An evaluation of EC2 rules for design of compression lap joints

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A B S T R A C T

This paper presents an evaluation of EC2 rules for design of compression lapped joints based around a database of approximately 150 individual test results reported in the literature. A comparison is provided between tension and compression laps, and a review of semi-empirical and empirical expressions reported in the literature is presented. Compared to laps of bars in tension, the influence of minimum concrete cover on compression lap strength is low or negligible, but the influence of transverse reinforcement is stronger. The performance criteria for lapped joints are discussed, and a difference noted between compression and tension laps.

The evaluation has been carried out by first determining the lap length required by EC2 to develop the design strength of a bar, and the strength of that lap then estimated using three different semi-empirical expressions each derived from part of the database. The outcome shows that EC2 procedures provide a greater margin of safety for compression laps than for tension laps. The margin of safety against failure of compression laps designed in accordance with EC2 is found to be broadly consistent with expectations for a concrete cover equal to one bar diameter, but reduces at larger cover/bar diameter ratios. Consequently it is recommended that for compression laps coefficient α_2 be independent of cover ratio and set to 1.0.

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Notation (parameters which appear only once are defined in the text).

A_{tr}	area of transverse reinforcement within spacing s_t which crosses potential splitting plane
ΣA_{tr}	total area of transverse reinforcement within lap length l_0 which crosses potential splitting plane
f_{cm}, f_{ck}	compressive strength of concrete cylinder, mean and characteristic values respectively
f_{scm}, f_{sck}	stress developed by lapped joint, mean and characteristic values respectively
k_m	represents the efficiency of confinement by transverse reinforcement.
K_{tr}	parameter representing transverse reinforcement according to ACI318, $K_{tr} = 40A_{tr}/(s_t.n_b)$.
$l_0, l_{0,d}$	lap length in tests and design lap length respectively
n_b	number of pairs of lapped bars
s_t	spacing of transverse reinforcement
α_2, α_3	coefficients representing confinement from concrete cover and transverse reinforcement in design calculations
$\alpha_{2,m}\ \alpha_{3,m}$	coefficients representing confinement from concrete cover and transverse reinforcement in mean strength expressions
δ	parameter representing location of transverse reinforcement within the lap length
ϕ	diameter of lapped bar

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1. Introduction

The adequacy of EC2 [1] rules for the design of tension lapped joints has recently been questioned by Cairns and Eligehausen [2]. This paper reports an equivalent analysis of EC2 design rules for lapped joints of compression bars.

There is relatively little test data for compression laps compared to that for laps of bars in tension. Up until 2010 less than 50 tests on compression lapped joints were reported in the literature, all undertaken before 1975, when strengths of both concrete and reinforcement were below those currently in use. The database of tension lap tests compiled by *fib* [3] and which extended the ACI 408 [4] database contains nearly 20 times this number of results. Since 2010 Chun and co-workers [5,6,7] have conducted over 100 further tests on compression laps, and this provides an opportunity to re-evaluate the current design rules in EC2 to complement a recently completed review of tension laps [2].

The relative scarcity of test data on compression laps is probably attributable to the greater demands on testing capacity rather than to any lack of importance in construction. The capacity of the testing equipment required for compression laps is around 10 times greater than that for tension laps, greater accuracy is required when setting up test specimens, and interpretation of results is more difficult. Such difficulties are not valid reasons to neglect compression laps, however. While it is often possible to locate tension laps away from points of maximum stress in reinforcement, compression laps commonly have to be located where stress in reinforcement is at its highest.

The aim of this paper is to assess whether EC2 rules provide the expected margin of safety against failure of compression lapped joints.

The scope of the paper is restricted to conventional non-coated ribbed steel reinforcing bars.

2. Comparison of tension and compression laps

A good understanding of the factors influencing strength of tension laps has been built from the extensive test data published in the literature, and can benefit from understanding the behaviour of compression laps. Several empirical or semi-empirical expressions, including Zuo and Darwin [8], Canbay and Frosch [9], and *fib* [10] are available to estimate the strength of tension laps. However, although there are obvious similarities between lapped bars in tension and in compression, there are also significant differences which mean that expressions derived empirically for tension laps cannot directly be applied to compression laps.

The principal difference between tension and compression laps is that bearing of the ends of bars on concrete contributes to force transfer in the latter case. The significant contribution that end bearing may make is clear from tests reported by Pfister and Mattock [11] who conducted two series of tests. One series consisted of rectangular columns with transverse reinforcement in the form of closed links while the other series comprised columns of circular cross-section with transverse reinforcement in the form of a helix. Extrapolated back to zero, lap strengths for tied and helically bound columns can be estimated at approximately 150 MPa and 250 MPa respectively (Fig. 1). Chun et al. [6] estimate the net contribution of end bearing for a C32/40 concrete at around 110 MPa, while Cairns and Arthur [12] estimated a contribution of around 95 MPa. Both observe that the net contribution of end bearing to lap strength is less than the bearing resistance of the end of the bar in the absence of bond.

Fig. 2 plots the variation in stress along the length of a tension bar embedded in a prism of concrete under uniform tension throughout its length. Bar stress reduces away from transverse cracks, and the 'in-and-out' bond stresses associated within transverse cracking add to those generated by the transfer of force within the lap. Clearly such stresses are absent from compression lap zones where transverse cracking does not occur. It can be speculated that in the absence of these additional bond stresses the average bond strength of compression bars at failure might be enhanced.

