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Design Provisions for Anchorages and Laps in the Revised EC2

Disposiciones de diseño para anclajes y solapes en la revisión del EC2

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ABSTRACT

The second generation of the Structural Eurocodes is expected to be published by 2026. This article describes design provisions for laps and anchorages of normal ribbed reinforcement in Sections 11.4 and 11.5 of FprEN_1992_1_1:2023, the forthcoming version of Eurocode 2, the European Code for Design of Concrete Structures. This article outlines why and how design provisions have been modified, demonstrates the physical rationale for the rules and notes the evidence on which the justification is based. It also indicates the impact of the revisions.

The article gives an overview of the factors influencing anchorage and lap strength and presents a historic perspective on the development of the revised rules. The influence of each factor as represented in current and revised Eurocode 2 are then compared. The revised rules are then validated against test databases for anchorages and for tension and compression laps, and the impact of the revisions on design practice for selected situations are briefly examined.

KEYWORDS: Structural concrete design, EC2, bond, anchorages, lap joints, lap splices, casting position.

RESUMEN

La segunda generación de Eurocódigos Estructurales tiene prevista su publicación en 2026. En este artículo se describen las disposiciones de diseño para solapes y anclajes de armaduras nervadas normales de las secciones 11.4 y 11.5 del borrador final de la próxima versión del Eurocódigo 2, el Código Europeo para el Diseño de Estructuras de Hormigón. Este artículo describe por qué y cómo se han modificado las disposiciones de diseño, demuestra la justificación física de las normas y señala las pruebas en las que se basa la justificación. También indica el impacto de las revisiones.

El artículo ofrece una visión general de los factores que influyen en el anclaje y la resistencia de solape y presenta una perspectiva histórica del desarrollo de las normas revisadas. A continuación se compara la influencia de cada factor tal como se representa en las normas actuales y en las revisadas. Las normas revisadas se validan con bases de datos de ensayos de anclajes y solapes a tracción y compresión, y se examina brevemente el impacto de las revisiones en la práctica del diseño para situaciones seleccionadas.

PALABRAS CLAVE: Diseño de hormigón estructural, EC2, unión, anclaje, solape, empalme.

1.
INTRODUCTION

The second generation of the Structural Eurocodes is expected to be published by 2026. This article describes design provisions for laps and anchorages of normal ribbed reinforcement in Sections 11.4 and 11.5 of FprEN_1992_1_1:2023 [1], the forthcoming version of Eurocode 2, the European Code for Design of Concrete Structures, which revises and enhances the current Standard EN1992_1_1:2004 (EC2) [2].

The basic expressions for design and anchorage which appear in EC2(2004) are essentially those proposed in the 1978 edition of the CEB-FIP Model Code [3] (MC78), although there were a few, generally modest, differences in the value of

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coefficients. Since that time there has been a general increase in the strengths of both concrete and reinforcement used in construction. For example, the characteristic strength of reinforcement in many European countries was around 400 MPa in 1978 but is currently 500 MPa. The CEB Bulletin on High Performance Concrete [4] (CEB 1995) recommended that concrete grades be extended from the then limit of C80/100 up to C100/125, and that the validity of current rules for bond and anchorage should be reconsidered. New materials and technologies with differing bond and anchorage capabilities have been introduced, for example headed and post-installed bars, and design rules need to be extended to cover these innovations. Some aspects of current EC2 design rules appear inconsistent with recent research findings, for example, research has demonstrated a markedly lesser difference in capacity between lapped joints and anchorages than current requirements suggest. As a considerable amount of research into behaviour of anchorages and laps has been carried out over the past 50 years since MC78 was drafted, a significant revision of the rules in the first generation document was considered necessary.

Anchorage and laps of reinforcement attracted a substantial number of comments at the recently completed enquiry stage, and there is evidently a need to explain the basis for the revisions. The objectives of this article are to outline why and how design provisions have been modified, to demonstrate the physical rationale for the rules where appropriate, to note the evidence on which the justification is based and to indicate the impact of the revisions, with the overall aim of promoting an understanding of the justification for the new rules.

Throughout this article, "EC2" denotes the current version of the EC1992-1-1:2004 and "FprEC2" denotes the 2023 Formal Vote draft of the enhanced version. Equations, tables, and figures have been numbered sequentially in citation order in this article. References to equations, tables, and figures taken directly from FprEC2 are additionally given in {curly brackets}. It does not reproduce sections of the Code in detail and is intended to be read alongside the revised Code. At the time of writing the Formal Vote process is about to begin and it is po1ssible that some minor adjustments will be introduced before a final version is published.

2.

BOND, ANCHORAGES AND LAPS: GENERAL CONSIDERATIONS

Bond and anchorage are the terms used to denote the transfer of force between reinforcement and concrete. Design rules for anchorages and laps are found in sections {11.4} and {11.5} respectively in FprEC2. Anchorages transfer force from bar to concrete, for example at ends of members or where bars are curtailed where a member has sufficient capacity without their contribution; the force in an anchored bar reduces to zero over the anchorage length. Laps provide continuity of force in reinforcement, transferring force from one of a lapped pair to the other bars via the surrounding concrete; the force in a lapped pair remains approximately constant over the lap length.

Bond has conventionally been described as a shear stress on the nominal perimeter of a bar, calculated as the change in bar force over a certain distance divided by the (nominal) area of bar surface over which this change takes place, Eq.1. This represents a major simplification as most bars produced today rely on the bearing of ribs rolled onto or indented into the surface of the bar during manufacture to transfer force. Although the transfer of force between reinforcement and concrete depends on adhesion and friction over the whole bar surface at low bond stress, as the ultimate limit state is approached bond relies increasingly on bearing of the ribs on the concrete. The definition of Eq. 1 is, nonetheless, a convenient one and is widely used.

$$f_b = \Delta\sigma_s A_s / (\pi\, \phi\, l_b) \tag{1}$$

where

f_b is the average bond stress over length l_b

$\Delta\sigma_s$ is the change in bar stress over l_b

A_s is the cross-sectional area of the bar

ϕ is the nominal diameter of the bar

l_b is the bond length over which $\Delta\sigma_s$ takes place

The simplicity of Eq. 1 can be misleading; the evaluation of bond resistance is complex, and while there has long been general agreement over the parameters which influence bond resistance, quantification of the magnitude of the contribution attributable to each parameter varies widely. The distribution of bond stress throughout an anchorage or lap length is non-uniform, a topic explored later in this article, see Figure 4. EC2 includes no less than 10 parameters for the calculation of anchorage or lap length. There are two broad forms of failure mode depending on whether or not concrete cover splits, and within the splitting mode there are a number of sub-modes dependent on section geometry. The one common conclusion on which all agree is that bond is not a fundamental property of the bar, as has been asserted in the past, but is a quantity influenced by bar and concrete section geometry, materials characteristics, and stress state.

Bond over a straight length of bar may be supplemented by other features which contribute to transfer of force between bar and concrete. These features may include welded cross bars, a hook or bend formed close to the end of the bar, a plate or head welded to the end of the bar, or in the case of bars in compression, bearing of the end of the bar on concrete. Because of the variation in bar concrete slip over a lap or anchorage length and differences in load-slip characteristics, the contributions of these other forms of anchorage cannot be directly summed with that of bond over the straight length of a bar, and it is necessary to consider their interaction to determine the combined resistance. Such analysis lies outside the scope of normal design, and for practical purposes a nominal allowance is given in Code rules to evaluate their contribution.

3.

BACKGROUND TO THE REVISION AND DEVELOPMENT OF DESIGN EXPRESSION

A comprehensive reappraisal of provisions for laps and anchorages was initiated by *fib* TG4.5 (now TG2.5) and published in *fib* Bulletin 72 [5] in 2014. Bulletin 72 reported a

TABLE 1.
Summary of fit of Eq. 2 to test results [5].

Database	*fib* TG 4.5[8]				Amin[9]
	Laps with links	Laps without links	Anchorages with links	Anchorages without links	Anchorages without links
Mean	1.00	0.97	0.98	0.93	1.01
Coefft. of Variation	0.132	0.150	0.176	0.118	0.16
Minimum	0.68	0.62	0.63	0.76	0.61
5% char. ratio	0.78	0.73	0.70	0.75	0.75
No. of results	288	255	18	21	164

detailed semi-empirical analysis in which a form of expression based on physical analysis of influencing parameters was calibrated using and validated against a database compiled by *fib* TG 4.5 comprising around 800 relevant results of tests on lapped joints and around 100 tests on end anchorages. Contributions of cover, secondary reinforcement and transverse compression are summative, in contrast to the multiplicative format in EC2. The format of the expression adopted reflects a view that the influence of each of these contributions acting in combination would tend to be equal to or less than the sum of their contributions taken individually, and that a factorial combination could potentially lead to less safe provisions. Limits were set on the range of accepted parameters to reflect normal practice as well as the limits to test parameters in the database: 15 MPa< f_{cm} < 110 MPa, $0.5 \le c_{min}/\phi \le 3.5$, $c_{max}/c_{min} \le 5.0$, $k_{tr} \le 0.05$, $l_b \ge 10\phi$. The mean strength expression for bond, anchorages and laps proposed and validated in *fib* Bulletin 72, Eq. 2, is well regarded and subsequent studies have independently confirmed its suitability as the basis of design provisions [6],[7]. Equation 2 is suitable for evaluation both of anchorages of individual bars and for lapped pairs of bars. A summary of the statistical fit of Eq. 2 to test results compiled by *fib* TG4.5 [8] and by Amin [9] is shown in Table 1.

