fib Model Code 2020
Shear and punching provisions,
needs for improvements with respect to new and existing structures

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Workshop *fib*
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Development of CEB – FIP – *fib* Model Codes

UNESCO International Code (joint project CEB + ACI)

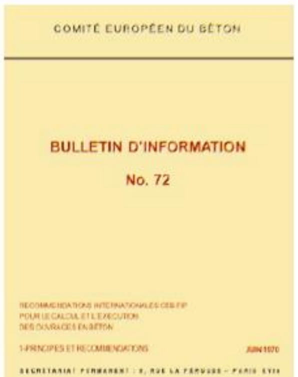
Several national codes

ENV 1992-1-1:1991
NBR 6118:1980

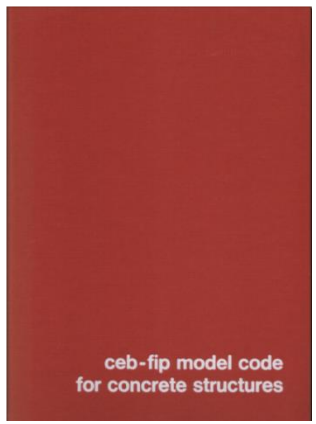
EN 1992-1-1:2004
NBR 6118:2003, 2014
SIA 262:2003

EN 1992-1-1:2023 ?
SIA 262:2013

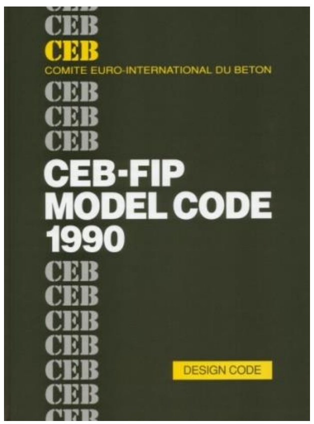
1964



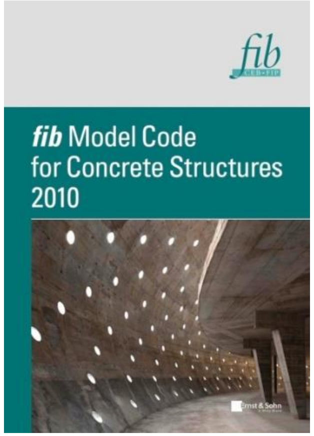
1970



1978



1990



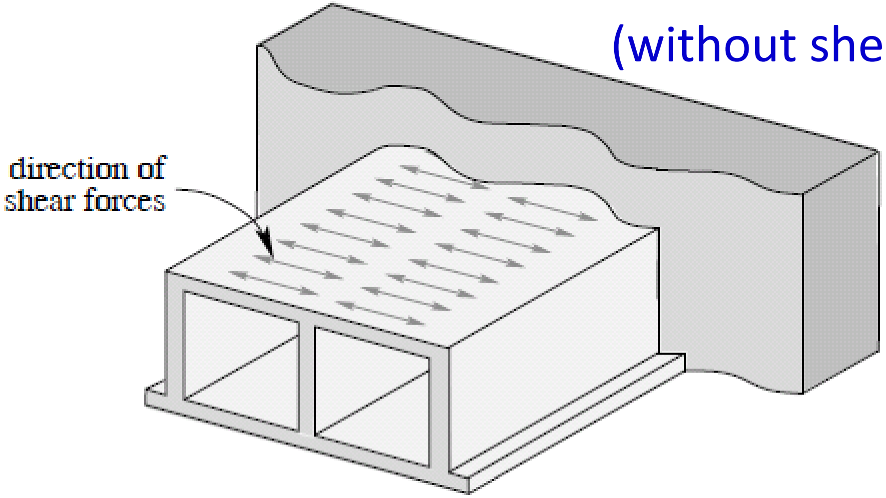
2010

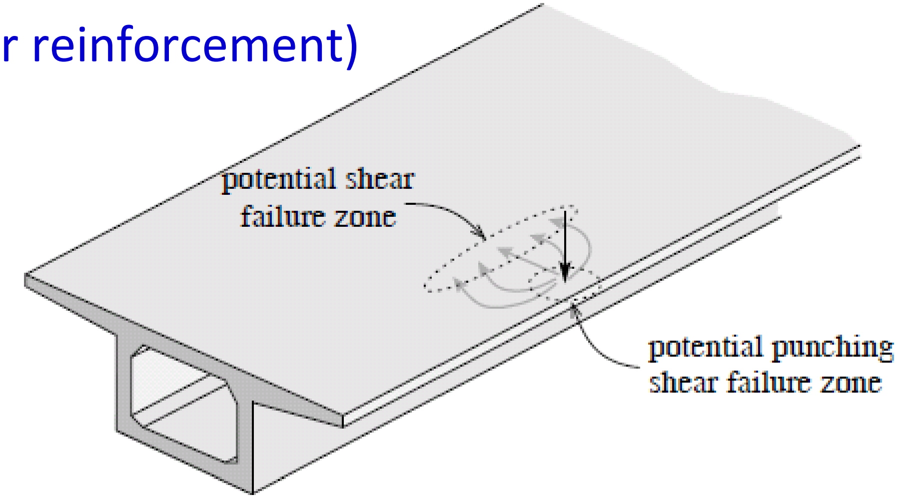
2020

Introduction: shear aand punching shear

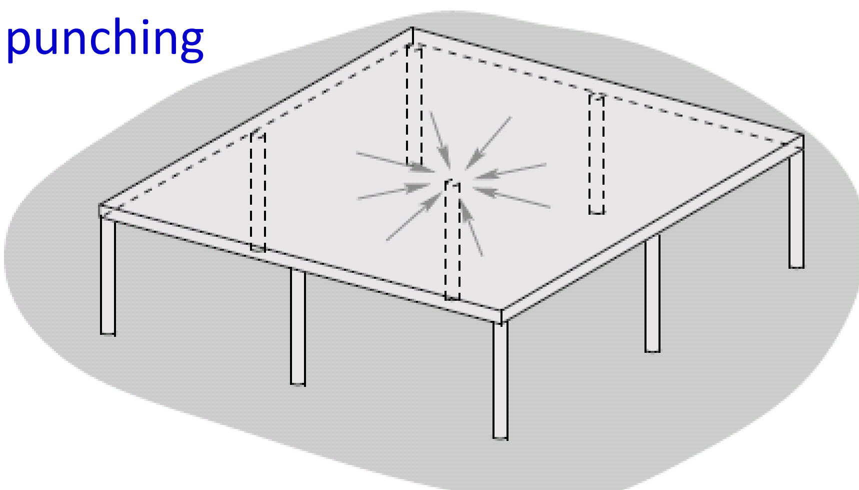
2) shear in slabs

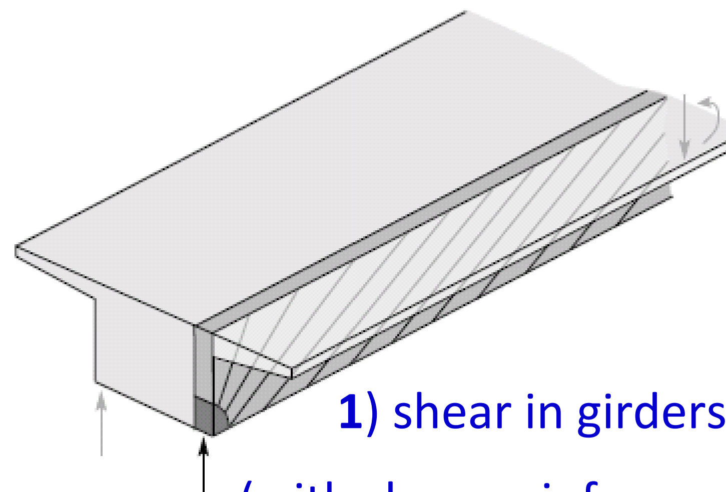
(without shear reinforcement)





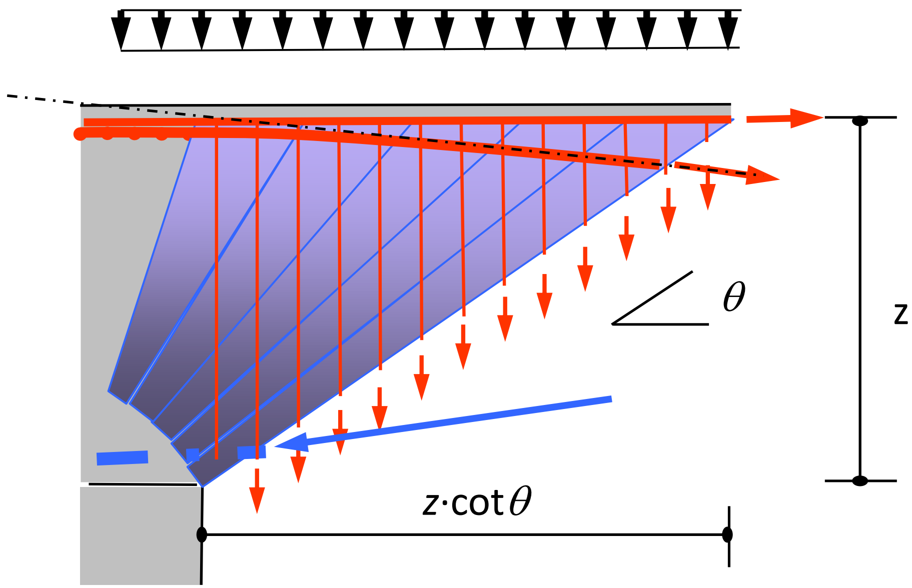
3) punching





1) shear in girders

(with shear reinforcement)