The variation in transfer of force between bars within a compression lapped joint is less uniform than that within a tension lapped joint (Fig. 3). Consider a tension lapped joint with all bars of equal diameter lapped at the same section located within a constant moment zone, and assume that concrete is incapable of carrying significant tension at the ultimate limit state. At the centre of the lap each lapped bar carries half the force of a single bar outside the lap. This is not the case in compression laps where concrete shares the load. Outside a compression lap, bars carry a share of load equal to $\rho\alpha_E / (1 + \rho\alpha_E)$, where ρ is the reinforcement ratio and α_E the modular ratio of steel to concrete. At
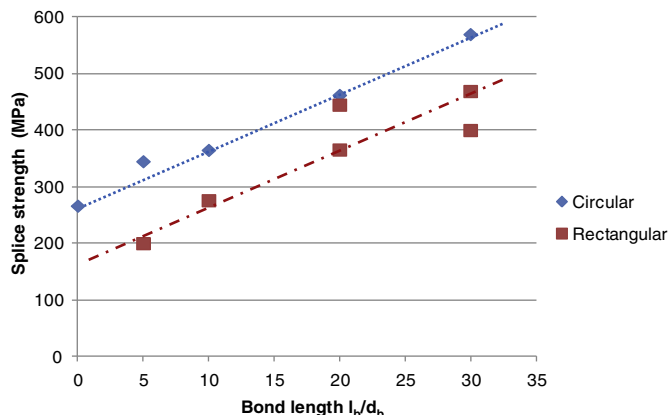
the centre of the lap, ignoring the possibility of significant bond slip and hence assuming that lapped bars and concrete are subject to identical strains, each lapped bar carries a share of the load equal to $\rho\alpha_E / (1 + 2 \cdot \rho\alpha_E)$. Bar stress at the centre of the lap then tends towards the value given by Eq. (1). Fig. 4 plots this function against reinforcement ratio and shows that bar stress at the centre of the lap tends to be markedly greater than half that outside. More than 50% of the force must therefore transfer within half a lap length from the end of the bar, and hence peak bond stresses (or at least the peak rate of transfer of force) will be higher in compression than in tension laps, therefore failure could be initiated at a lower average bond stress.

$$f_{s,in} = f_{s,out} \frac{(1 + \rho\alpha_E)}{(1 + 2\rho\alpha_E)} \tag{1}$$

where $f_{s,in}$ and $f_{s,out}$ are bar stresses at the centre and outside the lap respectively.

In both direct measurements on column laps and in a related semi-empirical analysis in which a regression fit to data for tension and for compression laps was compared, Cairns [13] noted differences in confinement. Longitudinal compression in concrete parallel to the axis of lapped or anchored bars will reduce tension resistance in the perpendicular direction, and hence confinement from concrete cover. This reduction appeared to be offset by an enhancement in link stress at failure, probably attributable to increases in bond of links as a result of the transverse longitudinal compression to which they are subjected. Measured strains indicate end links of compression bars reach yield at failure of compression laps, compared to stresses of typically 60–80 MPa in links near ends of tension laps [14] which fail in a splitting mode.

The performance required of a compression lap also differs from that of a tension lap. Unless minimum cover and clear spacing between laps exceed 3 and 6 times bar diameter respectively, failure of lapped joints invariably occurs in a very brittle splitting mode. To avoid a brittle mode of failure, lapped bars in tension laps must attain significant post-yield strains. By contrast the stress which concrete can sustain in compression peaks at a strain similar to that at which reinforcement reaches yield, and there is no benefit in designing for lapped bars in compression to attain significant post-yield strains.

Tension laps in EC2 [1] may often be shorter than compression laps as, although the same basic bond strength is used for both, coefficients for minimum cover and for transverse reinforcement in Table 8.2 of EC2 are set at 1.0 for compression laps but may be lower for tension laps. This contrasts with guidance in other Codes such as BS8110 [15] where bond strength for compression bars is 25% higher than for bars in tension.

3. Review of earlier analyses of compression lap strength

3.1. Cairns [13]

Cairns [13] presented an empirical expression for the strength of compression laps based on that proposed by Orangun et al. [16] for tension laps (Eq. (2)). The expression was derived from three investigations containing a total of 45 test results on column specimens of both circular and rectangular cross-sections, although the calibration was based on the latter. Concrete cylinder compressive strengths were in the range of 10 MPa to 36 MPa, the bar diameter ranged from 25 mm to 40 mm, and laps were confined by transverse reinforcement in all cases.

$$f_{scm} = \left(1.4\frac{l_0}{\phi} + 29.4 + 0.32\frac{\Sigma A_{tr}f_{yt}}{\phi^2 n_b} \right)\sqrt{f_{cm}}. \tag{2}$$

The range and distribution of covers within the data were insufficient to evaluate its contribution, and cover was therefore excluded as

Fig. 1. Variation is strength of lapped joint with lap length. From Pfister and Mattock [11].

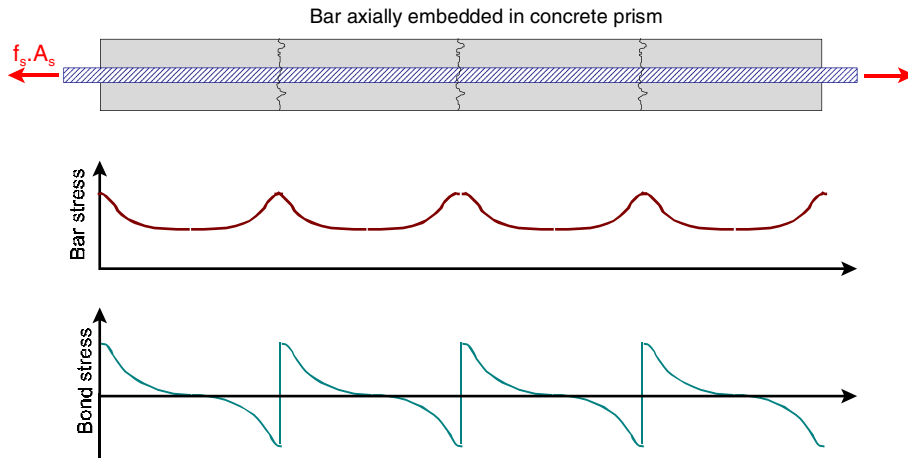Bar axially embedded in concrete prism

Fig. 2. 'In and out' bond stresses on tension bars due to transverse cracking.

a parameter. The term for the contribution of transverse reinforcement in Eq. (2) includes yield strength of transverse reinforcement, but subsequent work on tension laps determined that ties were typically lightly stressed at peak lap strength [9], hence the inclusion of f_{yt} in Orangun et al.'s expression may not be justified. The importance of locating links near the ends of compression laps where splitting initiates were recognized by Cairns & Arthur [12]. Where links were not located close to the ends of the lap the number of links contributing to ΣA_{tr} in Eq. (2) was taken as one less than the actual number present.

