULS of Torsion** $\rho_{Fw,min} \geq \rho_{w,min} - \dfrac{f_{Ftu,ef}}{f_{yk}} \geq 0.3\dfrac{f_{ctm}}{f_{yk}}$

  - **Shear and Torsion reinforcement can be replaced in BEAMS if $f_{Ftu,ef}/f_{yk} \geq \rho_{Fw,min}$**

Detailing of members and particular rules

Lightly reinforced SFRC structures ($A_s < A_{s,min}$)

- **May be only applied to statistically indeterminate structures** (elastically suported structures, piled slabs, shell-type components, precast containers, segmental linings)
- Linear elastic, plastic and non-linear analysis allowed
- For ULS shear $\tau_{\mathrm{Rd},cF} = \boldsymbol{f}_{\mathbf{Ftud}}$
- For foundations directly on ground SFRC 1b
- For foundation on piles SFRC 2c
- For tunnel lining segments SFRC 4c (if A_s = 0)

Conclusions

- The **first technical european harmonized** document realised by the CEN-TC250/SC2 **covering the design of FRC structures**

- **Covers the design of SFRC structures of any failure consequence class**

- **Is Informative** and each CEN member decides its status within the country

- **Allows for partial (or even total) replacement of the ordinary steel reinforcement** by steel fibres that meet the EN 14889-1

- Next steps: the **WG3 within the CEN-TC250/SC2** has started to **generate an harmonized guideline for covering the design of non-metallic fibre reinforced concrete structures**

Thank you for your attention