

Steel Fibre Reinforced Concrete Structures

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EUROCODES

EN 1992

Design
of concrete
structures

2nd generation of Eurocode 2 on concrete structures

Madrid, October 17th, 2023



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Disponible en www.hormigonyacero.com

Hormigón y Acero 2023; 74(299-300):169-186

<https://doi.org/10.33586/hya.2023.3124>

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

de la Fuente, A.^a, Monserrat-López, A.^{*,b}, Tošić, N.^a, Serna, P.^c

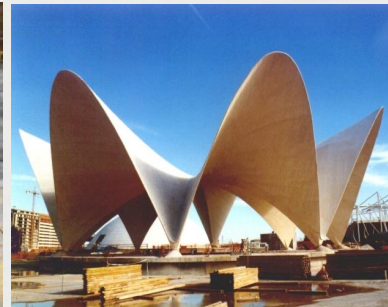
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Recibido el 20 de febrero de 2023; aceptado el 30 de marzo de 2023

Introduction



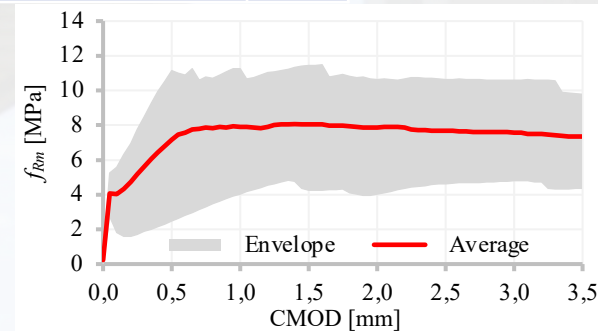
- FpEN 1992-1-1:2023 (Annex L) and 1992-1-2:2023 (Annex B)
- Annex L covers **steel fibre reinforced concrete** (EN 14889-1)
- **Informative** and each CEN member decides its status

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 $f_{R,k}$, K_O , K_G allows meeting target reliability levels

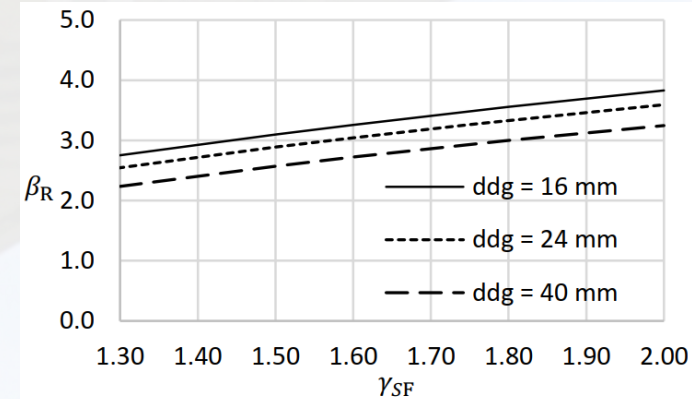
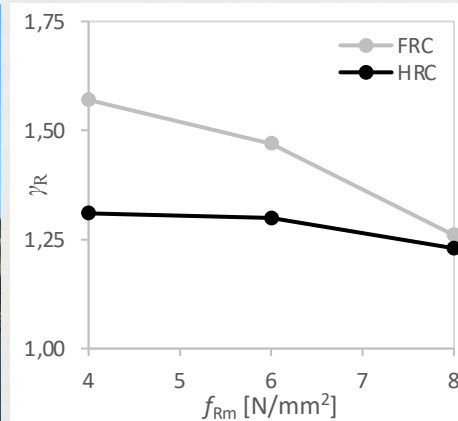
Design situations – Limit states	γ_{SF}
Persistent and transient design situations	1,50
Accidental design situations	1,20
Serviceability limit states	1,00



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)

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

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

ECOV (Cervenka 2013)

Tošić et al. (2021)

