Test Results and Comparison to Code Equations on Lap Splice Strength of Reinforcement in RC beams

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Abstract

The design of the lap splices will have a major change with the 2nd generation Eurocode prEN 1992-1-1 D7. One of the changes in prEN1992-1-1 D7 is the effect of the proportion of the lapped bars in tension in one cross-section. In the current Eurocode, a large proportion of the lapped bars in cross-section has led to a 1.5-fold lap length when comparing to anchorage, while, in prEN1992-1-1 D7, the lap length is in many cases similar to the anchorage length.

Questions have arisen about the strength and ductility of the member with lap splices. As a result, there is a need to have more experimental evidence of the behaviour of the lapped joints and, in particular, if they are placed near the plastic hinges.

In this context, this paper is part of a research project that aims to gain more information on the behaviour of the lapped bars in RC beams. This paper focuses on the effect of the lap length on the lap strength, while the latter part of the study deals with the lap splice ductility.

Test specimens were beams with a square cross-section, which were reinforced with four rebars on the tension side and they were tested under four-point bending conditions. The rebar size, lap length and proportion of the lapped bars were varied between the specimens. The lap length in the test beams was 20-60 times the bar diameter.

The results of the loading tests were compared to the code type models. Information was obtained on the lap strength and precision of different code models.

Keywords: *Lap strength, lap length, prEN 1992-1-1, bond, reinforcement.*

1. Introduction

An extensive experimental campaign of reinforced concrete (RC) beams with different lap lengths has been conducted by the Structural Laboratory of Tampere University. Work has been done in the Unit of Concrete and Bridge Structures. This paper focusses on lap strength. Later research will continue in the field of ductility and the plastic rotations of tested members.

This paper presents the results of the lap strength up to the yield strength of the reinforcement bars. The goal of this study is to compare the test results to the code type models for the lap strength. Obtained lap lengths from the models are defined based on the steel stress. The studied models were a) the model of current Eurocode 2 (EN 1992-1-1:2004); b) the model of the fib Bulletin 72, and c) the model of the 2nd generation Eurocode 2 (prEN 1992-1-1:2020, D7)

2. Experimental investigations

2.1. General

A total of 40 RC beam specimens were constructed and tested at the Structural Laboratory of Tampere University to investigate the effect of the lap length to the lap strength and to the ductility behaviour of the structure. The varied parameters were the bar diameter (ϕ = 12, 16, 20 and 25 mm), lap length and the proportion of the lapped bars. The maximum load of the bending test was reached in twenty beams before achieving the yield strength of the tensile rebars, or immediately after reaching the yield strength. This paper, mainly, discusses these beam specimens. The study is still ongoing and further analyses on the plastic behaviour of RC beams, especially with longer lap splice lengths, will be published as the research proceeds.

2.2. Materials and test specimens

The target compressive strength of concrete was f_c = 35 MPa with an upper aggregate size of 16 mm. Compressive strength f_{cm} and tensile splitting strength $f_{ctm;sp}$ were determined from the concrete cylinders for each batch of concrete in accordance with EN 12390-3:2019 and EN 12390-6:2009 respectively (Table 1). The cylinders and the test beams were stored at the same laboratory conditions. Concrete strength was tested at the same time as the associated beams were tested. Direct tensile strength value f_{ctm} was determined from the average splitting tensile strength according to *fib* Bulletin 42.

The beams had a square cross-section where the width and height depended on the bar diameter (Table 2). All beams were reinforced by using four tensile bars (B500), of which 100% or 50% were spliced at a section. In beams with 50% of bars lapped, the middle bars were spliced as shown in Figure 1.

Table 1. Concrete strength properties.

Concrete batch no.	1	2	3	4
f_{cm} (MPa)	36.4	41.0	31.0	34.4
$f_{ctm;sp}$ (MPa)	2.8	3.2	2.7	2.8
f_{ctm} (MPa)	2.4	2.8	2.2	2.4

Table 2. Design parameters of the test specimens.