The design shear resistance provided by stirrups is:

$$V_{Rd,s} = \frac{A_{sw}}{s_w} z f_{ywd} \cot\theta$$

The limits of the compressive stress field inclination θ, relative to the longitudinal axis of the member (Figure 7.3-10), are:

$$\theta_{min} \leq \theta \leq 45° \quad (7.3\text{-}35)$$

MC2010 for members with shear reinforcement (girders): compression strut strength

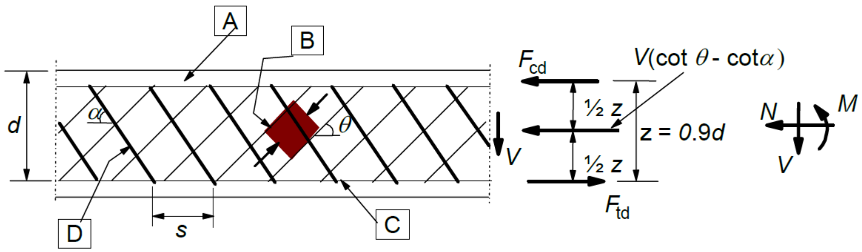
$$V_{Rd,\max} = k_c \frac{f_{ck}}{\gamma_c} b_w z \sin\theta\cos\theta$$

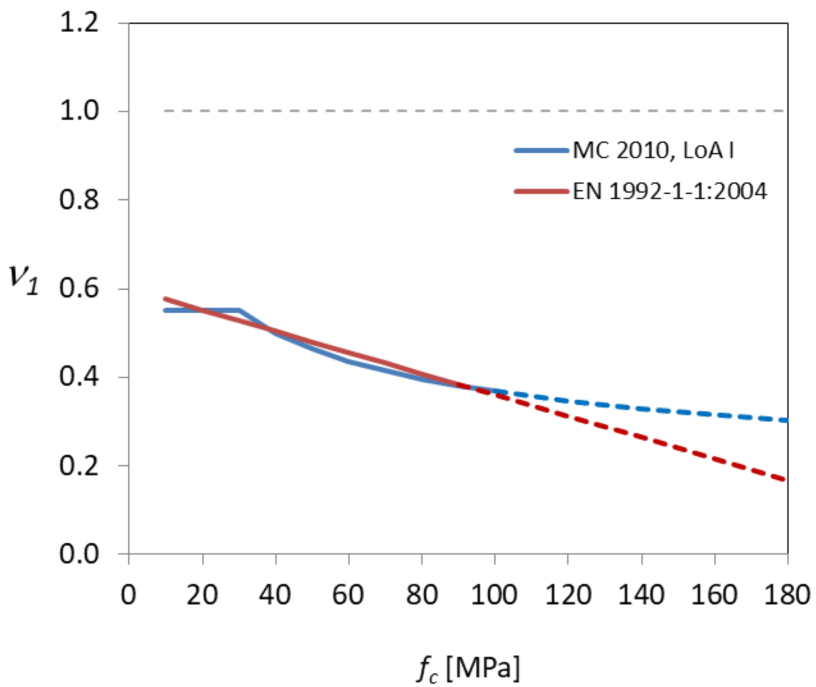
The strength reduction factor is defined as:

$$k_c = k_\varepsilon \eta_{fc}$$

Strain effect		**Brittleness effect**	
EN 1992-1-1:2004:	0.6	EN 1992-1-1:2004:	$1-f_{ck}/250$
NBR 6118:2014:	0.54	NBR 6118:2014:	$\alpha_{v2} = 1-f_{ck}/250$
MC2010 LoA I:	$k_\varepsilon = 0.55$	MC2010:	$\eta_{fc} = (30/f_{ck})^{1/3} \leq 1$

Effective concrete strength in webs





EN 1992-1-1:2004 , Efficiency factor ν_1

$$V_{Rd,max} = \alpha_{cw} b_w z \nu_1 f_{cd} / (\cot\theta + \tan\theta)$$

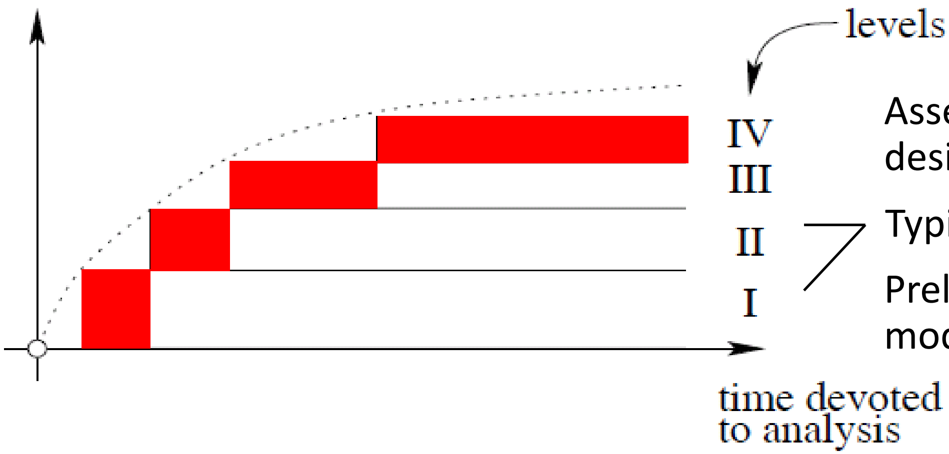
$$\nu_1 = 0.6 \cdot \left(1 - \frac{f_{ck}}{250\,\text{MPa}}\right)$$

MC 2010, LoA I

$$\nu_1 = 0.55 \cdot \underbrace{\left(\frac{30\,\text{MPa}}{f_{ck}}\right)^{1/3}}_{\leq 1}$$

=> Larger reduction for higher f_c due to more brittle behaviour

The levels-of-Approximation approach (θ_{min} and k_c)



Assessment of critical existing structures, design of special cases

Typical design

Preliminary design, non governing failure modes

The levels-of-Approximation approach: shear in girders with transverse reinforcement

$$\theta_{min} \leq \theta \leq 45°$$

$$k_c = k_\varepsilon \eta_{fc}$$

Level I

$\theta_{min} = 25°$ for members with significant axial compression or prestress
$\theta_{min} = 30°$ for reinforced concrete members
$\theta_{min} = 40°$ for members with significant axial tension

$$k_\varepsilon = 0.55$$

Level II

$$\theta_{min} = 20^0 + 10000\varepsilon_x$$

$$k_\varepsilon = \frac{1}{1.2 + 55\varepsilon_1} \leq 0.65$$

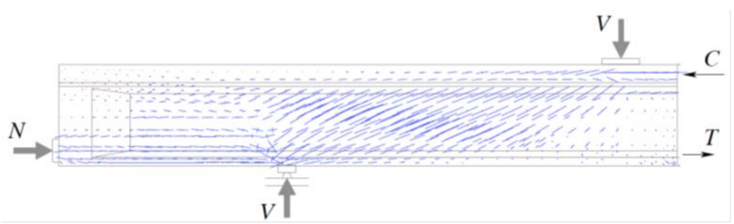
$$\varepsilon_1 = \varepsilon_x + (\varepsilon_x + 0.002)\cot^2\theta$$

Level III

$$V_{Rd} = V_{Rd,s} + V_{Rd,c}$$

$$k_v = \frac{0.4}{1 + 1500\varepsilon_x}\left(1 - \frac{V_{Ed}}{V_{Rd,max}(\theta_{min})}\right) \geq 0$$

Level IV

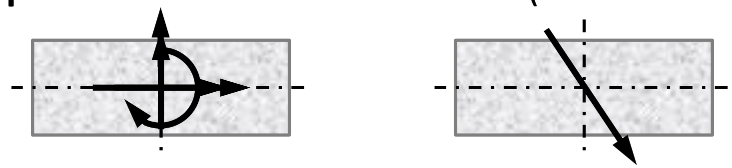


Topics where there is a need to improve MC2010 (1/3)

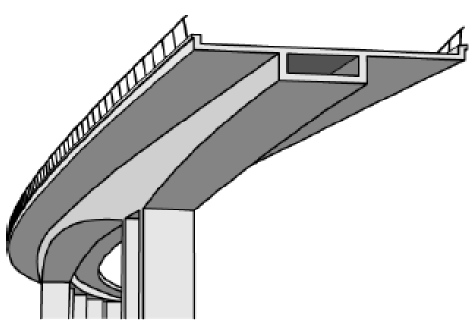
1) Provisions regarding cyclic loading should be improved for the verification of columns and walls subjected to **seismic actions**.