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

where

f_{stm} is the estimated stress developed in the bar (mean value)
f_{cm} is the measured concrete cylinder compressive strength
l_b and ϕ are the bond length and diameter of the lapped or anchored bar respectively,
c_{max} and c_{min} are defined in Figure 1.
$K_{tr} = n_l.n_g.A_{sv}/(l_b.\phi.n_b)$
n_g is the number of groups of links within the lap or anchorage length,
n_l is the number of legs of a link in each group which cross the potential splitting failure plane
A_{sv} the area of each leg of a link, and
n_s the number of bars lapped or anchored at the section
n_b is the number of individual anchored bars or pairs of lapped bars alternatively, $K_{tr} = n_l.A_{sv}/(s_v.\phi.n_b)$, where s_v is the spacing between groups of links
k_m is an 'effectiveness factor' for link confinement

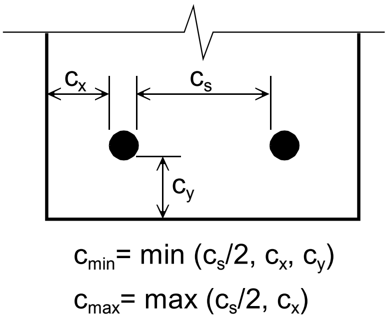


Figure 1. Definition of concrete cover dimensions.

Design values for bond stress in Bulletin 72 were derived from Eq, 2 in a relatively simple manner, assuming a normal distribution in the variability of tests results, determining a 95% lower bound characteristic value, and applying a partial safety coefficient of 1.5 to the characteristic value.

The derivation of design values for anchorage and lap length in FprEC2 has evolved through several stages since then. Mancini *et al* [10] subsequently performed a rigorous statistical analysis of the lap data compiled by fib TG4.5 and demonstrated that no significant trends of variation are found on the database. They note, however, that a log-normal distribution provided a better representation of the measured to estimated strength ratio of test results. A probabilistic calibration of the mean strength expression was performed defining the related model uncertainties, grounded on the experimental database, following the reliability format defined by Taerwe [11]. Focusing on ordinary structures with 50 years of service life, the accepted target level of reliability was taken to be β = 3.8. The semi-empirical Eq. 2 was processed accounting both for model uncertainties and random variability of concrete strength to derive a reliability-based design expression, although it was noted that concrete cover might also have been treated as a random variable. They noted that with EC2 provisions in which a uniform bond stress independent of the bar stress to be developed is assumed, reliability index β becomes significantly higher than the target 3.8 in case of low-stressed bars, but could become unconservative for high strength bars, thus prompting a move away from a notional average design bond strength towards direct calculation of anchorage and lap length. The analysis assumed that the variability assumed for concrete strengths was sufficient to cover the weaker or less well compacted concrete found in 'poor' casting conditions, although this assertion appears not to have been verified against 'top cast' data available in the ACI408 database.

Vollum and Goodchild [12] refined the analysis of Mancini *et al* by dividing test results into four stress bands, namely $f_{st,test} < 300$ MPa, 300 MPa $\leq f_{st,test} < 400$ MPa, 400 MPa $\leq f_{st,test} < 500$ MPa and $f_{st,test} \geq 500$ MPa, where the stress $f_{st,test}$ is the measured lap strength. Each stress band was analysed following the procedure of Mancini *et al.* referred to in the preceding paragraph. It is apparent that the ratio of strength measured in tests to that estimated by Eq. 2 was greater and the scatter reduced for higher strength laps. They proposed a bond length coefficient of 67 for bars designed for the full 435 MPa design strength of Grade 500 bars, a lower value than that proposed by Mancini *et al*. However, for the weaker strength intervals as used in their analysis the reduced coefficient would provide insufficient safety. To allow for this a linear relationship between the stress developed and bond length was proposed for design strengths of less than 435MPa, the design strength of a Grade 500 bar. The difference in the proposals is shown schematically in Figure 2. The Vollum & Goodchild proposal is rather conservative for medium strength anchorages, and for a stress of 250 MPa would require an anchorage 43% longer than Mancini *et al.*

$$l_{bd}/\phi = 67\ m\ (\gamma_c/1.5)^{0.64}(25/f_{ck})^{0.45}(\phi/25)^{0.36}/(\alpha_2+\alpha_3) \qquad (3a)$$

$$m = \mathrm{Max}\{\sigma_{sd}/435,\ (\sigma_{sd}/435)^{1.82}\} \qquad (3b)$$

$$\alpha_2 = (c_{min}/\phi)^{0.5}\ (c_{max}/c_{min})^{\ 0.15} \qquad (3c)$$

Where

l_{bd}	is the design value of anchorage length of reinforcing steel
67	is a dimensionless factor for calculating the design anchorage length.
ϕ	is the nominal bar diameter
σ_{sd}	is the design value of the reinforcing steel stress at the cross-section
f_{ck}	is the characteristic concrete compressive strength
c_{min} and c_{max}	are defined in Figure 1
α_3	represents confinement from transverse or confining reinforcement

Equation 3 subsequently evolved, with modifications, into the design expression in FprEC2, Eq. 4. Indexes in Eq. 4 are rounded from those in Eq. 3: only nominal adjustments have been made to indices on concrete strength, bar size and minimum cover. Index n_σ is a Nationally Defined Parameter [NDP] with a constant recommended value of 1.5 [NDP], thus moderating the conservatism of the Vollum & Goodchild proposal for bar stresses less than 435 MPa Bond length coefficient k_{lb} is a Nationally Defined Parameter (NDP). Vollum and Goodchild recommended a value of 67 as a bond length coefficient, Eq. 3a. Their analysis was based on a benchmark cover ratio of c_d/ϕ =1.0 and a bar size factor (ϕ/25), whereas Eq. 4 {11.3} is based on a benchmark of c_d/ϕ=1.5 and a bar size factor (ϕ/20). Making allowance for these differences results in an equivalent bond length coefficient $k_{lb} = 67(1.0/1.5)^{0.5}\ (20/25)^{0.33} = 50.8$ and rounding leads to the recommended value of $k_{lb} = 50$ in Eq. 4. Parameter c_{max}/c_{min} has only a very modest influence on design anchorage length and has consequently been dropped. An evaluation of Eq. 4 is presented later.

$$l_{bd} = k_{lb}\ k_{cp}\ \phi \left(\frac{\sigma_{sd}}{435}\right)^{n_\sigma} \left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}} \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \left(\frac{1.5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\ \phi \qquad (4)[11.3]$$

n_σ	is the exponent to consider effect of steel stress on anchorage length, equivalent to m in Eq. 3. n_σ = 1.5 (recommended value) for persistent and transient conditions (formerly permanent and variable)
c_d	is similar to c_{min} in Figure 1 but with some additional limits
k_{cp}	is a coefficient accounting for casting effect on bond conditions

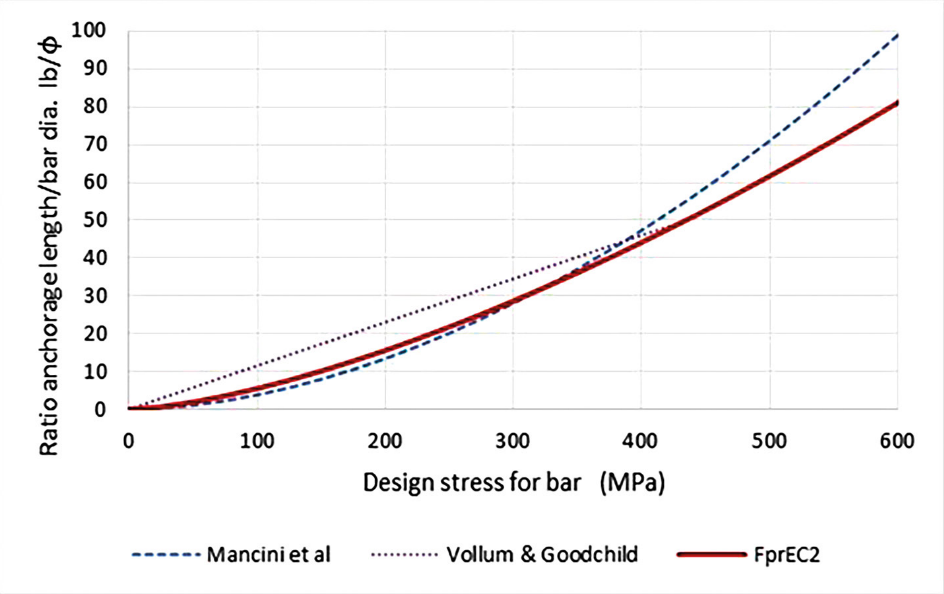


Figure 2. Comparison of proposals by Mancini et al [10], Vollum & Goodchild [12] and FprEC2 [1].