3.2. Chun et al. [7]

Following an extensive programme of tests, Chun et al. [5,6,7] proposed an empirical expression for strength of compression lapped splices based on a total of 94 tests on lap splices within columns of rectangular cross-section (Eq. (3)). Of this total 36 were confined by transverse reinforcement; the remainder was not confined by ties, and thus not representative of practice. Concrete strengths ranged from 49 MPa to 102 MPa, and were therefore all greater than those used in derivation of Eq. (2). Bar diameter was either 22 mm or 29 mm. The

stress developed by end bearing was determined from strains measured at a distance of one bar diameter from the end of the bar and would thus tend to overestimate its contribution. Lap strength was determined from bar strains measured inside the lap at a distance of one bar diameter from the end and would thus tend to underestimate the stress developed over the full lap length. The authors calibrated Eq. (3) using results from their own tests only.

$$f_{scm} = \left[\left(11.1 + 1.7\frac{K_{tr}}{\phi}\right)\sqrt{\frac{l_0}{\phi}} + 16.5 + 1.7\delta\right]\sqrt{f_{cm}}. \qquad (3)$$

As the authors found clear spacing between laps to have no influence on strength, Eq. (3) does not contain a cover parameter. Eq. (3) recognizes the influence of location of transverse reinforcement by introducing a parameter δ to reflect the influence of the positioning of confining within the lap length. δ is allocated a value of 1 if transverse reinforcement is placed at the ends of the lap or 0 if not.

3.3. fib Bulletin 72 (2014)

fib Bulletin 72 [10] reports the background to rules for bond and anchorage of reinforcement in the *fib* Model Code 2010 [17]. The expression for mean strength of compression splices is given by Eq. (4), and is derived by the addition of the net contribution of end bearing, represented by the second term within {} brackets, to the semi-empirical expression for strength of tension laps. The expression was calibrated using the same results as Cairns [13] together with results
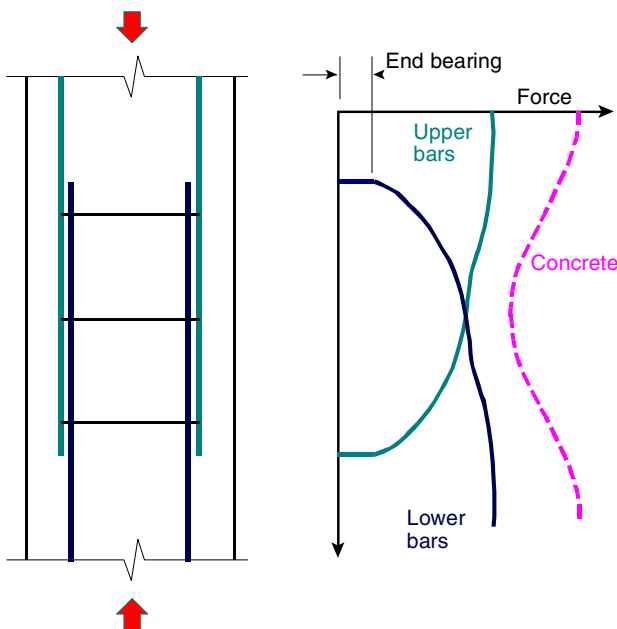

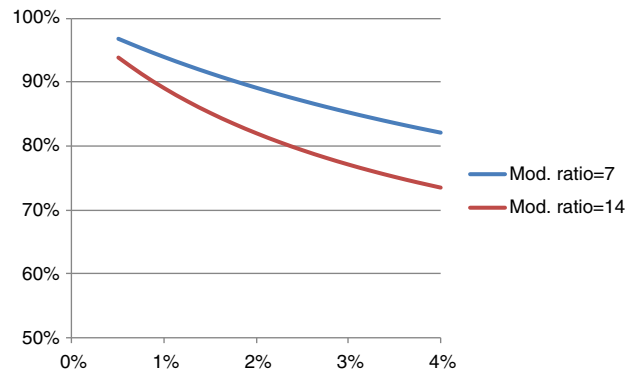**Fig. 3.** Variation in bar force through compression lap.

Fig. 4. Variation of steel stress at midlength of compression lapped joint with reinforcement area, from Eq. (1).

reported by Chun et al. in the first of their three papers on the topic [5].

$$f_{scm} = \left\{ 54 \left(\frac{f_{cm}}{25}\right)^{0.25} \left(\frac{l0}{\phi}\right)^{0.55} \left(\frac{25}{\phi}\right)^{0.2} + 60 \left(\frac{f_{cm}}{25}\right)^{0.5} \left(\frac{25}{\phi}\right)^{0.2} \right\} (\alpha_{2,m} + \alpha_{3,m}).$$

(4)

The coefficient of 54 in Eq. (4) has units of MPa. Parameters within circular brackets are dimensionless. Coefficients $\alpha_{2,m}$ and $\alpha_{3,m}$ represent confinement from cover concrete and transverse reinforcement respectively. Eq. 4 is calibrated for laps with links positioned close to both ends of the lap.

$$\alpha_{2,m} = \left(\frac{c_{min}}{\phi}\right)^{0.25} \left(\frac{c_{max}}{c_{min}}\right)^{0.1}.$$

c_{min} and c_{max} are cover/spacing dimensions, Fig. 5. $0.5 \leq c_{min}/\phi \leq 3.5$, $c_{max}/c_{min} \leq 5$

$$\alpha_{3,m} = k_m K_{tr}$$

k_m represents the efficiency of confinement by transverse reinforcement, Fig. 6.

$$K_{tr} = n_t A_{st}/(n_b \phi s_t) \leq 0.05$$

n_t is the number of legs of confining reinforcement crossing a potential splitting failure surface at a section
A_{st} is the cross sectional area of one leg of a confining bar
s_t is the longitudinal spacing of confining reinforcement
n_b is the number of anchored bars or pairs of lapped bars in the potential splitting surface.

4. Evaluation of 'best fit' expressions

This section presents a range of checks carried out to assess the fit of Eqs. (2), (3) and (4) to a database comprising all known tests where failure of compression laps occurred. An overall statistical analysis is presented first, followed by an examination of the influence of individual parameters.

4.1. Statistical fit to test data

Table 1 summarizes the fit of Eqs. (2), (3) and (4) to test data. Comparisons are based on four datasets:

1) The dataset on which the expressions were originally calibrated.
2) All tests in which lap failure occurred in a splitting mode in a database comprising results reported in publications by Chun et al. [5,6,
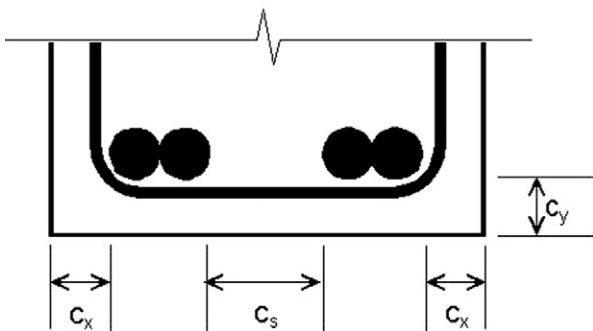
$c_{min} = min(c_x, c_y, c_s/2)$
$c_{max} = max(c_x, c_s/2)$

Fig. 5. Notation for cover dimensions.

