INVITED CONFERENCE
Anchorage and laps of reinforcing steel

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EUROCODES

EN 1992

Design of concrete structures

2nd generation of Eurocode 2 on concrete structures

Madrid, October 17th, 2023

FprEC2:2023 Sections 11.3 & 11.4

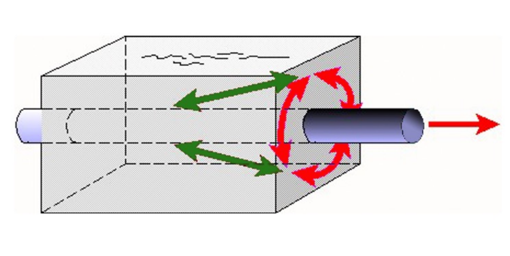
1. Some basics of bond behaviour
2. Calculation of anchorage length, straight bars in tension
3. Hooks, bends, U loops
4. Laps of bars in tension
5. Compression laps and anchorages
6. New content: Post-installed reinforcement, headed bars
7. Impact on design

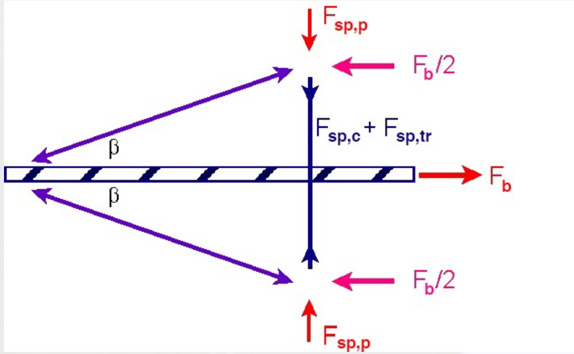
Aims:

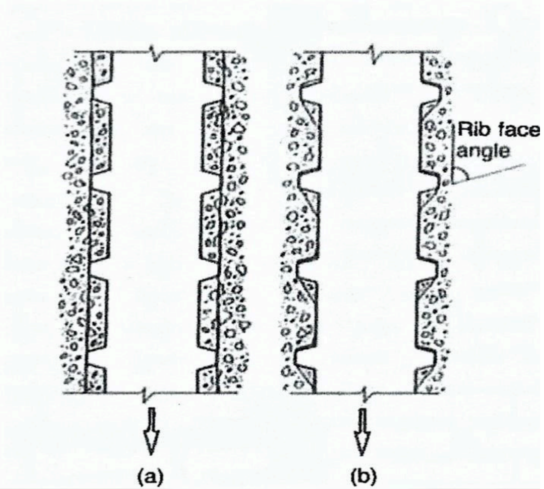
Describe change, explain rationale, quantify impact.

1.1 Some basics of bond behaviour

Splitting and pull-out modes





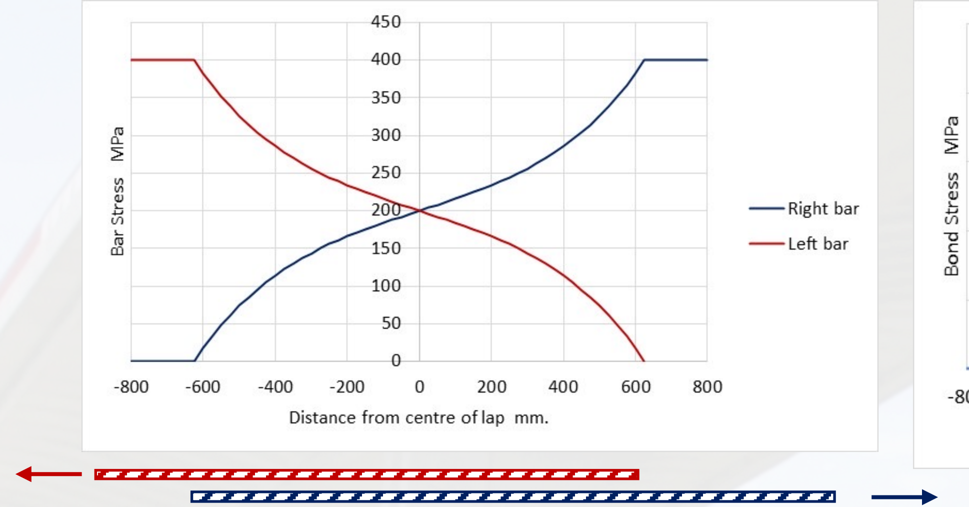


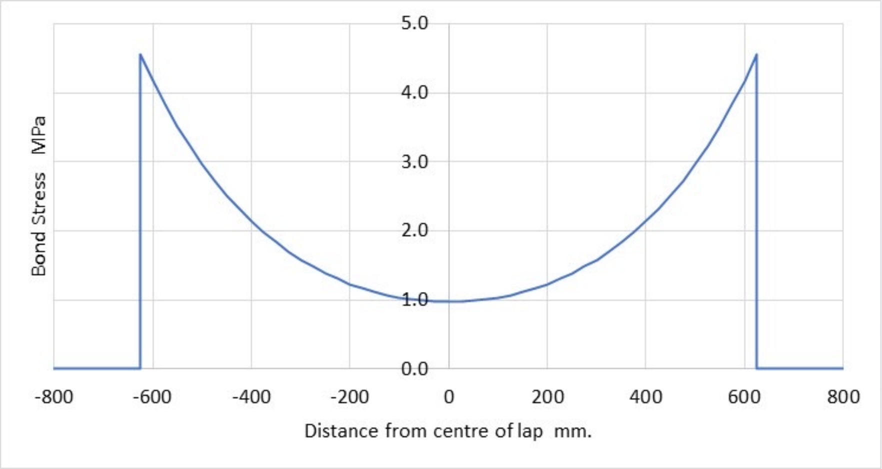
(a)	(b)
Shearing over tops of deformations	Bearing of deformations, splitting
Non-ductile	**Brittle**

1.2 Some basics of bond behaviour

Variation in stress over bond length is non-linear

Pair of lapped bars, ϕ = 25mm, l_b = 50ϕ, σ_{sd} = 400MPa





Bar stresses

(Plots based on linear elastic analysis using MC local bond-slip relationship)

Bond stresses

Principal sources

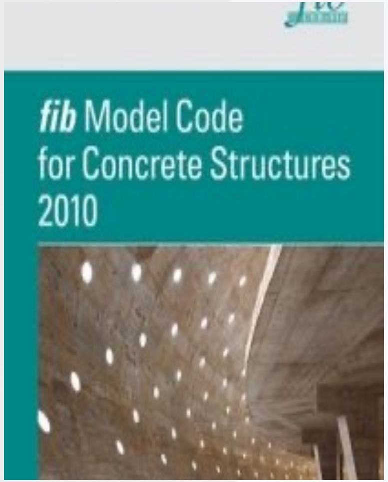
EC2:2004

Based on CEB-FIP
Model Code 1978,
(with some modifications)

FprEC2:2023

2014
Bulletin 72 Background

2013
MC2010 Sect. 6.1



2.1 Calculation of anchorage lengths, straight bars

EC2:2004

$$f_{bd} = 2{,}25\ \eta_1\ \eta_2\ f_{ctd}$$

$$l_{b,rqd} = (\phi / 4)\ (\sigma_{sd} / f_{bd})$$

$$l_{bd} = \alpha_1\ \alpha_2\ \alpha_3\ \alpha_4\ \alpha_5\ l_{b,rqd} \geq l_{b,min}$$

η_1, η_2 bar size, casting position

α: hook/bend, min. cover, transverse compression

Influencing parameters multiplicative

FprEC2:2023 : simplified provisions

Table 11.1 (NDP) — Anchorage length of straight bars divi

ϕ [mm]	Anchorage length l_{bd}/ϕ f_{ck} 20	25	30	35	40
≤ 12	47	42	38	36	33
14	50	44	41	38	35
16	52	46	42	39	37
20	56	50	46	42	40
25	60	54	49	46	43

Simplified provision *for ribbed bars $\phi \leq 32$ mm, indented bars $\phi \leq 14$ mm, $c_d \geq 1{,}5\phi$, $\sigma_{sd} = 435$ MPa, good bond conditions*