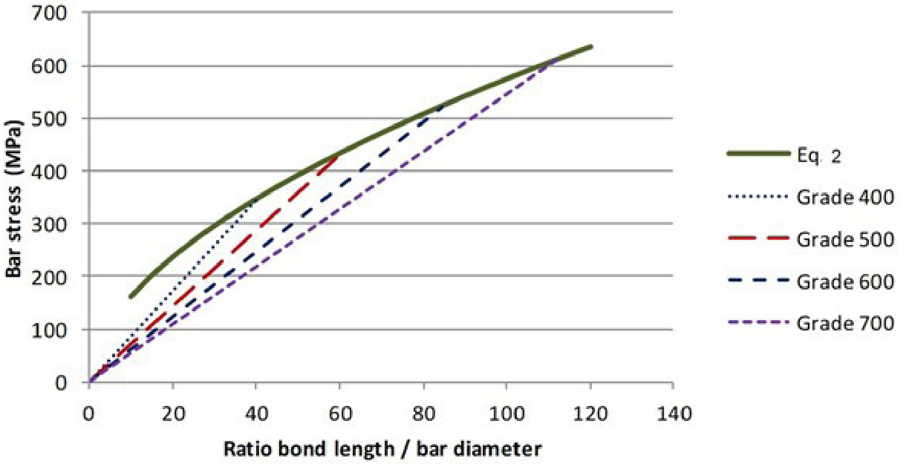


Figure 3. Influence of bond length on anchorage and lap strength.

$25/f_{ck}$ represents the influence of concrete strength
$\phi/20$ represents the influence of bar size
$1.5\phi/c_d$ represents splitting resistance provided by concrete cover.

4.
ANCHORAGE LENGTHS OF STRAIGHT BARS IN TENSION IN FPREC2 {11.4.2}

The format of design provisions in FprEC2 is markedly different from that in EC2. Anchorage length is calculated directly from material properties and geometric parameters, in contrast to EC2 provisions where an ultimate bond strength and a basic anchorage length are first obtained {from Eqs. 8.2 and 8.3 respectively}, the basic anchorage length then being modified by a set of α coefficients related to concrete cover, confining reinforcement, and transverse compression. Design bond length is no longer directly proportional to the stress to be anchored. In EC2 factors α_2, α_3 and α_5 for the contribution of cover, secondary reinforcement or pressure were multiplicative, in FprEC2 they are now summative, following the approach adopted in Bulletin 72, Eq. 2. The revised provisions do not require calculation of a notional bond strength as in the earlier version, and therefore provide a more direct route to design anchorage length.

The elimination of 'bond strength' from the revised provisions was made for several reasons. Firstly, the more direct approach should improve ease of use. More fundamentally, the concept of a 'bond strength' is potentially misleading and, it may be asserted, has already led to a reduction in the level of safety provided by current provisions. Figure 3 illustrates the relationship between the mean stress developed in a lap/anchorage and bond length. The solid line represents the observed relationship between mean bar stress developed for a specific set of material properties and geometric parameters and bond length ratio according to Eq. 2. The gradient of the broken lines represents the average bond strength over the lap/anchorage length required to develop the design strength of bars of various Grades: there is a different bond strength for each Grade. Neglect of this effect would mean that either longer bond lengths than necessary would be required for weaker bar Grades or that bond lengths would become increasingly non-conservative for stronger Grades. The concept of a bond stress on the perimeter of a bundle is also unsatisfactory, as discussed later.

Characteristic strength of ribbed bars was around 400MPa when MC78, which forms the basis of current EC2 design rules, was drafted. The main steel Grade in current practice is now 500MPa, an increase of 25%. To maintain a consistent level of safety, anchorages for Grade 500 bars should now be $(500/400)^{n\sigma}$ or $(500/400)^{m}$ times longer than those for Grade 400 bars according to Eqs. 4 and 2 respectively. With n_σ set at the recommended value of 1.5 (Eq. 4) or m = 1.82 (Eq. 3), this corresponds to 40% or 50% increases in bond length. The increase in bond length required by current EC2 provisions has been only 25%. An increase of between 12% and 25% in bond lengths over EC2 values must therefore be expected for this reason.

Tabulated values for anchorage length l_b/ϕ are provided for Grade 500 bars in 'good' bond conditions covering a range of bar sizes and concrete strengths to cover the most common situations and facilitate application of these provisions, {Table 11.1}. As coefficients k_{lb} and n_σ are both NDPs, tabulated values for l_b/ϕ are therefore also NDPs and anchorage lengths given by {Table 11.1} apply unless the National Annex gives different values. Tabulated values are conservative for $c_d > 1.5\phi$. However, if transverse reinforcement is provided or transverse compression is present, or if minimum cover $c_d > 1.5\phi$, a reduced anchorage length may be obtained through substitution of $c_{d,conf}$ in place of c_d in Eq. 4 (described later).

4.1. Influence of concrete strength

The influence of concrete strength on lap length is less strong in FprEC2. Bond failure typically occurs by splitting of the surrounding concrete cover unless minimum cover exceeds approximately 3-4 times bar diameter, very dense transverse reinforcement is provided, or transverse compression is present. Bond failure is consequently dependent on the tensile strength of concrete, which varies with $f_{ck}^{0.67}$ for concretes up

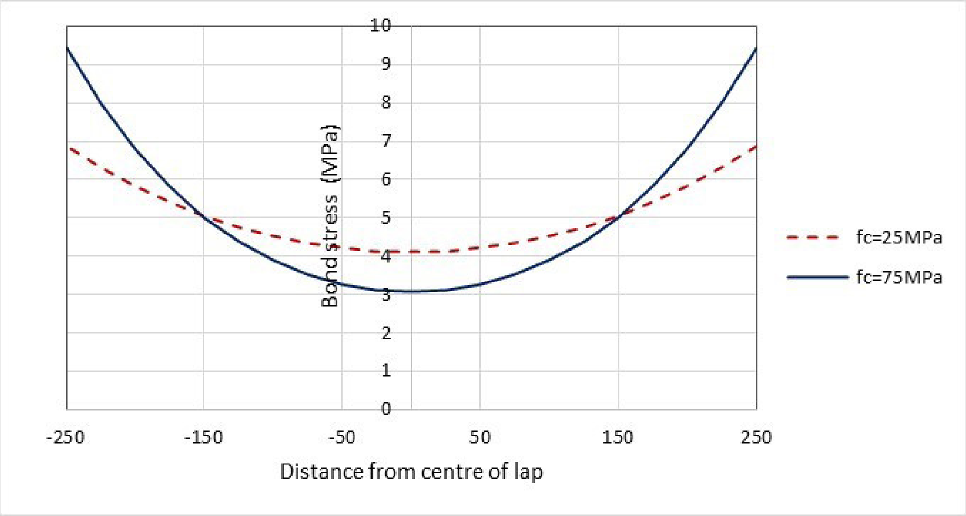


Figure 4. Variation in bond stress throughout a lap length.

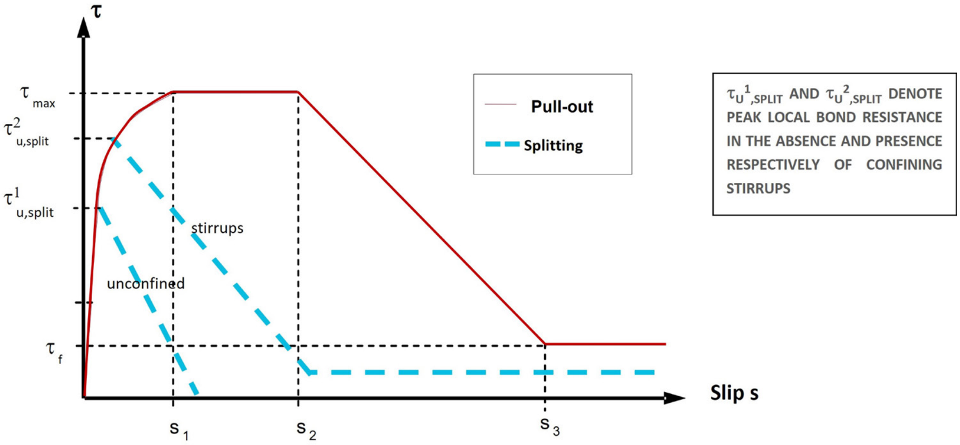


Figure 5. Local bond slip model, MC201014.

to and including Grade 50, FprEC2 {Table 5.1}. Bond strength was directly linked to concrete tensile strength in EC2, hence design anchorage length varied with $f_{ck}^{-0.67}$. The 0.67 index on f_{ck} is valid for short (5ϕ) bond lengths, but practical bond lengths commonly reach 40ϕ or longer. Bond stress along a long anchorage or lap is not uniform as suggested by Eq. 1 but varies over the bond length and is influenced by the bond-slip stiffness, which is itself dependent on concrete strength. Figure 4 compares bond stress distribution over a 40ϕ lap length of size 25 bars for concretes Grades C25 and C75 for a bar stress of 400 MPa. Stresses have been calculated using a linear elastic analysis similar to that used by Tepfers [13] and by Micaleff & Vollum [7], with bond-slip stiffness based on the local bond slip model for a splitting mode failure as given in the *fib* Model Code 2010 [14], Figure 5. Anchorage failure initiates near ends of the lap where bond stresses are highest. The bar stress developed over the end 5ϕ is 34% greater in the higher strength concrete. Tensile strength of a Grade C75 concrete is $(75/25)^{0.67}=2.1$ times that of a C25 concrete. Making allowance for the difference in bond stress distribution means that the stress anchored will increase by a factor of only $2.1/1.34=1.6$ as the 'peakier' bond stress distribution of the higher stiffness/strength concrete partially offsets the enhancement provided by its higher concrete tensile strength. This increase is commensurate with $(75/25)^{0.45}$, and therefore consistent with Eq. 2.