7], Pfister and Mattock [11], Cairns & Arthur [12], and Leonhardt and Teichen [18]. The zero bond length result from Pfister and Mattock has been excluded from the evaluation as has one result (for specimen 0.54/2) from Leonhardt and Teichen where the reported strength is markedly lower than that of its companion specimen and well below the overall trend. A further 3 results comprising the 3 longest lap lengths tested by Leonhardt and Teichen and in which estimated strength exceeded the yield strength of reinforcement by at least 20% have also been ignored ($l_0 = 37.5\phi$, tests 1.5/1, 1.5/2 & 1.5/3). The results of several specimens tested by Chun et al. in which failure was not attributable to bond and consequently rejected by them have also been rejected here.

3) A database filtered from Eq. (2) above in which specimens with a lap length of less than 10 bar diameters, minimum cover or half clear spacing of less than 0.5 bar diameters and concrete cylinder compressive strengths of less than 20 MPa are excluded. These values have been set taking account of limits in EC2, but recognizing that omitting lap lengths below the 15ϕ minimum specified in EC2 would exclude too large a proportion of the data.

4) A subset of the filtered database excluding specimens in which links were not located within 3ϕ of both ends of the lap.

Table 1 shows that variability of the strength estimates provided by Eqs. (2), (3) and (4) for the full database is greater than in the original evaluations. The 'goodness of fit' of empirical expressions should be assessed not on the fit to the data on which they were originally calibrated, but on their fit to an independent set of data. The difference in fit between the original and full datasets suggests that all three empirical expressions have shortcomings.

The fit to the 'End links only' dataset (Eq. (4)) is of greatest relevance to an evaluation of EC2, as tests in this dataset represent parameters closest to compliance with its detailing provisions. The 5% characteristic value listed for this dataset is calculated as the mean minus 1.64 times the standard deviation of the measured/calculated strength ratio. Eq. (3) has a 5% higher mean ratio than the other expressions, but otherwise all three (together with Eq. (5), a modified version of Eq. (4) presented below) show a near identical fit to test data.

A more detailed examination of the influence of each parameter within the expressions has therefore been conducted, and is presented in the following sections.

4.2. Concrete strength

Both Eq. (2) and Eq. (3) represent lap strength as dependent on $f_{cm}^{0.5}$, whereas Eq. (4) represents the bond contribution as dependent on $f_{cm}^{0.25}$ as accepted by a number of expressions for strength of tension laps, but with the end bearing contribution dependent on $f_{cm}^{0.5}$. Figs. 7(a) and 7(b) plot the ratio of measured lap strength to estimated strength according to Eqs. (3) and (4) respectively. The trend for the ratio obtained by Eq. (3) is horizontal (albeit with significant scatter) whereas that for Eq. (4) shows a marked tendency to increase with increasing concrete strength, indicating that its influence is underestimated. The data used in derivation of Eq. (3) embraced a much greater range of concrete strengths, and it appears to provide a better representation of the influence of concrete strength. This conclusion must be treated with a degree of caution, however, as there is a marked cross-correlation between concrete strength and lap length in the data reported by Chun et al. [7] and used in the calibration of Eq. (3). However, even if analysis is confined to specimens with a lap length of 10ϕ Eq. (3) continues to provide a better representation than Eq. (4).

4.3. Concrete cover & bar spacing

Minimum cover and bar spacing are known to exert a marked influence on strength of tension laps which EC2 recognizes through a coefficient α_2, but for compression laps $\alpha_2 = 1.0$. Cairns [13] omitted a cover
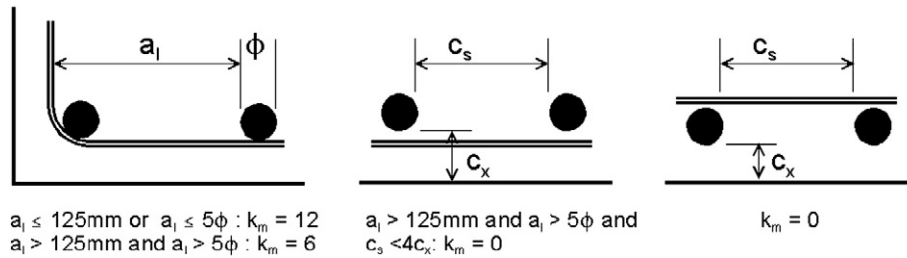
Fig. 6. Factor k_m for effectiveness of links.

parameter in Eq. (2) as a) it was not a variable in any of the investigations available at the time, b) although each investigation used a different cover to diameter ratio, other inter-series differences would have obscured any influence, c) any influence was not statistically significant, and d) the splitting resistance of concrete cover in the biaxial compression/tension stress field in the cover to compression laps would be expected to provide less restraint than the tension/tension stress field in cover to tension laps. Chun et al. [5,6,7] tested laps with clear spacing between laps of 1.5ϕ and 2.5ϕ, and found that clear spacing did not influence lap strength, also noting the effect of biaxial stresses on the strength of concrete cover in the circumferential direction.

Generally scatter is too large for any clear influence of cover to be apparent, and cover was included in Eq. (4) primarily for consistency with tension laps. It can be concluded that influence of minimum cover/bar spacing on lap strength is markedly lower for compression than for tension laps.

4.4. Confining reinforcement

Parameter α_3 represents the influence of confining reinforcement in EC2, but for compression laps $\alpha_3 = 1.0$. The variation in lap strength with confining reinforcement according to Eqs. (3), (4) and (5) is plotted in Fig. 8 for the lap detail shown in Fig. 9, assuming a concrete cylinder compressive strength of 30 MPa and a lap length of 20 bar diameters. The trend shown by Eqs. (3) and (4) is consistent, although Eq. (2) suggests a somewhat stronger influence. Overall, however, the difference between the three expressions does not exceed 10% from a spacing of 12ϕ, the maximum spacing at a lap permitted by EC2, down to 1.5ϕ.