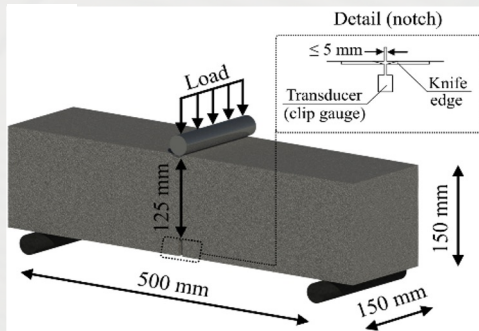
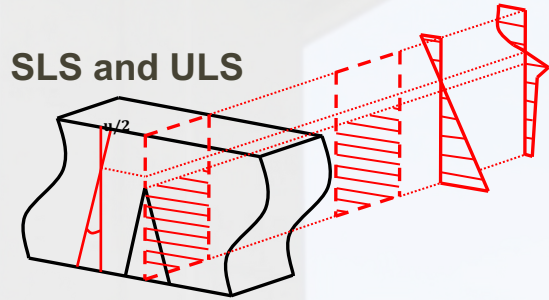
Material

General aspects

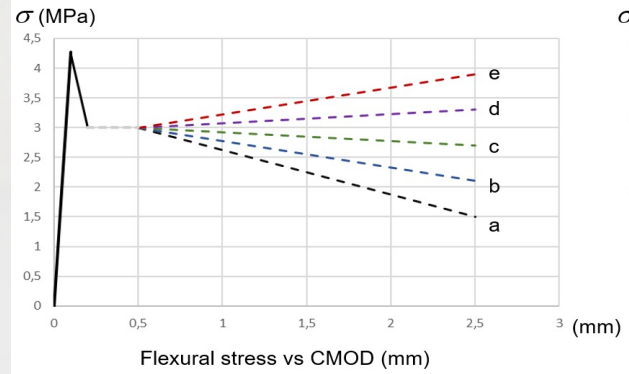
- Annex L refers to SF meeting the EN 14889-1 as potential replacement of ordinary steel reinforcement
- SF do not significantly modify the f_c , f_{ct} , E_c , ϵ_{cs} , φ_c (compression)
- SF provide residual tensile strength (f_{Ft}) to cracked sections in both SLS and ULS

Strength and ductility classification

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



EN 14651:2005



Llano-Torre et al. (2022)



Material

Design assumption for the material

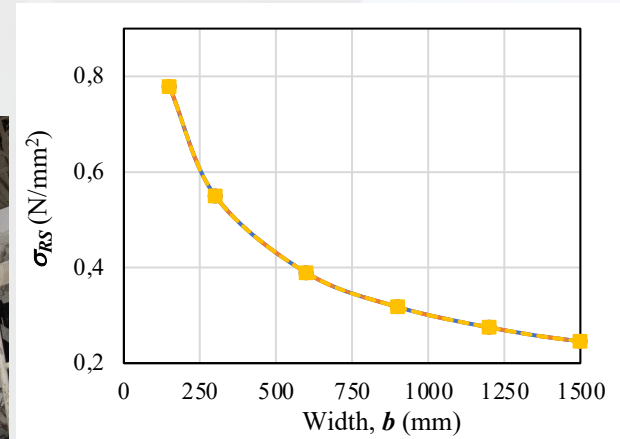
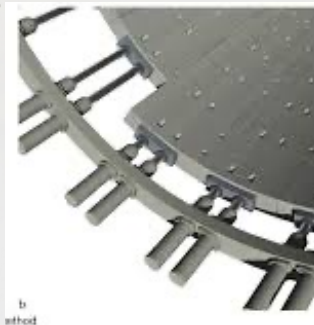
- $f_{R,1k}/f_{ctk;0.05} \geq 0.5$ (minimum material ductility after cracking)
- Service (f_{Ftd}) and ultimate (f_{Ftud}) residual tensile strength of SFRC to be computed as:

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

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

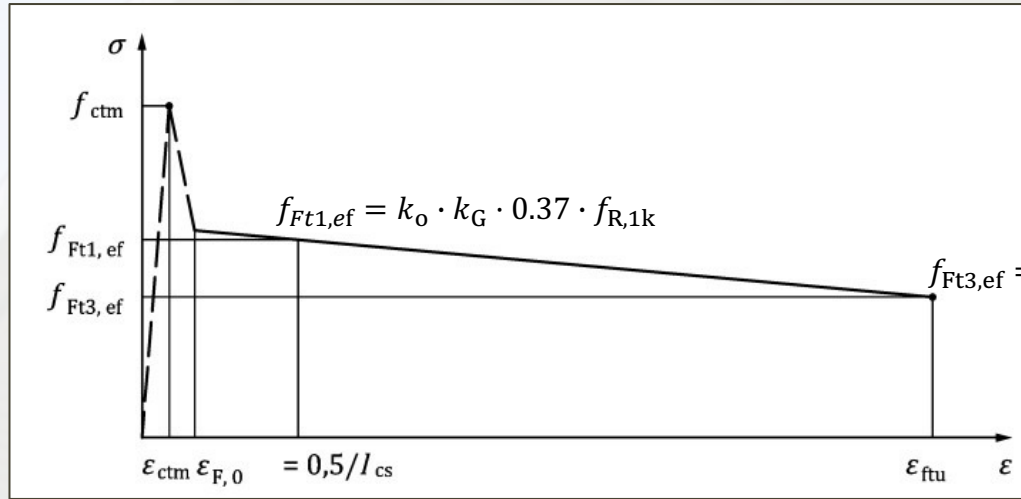


Material

Stress-strain relation for structural analysis

In tension

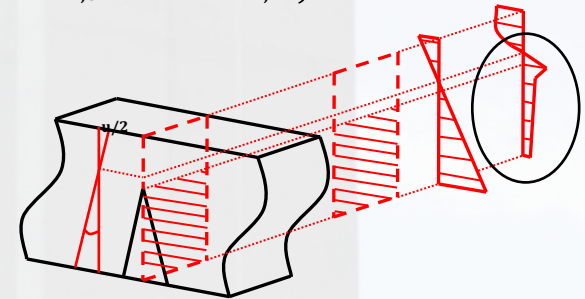
- a tri-linear constitutive law for the uniaxial stress-strain



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

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

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



Stress-strain relation for structural analysis

In compression



Disponible en www.hormigonyacero.com

Hormigón y Acero 2023; 74(299-300):187-198

<https://doi.org/10.33586/hya.2022.3092>

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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Recibido el 15 de julio de 2022, aceptado el 8 de diciembre de 2022