The limitation that $25/f_{ck} \geq 0.3$ effectively sets a limit of 83.3MPa to f_{ck}, a value derived from analysis of experimental data, and is an increase on the current restriction of C60/75.

4.2. Concrete cover

Parameter $(1.5\phi/c_d)$ represents the contribution of passive confinement from concrete cover and replaces parameter α_2 in EC2 provisions. Parameter c_d is similar to c_{min} in Figure 1 but shall not exceed 3.75ϕ in calculations. Figure 6 compares the influence of minimum cover ratio c_d/ϕ on bond length in EC2 and FprEC2. Note that the benchmark ratio of $c_d = 1.5\phi$ for FprEC2 provisions differs from that for current EC2 provisions in which $c_d = \phi$. Figure 6 shows the revised provisions allow a more rapid reduction in anchorage length for smaller bars and higher covers. The upper limit to cover ratio $c_d = 3.75\phi$ corresponds to a change from splitting to pullout failure mode, above which the rate of increase in bond is probably negligible.

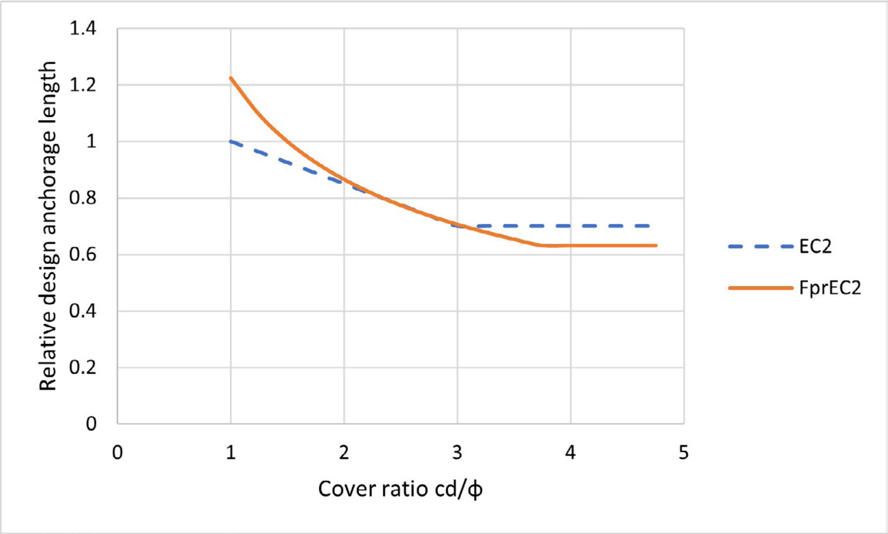


Figure 6. Influence of minimum cover/spacing ratio c_d/ϕ on anchorage length.

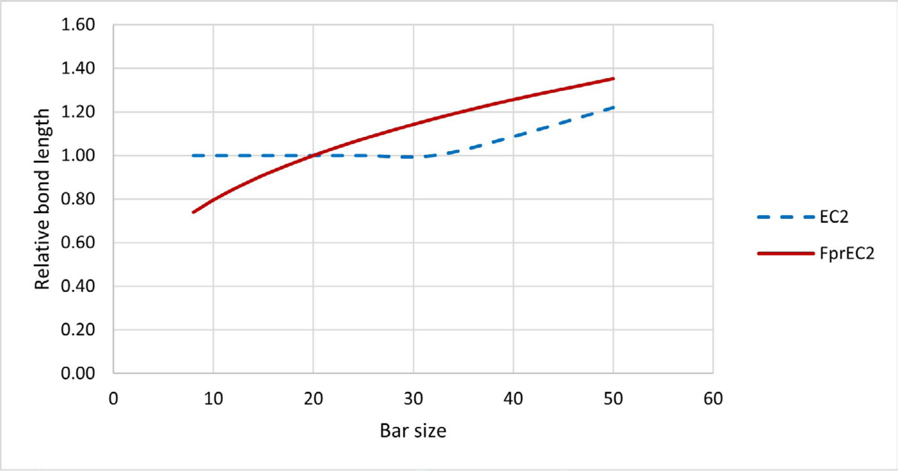


Figure 7. Influence of bar size on anchorage length (based to a ratio of 1.0 for size 20).

4.3. *Bar size*

The parameter $\phi/20$ in {Eq. 11.3} represents a size effect. It covers a wider range of bar sizes than parameter η_2 in the current version of EC2 which only affects bars larger than size 32, Figure 7. The requirement that $(\phi/20) \geq 0.6$ is derived from test data and effectively sets a lower limit of size 12 bars in the calculation and probably reflects the lower rib areas required for smaller size bars, FprEC2 Annex C. There are currently no provisions for indented bars larger than size 14 due to an absence of confirmatory test data, and there is a process to allow a country to extend the range via their National Annex once relevant data becomes available.

4.4. *Transverse and confining reinforcement and transverse compression*

If transverse reinforcement, confining reinforcement or transverse compression is present, or if minimum cover/spacing exceeds 1.5ϕ, a reduced anchorage length may be obtained through substitution of $c_{d,conf}$ in place c_d in Eq. 4 {11.3}, Eq. 5 {11.4}.

$$c_{d,conf} = \min\left\{c_x; c_y + 25\,\frac{\phi_t^2}{s_t}; \frac{c_s}{2}; 3.75\phi\right\} + \Delta c_d \leq 6\phi \qquad (5)\{11.4\}$$

$$\Delta c_d = (70\,\rho_{conf} + 12\,\sigma_{ccd} / \sqrt{f_{ck}})\phi \qquad (5b)$$

ρ_{conf} represents the density of confining reinforcement,

$$\rho_{conf} = \frac{n_c\,\pi\,\phi_c^2}{4\,n_b\,\phi\,s_c} \qquad (5c)$$

ϕ_t and s_t are size and spacing respectively of transverse reinforcement

ϕ_c and s_c are size and spacing respectively of confining reinforcement

n_c is the number of legs of confinement reinforcement crossing the potential splitting failure surface

n_b is the number of anchored bars or pairs of lapped bars in the potential splitting failure surface

σ_{ccd} is the design value of the mean compression stress perpendicular to a free surface near bars to be anchored or spliced.

Confining reinforcement in which legs of links run perpendicular to a potential splitting failure surface is more effective

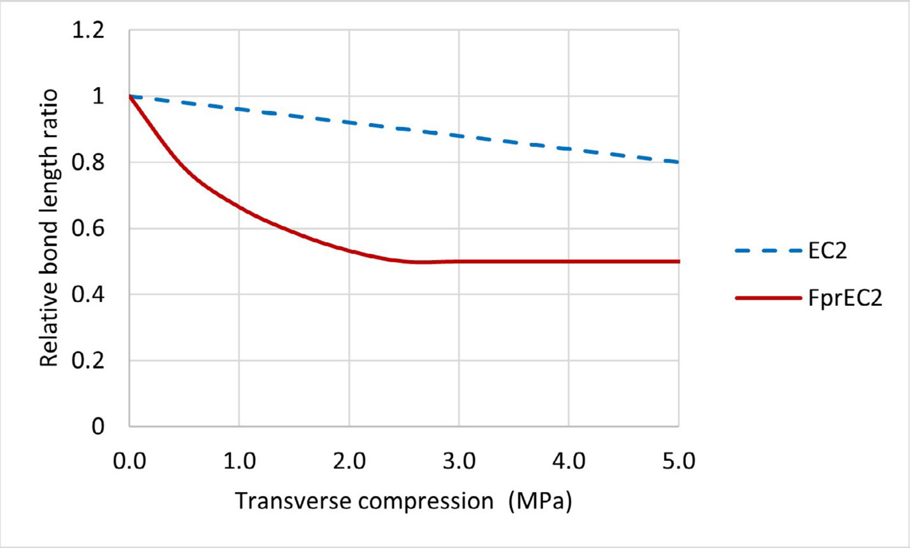


Figure 8. Influence of transverse compression on bond length.

than a similar quantity of transverse reinforcement in the form of distribution reinforcement in planar elements, {Figure 11.5}. Legs of links must be no further than 5ϕ distant from the anchored bar to be considered effective.