Test series	p (%)	ϕ (mm)	l_b/ϕ	ϕ_{st} (mm)	b, h (mm)	c_x (mm)	c_y (mm)	$c_s/2$ (mm)	c_y/ϕ	Concrete batch no.
B12-050	50	12	20*; 30*; 40; 50	8	270	48	28	17	2.3	3
B16-050	50	16	20*; 30*; 40; 50	10	350	50	30	26	1.9	2
B20-050	50	20	20*; 30*; 40; 50	12	450	62	32	34	1.6	3
B25-050	50	25	20*; 30*; 40*; 50	12	550	62	32	46	1.3	2
B12-100	100	12	20*; 30*; 40*; 50; 60	8	270	48	28	13	2.3	4
B16-100	100	16	20*; 30*; 40*; 50	10	350	50	30	20	1.9	1
B20-100	100	20	20*; 30*; 40*; 50; 60	12	450	62	32	28	1.6	4
B25-100	100	25	20*; 30*; 40; 50	12	550	62	32	38	1.3	1

* Comparison of the measured lap strength to the code equations presented in this paper.
p: percentage of lapped bars; ϕ: rebar diameter; l_b/ϕ: tested lap lengths; ϕ_{st}: stirrup diameter; b, h: width and height of the cross-section; c_x, c_y and c_s: see Figure 1.

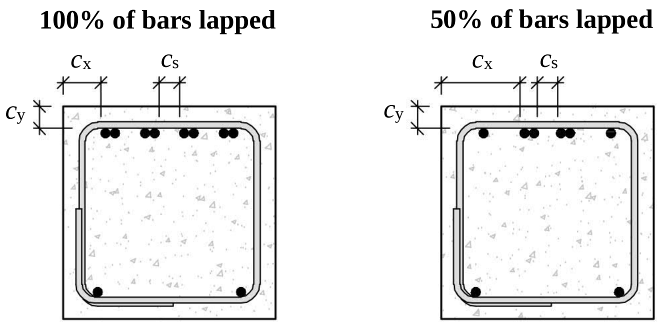

Figure 1. Beam cross-section.

The beams were cast so that the lap splices were located at the bottom of the formwork, where good bond conditions can be expected. Right after casting, the specimens were covered with plastic film to prevent water loss. After curing for 14 days, the moulds were removed.

2.3. Test setup and instrumentation

Beams were loaded tension side upwards in the same way as in the Micallef and Vollum (2018) study. This provides for a better observation of the lap splice region. Four-point bending tests were carried out by using the test arrangement as shown in Figure 2. Rebars were spliced in a constant moment region between the supports. The span length of the specimen varies depending on the tested bar diameter as shown in Table 3.

The applied load was measured by using the load cells under both hydraulic jacks. Vertical displacements were measured by using displacement transducers at the position of both jacks and at the mid-span.

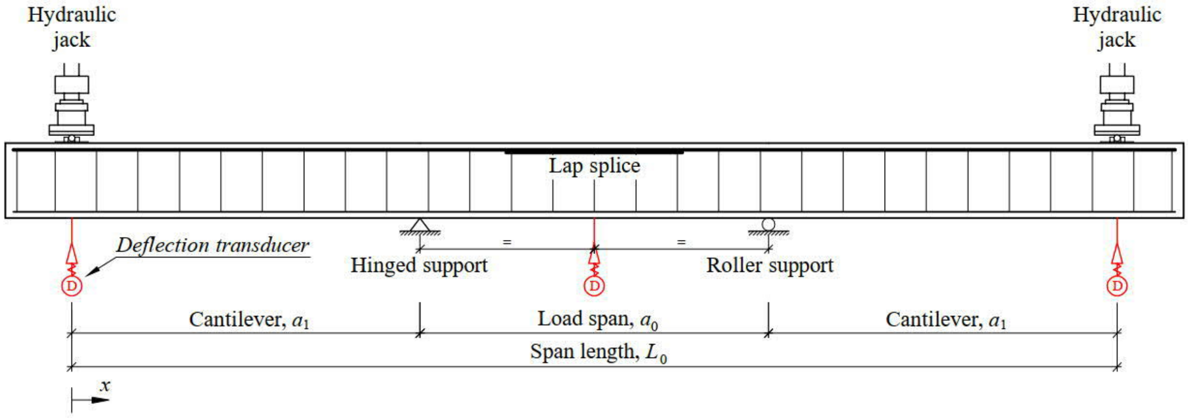

Figure 2. Test arrangement.

Table 3. Parameters of load arrangement.

