Lapped joints of bars in bundles

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ABSTRACT: The approach of European and North American Design Code rules for design of lapped joints of reinforcing bars within a bundle differ markedly, with the former permitting the same or shorter laps with respect to laps of individual bars, while the other requires longer laps. This paper reports an experimental investigation to evaluate performance of lapped joints in which individual reinforcing bars within a bundle of two or three bars are lapped. The results show that it is not necessary to increase lap lengths of individual bars within a bundle, and that failure is less brittle where lap joints confined by links are staggered longitudinally, whether the lap is between individual bars or is of one bar in a pair or bundle. The outcome does, however, question the validity of the reductions permitted in EC2 for staggering laps, and suggests that it would be prudent to suspend use of the α_6 reduction factor for proportion of bars lapped at a section pending more thorough investigation.

1 INTRODUCTION

In situations where reinforcement is congested, it may be advantageous to place bars in bundles of 2, 3 or 4 in preference to arranging bars individually (Concrete Society/IStructE 2006). Bundling permits flexibility in detailing where availability of larger bars is restricted and eases manual handling on site. Bundling of bars allows increased clear spacing, facilitating compaction of concrete. Bundles are more efficient than placing reinforcement in layers as effective depth of longitudinal bars is maintained. Some adjustments in detailing requirements for laps and anchorages are, however, necessary.

Bond action of ribbed reinforcing bars generates bursting forces which tend to split the surrounding concrete cover (fib 2000). Unless confinement is high (typically concrete cover >5 bar diameters or bars confined by dense transverse compression) bond failure of laps and anchorages commonly occurs in a splitting mode with formation of longitudinal cover cracks along the bond length. Bond strength is limited by the resistance of the section to these bursting forces. Most design Codes recognize this through bond strength and detailing provisions which are influenced by cover thickness, secondary reinforcement, and transverse stress. Although there is some limited test data on anchorage of bundled bars, there appears to be an almost complete absence of data for laps within bundles.

The only study known is reported by Bashandy (2009), but here entire bundles of up to 4 bars were lapped at the same cross section (giving a total of as many as 8 bars in contact within the lap length), and hence detailing was not representative of normal practice.

There are several factors which might be expected to affect the performance of lap joints of single bars within a bundle when compared with similar laps of individual bars:

- clear spacing between bars will be increased (for a given section breadth)
- for a given link diameter and spacing, confinement to each lap within a bundle will be increased as the laps are staggered
- a proportion of the bars will be continuous where a single bar within the bundle is lapped.
- the distribution of bond throughout the lap length.

There are differences between provisions for laps in bundles between EC2 and the ACI Building Code which suggest that the consequences of these differences is not well understood. The aim of this investigation is to compare strength of lapped joints of bars within a bundle with that of similar laps of individual bars.

2 REVIEW: CODE OF PRACTICE RULES FOR LAPS OF BUNDLED BARS

The EuroCode for Structural Concrete EC2(BSI 2004) limits bundles to a maximum of four bars in contact, hence the maximum bundle within which a bar may be lapped comprises 3 bars. EC2 utilises the ‘equivalent bar’ approach, in which the bundle is replaced by a single notional bar with an area equal to that of the entire bundle. Thus if all bars in the bundle are of the same diameter, the diameter of the equivalent bar φ_n is $\varphi\sqrt{n_b}$ where φ is the individual bar diameter and n_b the number of bars in the bundle. In two bar bundles with $\varphi_n \geq 32$mm laps must be staggered in the longitudinal direction, but if $\varphi_n < 32$mm, pairs of bars may be lapped at the same section, and lap lengths need not be staggered. Where it is required to lap all three bars in a bundle, the laps must be staggered longitudinally. The distance between adjacent laps is to be at least 0.3 times the required lap length. Where only a proportion of bars are lapped at a section the factor α_6 on lap length is reduced.