Table 1
Statistical evaluation of best fit expressions.

			Cairns (Eq. (2))	Chun et al. (Eq. (3))	*fib* Bulletin 72 (Eq. (4))	Eq. (5)
Dataset	Dataset (1) original	Mean	1.00	1.00	1.06	–
		Std. dev	0.13	0.10	0.13	–
		CoV	0.13	0.10	0.13	–
		Minimum	0.77	0.74	0.82	–
		No. of results	29	94	26	–
	Dataset (2) full	Mean	1.08	1.02	1.10	1.01
		Std. dev	0.17	0.14	0.19	0.15
		CoV	0.16	0.14	0.17	0.15
		Minimum	0.69	0.64	0.62	0.64
		No. of results	138			
	Dataset (3) filtered	Mean	1.05	1.01	1.07	0.99
		Std. dev	0.16	0.14	0.18	0.14
		CoV	0.16	0.14	0.17	0.14
		Minimum	0.69	0.64	0.62	0.64
		No. of results	95			
	Dataset (4) End links only	Mean	0.98	1.05	1.00	1.00
		Std. dev	0.14	0.15	0.14	0.15
		CoV	0.14	0.14	0.14	0.15
		Minimum	0.69	0.67	0.73	0.76
		5% characteristic	0.75	0.81	0.77	0.76
		No. of results	47			

Fig. 8 also includes a comparison between the increase in compression and tension lap strengths with increasing amounts of transverse reinforcement. The estimate of tension lap strength uses the expression of Zuo and Darwin [8]. Tension lap strength is lower than that of a similar compression lap as end bearing is not present, but the plot also indicates that the influence of transverse reinforcement is between 3 and 5 times stronger in compression laps. Cairns [13] noted a similar increase which he attributed to links attaining higher stresses at failure of compression laps. Both Cairns and Chun et al. [7] set the limit beyond which additional transverse reinforcement may be considered to enhance bond strength below the corresponding values for tension laps. These trends are consistent with measurements which show transverse reinforcement being more highly stressed at failure of compression laps.

4.5. Bar size

Bar size has been demonstrated to exert a significant influence on tension lap strength [10], and EC2 [1] includes a coefficient η_2 to reduce the average bond strength of bars greater than 32 mm in diameter.
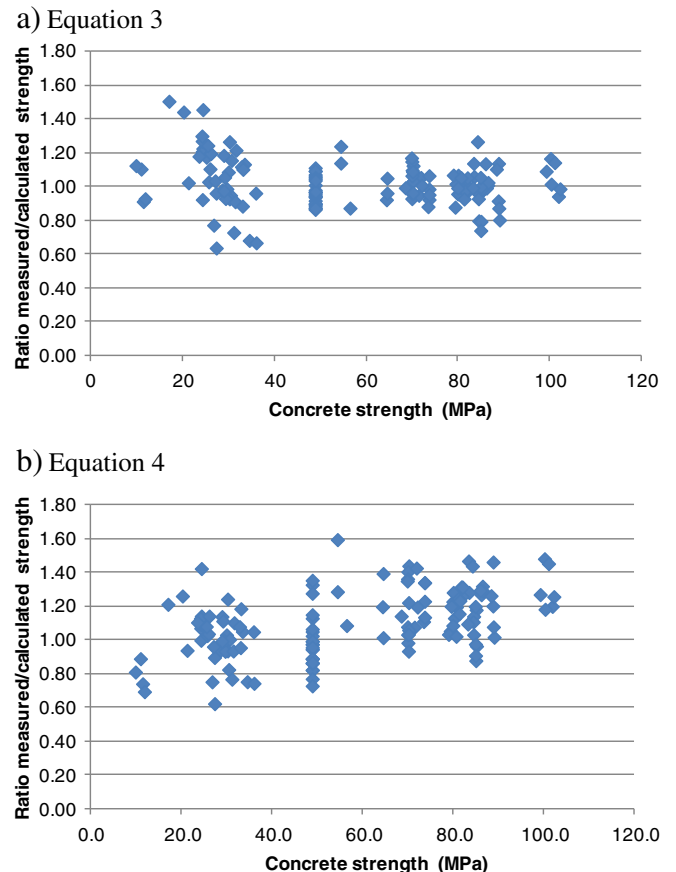
a) Equation 3

b) Equation 4

Fig. 7. Variation in the ratio of measured to calculated lap strength with concrete strength.
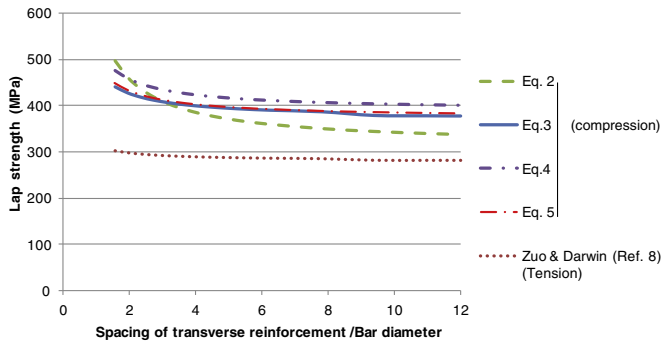
Fig. 8. Influence of transverse reinforcement on lap strength according to Eqs. (2)–(5), $l_0 = 20\varphi$.

Fig. 10. Variation in lap strength with lap length (mean values).

Cairns [13] reported that bar diameter did not affect strength of compression laps, although other inter-series differences may have obscured any influence. Chun et al.'s results [7] suggest little difference between 22 mm and 29 mm bars, but the narrow range would have made it difficult to discern any influence within the general scatter. On the available data, there is no clear justification for including bar diameter as a parameter in expressions for strength of compression laps, although in view of the limited data it is considered prudent to maintain the current EC2 rule for diameters in excess of 32 mm.