ϕ (mm)	d (mm)	a_0 (m)	a_1 (m)	L_0 (m)	L_{tot} (m)
12	235	1.25	1.25	3.75	4.30
16	310	1.65	1.65	4.95	5.70
20	405	2.10	1.90	5.90	6.80
25	505	2.60	2.10	6.80	8.90

2.4. Test procedure

All tests were conducted as displacement controlled. The initial loading rate of the hydraulic jack at the side of the fixed support of the test specimen was 0.1 mm/min, while the loading rate of the other hydraulic jack was adjusted to correspond to the same load level throughout the whole test. The loading rate was increased gradually after achieving the yielding load of the specimen. Loading was continued beyond the ultimate load of test specimens so that the post peak behaviour of the test specimens was also observed.

3. Determination of lap length

3.1. Model of current Eurocode 2

According to EN 1992-1-1:2004, the normalised lap length (L_b/ϕ) can be obtained from Equation 1 which has been derived here for the studied cases (straight lapped bars with no transverse pressure applied), and for the measured parameters (f_{ctk} => f_{ctm} and f_{yd} => f_{ym}).

$$\frac{L_{b,EC2}}{\phi} = \alpha_2\,\alpha_3\,\frac{\gamma_C \cdot \sigma_s}{6 \cdot f_{ctm}} \tag{1}$$

$$\alpha_2 = 1 - 0.15\left(\frac{c_{min}}{\phi} - 1\right), \qquad 0.7 \le \alpha_2 \le 1.0 \tag{2}$$

$$\alpha_3 = 1 - K\left(\frac{n_{st} \cdot \phi_{st}^2}{\phi^2} - \frac{\sigma_s}{f_{ym}}\right), \qquad 0.7 \le \alpha_3 \le 1.0 \tag{3}$$

where γ_C is the partial safety factor for concrete, σ_s is the measured lap splice strength, c_{min} is the minimum value from c_y, c_x and $c_s/2$ (Figure 1), K is the coefficient for confinement (K = 0.1 for confinement effect; K = 0 for no confinement effect), and f_{ym} is the measured yield strength of rebar. Coefficient α_6, taking account of the proportion of bars lapped in the cross-section, is assumed here as 1.5 also for 100% lapped specimens, although these specimens do not fully meet the requirements of EN 1992-1-1:2004 for the arrangement of lapped bars. In all cases, the tested specimens also did not meet the code requirements for minimum amount and placing of the transverse reinforcement. The transverse reinforcement ($\Sigma A_{st} = n_{st} \cdot A_{st}$) along the entire lap length L_b has been considered here for the effect of confinement. This has only a minor effect on the result of this model to the studied specimens.

Since the latter two studied models are based on the compressive strength of concrete, it is appropriate to derive also Equation 1 to be based on the compressive strength f_{cm}. With the analytical relations for the strength properties given in EN 1992-1-1:2004, Equation 1 results in:

$$\frac{L_{b,EC2}}{\phi} = \alpha_2\,\alpha_3\,\frac{\gamma_C \cdot \sigma_s}{1.8 \cdot (f_{cm} - 8[MPa])^{\frac{2}{3}}} \tag{4}$$

3.2. Model of *fib* Bulletin 72

The model for normalised lap length according to fib Bulletin 72 (2014) can be expressed for studied specimens by the following equation:

$$\frac{L_{b,fib72}}{\phi} = \left(\frac{\sigma_s}{54}\right)^{1.82} \left(\frac{f_{cm}}{25}\right)^{-0.45} \left(\frac{25}{\phi}\right)^{-0.36} \left(\left(\frac{c_{min}}{\phi}\right)^{0.25} \left(\frac{c_{max}}{c_{min}}\right)^{0.1} + k_m\,K_{tr}\right)^{-1.82} \tag{5}$$

$$K_{tr} = \frac{\pi \cdot \phi_{st}^2}{2 \cdot s_{st} \cdot \phi \cdot n_s} \leq 0.05 \tag{6}$$

where c_{max} is the maximum value from c_x and $c_s/2$ (Figure 1), k_m is the coefficient for confinement ($k_m = 12$ for confinement effect; $k_m = 0$ for no confinement effect), s_{st} is the spacing of the stirrups at lap splice and n_s is the number of pairs of lapped bars. All stress values are in MPa and dimensions in mm.