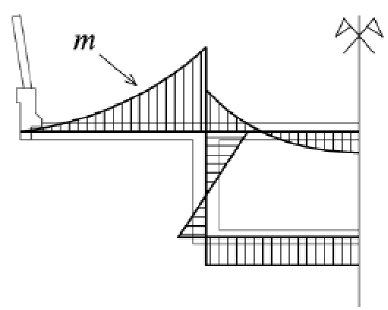
2) Improve provisions for **points loadings near supports** (girders)

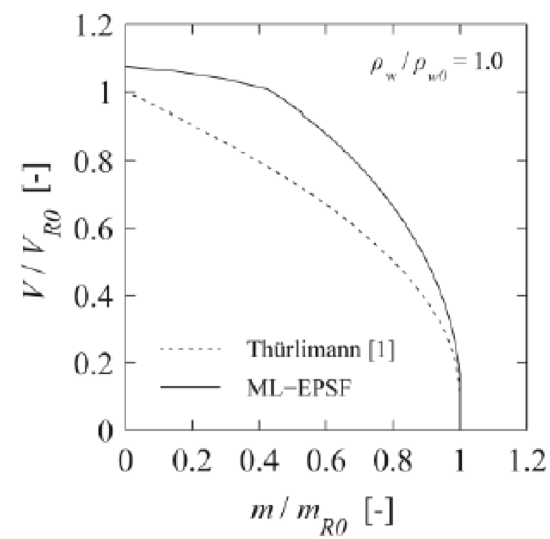
3) Combined actions – **Shear, torsion, bending; interaction with torsion in solid sections; shear forces not parallel to the principal axes of the cross sections** (Bi-axial shear in columns)



4) Simplified provisions to account for interaction with **transversal bending** (important for box girders or flanged beams)

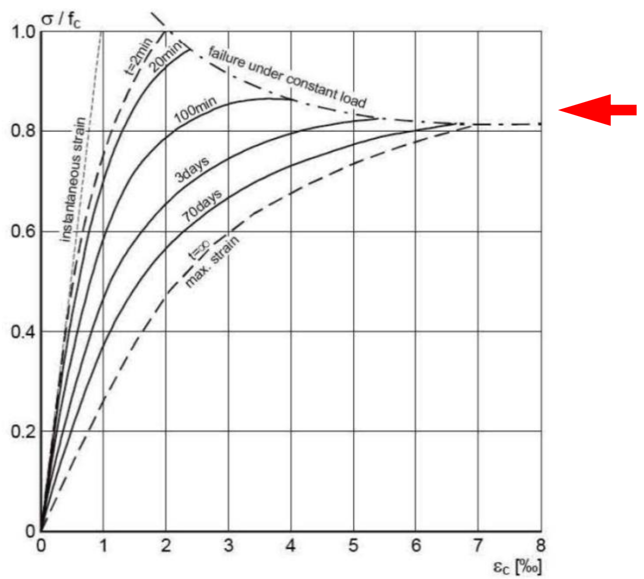






Topics where there is a need to improve MC2010 (2/3)

5) Shear in members with **bent-up-bars** and/or **plain reinforcement**
6) Shear in **prestressed members with poor longitudinal reinforcement at end supports**
7) Shear of members where the **transverse reinforcement is poorly anchored**
8) Shear in members where the **constructive rules are not fulfilled** (spacing of the transverse reinforcement, or less than minimum shear reinforcement for instance)
9) Sustained loading? (α_{cc})



Sustained loading ("Rüsch effect")

=> $\alpha_{cc} \approx 0.85$ **???**

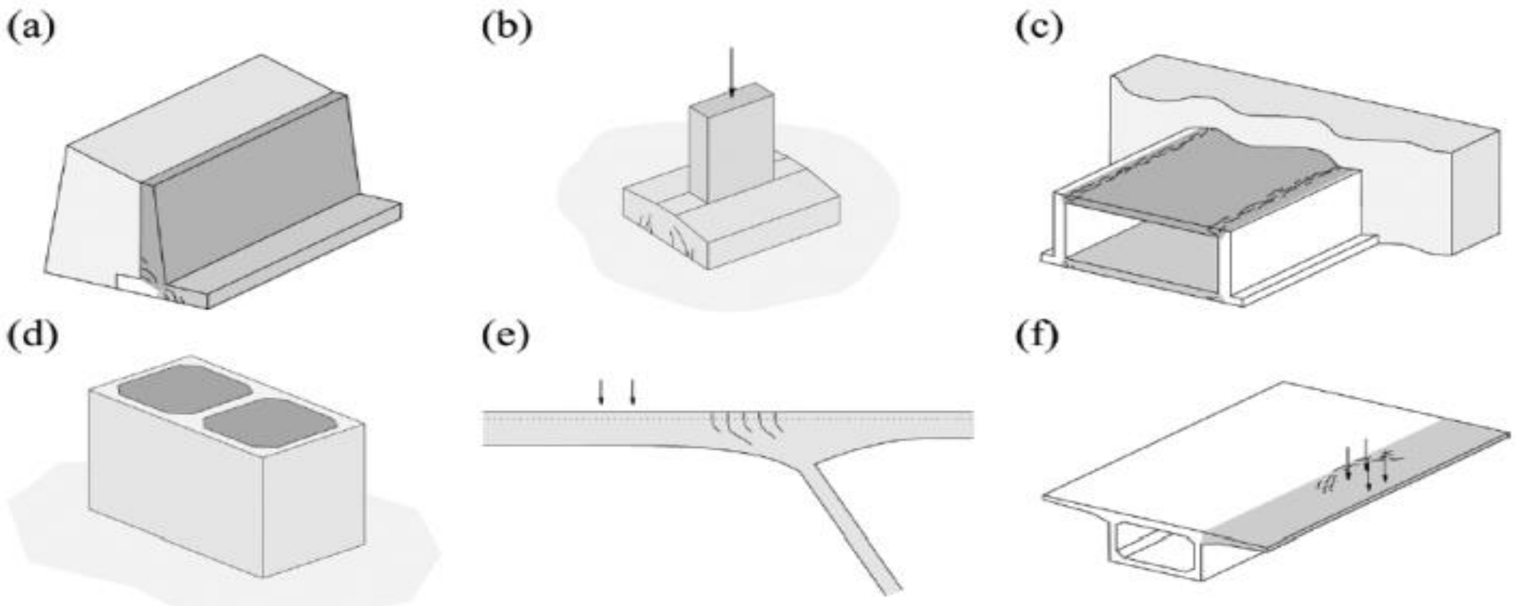
or strength reduction factor of 0.85 has another justification (NBR 6118:2014 and UK NDP) ??

Rüsch, H., "Research toward a general flexural theory for structural concrete." ACI Journal, 1960

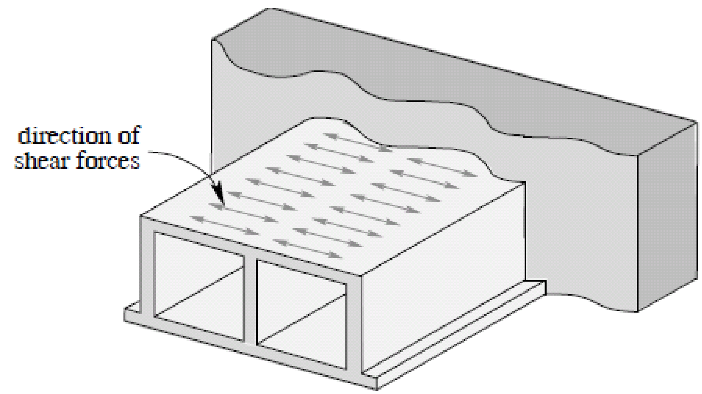
Topics where there is a need to improve MC2010 (3/3)

10) Influence of **flanges** (considerations should be included e.g. LoA II or III)
11) Shear **fatigue** considerations
12) Reliability & safety evaluation (TG 3.1): shear resistance functions
13) Bar cutoff effect overestimated?

Shear in slabs, or members not requiring shear reinforcement



Provisions for members without shear reinforcement: MC 90 and EC2:2004 approach



MC 90 and EC2:2004 approach

$$V_{R,c} = C \cdot b \cdot d \cdot k \cdot \rho^{1/3} \cdot f_{ck}^{1/3} + C_p \cdot b \cdot d \cdot \sigma_{cp}$$

- Prestressing (EC2:2004)
- Concrete strength
- Reinforcement ratio
- Size effect $k = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0$
- Area of cross section

One-way shear in MC 2010: MCFT as theoretical basis

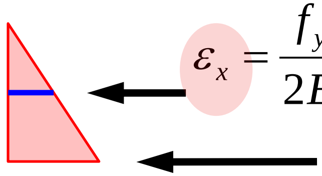
$$V_{Rd,c} = k_v \frac{\sqrt{f_{ck}}}{\gamma_c} z b_w$$

$$k_v = \frac{0.4}{1+1500\varepsilon_x} \cdot \frac{1300}{1000+k_{dg} z}$$

Strain effect

Size effect

Level I



$$\varepsilon_x = \frac{f_{yd}}{2E_s}$$

$$\varepsilon = \frac{f_{yd}}{E_s}$$

Level II

$$\varepsilon_x = \frac{1}{2\,E_s A_s}\left(\frac{M_{Ed}}{z} + V_{Ed} + N_{Ed}\left(\frac{1}{2} \mp \frac{\Delta e}{z}\right)\right)$$

Sigrist V., Bentz E., Fernández Ruiz M., Foster S., Muttoni A., Background to the fib Model Code 2010 shear provisions – part I: beams and slabs, Structural Concrete, 2013