Provisions of ACI318 (ACI 2011) differ markedly from those of EC2, as lap length for a single bar within a bundle is increased by 20% and 33% respectively for three and four bar bundles (this bundle size presumably refers to the number of bars within the lap). In some circumstances the required increase will be even greater, as the influence of confinement effects may be reduced as the equivalent bar diameter is used in place of the actual diameter when calculating development length. ACI318 permits laps only of individual bars within a bundle. The differing approaches of EC2 and ACI318 for staggered laps within a bundle are shown diagrammatically in Figure 1, and the difference in bond length factors for lapped bars in a bundle are shown in Figure 2. Figure 2 plots the lap length for a single staggered lap within a bundle against a reference lap length for an individual bar where all bars are lapped at the same section. The plot takes no account of possible differences in confinement from cover and links. Clearly the approaches and the consequent bundled bar lap factors in the two codes differ significantly.

The difference in the approach to bond of bundles also reflects a differing physical concept of bond action. The ACI318 approach treats bond strength as an interfacial shear stress on the bar surface that is constant under any specific confinement condition. As only the outer surface of the bundle is considered active in bond, Figure 1, the force that may be transferred is reduced when more than two bars are in contact. The concept underpinning EC2 is that lap or anchorage capacity is determined by the confinement from surrounding concrete and secondary reinforcement. This implies either that the whole circumference is active even when part lies within the bundle, which seems unlikely in view of the difficulty of compacting cement paste into the interstice inside the bundle, or that transfer of force is limited by confinement from concrete cover, transverse reinforcement or lateral pressure independent of the interfacial shear stress.

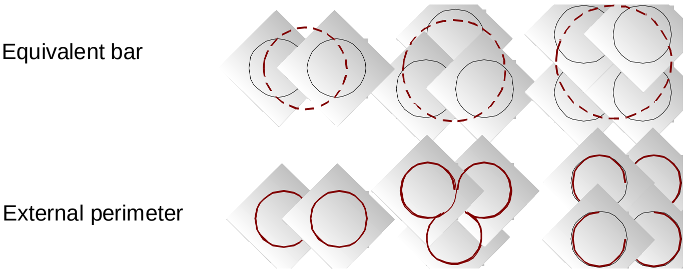

Figure 1. Equivalent bar and external perimeter.

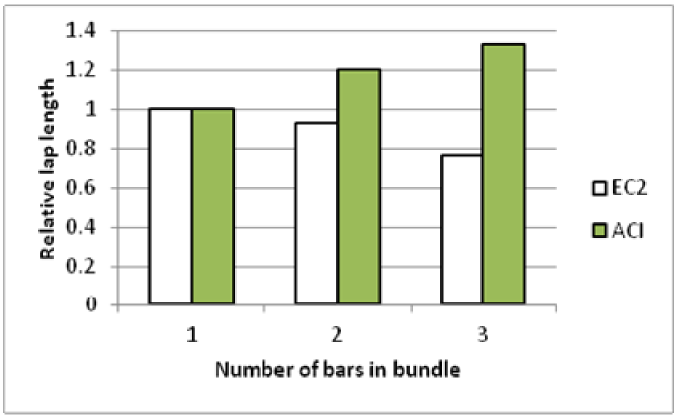

Figure 2. Comparison of EC2 and ACI318 rules.

Recent research by Bashandy (2009) has demonstrated that the equivalent bar approach is valid for simultaneous laps of a pair of bars in a bundle (the investigation in fact went well beyond good detailing practice by simultaneously lapping an entire four bar bundle, a practice not permitted in either EC2 or ACI318). However, the Author has found no evidence to validate either set of Code rules for staggered laps of individual bars within a bundle. This investigation was therefore undertaken to assess the validity of EC2 and ACI 318 rules for dimensioning of staggered lap joints of individual bars within a bundle.

3 EXPERIMENTAL PROGRAMME

3.1 *Design*

Three series of beams were tested in this investigation. Details of reinforcement layout for all specimens are shown schematically in Figure 3 with details of dimensions given in Table 1. Series A was a short exploratory investigation on small specimens, and comprised three beams, one with individual bars simultaneously lapped at midspan, A1, and the other two with bundles of two bars, A2 and A2L, one bar in each bundle being lapped to either side of midspan (bundle size refers to the number of bars in the bundle outwith the lap length). Bars were 12mm diameter, minimum side and bottom covers were 20mm.