3.3. Model of 2nd generation Eurocode 2

The 2nd gen Eurocode 2 (prEN 1992-1-1:2020, D7) expresses the normalised lap length for studied test specimens and for measured material properties (f_{ck} => f_{cm}) as follows:

$$\frac{L_{b,prEC2}}{\phi} = k_{lb} \left(\frac{\sigma_s}{435}\right)^{n_\sigma} \left(\frac{25}{f_{cm}}\right)^{\frac{1}{2}} \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \left(\frac{1.5\phi}{c_{d;conf}}\right)^{\frac{1}{2}} \tag{7}$$

$$c_{d,conf} = c_{min} + 30\phi \cdot k_{conf} \cdot K_{tr} \leq 3.75\phi \tag{8}$$

where:
- k_{lb} is the calibration parameter for the design situation: $k_{lb} = 50$ is for persistent and transient design situations (reliability index $\beta = 3.8$), $k_{lb} = 39$ match with the characteristic value of the results from *fib* Task Group 4.5 splice test database and Micallef and Vollum (2018) study, while $k_{lb} = 28$ match with the mean value of these results (Muttoni et al. 2021).
- $n_\sigma = 1.0$ for $\sigma_s \leq 435$ MPa, and $n_\sigma = 1.5$ for $\sigma_s > 435$ MPa
- $k_{conf} = 1.0$ for confinement effect; $k_{conf} = 0$ for no confinement effect
- All stress values are in MPa and dimensions in mm.

4. Results and discussion

The yield point of the tension rebars in test beams was estimated on the basis of the moment-deflection curves shown in Figure 3 in which the deflection is the measured vertical displacement difference, Δv, between the locations of the hydraulic jacks ($x = 0$ and $x = L_0$) and the mid-point of the member ($x = L_0/2$). Thus, the displacement values in Figure 3 include the effect of the constant moment region between supports without shear force and the effect of the decreasing moment region where the shear force also occurs. The studied lap splices are located at the constant moment region.

Ductility is not a focus of this paper, but an effect of the lap splices on stiffness properties can be still discussed. There are double rebars at the location of the lap splices which leads to a higher stiffness of the member on that region. Figure 3 shows clearly the normalised lap length (L_b/ϕ) which achieves the yielding of the rebar. For all tested bar diameters, the required lap length is around 40ϕ. If the lap length is greater, there are reserves to achieve plastic strains. In all cases of ϕ25 rebars and one case of ϕ16, the properties of the reinforcement are different than in other cases due to the rebar supplier mistake. This can clearly be seen in the differences in yielding points of ϕ25 rebars. Rebar size ϕ12 has been coiled and decoiled during the supplying process, whereas other sizes were supplied as straight bars.