FprEC2 permits a more rapid reduction in design anchorage length than EC2 as transverse compression increases. Figure 8 provides a comparison for a size 20 bar in a Grade C40/50 concrete where c_d=30mm and no transverse or confining reinforcement is present. The reduction is both more rapid at low transverse pressures and has a lower limit at higher values. Factor α_5 for transverse compression in EC2 appears to have been derived from tests in which a pullout failure mode predominated but this underestimates the enhancement for a splitting mode when cover is low, typically $c_d < \sim 3.75\phi$.

FprEC2 resolves two unsatisfactory details in EC2 rules for transverse or confining reinforcement. Firstly, EC2 does not recognize the possibility of a splitting surface forming parallel to transverse reinforcement through the plane of anchored bars which would not have intersected transverse reinforcement thereby rendering its contribution ineffective. Secondly, coefficient α_3 in EC2 for the contribution of transverse or confining reinforcement depends on the total area of that reinforcement within the anchorage or lap length. When link spacing has already been decided (to satisfy shear resistance for example) A_{st} and therefore α_3 are dependent on anchorage length and can only be determined once the anchorage length is known.

FprEC2 does not specify how to deal with situations where transverse compression acts over only part of the anchorage length. In circumstances where the anchorage cannot be accommodated within the bearing width l_{bw} it is suggested that the anchorage will have adequate strength provided Eq. 6 is satisfied:

$$\left(\frac{l_{bw}}{l_{bp}}\right)^{n_\sigma} + \left(\frac{(l_{bd}-l_{bw})}{(l_{b0}-l_{bw})}\right)^{n_\sigma} \geq 1.0 \qquad (6)$$

l_{bw} is the length over which transverse compression is taken to act

l_{bp} is the required anchorage length if pressure σ_{ccd} acted over the entire anchorage length

l_{b0} is the required anchorage length if no transverse pressure were present.

It may be assumed that transverse compression disperses through concrete cover at an angle of 45° from ends of the bearing to determine l_{bw}, Figure 9.

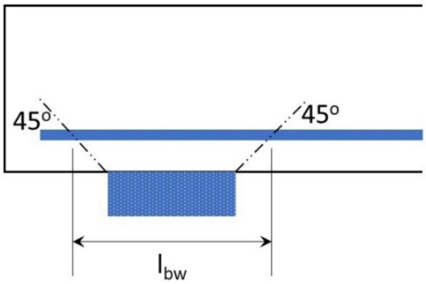


Figure 9. Determination of bearing length l_{bw}.

4.5. *Casting position*

The definition of a 'Poor' casting position for bars with an inclination less than 45° to the horizontal has been slightly modified in FprEC2 and bars up to 300 mm from the bottom of the formwork are now classified as in a 'Good' position, 50mm more than the value in EC2. Casting position factor k_{cp} for a 'Poor' casting position has been set to 1.2; factor η_1 = 0.7 on bond stress for a 'Poor' casting position in EC2 effectively resulted in a casting position factor of 1/0.7 = 1.43 and so FprEC2 reduces additional anchorage length for 'Poor' conditions by 16%. Although 'top cast' reductions exceeding 50% are reported in some investigations, these are invariably obtained from tests on short bond lengths. Figure 10 provides a general plot of top cast ratios, i.e., the ratio of the anchorage capacity for a bar cast near the top of a pour to that of a similar bar cast near the bottom, reported in several investigations, divided into three bond length ratio intervals. The lower bound to the top cast ratio is strongly dependant on bond length ratio. As the minimum anchorage length is set at 10ϕ, Eq. 4, results within the left column for $l_b/\phi \leq 10$ are not of practical significance. The average top cast ratio for bond lengths greater than 10ϕ comfortably exceeds 0.80. The lowest ratio in the middle interval is the average from two types of concrete from a 40 year old study, one of which had very high workability achieved without plasticisers, and thus unrepresentative of mix design today.

Recent work by Cairns and co-workers [15],[16], published too late for inclusion in FprEC2, demonstrates that the softer bond-slip stiffness in a poor casting position results in the top cast effect reducing with increasing anchorage length, and concludes that k_{cp} = 1.0 is reasonable for full strength laps of Grade 500 bars, with a higher factor required only for shorter/weaker laps, hence k_{cp} = 1.2 factor is conservative for full strength laps and anchorages of Grade 500 and above bars.

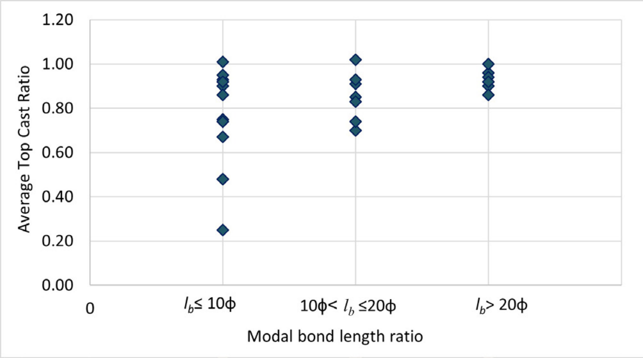


Figure 10. Influence of bond length on casting position observed in various investigations.

4.6. Bundled bars {11.4.3}

Equation 7 {11.6} for equivalent diameter of a bar bundle has been revised to address bundles containing a mix of bar sizes. Provisions now explicitly state that the equivalent diameter is to be used only when two or more bars in the bundle are anchored at a section, and that for a single bar forming part of a bundle the design anchorage length calculated by Eq. {11.3} should be based on its own diameter, covers, and confinement ratio for transverse/confining reinforcement. Research has confirmed that anchorage capacity is determined by the force to be transferred to/from a bar and not by a notional shear stress over the external perimeter of the bundle, hence equivalent diameter is only used when more than one bar is anchored at a section [17],[18].

$$\phi_b = \sqrt{\frac{4}{\pi} As} \qquad (7)[11.6]$$

where A_s is the total area of all bars contained in the bundle.

4.7. Anchorage of bars with bends, hooks and U-loops {11.4.4, 11.4.5, 11.4.6}

As with bond, an end hook, bend or U-loop typically fails in a splitting mode unless concrete cover is relatively high, and its contribution is therefore controlled by the same concrete material properties and geometric parameters as bond. Where a bar in tension terminates in a standard hook or bend anchorage length determined by Eq. {11.3} may be reduced by a length of 15 times the bar diameter and replaces the 30% reduction permitted by EC2 where minimum cover exceeds 3ϕ. The basis for the reduction is given in *fib* Bulletin 72. The revision generally permits shorter bond lengths where the stress to be anchored is below the design strength of a Grade 500 bar. It is not sensible that the contribution increases with increased bar strength as in EC2. Slip at the start of the bend would tend to reduce as bond length increases for higher strength bars, hence the contribution of the hook or bend would tend to reduce as bar stress increases. While it might be expected that a hook with α_{bend} exceeding 135° might provide a greater contribution than a bend with α_{bend} = 90°, this was not supported by experimental data and the same anchorage length reduction is therefore used for both shapes. A higher contribution of 20ϕ is permitted for U-loops however. Measurement of anchorage length is to the outside of the hook, bend or U-loop and is unchanged. As an alternative anchorage length may be based on the actual length of bar including the radiused part and the tail.

Anchorage of bars with welded transverse reinforcement {11.4.5} is treated in a similar manner to anchorage with hooks and bends, but as longitudinal and transverse bars may be of different diameter provisions are subject to a minimum amount of transverse reinforcement.

4.8. Anchorages with headed bars

This section is new. Provisions for headed bars have been derived through approaches developed for fastenings to concrete [19]. The head may be taken to anchor the design strength of a Grade 500 bar if a set of 'deemed to satisfy' criteria for minimum cover and spacing are satisfied, or a more detailed calculation may be undertaken. Bond over a straight length of bar may supplement head resistance to achieve the required anchorage capacity. As head resistance and bond resistance generally peak at different slips their individual peak resistances cannot simply be summed. The design bond length to provide the difference between design bar force and head capacity is accordingly increased by 10% above that calculated by Eq. 4.

4.9. Anchorage of bonded post-installed reinforcing steel {11.4.8}

This section is completely new. Straight lengths of bar may be installed by drilling an oversize hole into hardened concrete and bonding in an appropriate length of reinforcement with a suitable adhesive or mortar. Design provisions are broadly similar to those for cast in place bars, although additional limits on minimum cover are introduced mainly for reasons associated with the installation process. Such installations are generally undertaken by specialist sub-contractors. Design and installation of post-installed rebar is covered in detail in specialist documents such as the EOTA Report on Bonded Fasteners for Use in Concrete which should be consulted [20].

4.10. Compression anchorages {11.4.2(6)}

End bearing enhances the anchorage capacity of bars in compression, a contribution that FprEC2 now recognizes, and a reduction of 15ϕ in the design anchorage length is permitted provided the end of the bar is no closer than 5ϕ (measured parallel to the bar axis) to a free surface, Figure 11: a shorter distance could result in an end cone failure at a reduced capacity. EC2 does not permit any reduction for an end bearing contribution. The basis for the reduction is given in *fib* Bulletin 72. Although there is no benefit to anchorage length in providing an end hook or bend to compression bars if the 5ϕ end distance criterion is satisfied, there may be a benefit for end distances between 3.5ϕ and 5ϕ. There may also be practical benefits for fixing reinforcement and in maintaining capacity in the event of accidental tension. There is some suggestion that an end hook or bend might be detrimental to anchorage as pressure in the hook could lead to prising off thin side covers; ACI318 [21] does not permit bends at the end of compression anchorages. Concrete cover, transverse and confining reinforcement, and transverse compression now influence compression anchorage length: this was not the case in EC2, presumably because of a lack of evidence when MC78 was drafted.