One-way shear in NBR 6118:2014 : inspired by MC1978

19.4 Força cortante em lajes e elementos lineares com $b_w \geq 5d$

19.4.1 Lajes sem armadura para força cortante

As lajes maciças ou nervuradas, conforme 17.4.1.1.2-b), podem prescindir de armadura transversal para resistir as forças de tração oriundas da força cortante, quando a força cortante de cálculo, a uma distância *d* da face do apoio, obedecer à expressão:

$$V_{Sd} \leq V_{Rd1}$$

Sendo a força cortante resistente de cálculo dada por:

$$V_{Rd1} = [\tau_{Rd}\, k\, (1{,}2 + 40\, \rho_1) + 0{,}15\, \sigma_{cp}]\, b_w d$$

onde

$$\tau_{Rd} = 0{,}25\, f_{ctd}$$

$$f_{ctd} = f_{ctk,inf} / \gamma_c$$

$$\rho_1 = \frac{A_{s1}}{b_w d}, \text{não maior que} |0{,}02|,$$

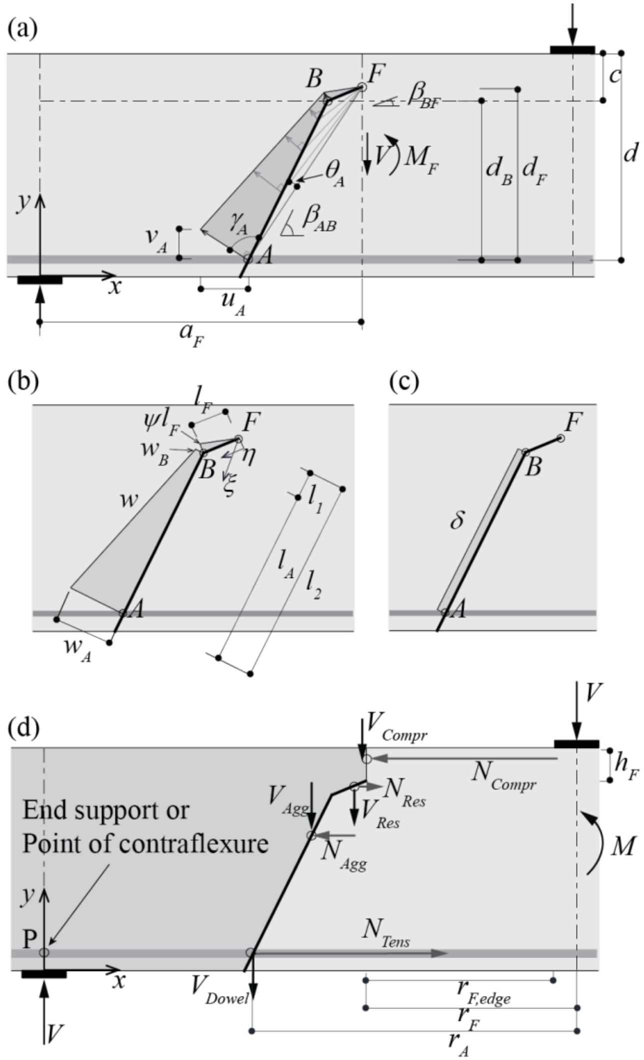
$$\sigma_{cp} = N_{Sd} / A_c$$

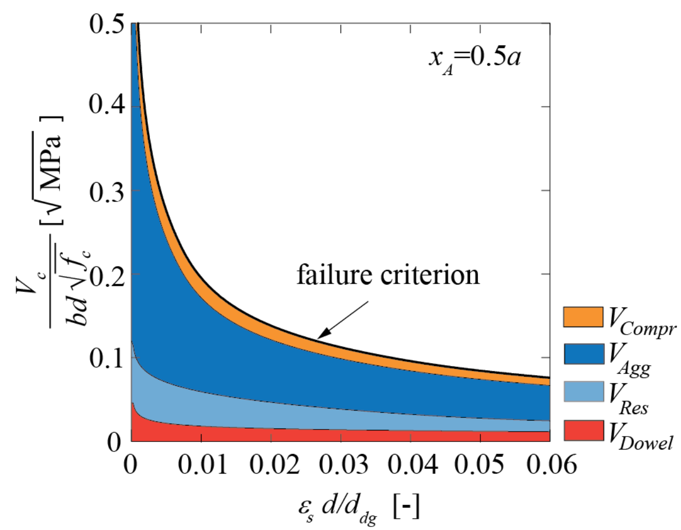
k é um coeficiente que tem os seguintes valores:

— para elementos onde 50 % da armadura inferior não chega até o apoio: $k = |1|$;

— para os demais casos: $k = |\, 1{,}6 - d\, |$, não menor que $|\, 1\, |$, com *d* em metros;

Development of closed-form equation for the 2nd generation of EN 1992-1-1





Fernández Ruiz M. , Muttoni A., Sagaseta J., (2015) *Shear strength of concrete members without transverse reinforcement: A mechanical approach to consistently account for size and strain effects*, Engineering Structures

Development of closed-form equation for the 2nd generation of EN 1992-1-1

$$\tau_{R,c} = \frac{0.3}{1+\varepsilon_v \cdot d \cdot k_{dg}} \cdot \sqrt{f_c}$$

now replaced by:

$$\tau_{R,c} = k \cdot \left(\frac{f_c \cdot d_{dg}}{d \cdot \varepsilon_v} \right)^{1/2}$$

$$\varepsilon_v = \frac{M_E}{z \cdot A_s \cdot E_s} = \frac{V_E \cdot a_{cs}}{z \cdot \rho_l \cdot b \cdot d \cdot E_s} = \frac{\tau_{R,c} \cdot b \cdot d \cdot a_{cs}}{z \cdot \rho_l \cdot b \cdot d \cdot E_s} = \frac{\tau_{R,c} \cdot a_{cs}}{z \cdot \rho_l \cdot E_s}$$

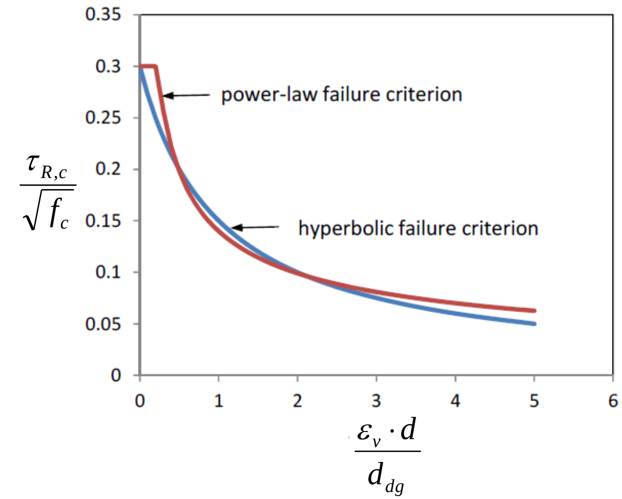
$$\tau_{R,c} = k \cdot \left(\frac{f_c \cdot d_{dg}}{d \cdot \tau_{R,c} \cdot a_{cs}} \rho_l \cdot E_s \cdot z \right)^{1/2}$$

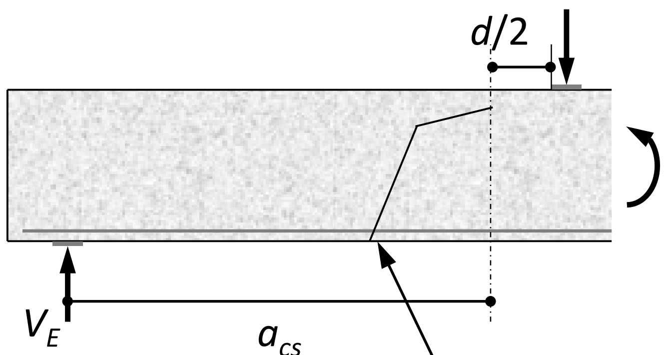
$$\tau_{R,c} = k^{2/3} \cdot \left(\rho_l \cdot E_s \cdot f_c \frac{d_{dg}}{a_{cs}} \frac{z}{d} \right)^{1/3}$$

$$\tau_{R,c} \cong 1.0 \cdot \left(100\rho_l \cdot f_c \frac{d_{dg}}{a_{cs}} \right)^{1/3}$$

influence of aggregate size

size and slenderness effects combined





$$\varepsilon_v = \frac{M_E}{z \cdot A_s \cdot E_s} = \frac{V_E \cdot a_{cs}}{z \cdot A_s \cdot E_s}$$

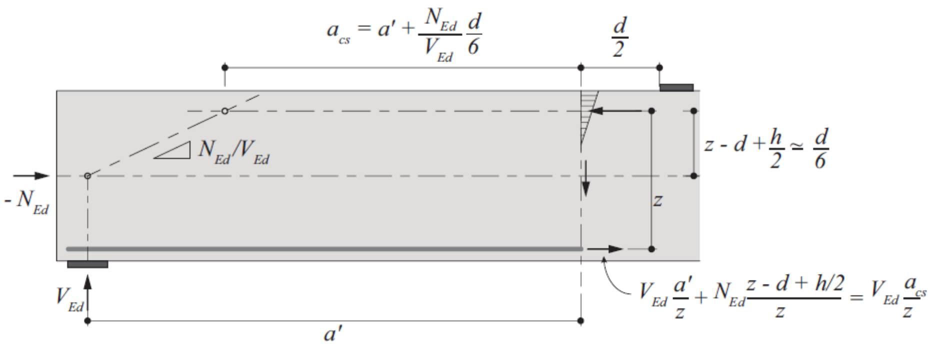
Muttoni, Fernández Ruiz, Cavagnis, *fib* Bulletin 2018

$$\tau_{Rd,c} = \frac{V_{Rd,c}}{b_w \cdot d} = \frac{1}{\gamma_c}\left(100 \cdot \rho_l \cdot f_{ck} \frac{d_{dg}}{a_{cs}}\right)^{1/3}$$

In presence of normal forces, the effective shear span a_{cs} shall be adapted as follows:

$$a_{cs} = \left|\frac{M_E}{V_E}\right| + \frac{N_E}{|V_E|} \cdot \frac{d}{6} \geq 0$$