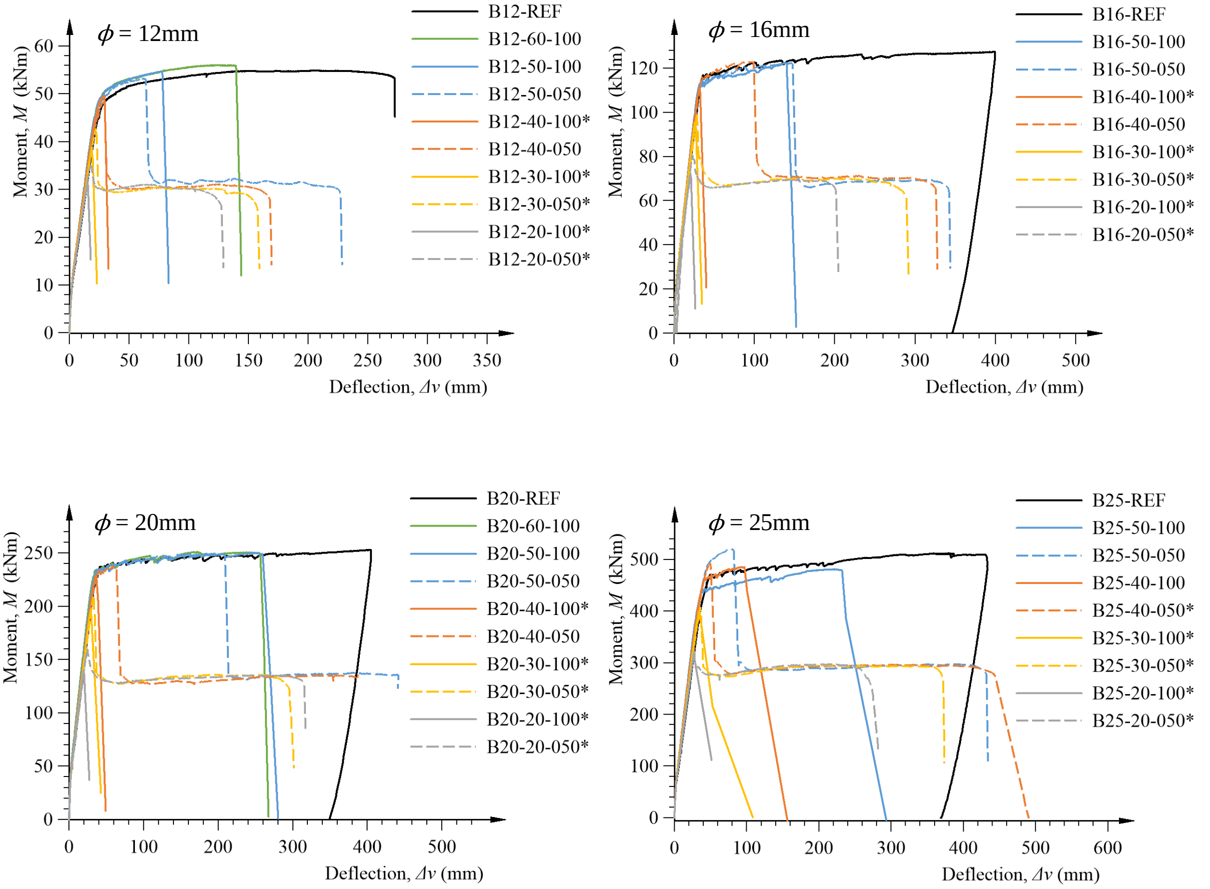

Figure 3. Moment-deflection curves (reported test specimens are marked as *).

The c_y/ϕ -ratio varied between different rebar sizes because the concrete cover thickness was set to constant (c_y = 20 mm), which is relevant for practical cases due to durability requirements. Based on the test results, this seems to have only a minor effect on the lap length in the studied specimens.

Rebars are at the corner of the stirrups and at the middle of the cross section. Theoretically, there is a favourable effect of confinement at the corner, while the rebars at the middle of the cross section do not have that positive effect. However, this difference was not achieved between 50 % and 100 % lapped specimens, because the failure surface passed through all the laps.

The test results (Table 4) were compared to the three different models presented in the previous paragraph. The comparison was made by using both full and no confinement effect in the calculations (Figures 4 and 5). The results of the models and tests are presented here as lap length divided by rebar diameter L_b/ϕ. This was selected because the draft of the 2nd generation Eurocode uses that format.

The spalling of the concrete cover was a failure mode in all specimens. The lap strength σ_s is determined from the maximum moment of bending tests by using the condition of equilibrium of the horizontal forces.

The analysis according to the model of the current Eurocode 2 was made with γ_C = 1,5 (design value), and with γ_C = 1,0. The latter of these make the model more comparable as the reliability aspect is not involved. The calculations according to the model of the 2nd gen Eurocode were made correspondingly with k_{lb} = 50 (design value) and k_{lb} = 28 (mean value).

Table 4. Results and parameters of the tests and analysis.