2.2 Calculation of anchorage lengths, straight bars :detailed provisions

FprEC2:2023 : detailed provisions

$$l_{bd} = k_{lb} \cdot k_{cp} \cdot \phi \cdot \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1{,}5\phi}{c_{d,conf}}\right)^{\frac{1}{2}} \geq 10\phi \qquad (11.3)$$

$$c_d = \min\{0{,}5c_s;\ c_x;\ c_y;\ 3{,}75\phi\}$$

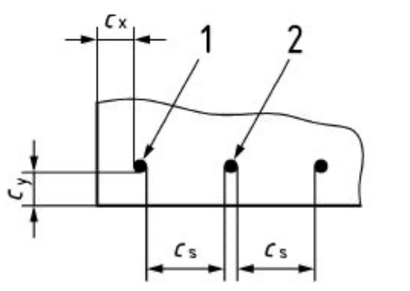
$$(\phi/20\text{ mm}) \geq 0{,}6 \text{ and } (25/f_{ck}) \geq 0{,}3$$

$$c_{d,conf} = \min\left\{c_x;\ c_y + 25\frac{\phi_t^2}{s_t};\ \frac{c_s}{2};\ 3{,}75\phi\right\} + \Delta c_d \leq 6\phi \qquad (11.4)$$

$$\Delta c_d = (70\rho_{conf} + 12\sigma_{ccd}/\sqrt{f_{ck}})\phi;$$

Where transverse compression or an appreciable quantity of secondary reinforcement restrain splitting failure

Confinement parameters summative



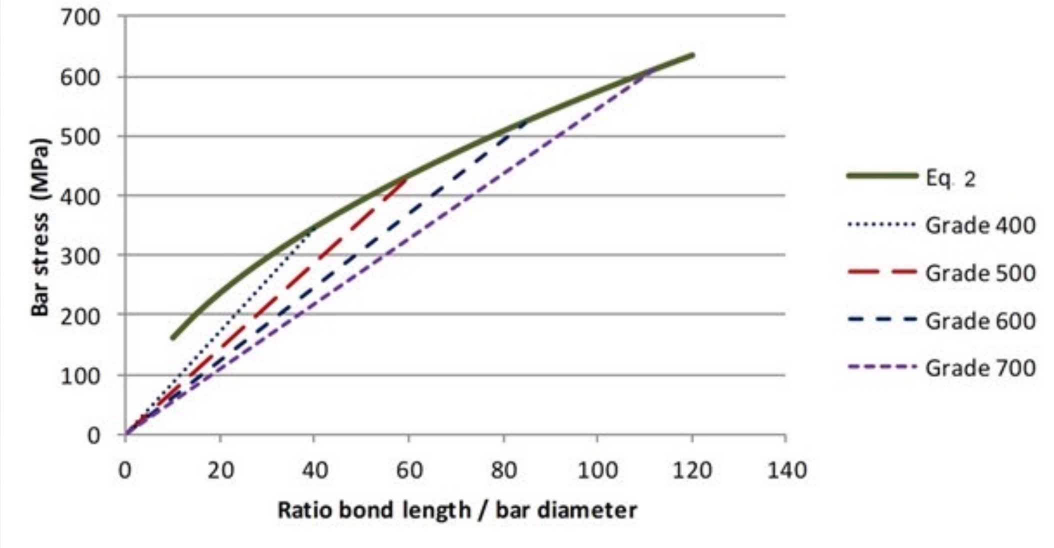
c) conditions for c_d

2.2a Bond length and elimination of ultimate bond strength

$$f_{stm} = 54\left(\frac{f_{cm}}{25}\right)^{0.25}\left(\frac{l_b}{\phi}\right)^{0.55}\left(\frac{25}{\phi}\right)^{0.2}\left[\left(\frac{c_{min}}{\phi}\right)^{0.25}\left(\frac{c_{max}}{c_{min}}\right)^{0.1} + k_m K_{tr}\right] \qquad \text{Eq 2}$$

Eq 2 mean anchorage strength expression, from fib Bulletin 72

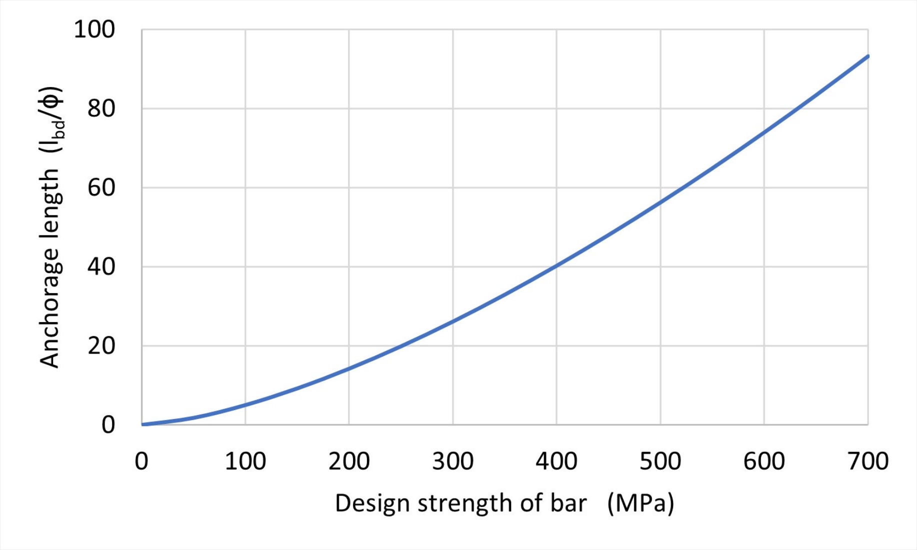
Gradient of straight lines represents average bond stress



2.2b Influence of design strength of bar

$$l_{bd} = k_{lb} \cdot k_{cp} \cdot \phi \cdot \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1{,}5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\phi \qquad (11.3)$$

$n_\sigma = 1.5$



$f_{ck} = 30\text{MPa}$
$\phi = 20\text{mm}$
$c_d = 30\text{mm}$

Non-linear influence of bond length

2.3 Influence of concrete strength

EC2:2004

$$f_{bd} = 2,25\ \eta_1\ \eta_2\ f_{ctd}$$

Tensile strength of concrete

$$f_{ctd} = fn(f_{ck})^{0.67}$$

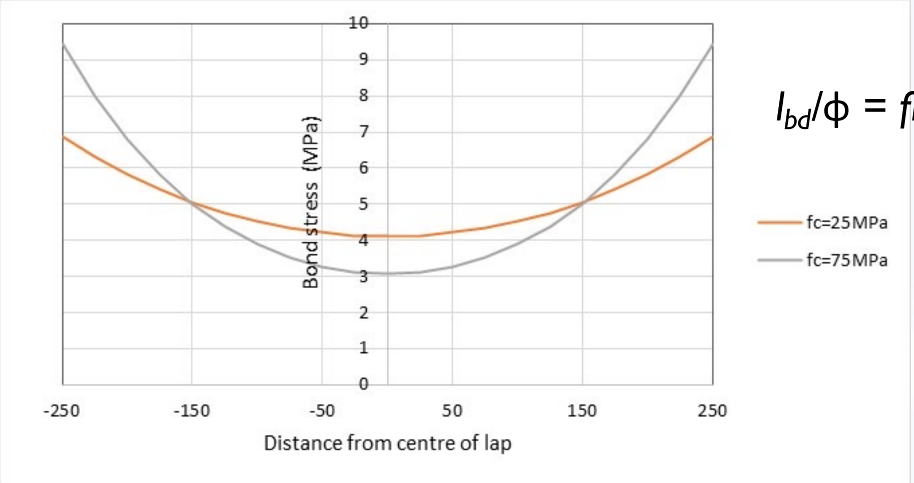
=>

$$l_{bd}/\phi = fn(f_{ck})^{0.67}$$

Valid only for short bond lengths

FprEC2:2023

$$l_{bd} = k_{lb} \cdot k_{cp} \cdot \phi \cdot \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1,5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\phi$$