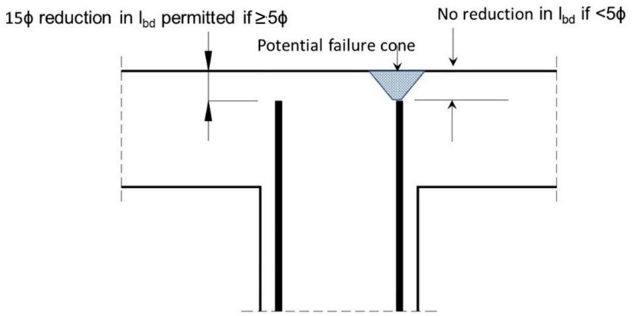


Figure 11. Minimum distance from end of compression bar to free face.

5.
LAPS IN TENSION AND COMPRESSION

Laps, lapped joint and lapped splice are equivalent terms used to describe situations where the force in one set of bars is transferred to another set via the surrounding concrete to provide continuity of reinforcement. Lap lengths l_{sd} in FprEC2 are also based on Eqs 4 & 5 {11.3 & 11.4}, the expressions used for anchorages. Camps *et al* [22] compared design tension anchorage and lap lengths calculated according to EC2 and FprEC2. They noted that anchorages designed to FprEC2 tended to be longer than those designed to EC2, but that laps tended to be shorter, in one example by as much as 48%. They concluded on the basis of precedent that there should be a distinction between the k_{lb} value for anchorages and laps. Anchorage length l_{bd} in FprEC2 is multiplied by a factor k_{ls}, an NDP with a recommended value k_{ls} = 1.2, to obtain lap length, effectively a bond length coefficient of 60 for laps as opposed to the 50 for anchorages. This is a significant change from EC2 where lap length factor α_6 depends on the proportion of bars lapped at the section and varies from 1.2 where a maximum of 20% of the bars are lapped at a section to 1.5 where more than 50% of bars are lapped. Values for α_6 in EC2 were moderated from those in fib MC90, which formed the basis of EC2 rules for bond, and had a maximum of α_6 = 2.0. Early strength models by Tepfers [13] and by Ferguson [23] considered bond action to exert a hydraulic pressure around the bars, consequently the bursting force generated by bond in a direction perpendicular to a plane through the lapped pair would be double that exerted by a single anchored bar, Figure 12. These analyses also assumed bond generates a radial stress proportional to the local bond stress, from which it was concluded that in a splitting failure mode strength of a lap would be half that of an equivalent anchorage, and hence that lap lengths should be double those for single bar anchorages. Experimental evidence has since contradicted these models [24]. Investigations on tension laps by Cairns [25] and by Metelli [26] have demonstrated the proportion of bars lapped at a section has no appreciable influence on lap strength. Cairns also noted that the greater stiffness of a lapped pair over the lap length (compared to that of a continuous bar over the same distance) caused a small strength reduction when allowance was made for the increase in spacing of lapped pairs due to the greater stiffness of the lapped bars attracting a greater share of the total force. However, both studies also noted lap failure became less brittle as the proportion lapped reduced (see also following section on ductility).

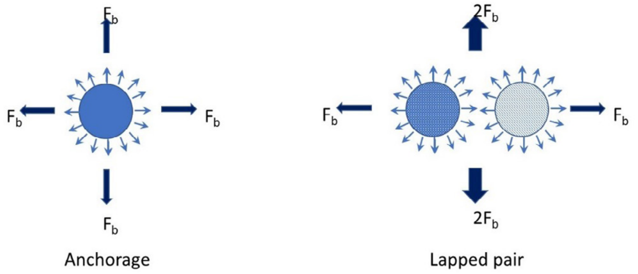


Figure 12. Historic hydraulic pressure analogy model.

Earlier drafts of FprEC2 did not include parameter k_{ls} for laps, but an evaluation carried out by Camps *et al* [22] at a late stage in the development of FprEC2 noted that this resulted in a lower safety margin for laps than for anchorages. The finding was not expected as Eq. 2, from which FprEC2 design expressions are derived, was found to be equally valid for both anchorages and laps, Table 1. Various North American studies have also moved away from the hydraulic pressure hypothesis and concluded that lap and anchorage lengths may be calculated by the same expression, and ACI 318 [21] allows lap lengths to be calculated using the same expressions as those for anchorages provided the area of reinforcement is at least double that required or no more than 50% of bars are lapped.

It is not clear whether the need to introduce k_{ls} is due to systemic or accidental factors. The index on the ratio l_{bd}/ϕ has been rounded down from the 'accurate' value of 1.82 proposed in fib Bulletin 72 [5] to 1.5 in FprEC2 introducing some conservatism at capacities below 435MPa, Figure 2. The average stress developed in tests without links or transverse pressure is 364MPa for anchorages, whereas that for laps is 424MPa. The difference in bar stress between the two groups may have produced a slight bias in favour of anchorages in Camps' analysis. Approximations in the transition from Eq. 2 to Eqs. 4 and 5 might accidentally have contributed to an apparent difference between laps and anchorages. Eq. 2 must be rearranged to calculate the bond length required to develop a given bar stress, and indexes and coefficients have then been rounded in Eqs. 4 and 5 to obtain more 'user friendly' values. Due to the summative nature of the confinement terms in Eq. 2 this re-arrangement is not algebraically straightforward and is partly empirical. Whatever the reason, the evaluations presented later show that the introduction of $k_{ls} = 1.2$ gives a more consistent margin of safety.

As with anchorages, where only a single bar within a bundle is lapped at a section design lap length should be based on the bars own diameter, covers, and confinement by secondary reinforcement.

In the calculation of bond lengths where only a portion of bars are lapped at a section, clear bar spacing c_s is the dimension of concrete between lapped pairs. Figure 13, equivalent to Figure {11.10} in FprEC2, shows dimension c_s where 50% of bars are lapped at a section and pairs of lapped bars are in contact.

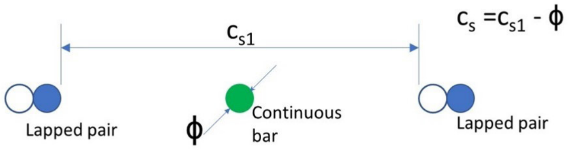
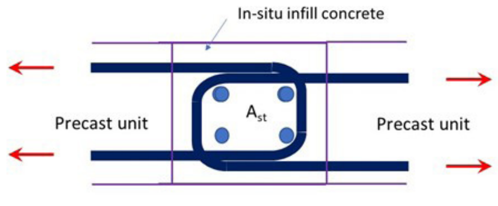


Figure 13. Definition of c_s where 50% of bars are lapped at a section.

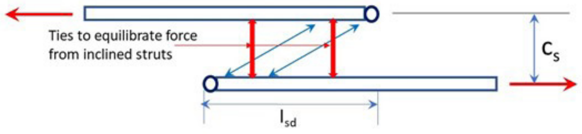
The contribution of end bearing will frequently permit lap length of bars in compression to be reduced with no further reduction being gained by the presence of a hook or bend.

5.1. Laps using U-bar loops

U-bar loops are commonly used to provide tying and/or structural continuity between precast units. Failure may occur by crushing of the infill joint concrete or mortar within the loop, by splitting of the in-situ joint concrete in the plane of the overlapping loops, or by yielding and eventual rupture of reinforcement. The design philosophy requires that concrete failure does not occur before yielding of reinforcement [27]. The force to be resisted by the concrete strut is influenced by its inclination, represented by the ratio c_s / l_{sd}, and its resistance is determined by the properties of the joint infill concrete and the area of concrete mobilised. A minimum area of confining reinforcement is to be provided perpendicular to the plane of the loops to equilibrate the inclined compression struts, Figure 14.



a) Elevation



b) Plan

Figure 14. Strut and tie representation of forces at a U-bar lap.

6.
DUCTILITY AND REQUIREMENTS FOR ROBUSTNESS

The splitting mode of anchorage and lap failure may be extremely brittle. It is good practice to locate laps where bar stress is relatively low whenever possible. If, however, advantage is taken of moment redistribution or plastic analysis to improve structural efficiency, bars could be required to develop strains exceeding yield. FprEC2 introduces new provisions for tension laps located in the vicinity of a plastic hinge or yield line. Three alternatives are available in FprEC2 to provide the requisite deformation capacity and avert the risk of sudden collapse of the member:

1 increased confining reinforcement to counter the bursting forces generated by bond action and thus limit rate of loss of anchorage capacity in the event of capacity being reached.
2 restrictions on the proportion of bars lapped at a section to ensure continuous bars to accept a share of the load taken by a failing lap are present.
3 laps to be designed for a stress 20% above the design strength of the bar with the aim of ensuring that lapped bars can develop strains greater than ε_y the strain at which appreciable plastic elongation starts to develop.