Test specimen	Measured geometrical properties					σ_s (MPa) f_y (MPa)	$l_{b;test}$ (mm)	Calculated lap length (without confinement effect)				
	c_x (mm)	c_y (mm)	$c_s/2$ (mm)	s_{st} (mm)	n_{st}			$l_{b;EC2}$ (mm)		$l_{b;fib72}$ (mm)	$l_{b;prEC2}$ (mm)	
								$\gamma_C=1.0$	$\gamma_C=1.5$		$k_{lb}=28$	$k_{lb}=50$
B12-20-050	48	33	16	175	2	394 529	240	311	466	226	248	444
B12-30-050	47	30	16	260	2	469 529	360	369	553	311	306	546
B16-20-050	52	34	24	220	2	386 521	320	310	391	284	290	518
B16-30-050	44	30	26	200	3	463 521	480	363	480	397	344	614
B20-20-050	52	34	42	300	2	375 540	400	463	589	417	410	733
B20-30-050	55	33	40	250	3	483 540	600	597	464	654	558	997
B25-20-050	61	34	47	200	3	397 588	500	507	545	590	564	1008
B25-30-050	63	33	48	217	4	491 588	750	633	482	875	758	1354
B25-40-050	62	33	46	225	5	586 588	1000	755	633	1211	989	1766
B12-20-100	45	30	13	175	2	352 529	240	261	718	186	229	408
B12-30-100	44	29	12	260	2	426 529	360	320	695	273	294	525
B12-40-100	45	29	13	190	3	529 529	480	393	896	391	381	681
B16-20-100	47	30	19	220	2	346 565	320	322	589	266	309	552
B16-30-100	51	33	18	200	3	452 521	480	422	805	429	417	746
B16-40-100	47	31	20	200	4	519 521	640	479	923	551	496	886
B20-20-100	62	32	26	300	2	329 540	400	393	760	324	385	688
B20-30-100	60	33	28	250	3	454 540	600	537	950	578	532	949
B20-40-100	60	32	28	250	4	521 540	800	615	1133	743	652	1164
B25-20-100	75	32	49	200	3	390 562	500	556	835	589	604	1078
B25-30-100	64	34	35	217	4	488 560	750	688	1031	898	776	1386

Generally, all models will produce a reasonable good match when comparing the test results with the calculated results if no confinement effect was taken into account. The results were, on average, significantly lower than the measured lap lengths if the confinement effect of transverse reinforcement was considered according to fib Bulletin 72 ($k_m = 12$) and the 2nd gen Eurocode ($k_{conf} = 1.0$). This is in line with the fib Bulletin 72 and 2nd gen Eurocode definitions for the minimum spacing of the lap joints and for the maximum distance between the lap splice and the nearest vertical leg of a link, which would have made it possible to reduce the lap length due to confinement. These requirements were mainly not met in the test specimens. The distance between the leg of the link and the spliced bar in the middle of the cross-section is, however, quite close to the limit value of 5ϕ given in both 2nd generation Eurocode and fib Bulletin 72. This might indicate that the reduction to the lap length due to the confinement would be too high at the limit value of the link distance. The confinement effect of the transverse reinforcement used in the test beams did not significantly reduce the obtained lap length according to the model of the current Eurocode.

The calibration parameter k_{lb} of the model of the 2nd gen Eurocode was adjusted to the test results of this study and it was found that $k_{lb} = 31$ would have been the best fit for regression $y = 1.0x$ if the confinement effect is not considered.

As can be seen in Figure 4 and in Table 5, the design values for the lap length, using the measured parameters, are much lower with the current Eurocode model than with the model of 2nd gen Eurocode. On this basis, the reliability obtained by current Eurocode would be relatively low. However, it should be mentioned that the calculations are made here with the measured compressive strength values of concrete, while the equations of design codes uses the characteristic strength values. Furthermore, the current Eurocode model (Equation 1) is based on the tensile strength of concrete, while the model of the 2nd gen Eurocode (Equation 7) is based on the compressive strength of concrete. As can be seen from the background document of the 2nd gen Eurocode (Muttoni et al. 2021), the reliability is allocated in a different way in these design codes. Using the Eurocode relation between the characteristic and the mean strength, the calculated lap length according to current Eurocode will be 0.70-fold, if the measured strength is used instead of characteristic strength value, while with the model of the 2nd gen Eurocode, the ratio will be 0.87-0.91 for the concrete strength level used in this study. Thus, using the measured strength instead of characteristic strength values has a different effect between these design codes, which makes it difficult to compare design values with each other.

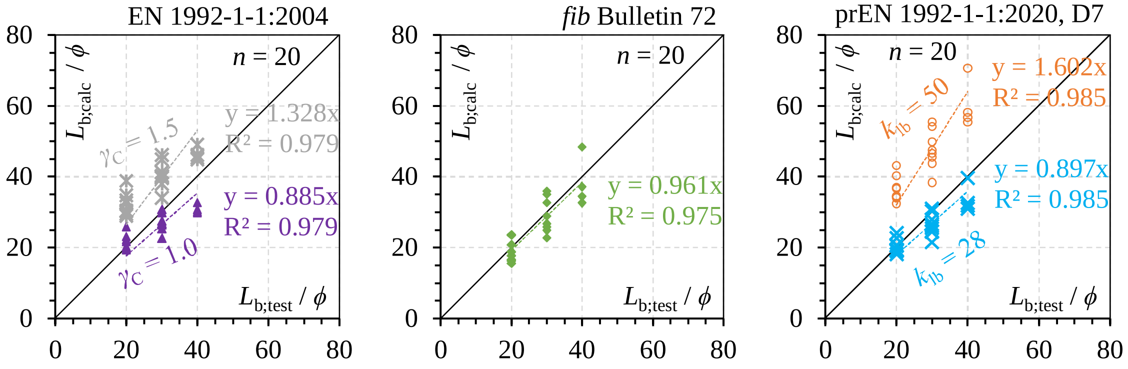

Figure 4. Comparison between test results and models without confinement effect.