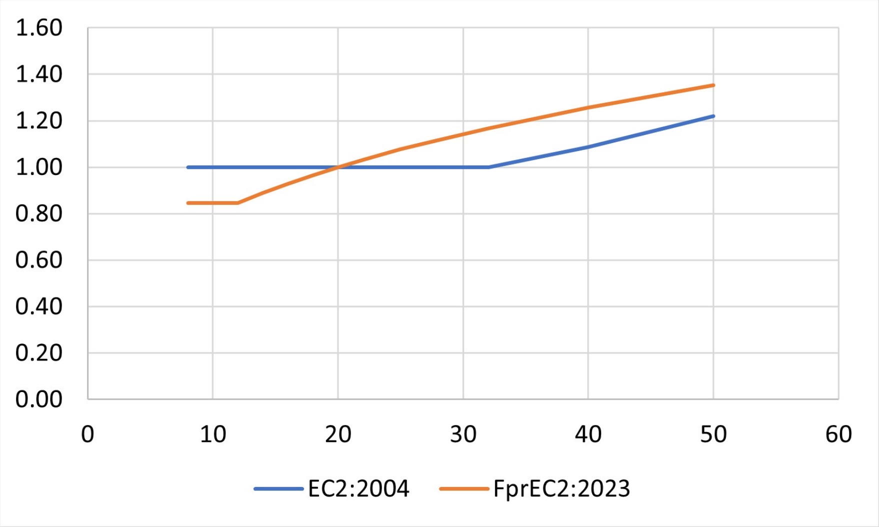
$$l_{bd}/\phi = fn(f_{ck})^{0.5}$$

Pair of lapped bars, ϕ = 25mm, l_b = 20ϕ, σ_s = 400MPa

2.4 Influence of bar size

EC2:2004

$\eta_2 = 1{,}0$ for $\phi \leq 32$ mm
$\eta_2 = (132 - \phi)/100$ for $\phi > 32$ mm



FprEC2:2023

$$l_{bd} = k_{lb} \cdot k_{cp} \cdot \phi \cdot \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1{,}5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\phi$$

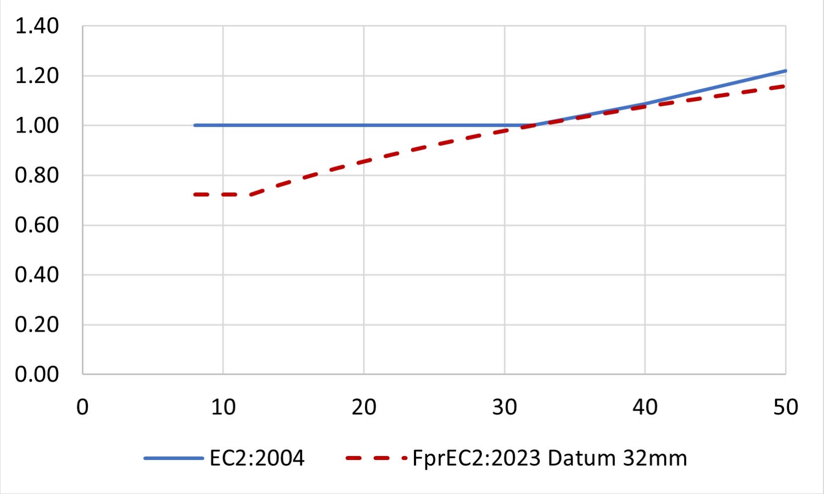
$\phi/20 \geq 0.6$ based on test data and lower rib area required for bars <12mm:

Value of function for bar size

2.4 Influence of bar size

EC2:2004

η_2 = 1,0 for $\phi \leq 32$ mm
η_2 = (132 - ϕ)/100 for $\phi > 32$ mm



FprEC2:2023

$$l_{bd} = k_{lb} \cdot k_{cp} \cdot \phi \cdot \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1,5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\phi$$

$\phi/20 \geq 0.6$ based on test data and lower rib area required for bars <12mm:

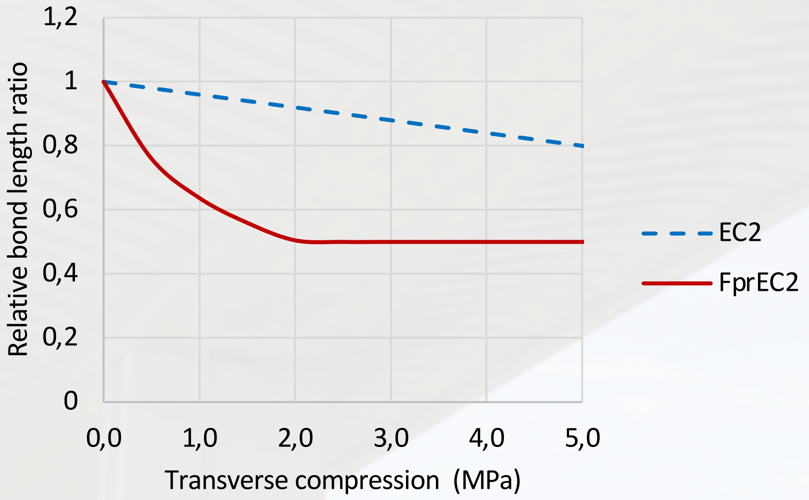
Influence on bond length, rebased to common datum (32mm)

2.5 Influence of transverse compression

EC2:2004

$\alpha_5 = 1{,}0 - 0.04p$

$0.7 \leq \alpha_5 \leq 1.0$



FprEC2:2023

$$\Delta c_d = (70\rho_{conf} + 12\sigma_{ccd}/\sqrt{f_{ck}})\phi;$$

(FprEC2 relative bond length dependent on other contributions to confinement)

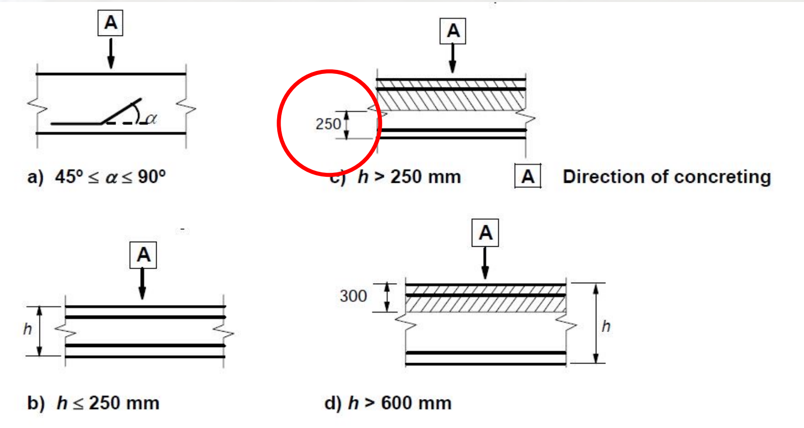
2.6 Casting position (bars < 45° to horizontal)

EC2:2004

Coefficient η_1 applied to bond strength:

η_1 = 1.0 and 0.7 for good and poor bond conditions respectively.

Equivalent to 43% greater bond lengths for poor condition



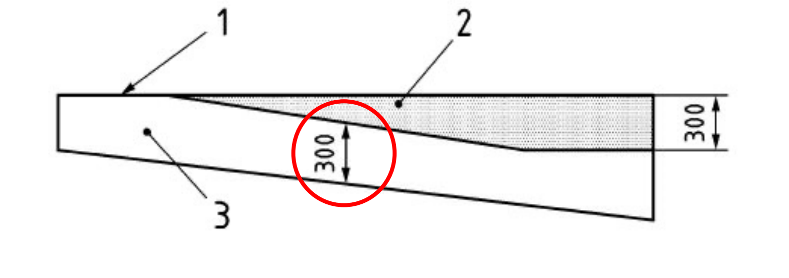
FprEC2:2023

Coefficient k_{cp} applied to bond length:

k_{cp} = 1.0 for good bond conditions

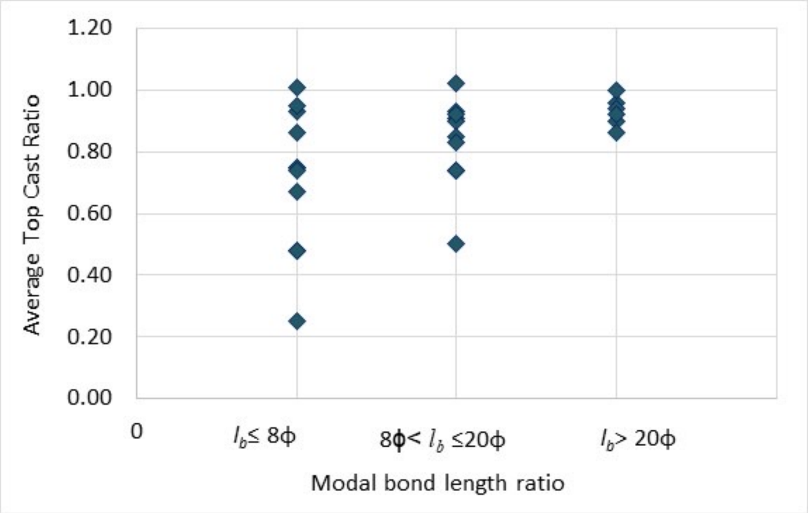
k_{cp} = 1.2 for poor bond conditions

k_{cp} = 1.4 under bentonite or similar



2.6a Casting position

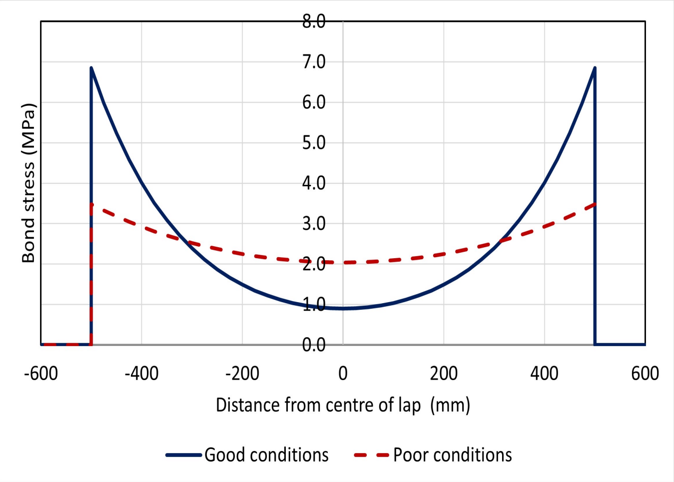
Top cast ratio = maximum stress anchored in bar cast near top of pour/ that in bar cast near the bottom

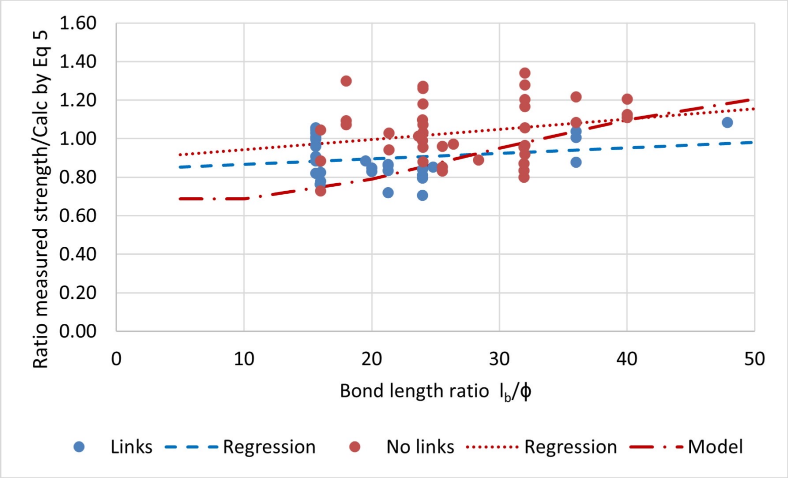


Wide range reported

2.6b Casting position

Analysis of distribution of bond stress through lap using MC2010 local bond-slip model





Over practical bond lengths, more uniform distribution of bond stress through a 'top cast' lap partially compensates for weaker bond strength in a 'poor' casting position

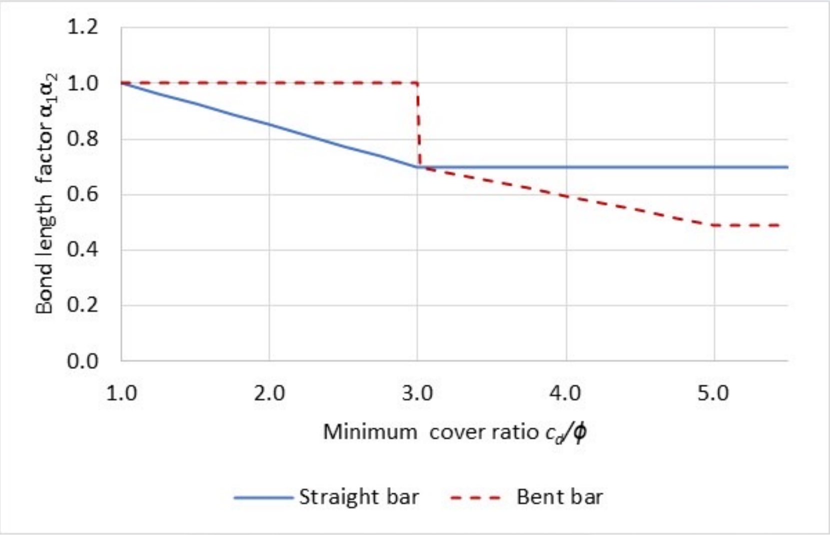
3 Contribution of end hooks and bends to tension anchorages

EC2:2004

Influencing factor	Type of anchorage	Reinforcement bar: In tension
Shape of bars	Straight	$\alpha_1 = 1{,}0$
	Other than straight (see Figure 8.1 (b), (c) and (d)	$\alpha_1 = 0{,}7$ if $c_d > 3\phi$ otherwise $\alpha_1 = 1{,}0$ (see Figure 8.3 for values of c_d)

30% reduction in anchorage length for hook or bend, provided $c_d/\phi > 3.0$

- Contribution of a bend increases with stress to be anchored
- No reduction in l_{bd} for $c_d \leq 3\phi$?



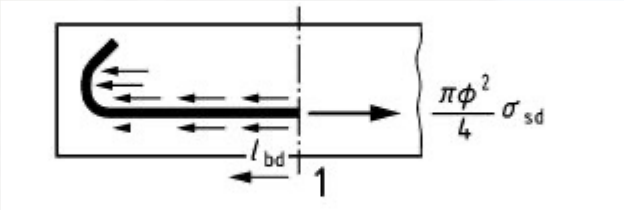
3b Contribution of end hooks and bends to tension anchorages

EC2:2004

Influencing factor	Type of anchorage	Reinforcement bar: In tension
Shape of bars	Straight	$\alpha_1 = 1{,}0$
	Other than straight (see Figure 8.1 (b), (c) and (d)	$\alpha_1 = 0{,}7$ if $c_d > 3\phi$ otherwise $\alpha_1 = 1{,}0$ (see Figure 8.3 for values of c_d)

30% reduction in anchorage length for hook or bend, provided $c_d/\phi > 3.0$

FprEC2:2023



The design anchorage length may be reduced by:

15ϕ for standard hooks and bends

20ϕ for U-loops

4 Tension laps, straight bars

EC2:2004

Percentage of lapped bars relative to the total cross-section area	< 25%	33%	50%	>50%
α_6	1	1,15	1,4	1,5
Note: Intermediate values may be determined by interpolation.				

$$l_0 = \alpha_1 \alpha_2 \alpha_3 \alpha_5 \alpha_6 l_{b,rqd} \geq l_{0,min}$$

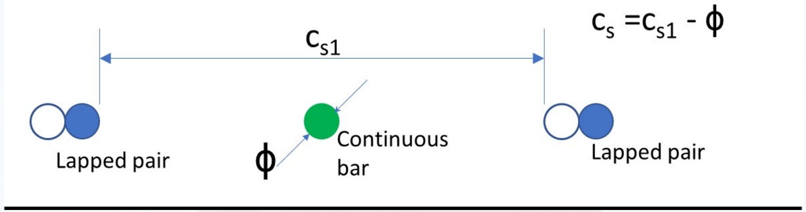
Rules similar to anchorages but with factor α_6 dependent on percentage bars lapped at section

FprEC2:2023

k_{ls} = 1,2

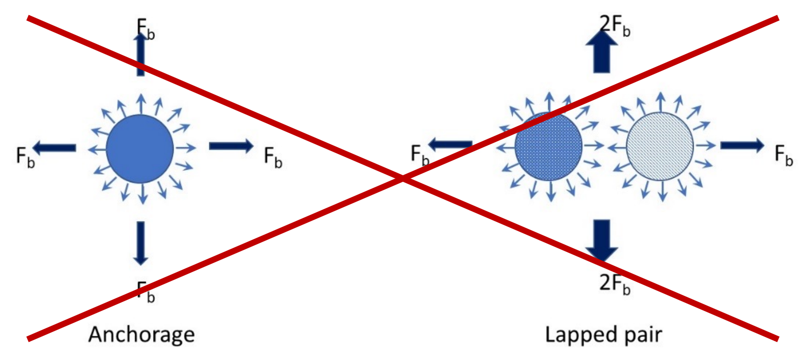
Rules similar to anchorages but with factor k_{ls} = 1,2 (NDP) independent of percentage bars lapped at section