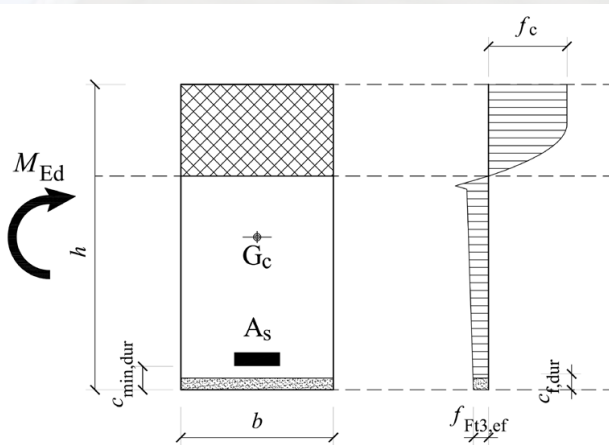


Durability – Minimum cover

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

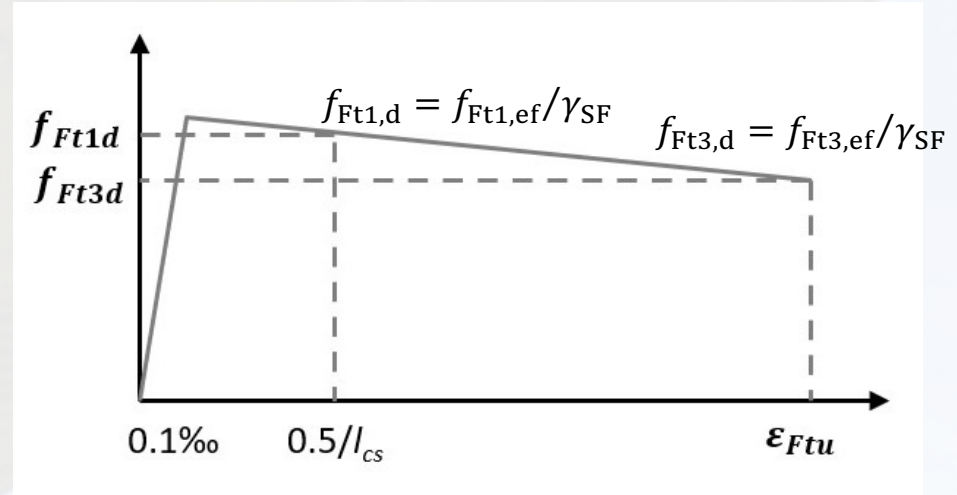
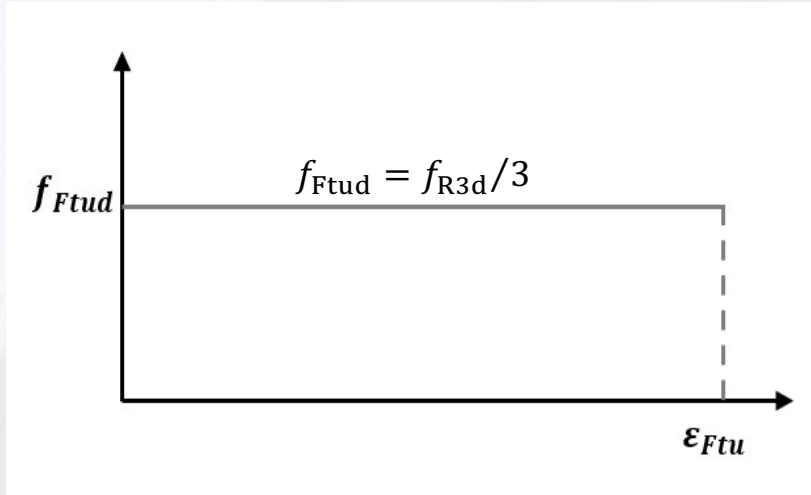
2. SFRC under XC2–XC4, XD1–XD3, XS1–XS3 designed to be *cracked* at SLS

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

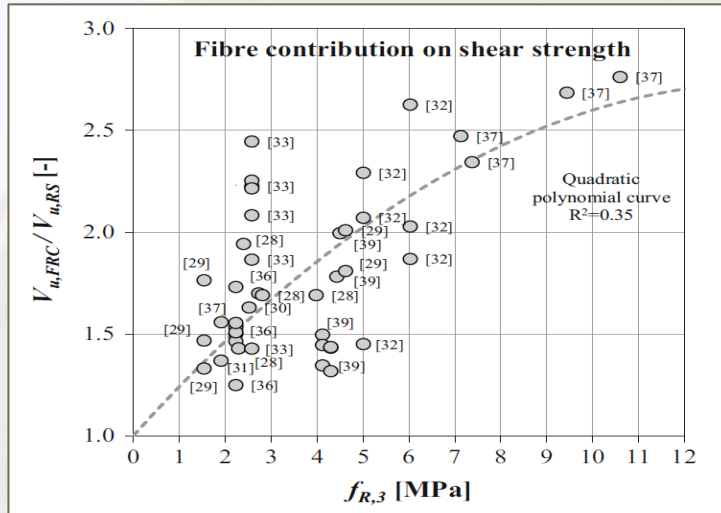
Two simplified stress–strain constitutive models: (1) rigid-plastic and (2) bi-linear



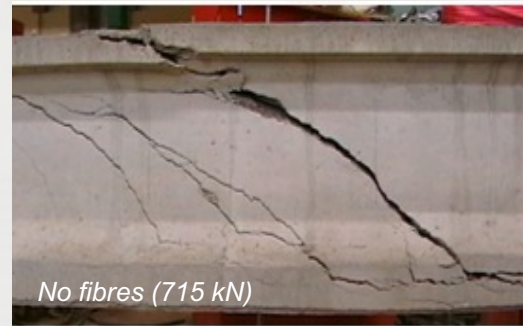
- The rigid-plastic has been proven to be reliable on large datasets ($\mu = 1.011$; $\text{CoV} = 8\%$)
- The rigid-plastic model should be used for ductility classes **a**, **b**, **c**; for **d**, **e** only to determine ULS capacity at ϵ_{Ftud} .

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 and the aggregate interlock capacity



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



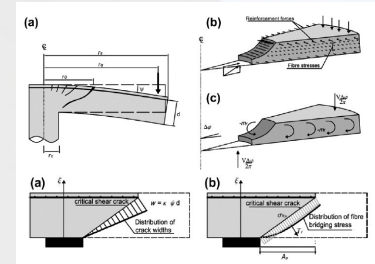
Cuenca and Serna (2013).