N_E<0 : compressive normal forces



Muttoni, Fernández Ruiz, Cavagnis, *fib* Bulletin 2018

fib MC2010

$$V_{Rd,c} = k_v \frac{\sqrt{f_{ck}}}{\gamma_c} z b_w$$

$$k_v = \frac{0.4}{1+1500\varepsilon_x} \cdot \frac{1300}{1000+k_{dg} z}$$

MC1990
EC2:2004

$$V_{Rd,c} = [C_{Rd,c} k (100\, \rho_l\, f_{ck})^{1/3} + k_1\, \sigma_{cp}]\, b_w d$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0 \text{ with } d \text{ in mm}$$

EC2:2023?

$$\tau_{Rd,c} = \frac{V_{Rd,c}}{b_w \cdot d} = \frac{1}{\gamma_c}\left(100 \cdot \rho_l \cdot f_{ck} \frac{d_{dg}}{a_{cs}}\right)^{1/3}$$

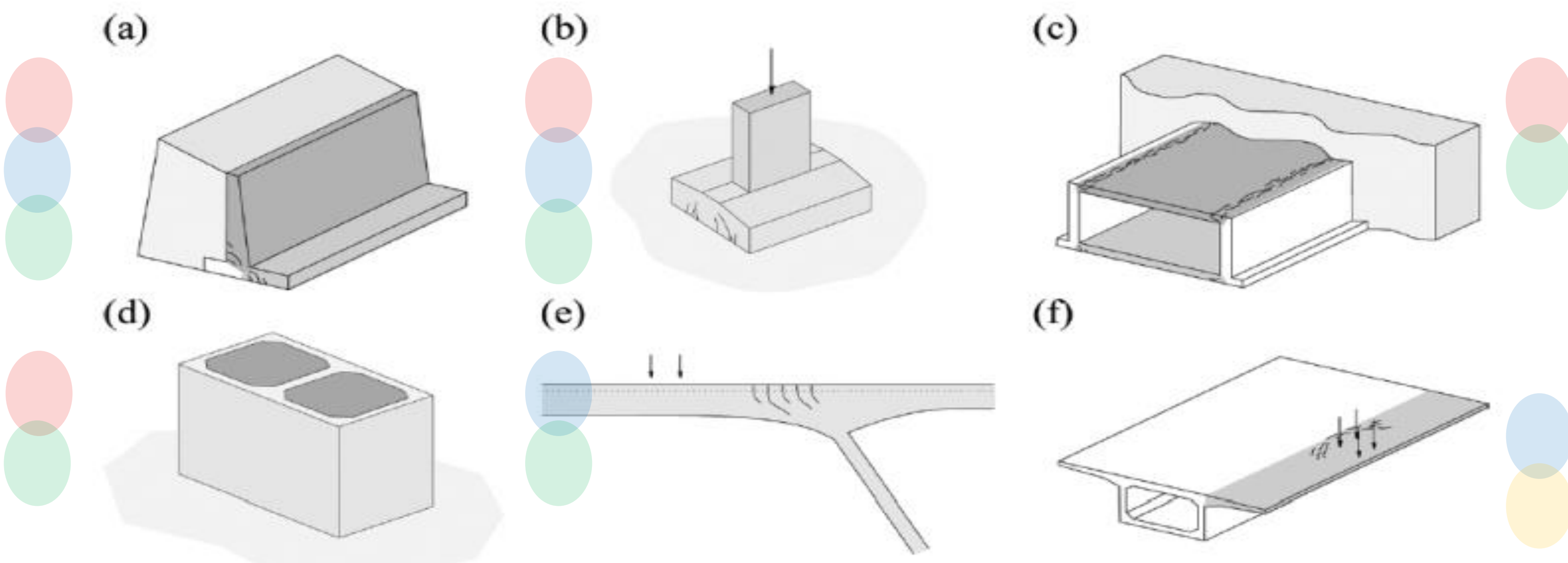
NBR 6118:2014

$$V_{Rd1} = [\tau_{Rd}\, k\, (1{,}2 + 40\, \rho_1) + 0{,}15\, \sigma_{cp}]\, b_w d$$

$k = |\ 1{,}6 - d\ |$, não menor que $|\ 1\ |$;

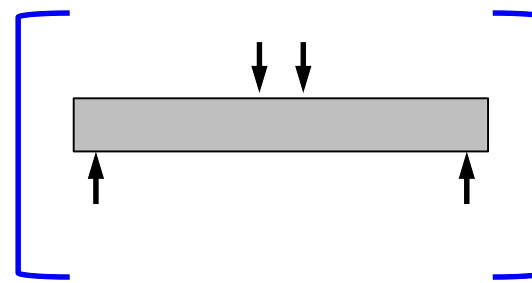
ACI 318

????



Topics where there is a need to improve MC2010

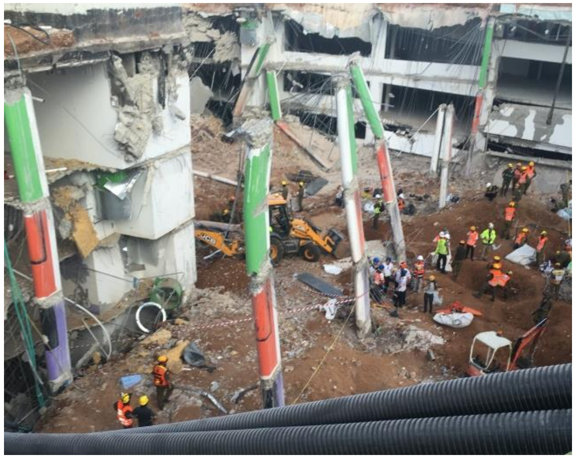
1) provisions regarding **distributed loads**
2) account for **variable depth**
3) provisions for **loadings near supports**
4) provisions for **points loadings near linear supports**



Bluche, Switzerland, 1981

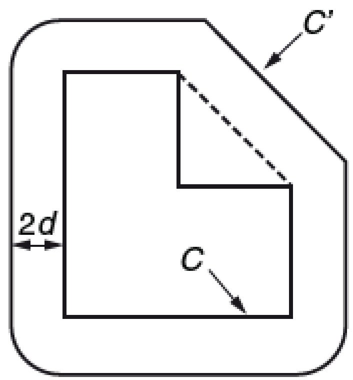
Cagliari, Italy, 2004

Vitoria, Brazil, 2016



Tel Aviv, Israel, 2016

EC2:2004
NBR 6118:2014



A verificação de tensões na superfície crítica *C'* deve ser efetuada como a seguir:

$$\tau_{Sd} \leq \tau_{Rd1} = 0{,}13\left(1+\sqrt{20/d}\right)(100\,\rho\, f_{ck})^{1/3} + 0{,}10\,\sigma_{cp}$$

Essa verificação deve ser feita no contorno *C*, em lajes submetidas a punção, com ou sem armadura. Deve-se ter:

$$\tau_{Sd} \leq \tau_{Rd2} = 0{,}27\alpha_v\, f_{cd}$$

onde

$\alpha_v = (1 - f_{ck}/250)$, com f_{ck} em megapascal;

fib MC2010

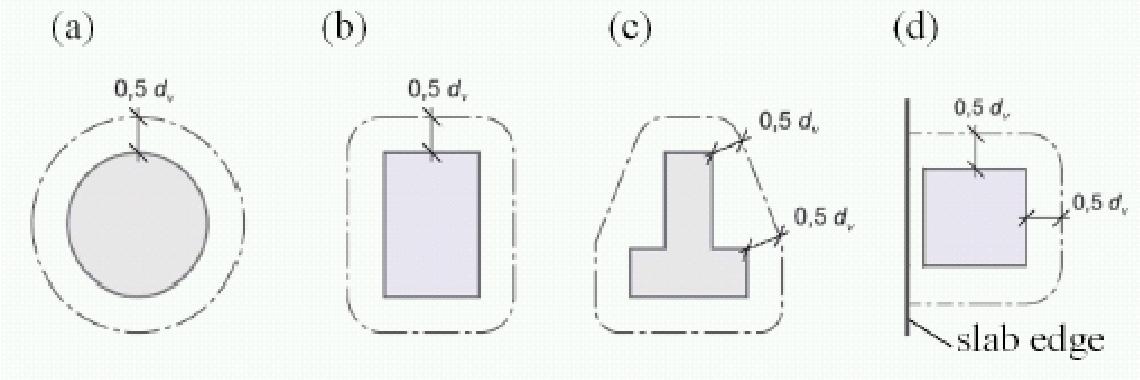
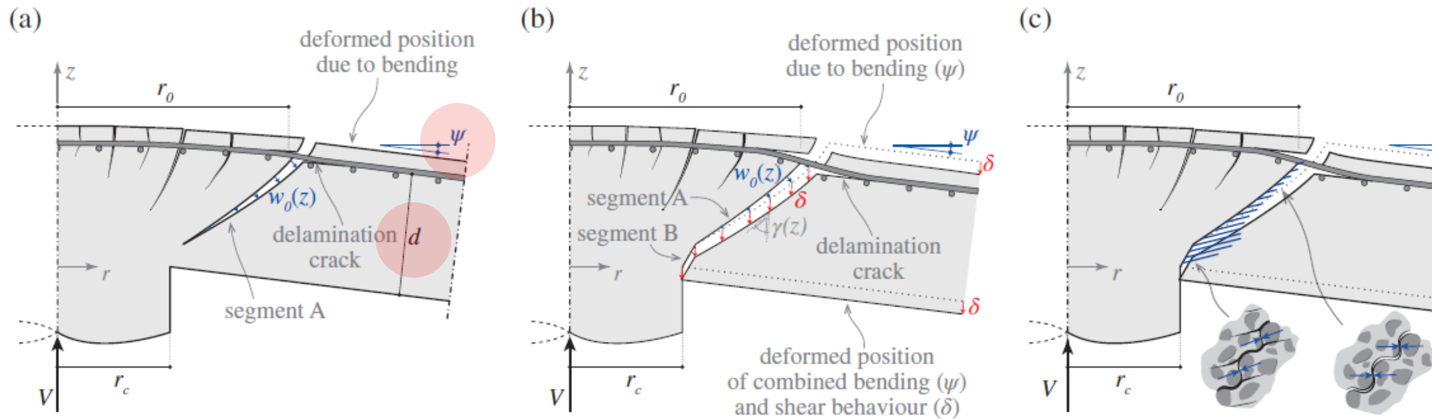
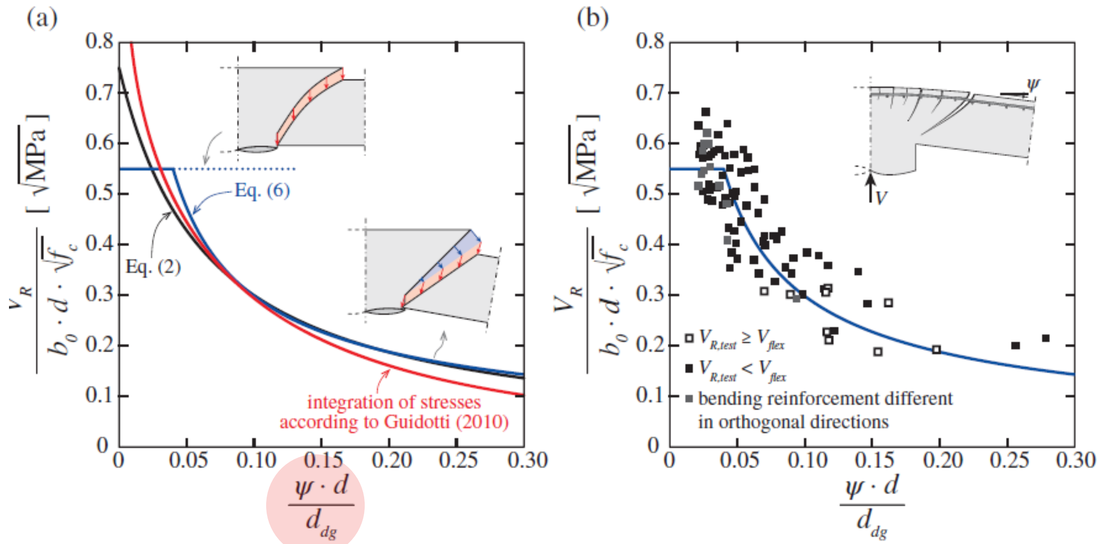