Clarification of bar spacing dimension for staggered laps



4.1 Tension laps, straight bars

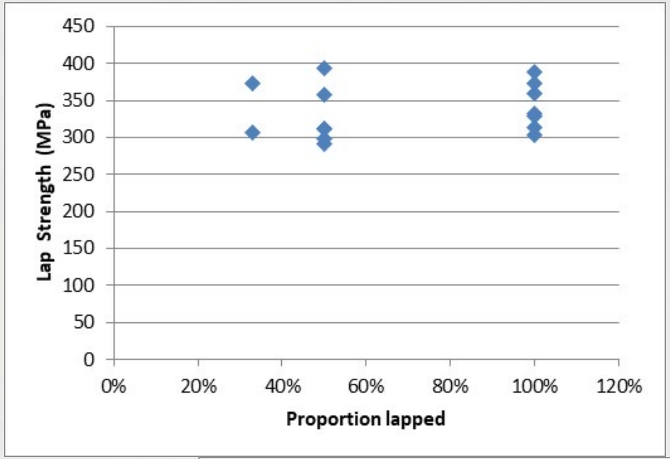
1975: Hydraulic pressure analogy laps vs. anchorages



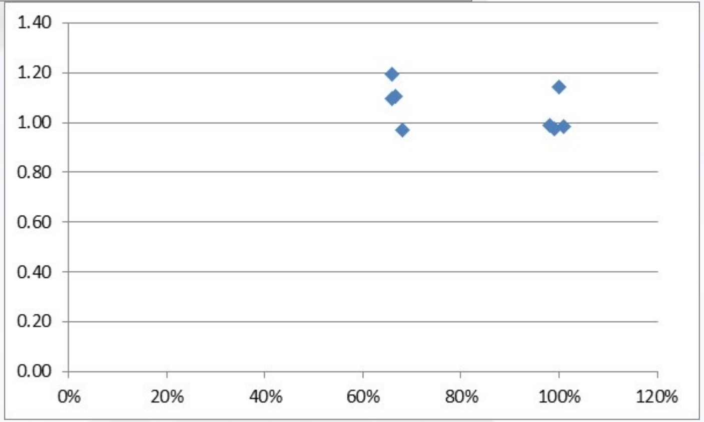
Laps produce double the splitting of anchorages

α_6 factor in EC2:2004 inconsistent with test results

Test evidence

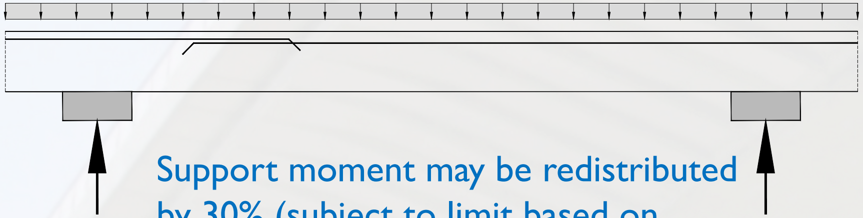


Cairns 2014

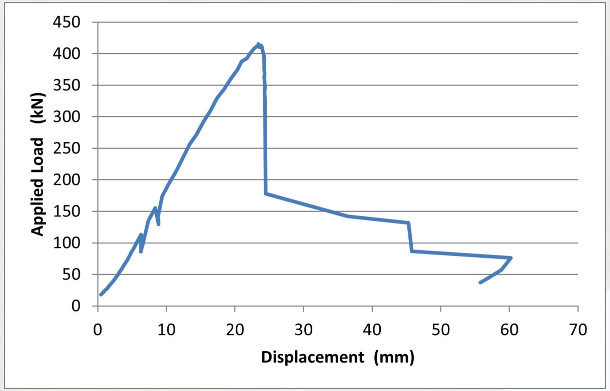


Thompson Jirsa
Breen Meinheit
1975

4.2 Tension laps, robustness

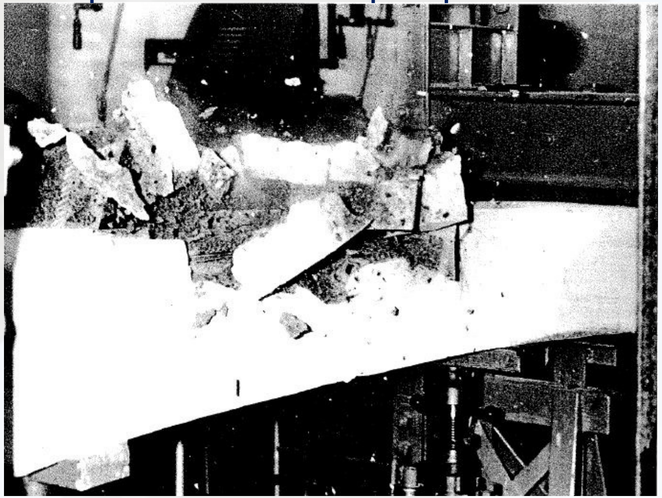


Support moment may be redistributed by 30% (subject to limit based on section ductility)



>50% strength loss immediately after peak load

Explosive failure of lap, Tepfers 1974

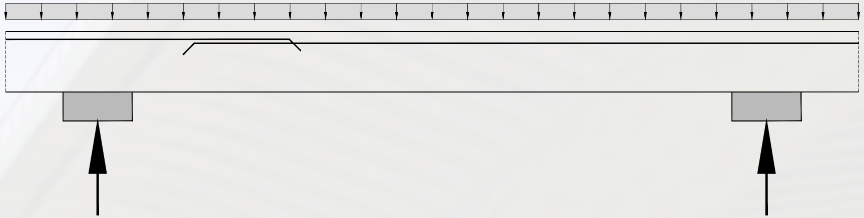


Locate laps away from areas of high bar stress wherever possible

4.2a Tension laps, robustness

EC2:2004

No specific requirements



FprEC2:2023

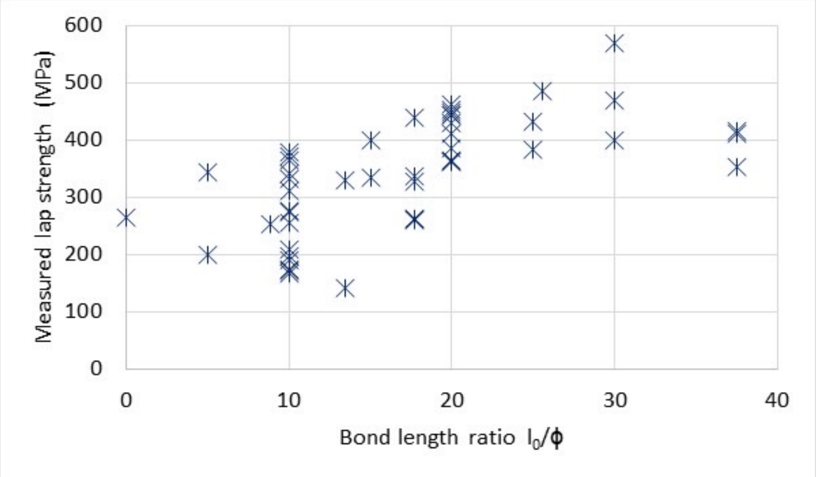
Additional requirements for laps in vicinity of plastic hinges/yield lines :