Six beams were tested in Series B. In the first group of three specimens, B11, B12 and B13 all had a geometric reinforcement ratio $\rho = 100A_s/bd$ of around 1%. B11 contained 4 sets of 12mm bars individually lapped, B12 contained a pair of 12mm two bar bundles, and B13 a pair of 16mm individually lapped bars, the cross sectional area of which was approximately equivalent to that of the bundled pairs. In the second more heavily reinforced group (ρ =1.6%), B21 and B21L both contained pairs of 12mm three bar bundles (but with slightly differing lap lengths) while B23 contained a pair of 20mm individually lapped bars, the cross sectional area of which was approximately equivalent to that of the bundle of three. Individually lapped bars were all lapped simultaneously whereas laps of bars in bundles were staggered. Minimum covers were 25mm in Series B. No secondary reinforcement was provided in the lap zones of specimens in Series A or B.

In Series C lap joints of individual bars were staggered longitudinally in a pattern consistent with that for their companion bundled bar laps wherever feasible. The principal parameter investigated was the number of bars in the bundle. All beams in this series contained 1.3% longitudinal reinforcement, and minimum covers were 20mm, equal to the largest individual bar and equivalent bar size tested. One pair of replicate specimens CB3a and CB3b were each reinforced with 2 no. 3 bar bundles, the laps being staggered in three zones longitudinally. Another pair of replicate specimens CB2a and CB2b were each reinforced with 3 no. 2 bar bundles of 12mm diameter bars, the laps in this case being staggered in two zones longitudinally. CS3 and CS2 each contained individual lapped bars of the same diameter as their companion CB specimens, and with laps staggered longitudinally in the same way. Four further beams with a similar geometric ratio of longitudinal reinforcement but using larger diameter individual bars were also tested. CE3 replaced bundles of 3no. 12mm bars with a pair of individual 20mm bars having approximately the same area, and CE2 similarly replaced bundles of 2no. 12mm bars with three individual lapped 16mm bars. Laps were staggered longitudinally in the same way as companion CB specimens. CR2 and CR3 used the same longitudinal reinforcement as CE2 and CE3, but with all bars lapped at midspan.

Bundled bar specimens were replicated in view of the scarcity of test data, but it was not considered necessary to replicate tests on individual bar laps which could be benchmarked against an extensive database of test results and semi-empirical expressions calibrated against it.

A modest quantity of secondary reinforcement in the form of closed links was provided in the lap zones of these specimens. The quantity was kept fairly low to minimize uncertainties in interpretation of the influence of links on the strength of the differing joint details.