4.6. Lap length

Fig. 10 plots the influence of lap length on lap strength as determined by Eqs. (2), (3) and (4) for the lap detail shown in Fig. 9. Concrete cylinder compressive strength is taken as 30 MPa and link spacing as 150 mm. Increases in lap strength are less than proportional to lap length due both to end bearing and to the trend for average bond strength over the straight portion of a bar to decrease with increasing lap length, as observed in tension laps [8,9,10]. The various equations examined here provide a consistent estimation of lap strength for this concrete Class, although at higher strengths the spread between strength estimates increases, primarily due to the differing
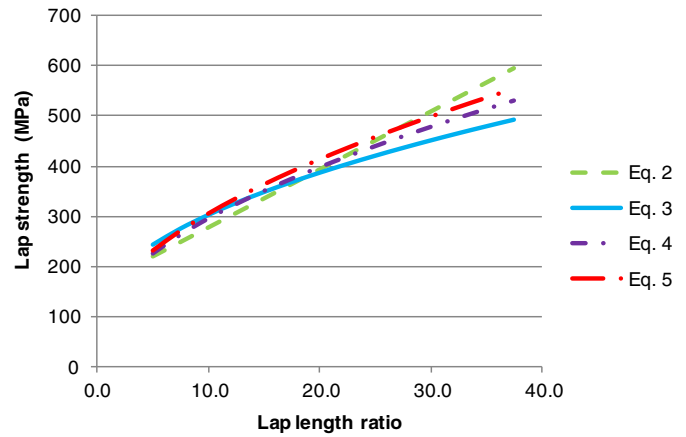
sensitivity to concrete strength between Eq. (4) and the other two expressions.

4.7. Relative rib area

Relative rib area is known to influence bond strength, and this parameter is included in the empirical expression of Zuo and Darwin [8] for strength of tension laps. Cairns [13] noted a difference in bond strength between the two types of bar included in his tests on compression laps. The parameter values are not stated in other investigations in the database, hence it cannot be represented in this analysis. However, it is likely to have contributed to scatter.

4.8. Reinforcement percentage

It has been inferred from Eq. (1) that reinforcement percentage ρ might influence lap strength. No supporting evidence is apparent from the experimental data, however, although scatter in results is rather wide. The assumption of zero bond slip may be incorrect in the relatively short laps which make up the bulk of test data.
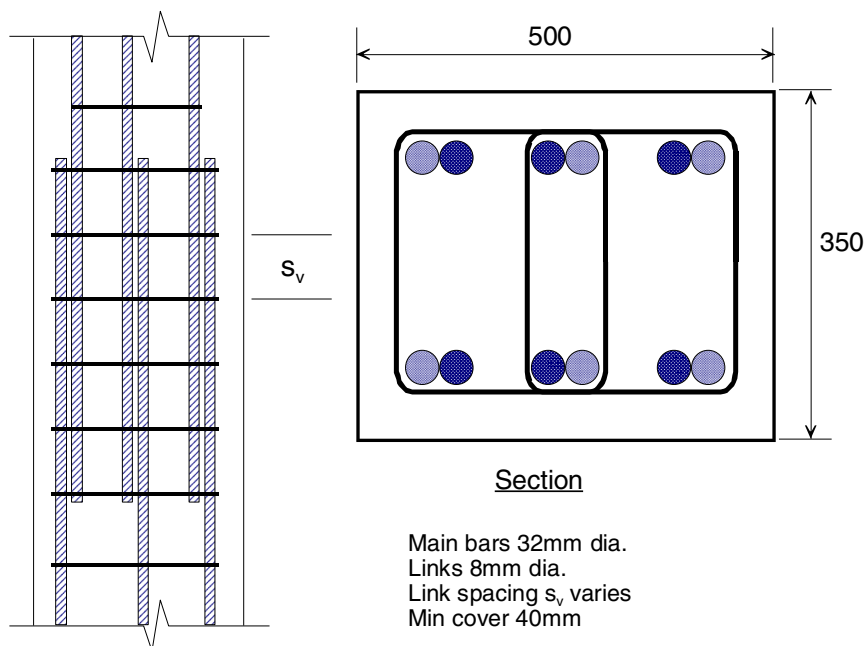

Main bars 32mm dia.
Links 8mm dia.
Link spacing s_v varies
Min cover 40mm

Fig. 9. Example lap detail.

4.9. Revision to fib Bulletin 72 expression

As discussed above, Eq. (4) does not provide a good description of the observed influence of concrete strength. In addition, no justification was found for inclusion of bar diameter or concrete cover/bar spacing as influencing parameters. Further analysis also showed a slight improvement in fit if the contribution of confining reinforcement applied to the bond contribution only, and not to the end bearing contribution. Except for the helically bound columns tested by Pfister & Mattock [11], the first link outside the lap was at least five bar diameters away from the ends. This would be too far for the confining links to restrain the bursting force generated by end bearing. To take account of these observations, Eq. (5) is proposed here. The influences of confining reinforcement and of lap length on lap strength calculated according to Eq. (5) are also plotted in Figs. 8 and 10 respectively. The statistical fit of Eq. (5) to test data is given in Table 1, and differs little from Eqs. (2)–(4). Accordingly, Eq. (5) will be used in place of Eq. (4) in further analysis and evaluation.

$$f_{scm} = \left\{ 54 \left(\frac{l_0}{\phi} \right)^{0.55} (1 + \alpha_{3,m}) + 60 \right\} \left(\frac{f_{cm}}{25} \right)^{0.5}. \tag{5}$$

It is worth emphasizing that the aim of this study is to evaluate the safety provided by EC2 rules, not to derive an optimum expression for lap strength. It was noted above that the fit of Eqs. (2)–(4) was degraded when assessed against data independent of that on which they were calibrated, and all must therefore be considered questionable to some degree. The inclusion of Eq. (5) is justified more by an intention to provide a robust evaluation against a number of diverse expressions rather than against any single if allegedly more accurate expression.

5. Evaluation of EC2 provisions for compression lap lengths and suggested revisions

EC2 [1] provisions for design of lap lengths of both tension and compression bars are based on an average bond strength acting over the nominal surface of a bar throughout the lap length. In contrast, Eqs. (2)–(5) all represent lap strength as composed of a 'bond' component related to lap length plus an end bearing contribution dependent only on concrete strength. In the EC2 format an end bearing contribution would be 'smeared' over a full design lap length. If this 'smeared' stress were considered to act over a shorter lap length the true contribution of end bearing would be underestimated. A direct comparison between lap strength measured on short lap lengths and lap strength calculated on the basis of EC2 design rules would consequently lead to a non-conservative estimate of the margin of safety against failure.