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 f_{Ftud}
 - parameter η_F** to express that the effect is not fully additive to the concrete contribution

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

with stirrups: $\tau_{Rd,sF} = (\eta_{sw} \cdot \rho_w \cdot f_{ywd} + \eta_F \cdot f_{Ftud}) \cdot \cot \theta \geq \rho_w \cdot f_{ywd} \cdot \cot \theta$



- Annex L for Punching (similar to Shear)

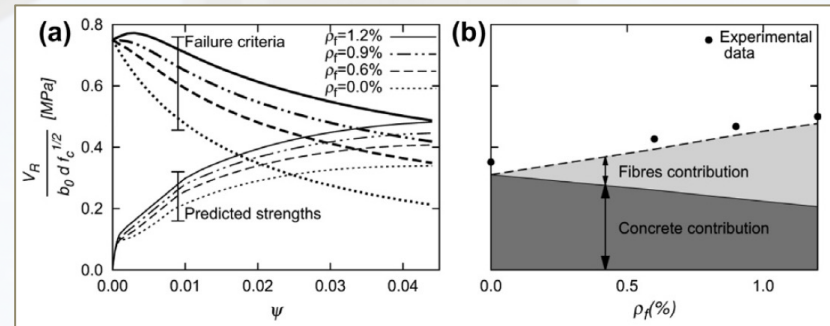
- $\eta_F = 0.4$

without stirrups

$$\tau_{Rd,cF} = \eta_c \cdot \tau_{Rd,c} + \eta_F \cdot f_{Ftud} \geq \eta_c \cdot \tau_{Rd,c,min} + f_{Ftud}$$

with stirrups

$$\tau_{Rd,csF} = \eta_c \cdot \tau_{Rd,c} + \eta_s \cdot \rho_w \cdot f_{ywd} + \eta_F \cdot f_{Ftud} \geq \rho_w \cdot f_{ywd} + \eta_F \cdot f_{Ftud}$$



Maya et al. (2012)



ELU: Torsion

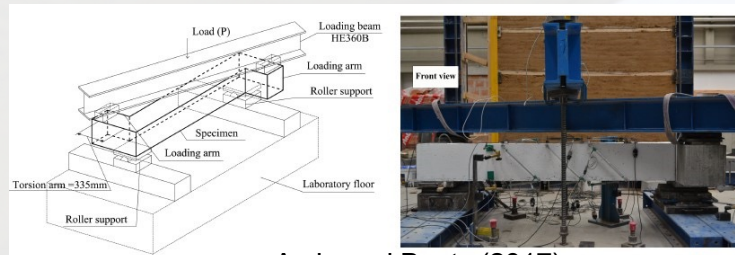
Torsion provisions follow the philosophy adopted for shear:

- **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

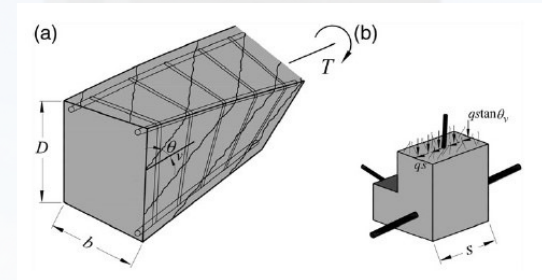
$$\tau_{t,Rd,swF} = \eta_{sw} \tau_{t,Rd,sw} + \eta_F f_{tud} \geq \tau_{t,Rd,sw}$$

$$\tau_{t,Rd,sIF} = \eta_{sl} \tau_{t,Rd,sIF} + \eta_F f_{tud} \geq \tau_{t,Rd,sl}$$

- 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)



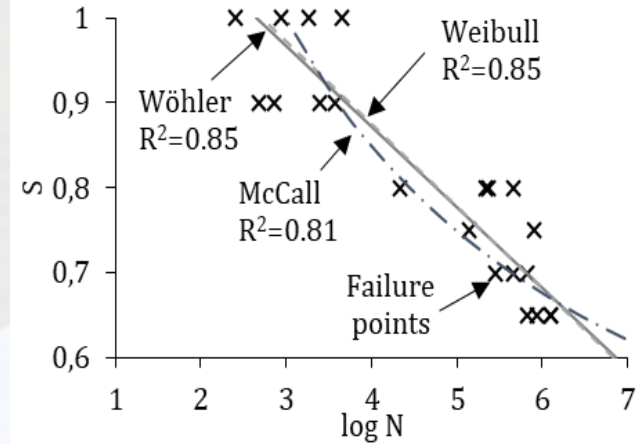
Amin and Bentz (2017)