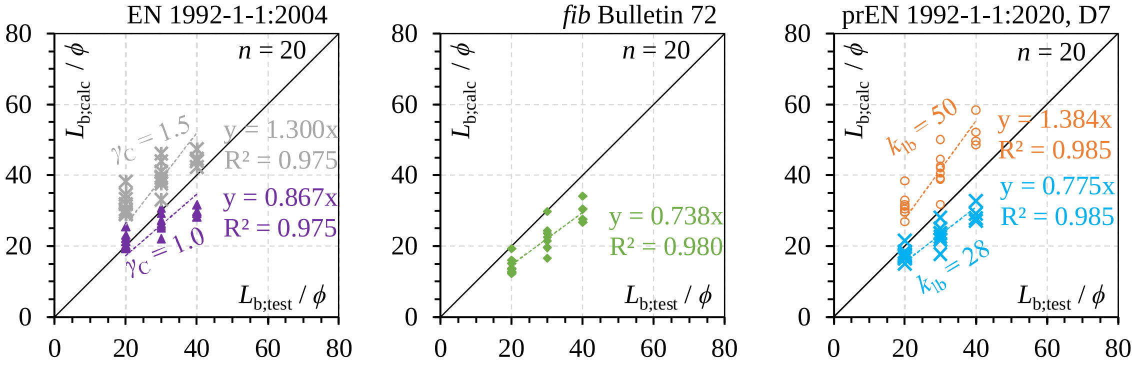

Figure 5. Comparison between test results and models with confinement effect to corner and middle bars.

Generally, it can be concluded that there are no remarkable trends when results are drawn based of the bar diameter or the lap strength (Table 5 and Figure 6). On the other hand, the number of specimens is not so high that a clear conclusion of this kind can be made. However, all specimens are from the same research and test series which gives more support to have these kinds of results.

There is a small trend that large-diameter bars have higher $L_{b;calc}/L_{b;test}$ -ratios than the small-diameter bars with the model of the 2nd gen Eurocode and fib Bulletin 72. Some small trend can also be found based on lap strength with the model of the 2nd gen Eurocode and also with the current Eurocode. With higher stresses, the ratio $L_{b;calc}/L_{b;test}$ is decreasing. On the other hand, the highest stress was obtained with rebar ϕ25 which gives a reasonable result with the model of the 2nd gen Eurocode.

If the calculation with the current Eurocode had been made by using the measured tensile strength of concrete, instead of measured compressive strength, the calculated lap lengths would have been 8-16 % higher and the correlation between the test results and the calculated results would have been even better.

Table 5. Ratios between models and test results ($L_{b;calc}/L_{b;test}$) without confinement.

		Rebar sizes				Measured lap splice strength, σ_s (MPa)			
Bar diameter, ϕ (mm) Relative rib area, f_R		12 0.09	16 0.08	20 0.09	25 0.08	< 400	400-500	>500 <f_{ym}	All
		n = 5	n = 5	n = 5	n = 5	n = 8	n = 8	n = 4	n = 20
prEN 1992-1-1:2020, D7 k_{lb} = 28	$\bar{x}$	0.89	0.85	0.92	1.07	1.02	0.89	0.84	0.93
	CoV	11.4%	11.9%	8.6%	8.5%	9.8%	11.7%	11.7%	13.2%
prEN 1992-1-1:2020, D7 k_{lb} = 50	$\bar{x}$	1.59	1.51	1.65	1.92	1.83	1.59	1.51	1.67
	CoV	11.4%	11.9%	8.6%	8.5%	9.8%	11.7%	11.7%	13.2%
EN 1992-1-1:2004 γ_C = 1.0	$\bar{x}$	1.02	0.87	0.96	0.93	1.08	0.90	0.77	0.95
	CoV	18.1%	13.5%	14.9%	15.1%	10.2%	9.3%	4.1%	15.6%
EN 1992-1-1:2004 γ_C = 1.5	$\bar{x}$	1.53	1.31	1.44	1.39	1.62	1.35	1.16	1.42
	CoV	18.1%	13.5%	14.9%	15.1%	10.2%	9.3%	4.1%	15.6%
fib Bulletin 72	$\bar{x}$	0.83	0.86	0.97	1.19	0.96	0.97	0.95	0.96
	CoV	9.0%	3.6%	11.2%	1.5%	16.9%	16.9%	18.6%	16.3%