While some aspects of alternatives 1 & 2 are present in EC2 they appear to have been intended to address strength issues rather than deformation capacity.

7.
ASSESSMENT {APPENDIX I.11.4}

Equation 3 may also be used for assessment of anchorage and laps in existing construction. Cover and spacing dimensions from observations on existing structures may be used instead of those specified for construction. New expressions for anchorages and laps of hot-rolled plain surface bars are presented derived from work by Feldman *et al* [28].

8.
EVALUATION AGAINST TEST DATABASES

This section evaluates design rules for laps and anchorages in FprEC2 against test databases. Eq. {11.3} (Eq. 4 of this paper) has been re-arranged to estimate bar stress σ_s from dimensions and concrete strength given in the fibTG4.5 [8] and Amin [9] databases, Eq. 8. Dimension l_{bd} is the bond length in the test specimen. Characteristic concrete strength f_{ck} equals f_{cm} - 5MPa, the margin of 5MPa conservatively substituted for the 8MPa given in FprEC2 to account for tighter control in laboratory research compared to practical construction. Specimens in which $f_{ck} < 12$MPa or $c_d < 0.95\phi$ have been filtered out as they lie outside the range covered by FprEC2 and normal practice, as do anchorage lengths $l_{bd} < 10\phi$ and lap lengths $l_{sd} < 15\phi$, although lengths down to 7.5ϕ have been retained for anchor-

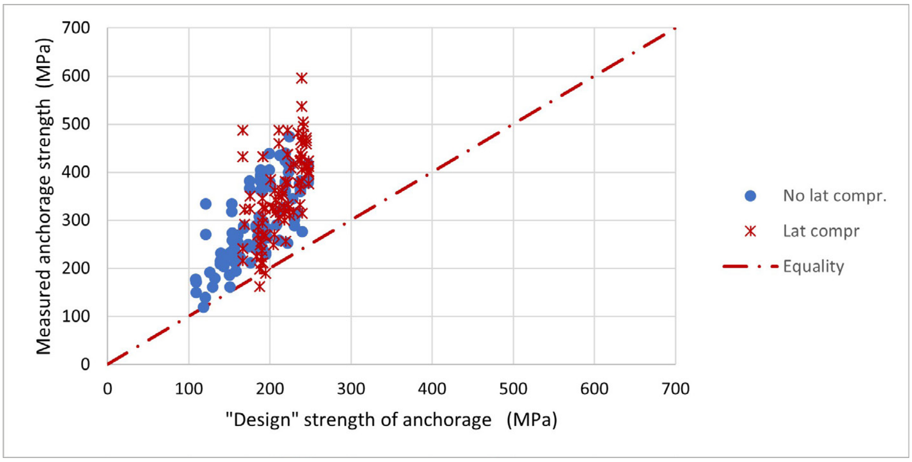


Figure 15. Evaluation of FprEC2 design rules for straight tension anchorages.

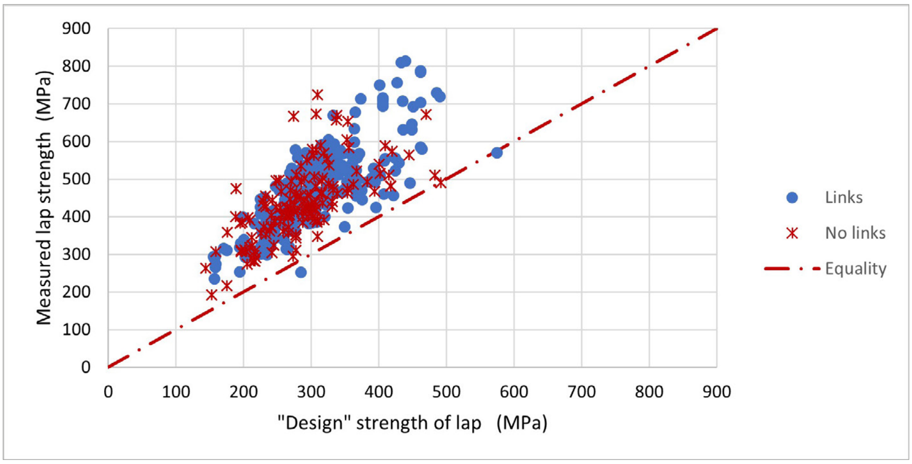


Figure 16. Evaluation of FprEC2 design rules for straight tension laps.

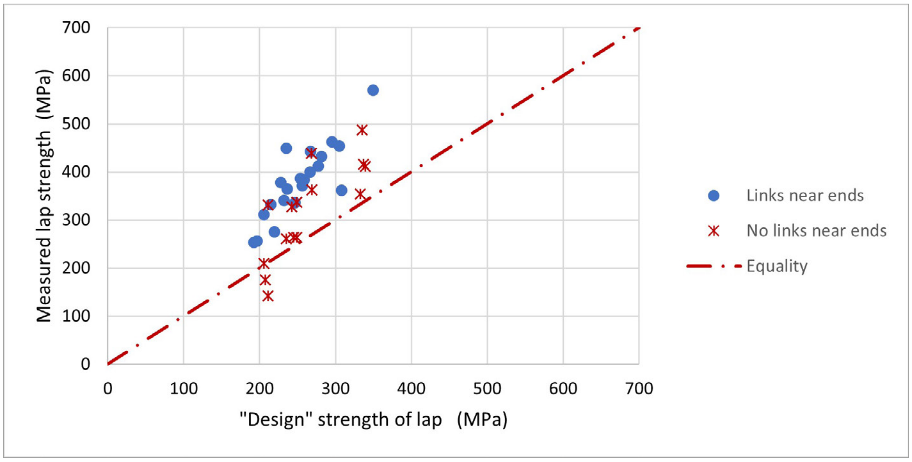


Figure 17. Evaluation of FprEC2 design rules for compression laps.

ages subject to transverse compression in view of a scarcity of data for longer lengths. Results for tension anchorages are plotted in Figure 15 and for tension laps in Figure 16. Results which plot above the chain-dashed line of equality are "safe". A statistical summary is given in Table 2.

$$\sigma_s = 435\,(k_{lb}\,k_{ls})^{-0.67}\left(\frac{l_{bd}}{\phi}\right)^{0.67}\left(\frac{f_{ck}}{25}\right)^{0.33}\left(\frac{20}{\phi}\right)^{0.22}\left(\frac{c_d}{1.5\phi}\right)^{0.33} \qquad (8)$$

where

$k_{lb} = 50$, $k_{ls} = 1.0$ and 1.2 for anchorages and laps respectively

Results for compression laps are presented in Figure 17. Here a length of 15ϕ is added to the lap length provided in tests, Eq. 9. Lap lengths down to 7.5ϕ and minimum cover down to 0.75ϕ are included in view of a scarcity of data for longer lengths and thicker covers. Two sets of results are plotted, one for specimens in which at least one link was located within the lap length and no further than 2ϕ or 50mm from the end of the lap {Figure 11.12}, the other for specimens in which this requirement was not satisfied. All results for specimens in which the link location limit was satisfied lie in the 'safe' zone,

TABLE 2.
Statistical summary of design rules

	Tension Anchorages		**Tension Laps**		**Compression laps**	
	σ_{ccd}=0	σ_{ccd}>0	Links	No links	End links	No end links
Average	1.61	1.67	1.59	1.58	1.49	1.20
Std Dev.	0.31	0.35	0.20	0.28	0.16	0.26
CoV	0.19	0.21	0.13	0.17	0.11	0.22
Min	1.01	0.87	0.88	1.00	1.17	0.67
No. results	104	97	291	163	21	15
No. <1.0	0	2	1	0	0	2
% <1.0	0.0%	2.1%	0.3%	0.0%	0.0%	13.3%

but 2 out of the 15 results for specimens which did not satisfy the limit do not, and the average ratio of measured/design strength where links did not satisfy the limit is 20% below that for those which did.

$$\sigma_s = 435\ (k_{lb}\ k_{ls})^{-0.67} \left(\frac{l_{bd}}{\phi} + 15\right)^{0.67} \left(\frac{f_{ck}}{25}\right)^{0.33} \left(\frac{20}{\phi}\right)^{0.22} \left(\frac{c_d}{1.5\phi}\right)^{0.33} \qquad (9)$$

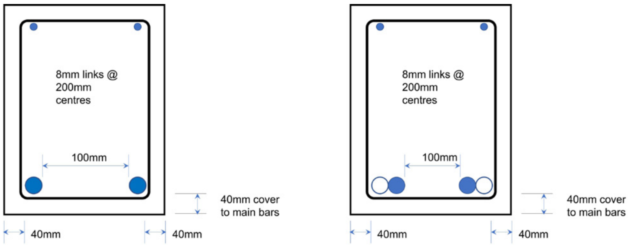
The average ratio of measured to 'design' strength is consistent for all categories complying with FprEC2 provisions at around 1.6, Table 2. Test strength fell below design strength in 2 out of a total of 201 anchorage specimens. The two transverse compression tests falling below the equality line were from the same investigation with l_{bd}/ϕ = 8.6 and a low concrete strength and do not comply with limits set in FprEC2. They only appear in this evaluation as the quantity of test data was somewhat limited. The single tension lap result in Figure 16 which falls below the equality line cannot be justified in a similar way and appears to be an outlier; the next lowest ratio is well above the equality line with a ratio of 1.07, and there is a clear gap between this individual result and the body of test data. This single result does not appear sufficient reason to further increase k_{ls}.