Figure 7.3-211: Basic control perimeters around supported areas.

fib MC2010



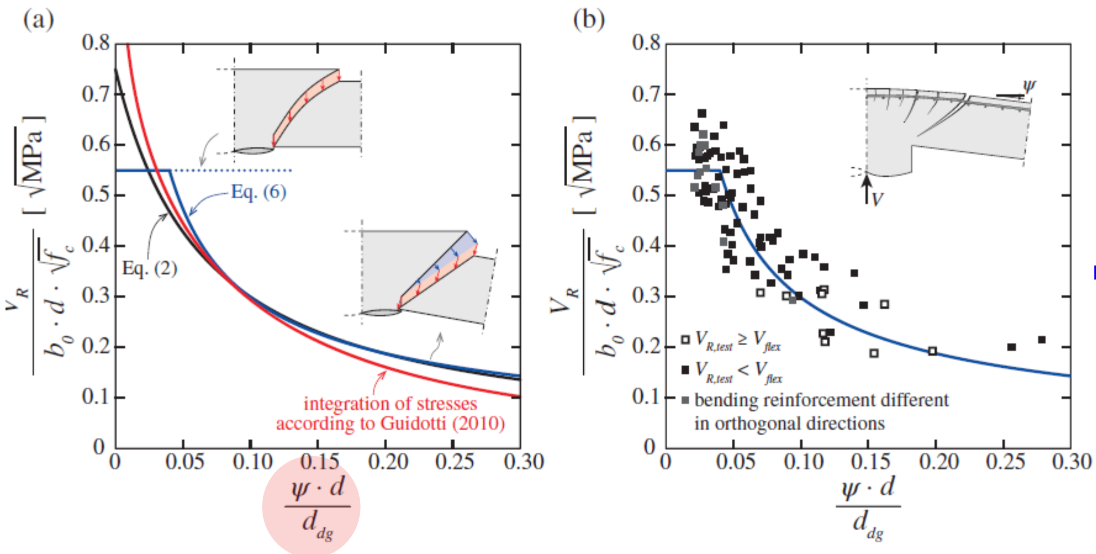


$$V_{Rd,c} = k_\psi \frac{\sqrt{f_{ck}}}{\gamma_c} b_0 \, d_v$$

$$k_\psi = \frac{1}{1.5 + 0.9 k_{dg} \psi d} \leq 0.6$$

$$\psi = 1.5 \cdot \frac{r_s}{d} \frac{f_{yd}}{E_s} \cdot \left(\frac{m_{sd}}{m_{Rd}} \right)^{1.5}$$

Muttoni A., Fernández Ruiz M., Bentz E., Foster S., Sigrist V., *Background to fib Model Code 2010 shear provisions – part II: punching shear*, Structural Concrete, 2013



$$\tau_{Rd,c} = \frac{k_b}{\gamma_C}\left(100\rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{a_p}\right)^{1/3} \leq \frac{0.6}{\gamma_C}\sqrt{f_{ck}}$$

$$1 \leq k_b = \sqrt{8 \cdot \mu \cdot \frac{d}{b_0}} \leq 3$$

WILEY *fib*

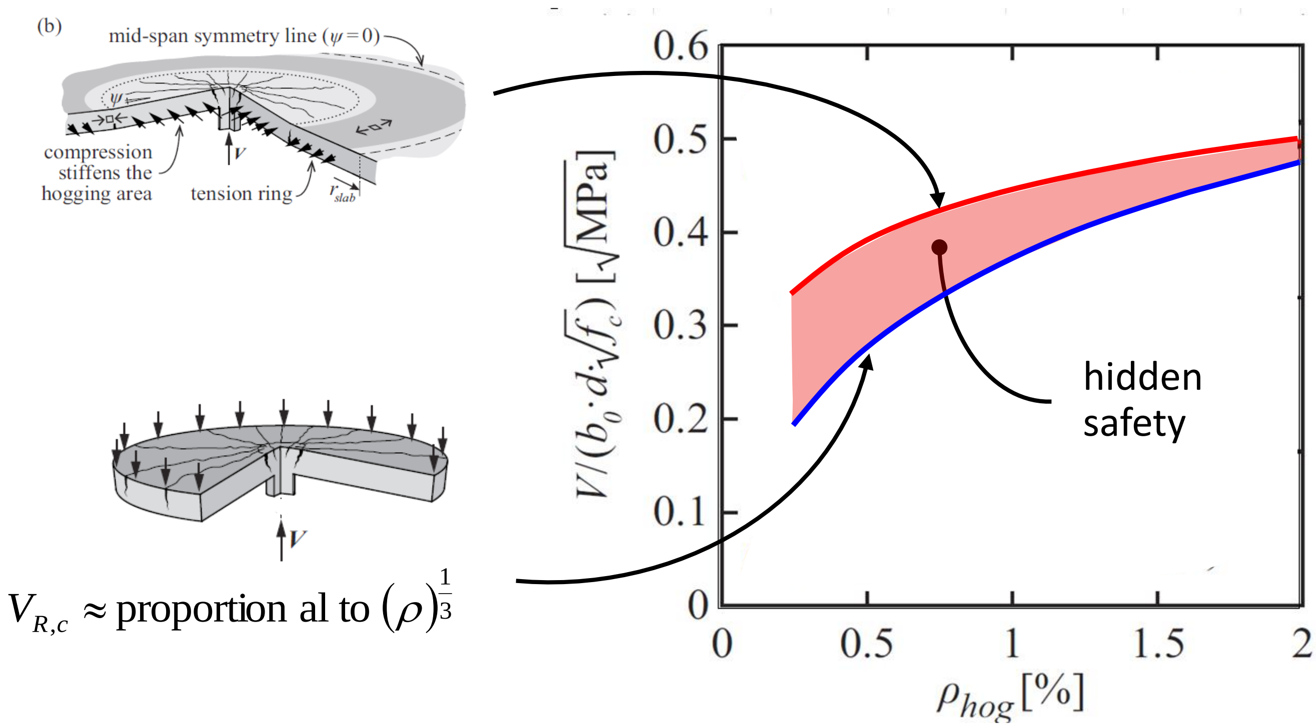
TECHNICAL PAPER

The theoretical principles of the critical shear crack theory for punching shear failures and derivation of consistent closed-form design expressions

Aurelio Muttoni | Miguel Fernández Ruiz | João T. Simões

The MC2010 model already suitably addresses needs related to assessment and strengthening

a) Influence of slab continuity and compressive membrane action (important for assessment)



$$V_{R,c} \approx \text{proportion al to } (\rho)^{\frac{1}{3}}$$

Einpaul J., Fernández Ruiz M., Muttoni A., Influence of moment redistribution and compressive membrane action on punching strength of flat slabs, Engineering Structures , 2015)

Einpaul J., Ospina C. E., Fernández Ruiz M., Muttoni A., Punching Shear Capacity of Continuous Slabs, ACI, Structural Journal, 2016