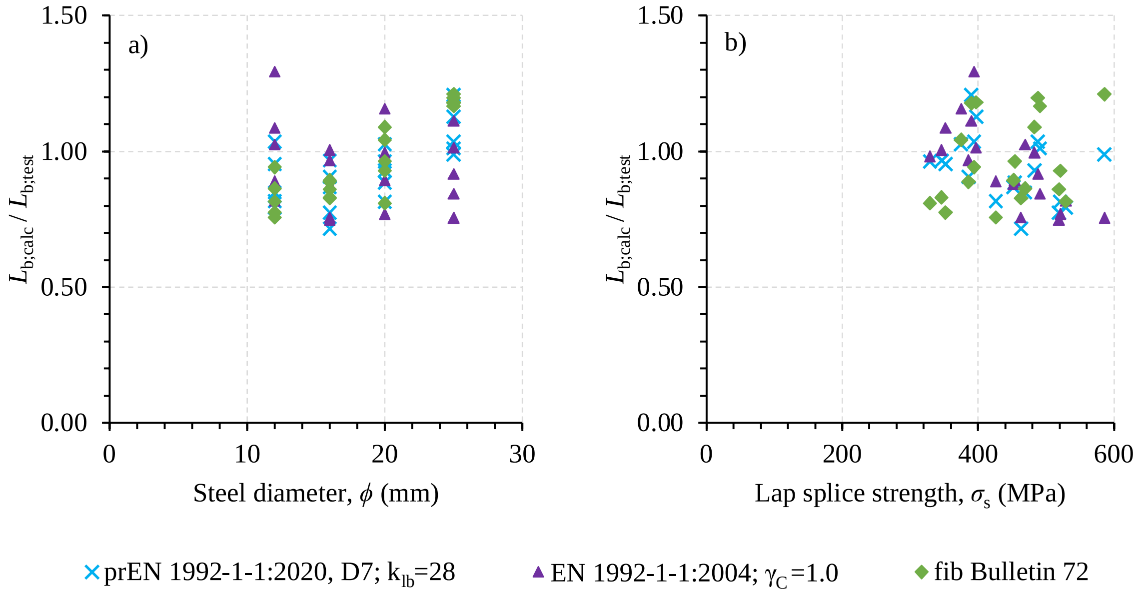

Figure 6. Influence of a) steel diameter ϕ and b) measured lap splice strength σ_s, n = 20.

5. Conclusions

An experimental study on lap splice behaviour was conducted. This paper focusses on lap splice strength and a comparison to code provisions. Based on this study, the following conclusions can be drawn:

- The revision of the model for lap lengths from current to 2nd generation Eurocode has been justified based on test results of this research.
- Even if the rebar at the corner of the stirrup has a favourable effect of confinement, it is not helpful if rebars at the middle of a cross section have no effect. The first probable reason for this is the failure surface which passes both laps. The second probable cause for this is that stresses are redistributed from rebars at the middle to the corner rebars during spalling of the concrete cover because there might be a difference in axial stiffness.
- Some indication was found that the allowable reduction to the lap length due to the confinement might be too high at the 2nd generation Eurocode limit value of 5ϕ for the distance of the lapped bar from the leg of the stirrup. Due to the relatively small size of the test series, further tests will need to be conducted to confirm this.
- Tests for the lap strength were conducted by beam test and the model of the 2nd generation Eurocode yielded a good prediction when compared to the actual full-scale structure. The best fit for the results of this study for the calibration parameter k_{lb} would be $k_{\mathrm{lb}} = 31$, while the background document of the 2nd gen Eurocode gives $k_{\mathrm{lb}} = 28$ for the mean value.

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