- additional confining reinforcement provided
- area lapped ≤ 35%

Alternatively

- Design for 1,2 σ_{sd}

5 Compression laps and anchorages



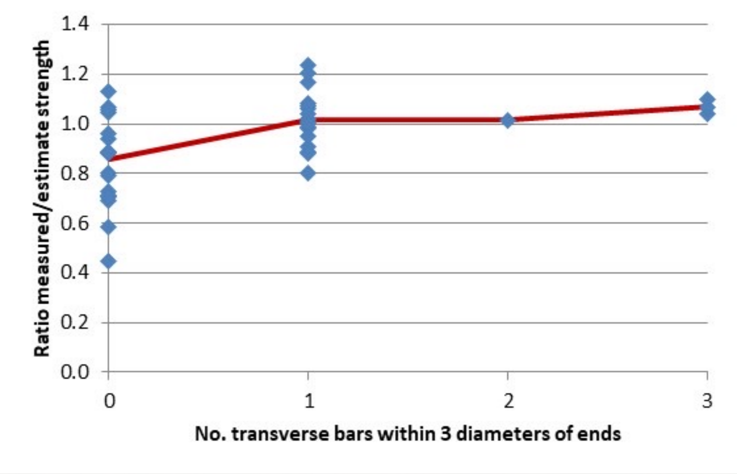
Strength of compression laps, all test results

FprEC2:2023

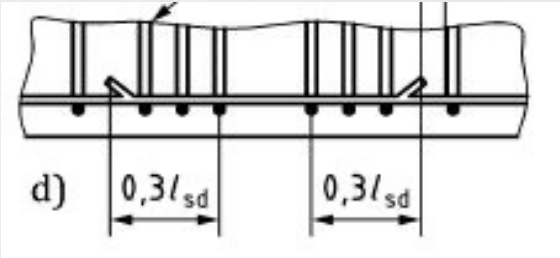
Expressions 11.3 and 11.4 as for bars in tension

Design anchorage length may be reduced by 15ϕ provided requirements for detailing of links near ends of laps are satisfied

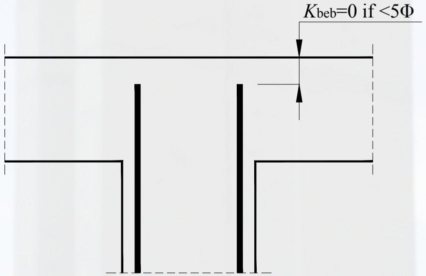
5b Compression laps and anchorages



Weaker anchorage if no links near ends



Confining reinforcement to be located close to ends of compression laps



No allowance for bars ending near a face

6 New content

Bonded post-installed reinforcing steel

Broadly consistent with cast-in, but additional requirements on anchoring mortar, cover.

Additional restrictions on concrete grade, σ_{sd}

Headed bars

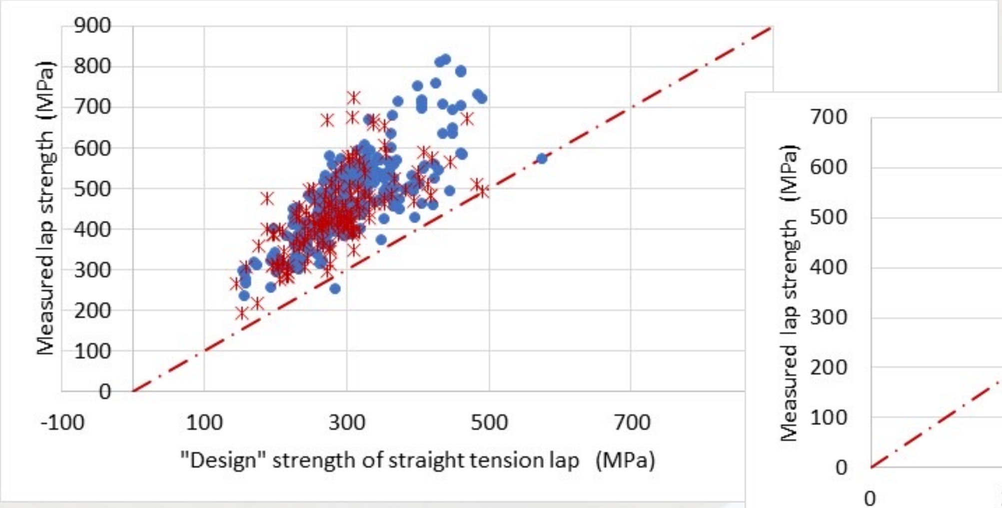
Head can provide full anchorage for Grade 500 bars if specified conditions of cover, spacing, head geometry, concrete strength are satisfied.

Detailed provisions for head capacity in other circumstances

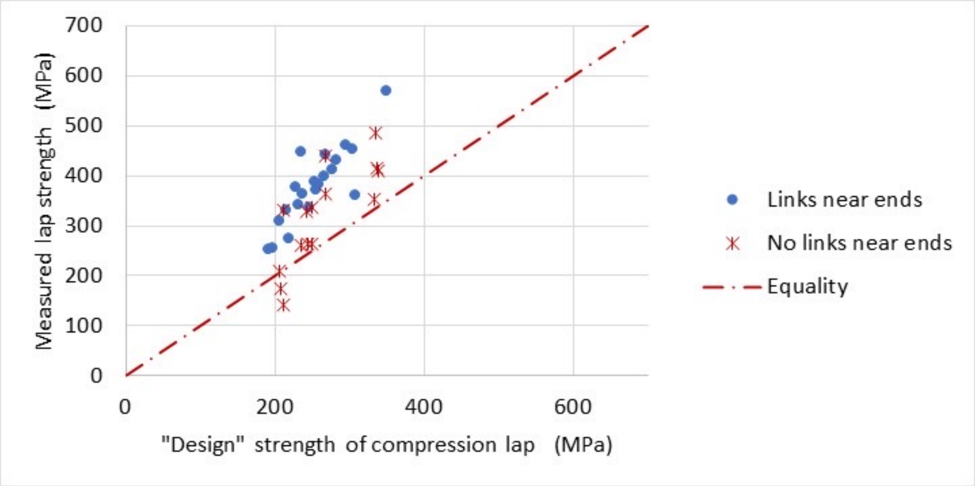
Additional 10% on bond length where head and straight length of bar act in combination

7 Impact on design

FprEC2:2023 provisions validated against extensive sets of data



Tension laps



Compression laps

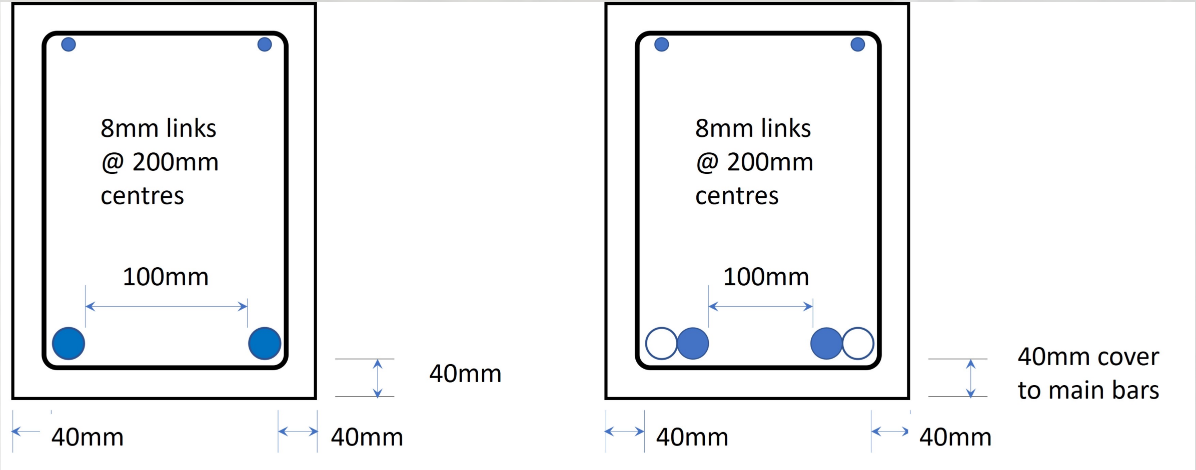
7 Impact on design

Sample sections

Bar sizes 12 and 25 (c_d/ϕ 3.33 and 1.6)