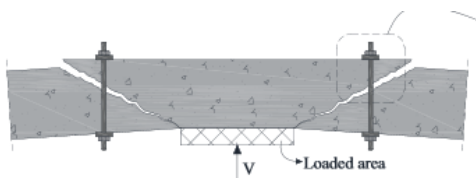
The MC2010 model already suitably addresses needs related to assessment and strengthening

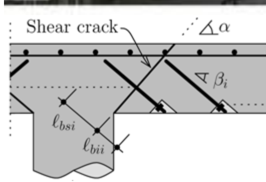
b) Strengthening

- Retrofitting using externally bonded FRP's

D. M. V. Faria D., Einpaul J., M. P. Ramos A., Fernández Ruiz M., Muttoni A., 2014, On the efficiency of flat slabs strengthening against punching using externally bonded FRP's, Construction and Building Materials, 2014

- Retrofitting using post-installed reinforcement





Fernández Ruiz M., Muttoni A., Kunz J., 2010, Strengthening of flat slabs against punching shear using post-installed shear reinforcement, ACI Structural Journal

Topics where there is a need to improve MC2010 (1/2)

1) Provisions regarding cyclic loading (flat slabs subjected to seismic actions).
2) Shear in slabs with bent-up-bars and/or plain reinforcement
3) Shear of slabs where the transverse/longitudinal reinforcement is poorly anchored
4) Shear in slabs where the constructive rules are not fulfilled (spacing of the transverse reinforcement for instance)
5) Influence of compressive membrane action (account for slab continuity) -> explicit formulation
6) Verify/adjust level of safety (parameters to be adjusted according to a reliability analysis)
7) Better define the aim of LoA I (not a simplified design tool, but a first check to verify whether shear is a concern)

Topics where there is a need to improve MC2010 (2/2)

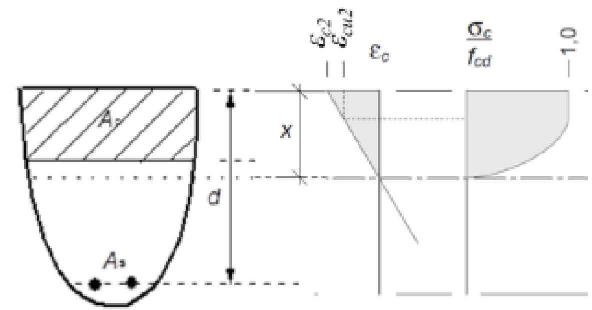
8) Simplified expressions / closed-form expressions?
9) Influence of imposed deformations (columns settlements)
10) Update expressions where recent knowledge indicates a need. For instance: (i) k_e for edge and corner columns; (ii) expression for transverse reinforcement based on recent improvements of the mechanical model (footings for instance); (iii) Provisions for integrity reinforcement
11) Tailored design methods for strengthening of slabs against punching
12) Punching with medium - low slenderness: between 1 and 2 (e.g. pile caps)
13) Redistribution of shear in asymmetrical cases (ψ_{max} versus ψ_x and ψ_y)
14) Performance and safety on different LoAA
15) Role of integrity reinforcement (although further work is needed)
16) Structural robustness of flat slab structures (new & existing structures)

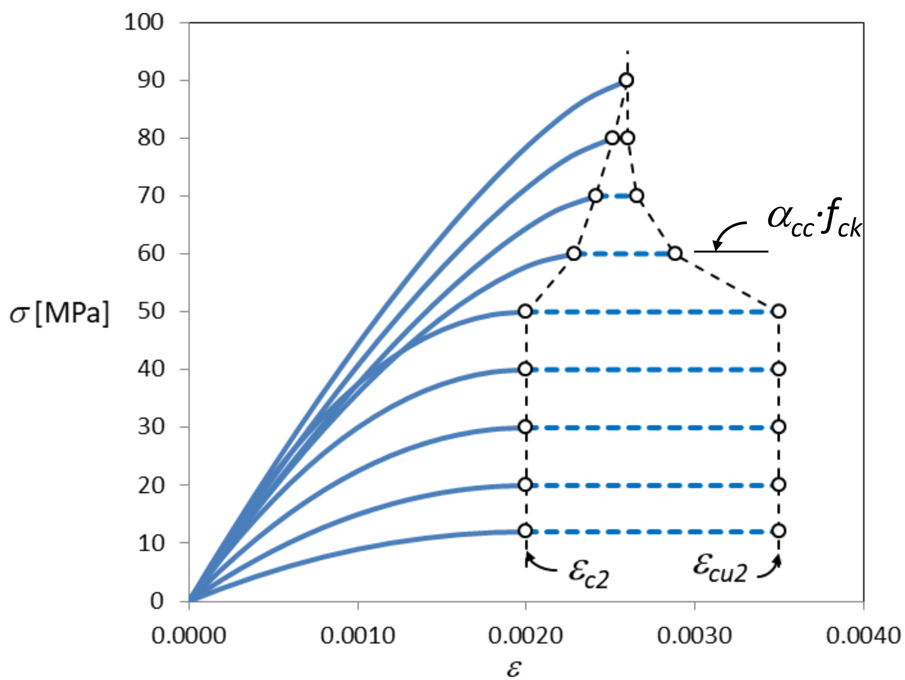
New Bulletins

1) *fib* Bulletin on “Seismic behaviour of flat slabs”
2) *fib* Bulletin on “Strengthening of flat slabs against punching”
3) *fib* Bulletin on “Robustness of flat slabs”
4) *fib* Bulletin on “Design and assessment of slabs using linear and nonlinear analysis”