Due to constraints to beam span in the laboratory,

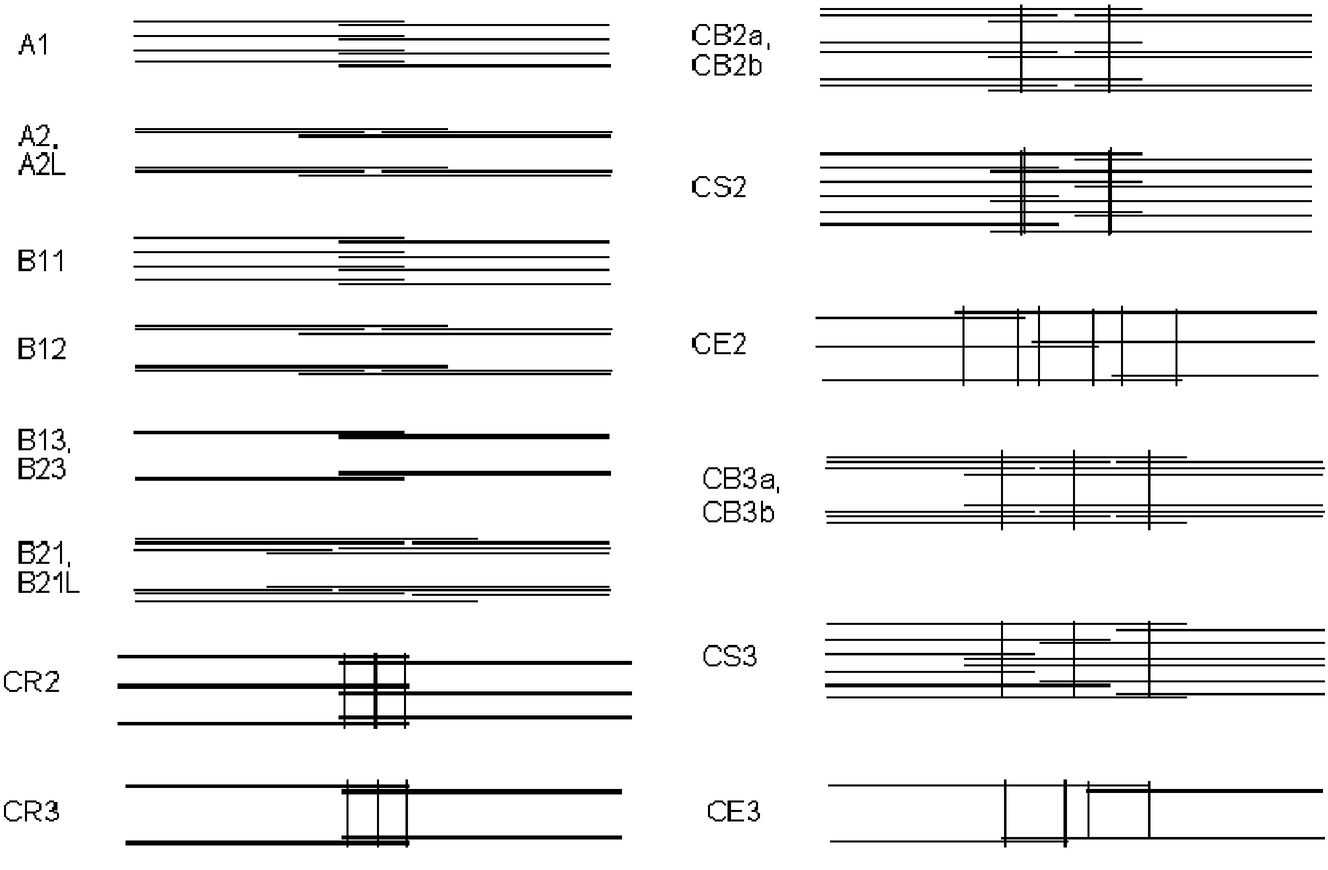

Figure 3. Details of lapped joints

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Table 1. Details of test specimens.

Beam Ref.	Concrete cube strength	Bar dia.	Total no. bars	No. of bundles	Bars in bundle	Prop. Lapped	Lap length	Section breadth	Section depth	No. of links/lap zone
	f_{cu}	φ					l_o	b	h	
	MPa	mm					mm	mm	mm	
A1	37	12	4	4	1	100%	200	200	150	-
A2	39	12	4	2	2	50%	200	200	150	-
A2L	33	12	4	2	2	50%	280	200	150	-
B11	34	12	4	4	1	100%	240	250	200	-
B12	35	12	4	2	2	50%	240	250	200	-
B13	35	16	2	2	1	100%	320	250	200	-
B21	39	12	6	2	3	33%	240	250	200	-
B21L	39	12	6	2	3	33%	264	250	200	-
B23	48.4	20	2	2	1	100%	400	250	200	-
CB3a	41.2	12	6	2	3	33%	240	258	241	1
CB3b	41.2	12	6	2	3	33%	240	258	241	1
CB2a	46.7	12	6	3	2	50%	240	258	241	1
CB2b	46.7	12	6	3	2	50%	240	258	241	1
CS3	41.2	12	6	6	1	33%	240	266	258	1
CS2	46.7	12	6	6	1	50%	240	258	260	1
CR3	43.1	20	2	2	1	100%	400	226	270	3
CR2	43.1	16	3	3	1	100%	320	226	254	3
CE3	42.0	20	2	2	1	50%	400	224	303	2
CE2	43.1	16	3	3	1	33%	320	228	255	2

the gap between the ends of laps throughout the test programme was only 4 times the diameter of the lapped bar, equivalent to 0.2 times the lap length tested. EC2 requires a gap of 0.3 times lap length for laps to be classified as staggered.