Concrete strength f_{ck} 25MPa and 60MPa

Design for σ_{sd} = 435 MPa



c_d = 40mm

Anchorage

Lap

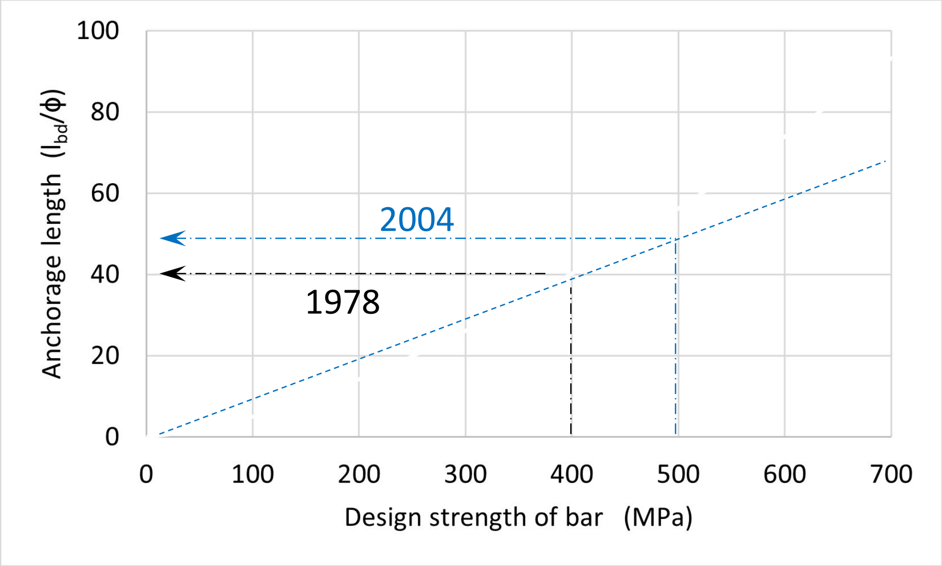
7.1 Impact on design

Evolution of bar strength

1978 : f_{yk} ~ 400MPa

Say bond length corresponds to 40ϕ

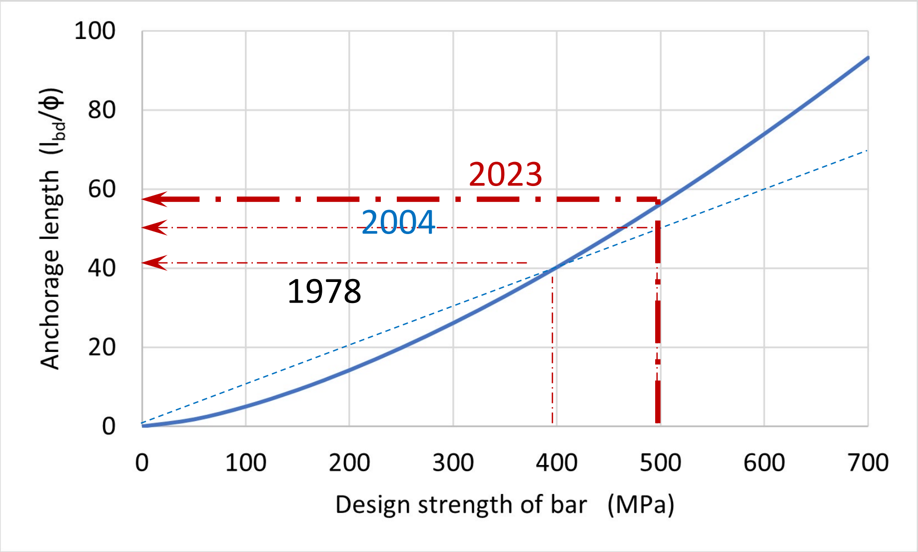
7.1 Impact on design



1978 : f_{yk} ~ 400MPa

f_{yk} now ~ 500MPa
EC2:2004 provisions => l_{bd} = 50 ϕ
a +25% increase

7.1 Impact on design



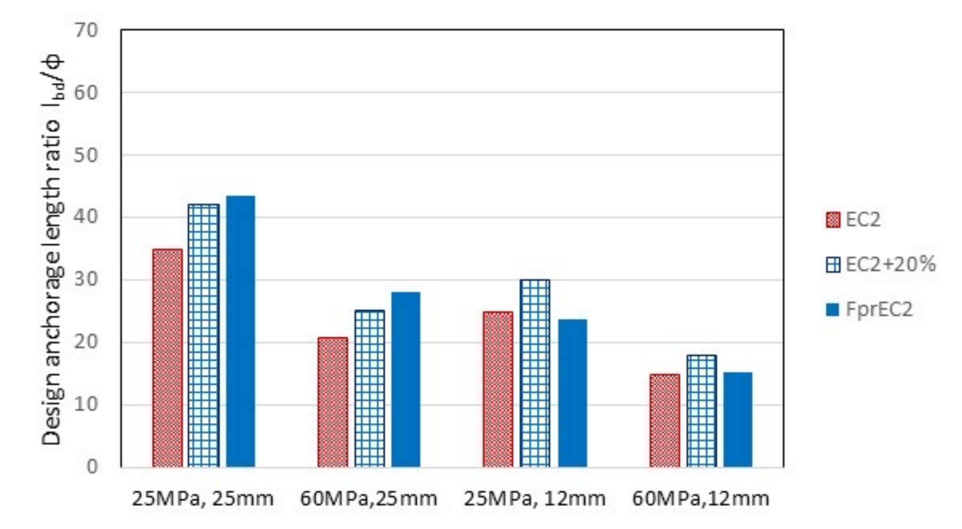
1978 : f_{yk} ~ 400MPa

f_{yk} increased to ~ 500MPa
EC2:2004 provisions => l_{bd} = 50 ϕ
a +25% increase

But allowing for non-linear behaviour
=> l_{bd} = 55.9ϕ
i.e. 12% greater increase

MC2020 indicates 20% increase

7.2a Impact on design



EC2 : design bond length according to EC2:2004, the current EuroCode

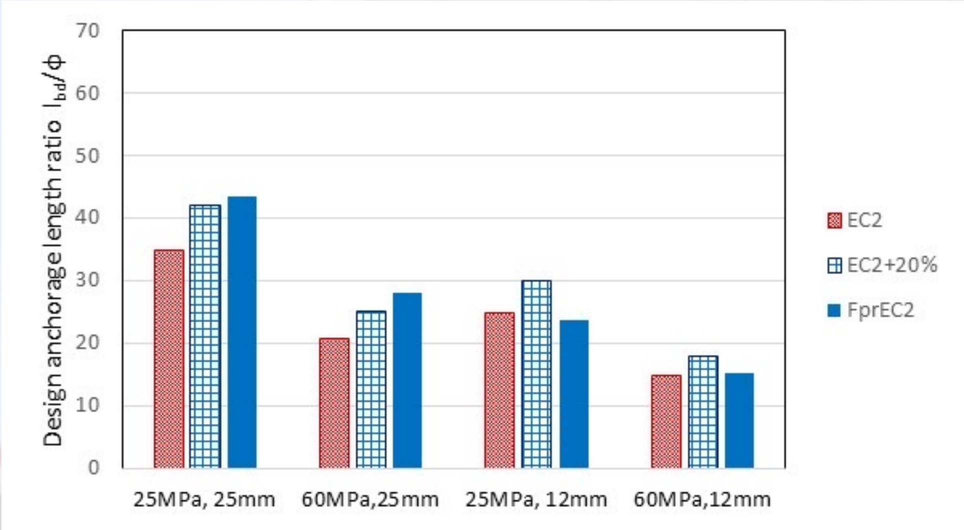
EC2+20% : design bond length according to EC2:2004 with correction for steel strength

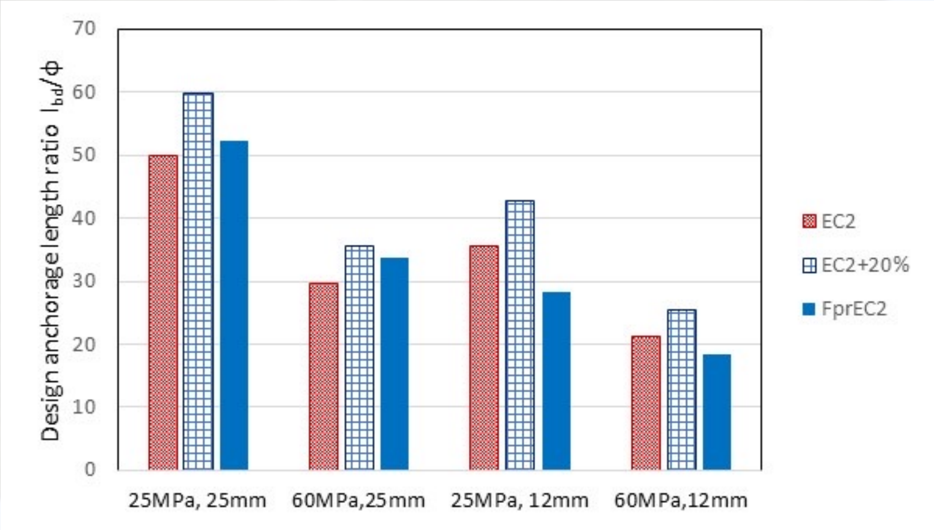
FprEC2 : design bond length according to FprEC2:2023, the revised EC