MC 2010 -> MC2020, Stress distribution in the compression zones

Stress distributions according to EN 1992-1-1:2004
MC 2010
NBR 6118:2014





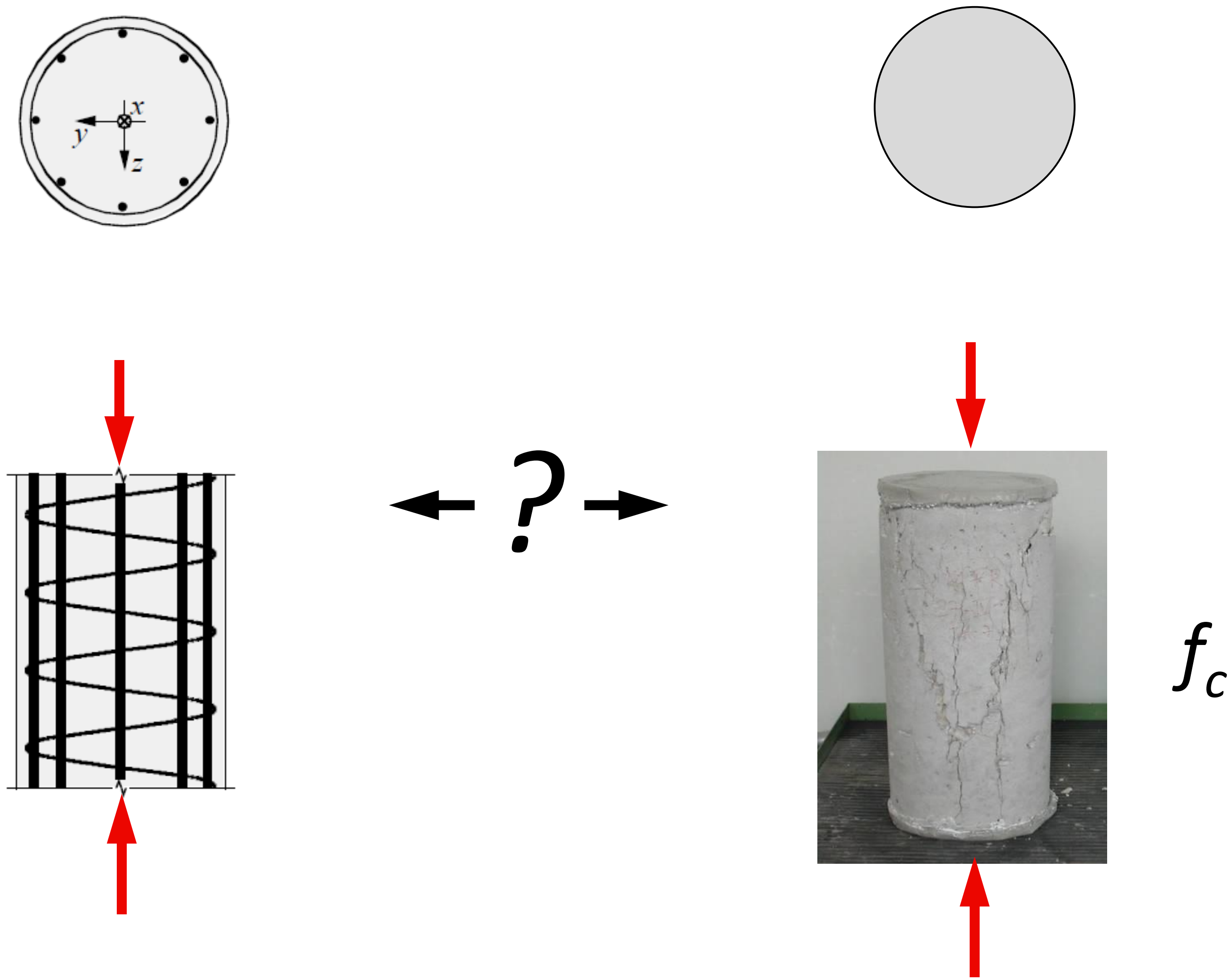
for f_{ck} ≥ 50 Mpa

$\varepsilon_{c2}(^0/_{00})=2{,}0+0{,}085(f_{ck}-50)^{0{,}53}$

$\varepsilon_{cu2}(^0/_{00})=2{,}6+35[(90-f_{ck})/100]^4$

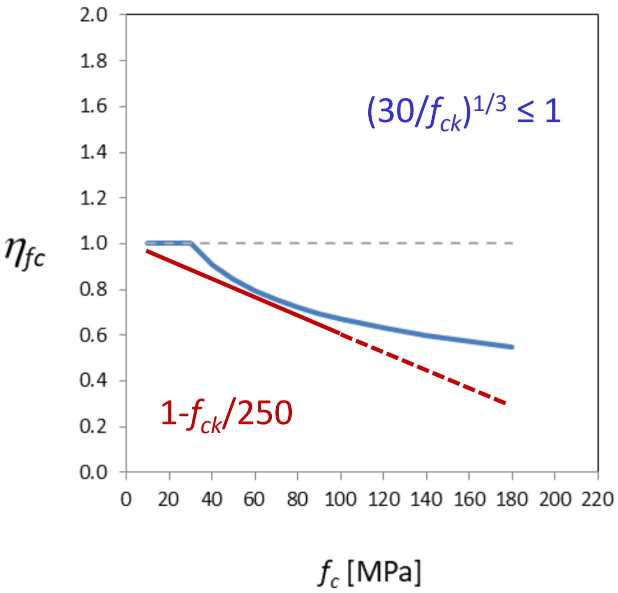
ENV 1992-1-1:1991
(unchanged since CEB 1964)

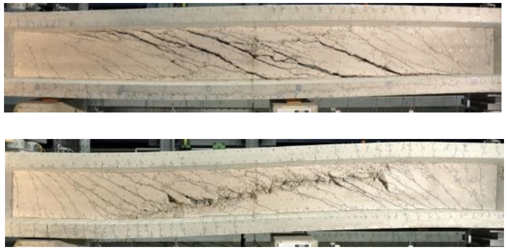
Effective concrete strength in columns



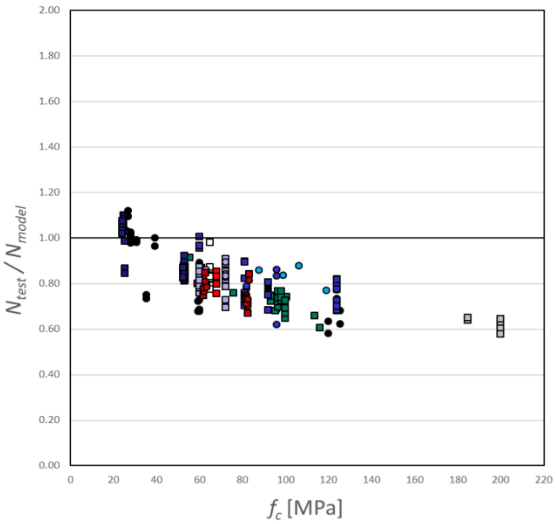
Similarities between the effective concrete strength in webs and in columns

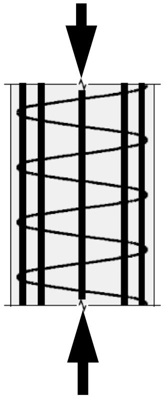
Webs



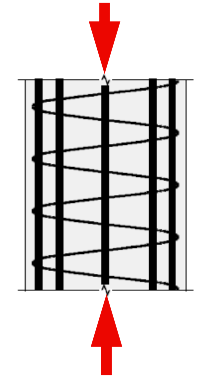


Columns





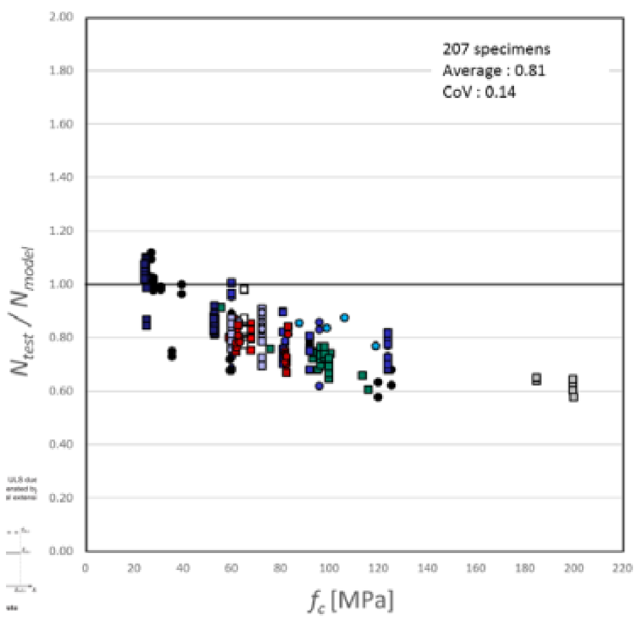
Comparison between columns tests and code calculation

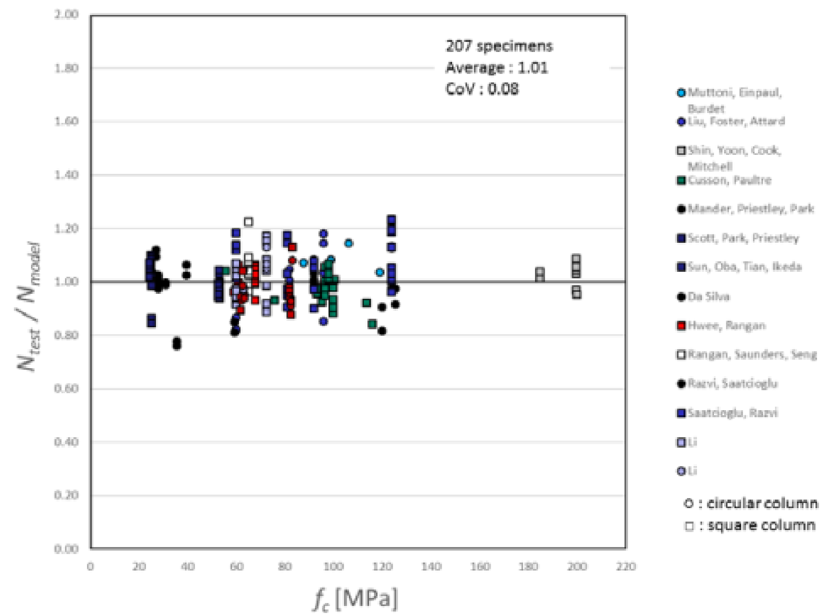


EN 1992-1-1:2004

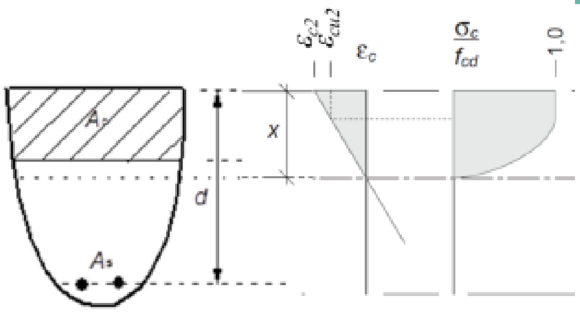
Unreduced concrete strength in the column

reduced concrete strength in the column: $(30/f_{ck})^{1/3} \leq 1$

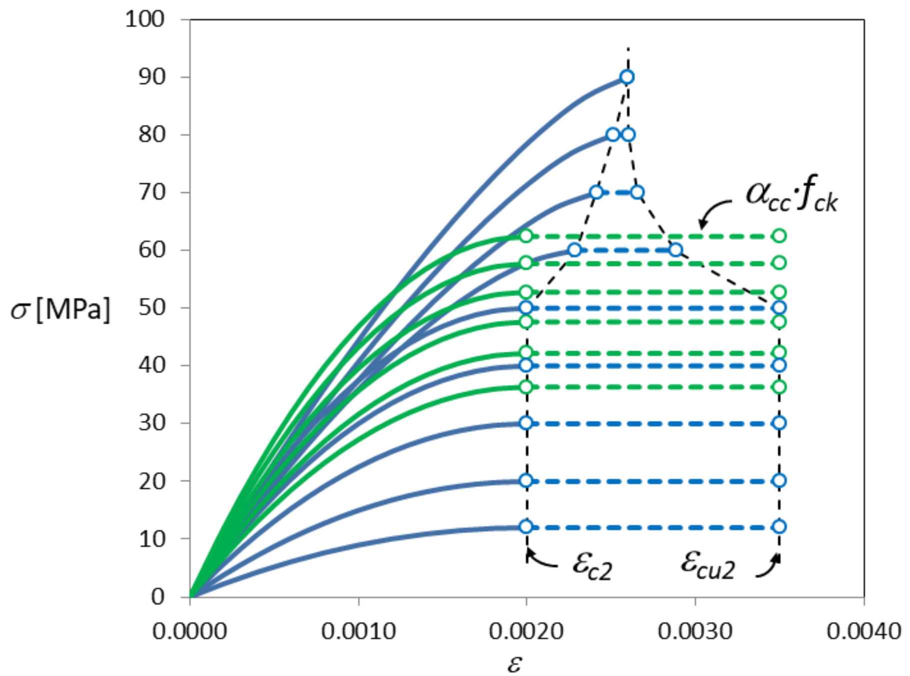




Stress distribution in the compression zones may potentially be simplified



$\alpha_{cc} = (30/f_{ck})^{1/3} \leq 1$



same parabola-rectangle distribution (CEB 1964) may be used also for f_{ck} > 50 MPa