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 – $w_k = k_w \cdot S_{r,m,cal} \cdot (\epsilon_{sm} - \epsilon_{cm})$

Two cases are considered for SFRC

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

- *In the first case*

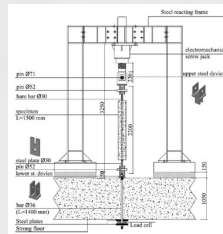
$$k_w = 1.7$$

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

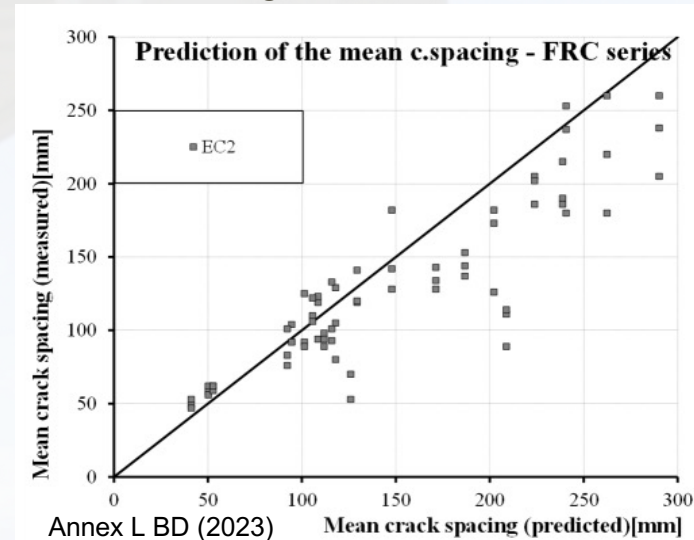
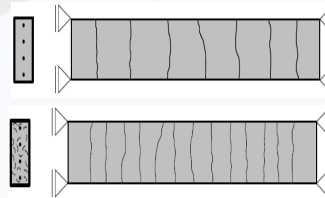
- *In the second case*

$$k_w = 1.3$$

$$S_{r,m,cal,F} = h - x$$



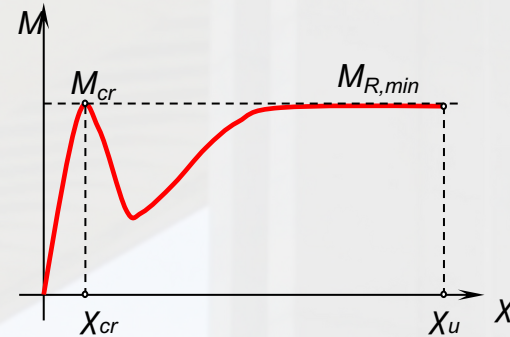
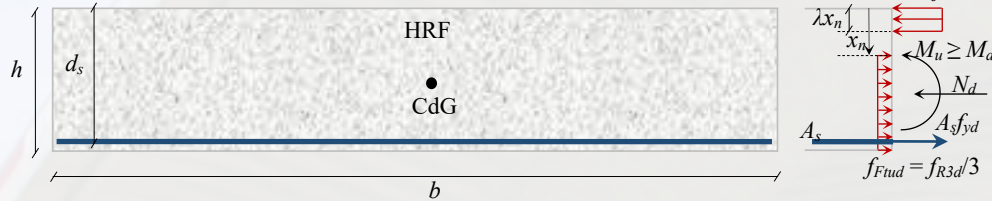
Tiberti *et al.*, 2023



Detailing of members and particular rules

Rules for minimum 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 $\rho_{Fw,min} \geq \rho_{w,min} - \frac{f_{Ftu,ef}}{f_{yk}} \geq 0$
- In ULS of Torsion $\rho_{Fw,min} \geq \rho_{w,min} - \frac{f_{Ftu,ef}}{f_{yk}} \geq 0.3 \frac{f_{ctm}}{f_{yk}}$

- 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 supported structures, piled slabs, shell-type components, precast containers, segmental linings)
- Linear elastic, plastic and non-linear analysis allowed
- For ULS shear $\tau_{Rd,CF} = f_{ttd}$
- 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