3.2 *Materials*

Longitudinal reinforcement was of Grade 500B to BS4449 (BSI 2009). Bars had a pair of crescent shaped ribs on opposite sides of the bar which merge into the core. Relative rib area was not measured on these particular bars, but has been found to typically lie in the range 0.055-0.065 from similar production. 6mm plain round mild steel links provided to each lap zone in Series C as detailed in Table 1.

Concrete was of medium workability (slump 50-70mm) supplied by a local readymix company. Three specimens were cast from each batch, and compacted by internal vibration. Standard control specimens were taken from each batch and tested at the same time as the beams.

3.3 *Test procedure*

Beams were tested in four point bending, with the lap zones positioned within the constant moment zone Load was monotonically increased to failure over a period of approximately 30 minutes. Load was applied in increments of approximately 10% of predicted failure load, with crack development marked at each stage. Loading was continued until residual strength dropped back by at about 25% after peak load had been passed. The rate of loading was increased during this stage. Load and midspan deflection were logged at 2 second intervals throughout the loading sequence.

4 RESULTS

Load deflection response of all beams was close to linear up to peak load. Minor departures were evident at low loads prior to initiation of flexural cracking where stiffness was slightly greater, and close to failure, where the response softened slightly. Vertical flexural cracks formed first within the constant moment zone, followed by slightly inclined flexural cracks within the shear spans. Failure occurred suddenly on formation of longitudinal cracks within the lap zone along the main tension bars. Load dropped immediately after the peak was reached. Where no confining links were present, loss of strength was too rapid to allow the descending branch to be followed. Specimens with staggered laps confined by links exhibited less brittle behaviour, Figure 4, although load still dropped back without even a short plateau.

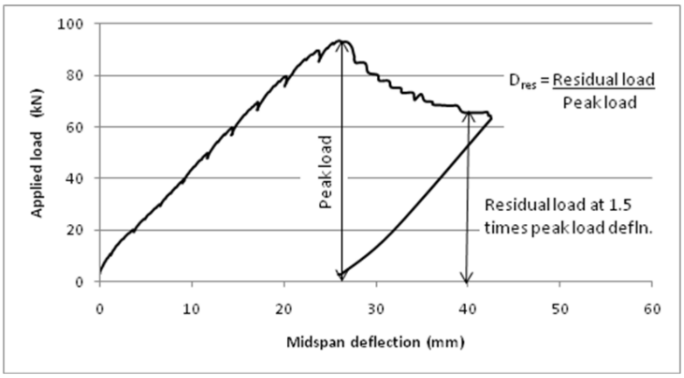

Figure 4. Typical plot of load vs. Deflection, Beam CB2a, showing calculation of deformability index D_{res}.

Table 2 lists peak loads and bond strengths for all specimens. The tension force in bars at peak load is determined from the moment at peak load by transformed section analysis, neglecting any contribution from concrete in tension. The average ultimate bond strength f_{bu} over the lap length is then given by Equation 1. An indication of the brittleness of failure is also given for series C specimens by the quantity D_{res} , calculated as the ratio of residual load at a deflection equal to 1.5 times the peak load deflection to the peak load itself.

$$f_{bu} = \frac{f_s}{4^{l_o}/_{\emptyset}} \tag{1}$$

where f_s is the peak load bar stress, l_o is the lap length and ø the individual bar diameter.

Figure 5 plots the variation in bond strength with the number of bundled bars for the nine beams in Series A and B. The graph shows a reduction in bond strength of up to 20% for lapped joints within a bundle of three bars compared to that of individual bars, therefore suggesting that lapped joints within a bundle are weaker than equivalent laps of individual bars. This interpretation must be treated with caution, however, as in series A and B the number of bars in a bundle correlates with the proportion of bars lapped at a section, a parameter which influences lap lengths in EC2 and in ACI318.