A more valid approach to assess safety of EC2 rules is to determine the bar stress which lap lengths calculated in accordance with EC2 for the full design strength of a bar would develop. This avoids uncertainties associated with testing of relatively short laps where end bearing makes a major contribution to force transfer, and allows confining reinforcement to be represented in strict accordance with provisions of EC2. The design lap length is determined from Eqs. (6) and (7).

$$f_{bd} = 2.25 \, \eta_1 \eta_2 f_{ctd} \tag{6}$$

$$l_{0,d} / \phi = \frac{\sigma_{sd}}{4 f_{bd}} \alpha_1 \alpha_2 \alpha_3 \alpha_4 \alpha_6 \tag{7}$$

where η_1 is a coefficient related to the position of the bar during concreting. This evaluation is based on bars in a 'good' casting position, for which $\eta_1 = 1.0$.

η_2 is related to bar diameter: $\eta_2 = 1.0$ for $\phi \le 32$ mm; $\eta_2 = (132 - \phi)/100$ for $\phi > 32$ mm.

f_{ctd} is the design tensile strength of the concrete, from Eq. (3.16) of EC2,

σ_{sd} is the design strength of the bar.

α_1 represents the contribution of a bend or hook at the end of the bar, and is set at 1.0 for compression bars.

α_2 and α_3 represent the influence of concrete cover and of confining reinforcement respectively and allow reductions in lap length of bars in tension, but are set at 1.0 for compression laps. Minimum area of transverse reinforcement is the area of a single lapped bar.

α_4 represents the contribution of welded transverse reinforcement and is taken as 1.0 in the absence of transverse bars.*

α_6 is a coefficient representing the proportion of longitudinal bars lapped at the section. It is assumed here that all reinforcement is lapped at the same section, hence $\alpha_6 = 1.5$.

$l_{0,d}$ and ϕ are design lap length and diameter of the lapped bar respectively.

Comparisons are based on laps of Class 500 reinforcement [19], for which the design stress σ_{sd} is taken as 435 MPa, the specified characteristic yield strength of 500 MPa divided by the partial safety factor of 1.15 recommended by EC2. Mean concrete strength f_{cm} is taken as characteristic strength $f_{ck;0.05} + 8$ MPa. The limitation of concrete strength to the value for C60/75 proposed by EC2 has not been applied here as earlier analysis has demonstrated increases in bond strength with stronger concretes.

The comparison is based on the reinforcement detail shown in Fig. 9. Benchmark values for the analysis are taken as: $\phi = 32$ mm, minimum cover = 40 mm and $f_{ck} = 40$ MPa. The area of transverse reinforcement within the lap length is taken as the minimum required by EC2.

To obtain a characteristic value for lap strength f_{sck}, Eqs. (2), (3), and (5) are multiplied by the corresponding characteristic strength ratio for dataset (Eq. (4)) given in Table 1. Thus in Eq. (5), for example, the coefficient of 54 MPa for the mean lap strength reduces to a value of $54 \times 0.76 = 41$ MPa for characteristic lap strength. The characteristic expressions are given as Eqs. (2k), (3k) and (5k).

$$f_{sck} = 0.75 \left(1.4 \frac{l_{0,d}}{\phi} + 29.4 + 0.32 \frac{\Sigma A_{tr} f_{yt}}{\phi^2 n_b} \right) \sqrt{f_{cm}} \tag{2k}$$

$$f_{sck} = 0.81 \left[\left(11.1 + 1.7 \frac{K_{tr}}{\phi} \right) \sqrt{\frac{l_{0,d}}{\phi}} + 16.5 + 1.7\delta \right] \sqrt{f_{cm}} \tag{3k}$$

$$f_{sck} = 41 \left(\frac{f_{cm}}{25} \right)^{0.5} \left(\frac{l_{0,d}}{\phi} \right)^{0.55} (1 + \alpha_{3,m}) + 46 \left(\frac{f_{cm}}{25} \right)^{0.5}. \tag{5k}$$

Fig. 11 plots the variation in f_{sck} calculated by Eqs (2k), (3k) and (5k) with concrete compressive strength. Plots for Eqs. (3k) and (5k) are in close agreement, with Eq. (2k) showing a similar trend but slightly higher lap strength for the detail considered. All three plots show strength of laps designed to EC2 increases with increasing concrete strength, the strength of a design lap in Class 100 concrete being 35%–40% stronger than that in Class 20 concrete. While this might appear to show that EC2 provisions do not provide a consistent margin of safety over the practical range of concrete strengths, the following consideration of performance objectives for compression laps shows this may not be the case.

Compressive stress in concrete reaches a peak at a strain of between 0.0018 and 0.0028 according to the relationships provided in EC2 Table 3.1. A strain of 0.0018 corresponds to a reinforcement stress of around 360 MPa, 17% less than the design strength of Class 500 reinforcement. The reinforcement strain at which a column reaches its maximum capacity is dependent on many factors including section

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* EC2 gives α_5 and not α_4 in Eq. (7), but this would appear to be incorrect.
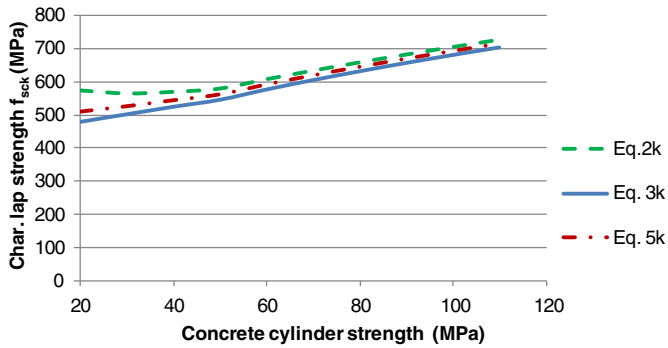
Fig. 11. Influence of concrete strength on characteristic strength of compression laps designed to EC2.

geometry and loading eccentricity in addition to concrete Class, but it would nonetheless seem more rational for compression laps to be designed to develop a strain of ε_{c1}, the strain at peak stress of the concrete rather than a single design stress. Eq. (8) gives the value of strain at peak stress stated in Table 3.1 of EC2.

$$\varepsilon_{c1} = 0.7 f_{cm}^{0.31}. \tag{8}$$

Fig. 12 plots the ratio of stress at failure of a lap designed to EC2 to the reinforcement stress corresponding to strain at peak stress ε_{c1} over a range of concrete strengths. The stress ratio at lap failure σ_r is given by Eq. (9), with E_s the modulus of elasticity of steel taken as 200 GPa.

$$\sigma_r = \frac{f_{sck}}{\varepsilon_{c1} \cdot E_s}. \tag{9}$$

According to Eqs. (3k) and (5k), the stress ratio varies by no more than 10% over a range of concrete strengths from 20 MPa to 100 MPa, and on this basis it may be concluded that EC2 rules for compression laps provide a reasonably consistent margin against lap failure over the practical range of concrete strengths.