Anchorage, good casting position

Longer anchorage lengths for larger bars

7.2a Impact on design





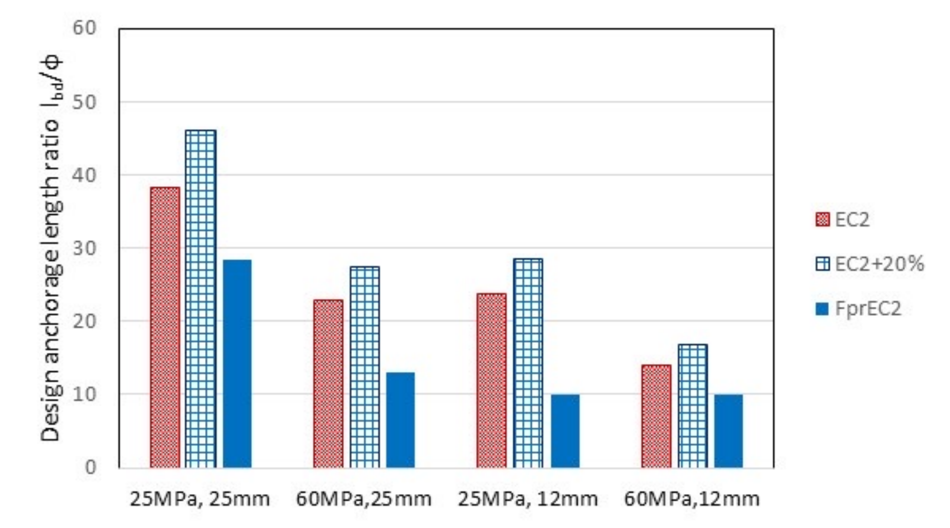
Anchorage, good casting position

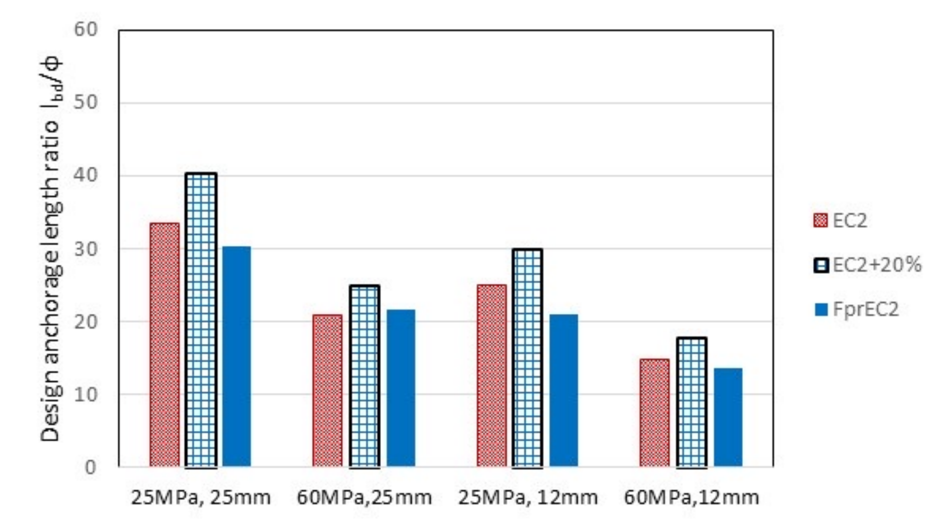
Longer anchorage lengths for larger bars

Anchorage, poor casting position

Little difference larger bars, shorter small bars

7.2b Impact on design





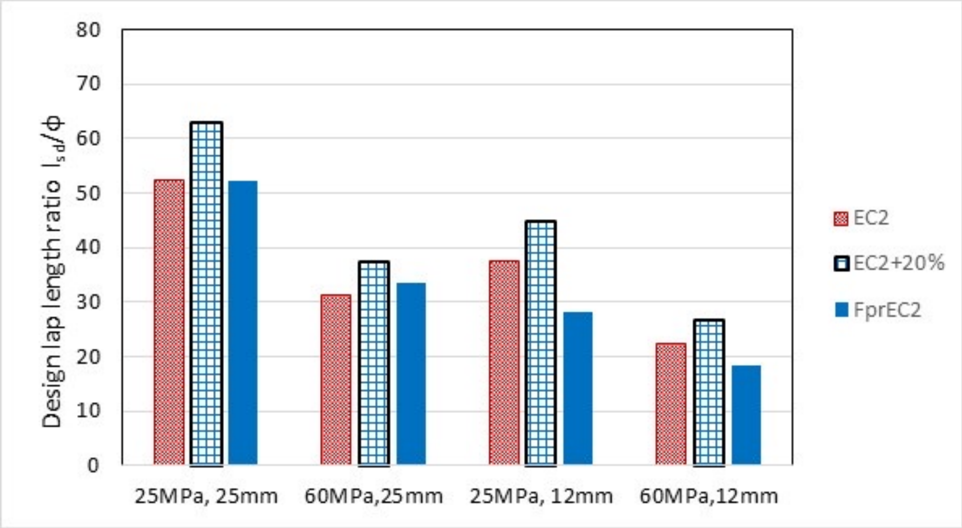
Hook/bent bar, good casting position

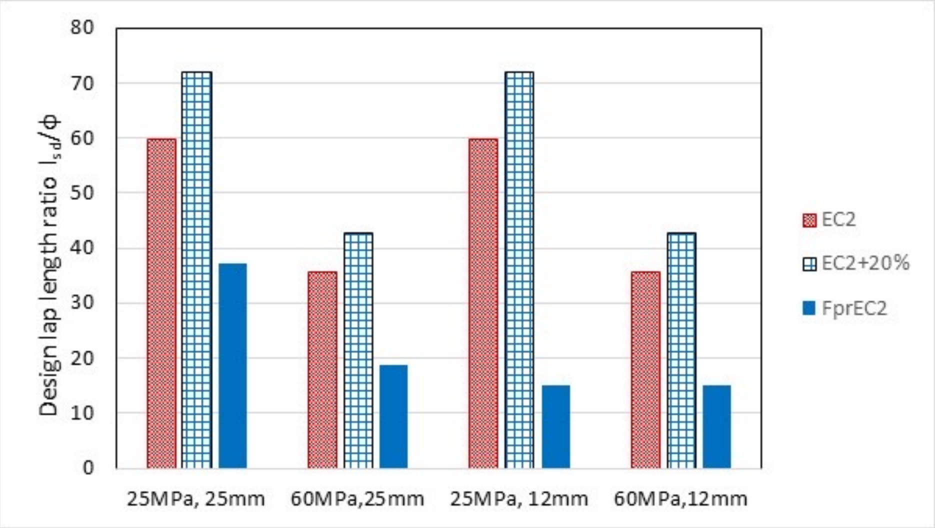
Shorter anchorage lengths

Anchorage subject to 1.0 MPa transverse compression, good casting position

Shorter anchorage lengths

7.2c Impact on design





Tension lap, good casting position, 100% lapped

Generally slightly shorter lap lengths

Compression lap, good casting position

Considerably shorter lap lengths

Summary

1. Extensive revision of section on anchorage and laps of reinforcing steel in FprEC2:2023
2. *fib* Bulletin 72 has formed the basis for many of the revised provisions
3. 'Bond strength' eliminated, non-linear variation in capacity with bond length recognized, hence bond lengths now calculated directly
4. Look-up table for routine situations, detailed expressions account for greater (or lesser) confinement from cover, transverse reinforcement or transverse pressure
5. Hooks/bends contribute an equivalent straight bond length, reduced influence of poor casting position, etc.
6. Compression laps/anchorage treated in a more consistent and rational manner
7. New content on PIR, headed bars, assessment
8. Typically modest increase in design anchorage lengths of larger size straight bars, reductions for bent/hooked bars or U-loops, bars in compression

Thank you for your attention

John Cairns