9.
IMPACT OF CHANGES ON ANCHORAGE LENGTH

As stated earlier, bond and anchorage capacity are dependent on many factors. Differences in the format of design expressions between EC2 and FprEC2 means it is not possible to generalise the impact of differences between the two Codes. Selected comparisons for typical situations are presented here.

Figure 19 compares design anchorage lengths from EC2 and FprEC2 for anchorages in the beam section shown in Figure 18 where transverse compression is not present. Comparisons are presented for two concrete Grades, C25/30 and C60/75, and two bar sizes, 12 mm and 25 mm. Minimum cover c_d=40 mm in all cases. Confining reinforcement is size 8 bars at 200 mm centres. Three design anchorage lengths are plotted for each combination of bar size and concrete strength: design length from EC2, design length from FprEC2, and the design length from EC2 had it been revised to reflect the adjustment to bond strength that should have been applied to maintain the margin of safety pertaining for a bar strength of 400 MPa after bar strength increased from 400 MPa to 500 MPa. An increase of 20%, midway between the values obtained for n_σ =1.5 and n_σ =1.82 has been applied.

Figure 19 shows that in good casting positions anchorage lengths have generally increased relative to EC2 where transverse compression is absent. However, had EC2 bond strengths been adjusted to take account of the increase in steel strength between the time EC2 rules were developed and the present day, the new rules would reduce anchorage lengths of small bars by around 15% and lead to an increase averaging around 10% for size 25 bars, with greater increases for larger sizes due to the wider range of influence of bar size in FprEC2, see Figure 7. Longer anchorage lengths are required in poor casting positions, Figure 20. Relative to current EC2 rules, anchorage lengths for small bars calculated to FprEC2 average around 15% shorter while lengths for size 25 bars are around 10% longer.



a)Anchorage b) Lap

Figure 18. Sample beam sections.

Results of an analysis using the same parameters but with transverse compression σ_{ccd}=1.0 MPa are shown in Figure 21. As noted earlier, FprEC2 allows a more rapid reduction in bond length with increasing transverse reinforcement and transverse compression, and shorter anchorage lengths are permitted in most cases of the parameters selected here. Shorter anchorage lengths will generally result for directly supported end anchorages under the revised rules (provided the minimum anchorage length of 10ϕ is exceeded).

Figures 22 and 23 compare lap lengths in tension and in compression respectively where all bars are lapped at the same section, using the same parameters as the anchorage comparisons in Figures 19-21. FprEC2 generally results in shorter ten-

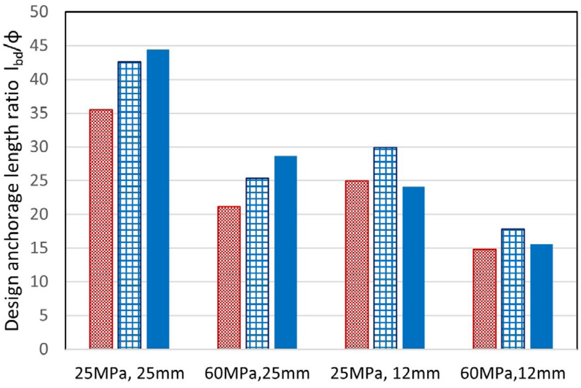


Figure 19. Comparison of design provisions, tension anchorages, good casting position.

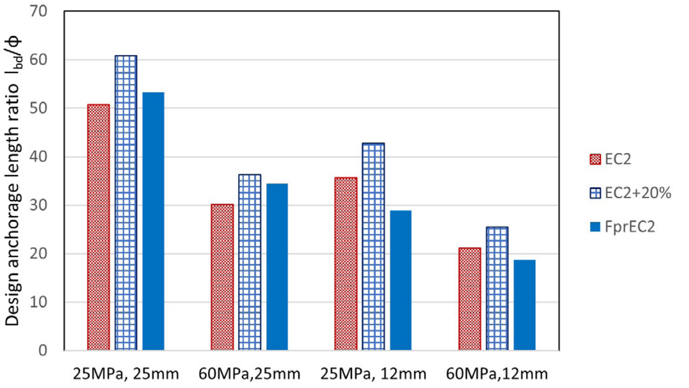


Figure 20. Comparison of design provisions, tension anchorages, poor casting position.

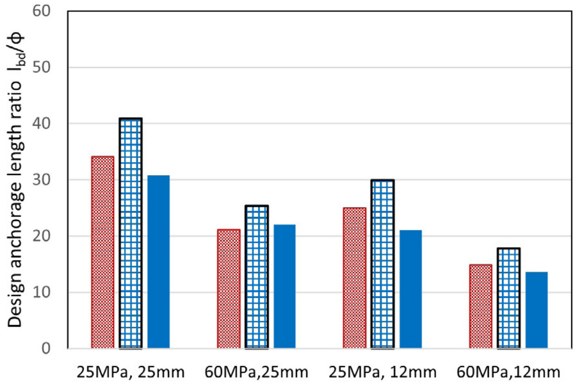


Figure 21. Comparison of design provisions, tension anchorages with transverse compression in a good casting position.

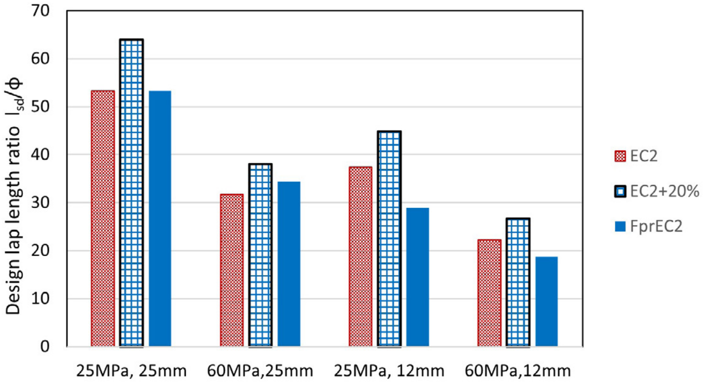


Figure 22. Comparison of design provisions, tension laps, good casting position.

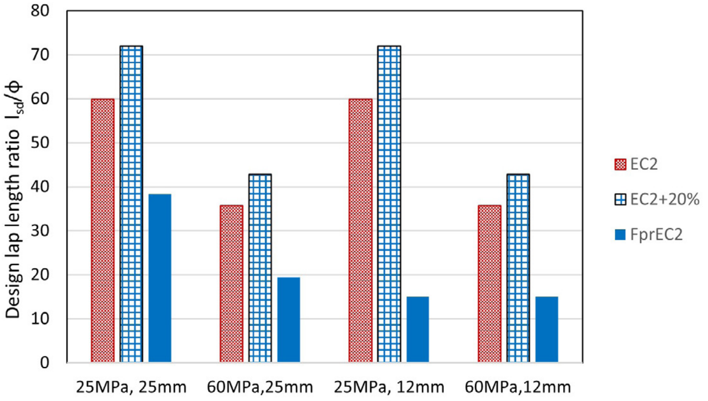


Figure 23. Comparison of design provisions, compression laps, good casting position.

sion lap lengths compared to EC2, and in all cases compared to EC2 adjusted for the increase in bar strength from 400 MPa to 500 MPa. There are marked reductions in all cases for compression laps as EC2 took no account of the contribution of end bearing.

10.
CONCLUSIONS

This article has traced the development of provisions for anchorages and laps in the forthcoming revision to Eurocode2 for design of concrete structures and explained the main reasons for change. The format of expressions for design have changed and the several parameters influencing strength are now combined in a summative instead of a multiplicative way. Design anchorage and lap length are no longer proportional to the stress developed and now vary with $\sigma_{sd}^{n\sigma}$. While the influence of concrete strength has been reduced in the revision, the influence of confinement from cover, secondary reinforcement and transverse compression has increased. The bar size effect is not restricted to sizes above 32 and now influences a wider range of sizes. The contribution of end termination by a hook or bend or of welded transverse bars in a tension anchorage or lap is now a fixed length of 15ϕ rather than a 30% reduction. Provisions for compression laps have been made more consistent with those for tension laps and the contribution of end bearing is recognised.

Practical design of anchorages and laps has been and will continue to be based on an ultimate strength. However, it has been shown that bond-slip stiffness plays a significant role in performance and must be considered in the formulation of ultimate strength rules.

Revised design provisions are evaluated against two databases, one for anchorages and another for laps, and shown to be safe.

A few comparisons show that in the absence of transverse compression the new rules may lead to increased anchorage lengths for larger bar sizes and lower covers but will otherwise tend to result in shorter bond lengths.

References

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