EC2 recommends a partial factor of safety of 1.5 be applied to characteristic strength to obtain design values for bond strength. Fig. 12 shows that when assessed against the failure criterion proposed here, the lowest stress ratio is found with a Class C60 concrete. Characteristic strength of the lap detail in Fig. 9 as estimated by Eqs. (2k), (3k) and (5k) for Class 60 concrete averages 600 MPa, 38% greater than the design strength of 435 MPa for Class 500 reinforcement. Although this represents a margin against failure 8% less than the EC2 recommended partial safety coefficient of 1.5, in the absence of any documented failures in service it does not suggest a serious shortcoming in EC2 design
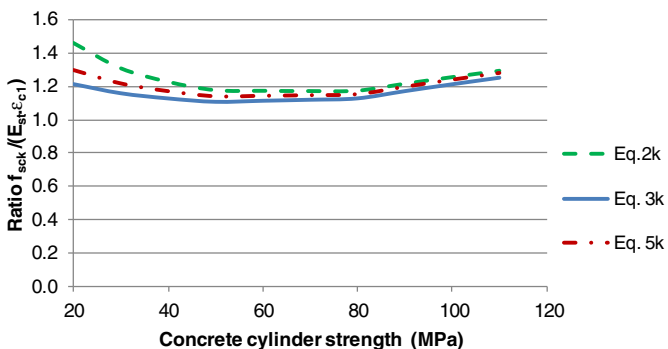
provisions. This finding contrasts with that of previous work on tension laps which found that estimated characteristic strength may fall below the design strength of reinforcement [2]. It is recommended, however, that a more detailed statistical analysis be conducted taking account of the variability in both bond resistance as estimated by Eqs. (3k) and (5k) and in parameters relevant to the proposed failure criteria.

EC2 does not allow a reduction in lap length of compression bars when transverse reinforcement in excess of the specified minimum is provided even though the review presented earlier in Fig. 8 has shown that compression laps are more sensitive to transverse reinforcement. There seems to be no justification to permit $\alpha_3 < 1.0$ in tension but not in compression laps (even if the allowable reduction in lap length can hardly be justified by the necessary increase in transverse reinforcement).

Although test data suggests that strength of compression laps is insensitive to bar size, the inter-series differences and limited spread in the data do not provide a high degree of confidence, and it would be reasonable to maintain coefficient η_2 as currently defined as lap failure of large bars is generally considered to be more brittle. EC2 does not recognize any influence of minimum concrete cover or bar spacing, consistent with the limited observations reported.

The format adopted in EC2 design rules implies that the contribution of end bearing is 'smeared' over the lap length and included within an average bond strength. For shorter laps, this average bond strength would tend to give a conservative estimation of lap capacity. For the assessment of existing structures with sub-standard lap lengths, there would be an advantage in reformatting rules based on the summation of contributions from bond over the straight length of the bar and a net stress contributed by end bearing, as in Eqs. (3k) and (5k). This format would also enable a more accurate and reliable treatment of different strength classes of reinforcement.

End bearing could be impaired in situations where minimum end cover to a lapped bar is low (Fig. 13). The *fib* Model Code 2010 [17] advises that end bearing should only be considered to contribute to strength where the end cover is at least 3.5ϕ.

There appears to be a typographical error in Eq. (8.10) of EC2 [1] (Eq. (7) here), and that α_5 should be replaced by α_4, as the entry for α_5 for compression bars in Table 8.2 is blank but the entry for α_4 is not, and it is most unlikely that transverse compression would be present at a lap.

6. Conclusions and recommendations

1. End bearing makes an appreciable contribution to strength of lapped bars in compression.
2. The influence of minimum concrete cover or clear spacing on strength of compression laps is much reduced in comparison with
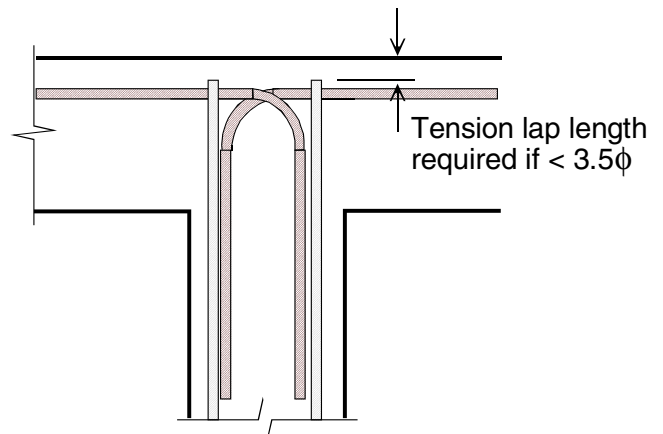

Fig. 12. Variation in ratio of strain capacity of compression lap designed to EC2 to ε_{c1} concrete strain at peak compressive stress.

Fig. 13. Limitation on contribution of end bearing when end cover is low.

tension laps, consequently coefficient α_2 in Table 8.2 of EC2 should be taken as 1.0 for compression laps.

3. The influence of transverse reinforcement is greater for compression laps than for tension laps, hence there is no valid reason for setting coefficient α_3 in Table 8.2 of EC2 at a more conservative value than for tension laps.

4. The margin of safety against failure of compression laps designed to EC2 is around 8% less than might be expected, but in the absence of reported failures may be considered adequate.

5. Due to the contribution of end bearing, the strength of compression laps is not proportional to lap length. Consideration should be given to reformatting rules for assessment of existing structures with lap strength calculated as the summation of contributions from bond and end bearing.

6. Design rules should identify situations in which end bearing may be reduced by minimum cover to the end of a bar.

7. It is recommended that a more detailed statistical analysis be conducted taking account of the variability in both bond resistance as estimated by Eqs. (2), (3) and (5) and in parameters relevant to the failure criterion for compression laps proposed here.

8. It is noted that Table 8.2 and Eq. 8.10 of EC2 appear inconsistent, and it is recommended that a correction be introduced.

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