Results from Series C are plotted in Figure 6. Bond strengths are higher than for Series A and B on account of both the stronger concrete and the presence of confining reinforcement. Results from replicate specimens are consistent. Bond strength of 12mm bars shows a slight increase of 5% in bond strength between a lap of one bar in a bundle of three and laps of individual bars, the opposite trend to that observed in Series A and B, although, the difference lies well within the typical scatter of bond strength measurements and may not be significant.

A direct comparison of bond strengths such as those presented in Figures 5 and 6 does not, however, consider the influence of confinement from concrete and links. The confinement provided to an individual lap, whether part of a bundle or not, was increased where laps were staggered. Thus where all bars were lapped at the same section, bond resistance would be expected to reduce as confinement to each lap would be lower. Various empirical and semi-empirical expressions have been proposed to account for the influence of minimum cover, clear spacing between bars, and confining reinforcement (Canbay & Frosch, 2005, Zuo & Darwin 2000). One such expression, taken from the fib Draft Model Code 2010 (fib 2010), is given below as Equation 2.

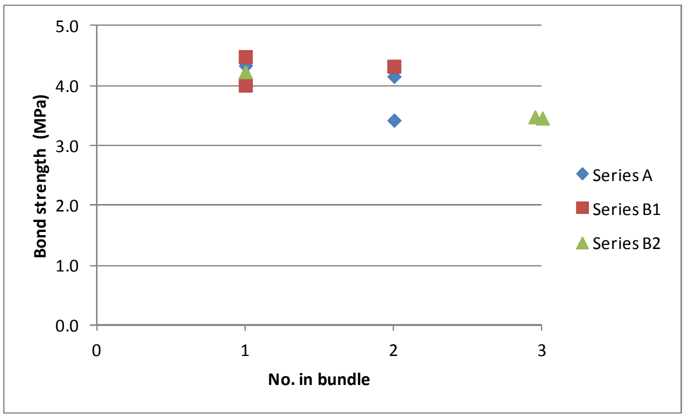

Figure 5. Results from Series A & B.

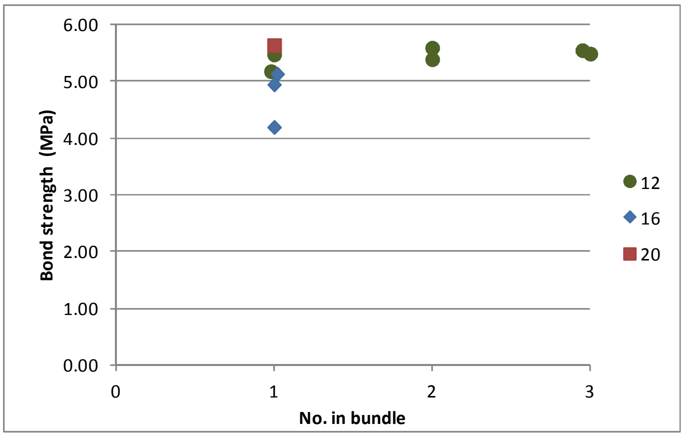

Figure 6. Results from Series C.

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

where f_{stm} = the estimated stress developed in the bar (mean value); f_{cm} = the measured concrete cylinder compressive strength; l_b and φ = the bond length and diameter respectively of the bar; c_{max} and c_{min} are defined in Figure 7; and

$$K_{tr} = n_{leg}.A_{sv}/(l_b.\varphi) \tag{2a}$$

where n_{leg} = the number of legs of link crossing the splitting failure plane; A_{sv} = area of each leg of a link; and k_m = an 'effectiveness factor', equal to 12 for corner and 6 for centre bar locations in the current tests.

Table 2 lists the ratio of measured bond strength to that calculated using Equation 2. The variation in this ratio with bundle size and with proportion lapped is plotted for Series C specimens in Figures 8 and 9 respectively.

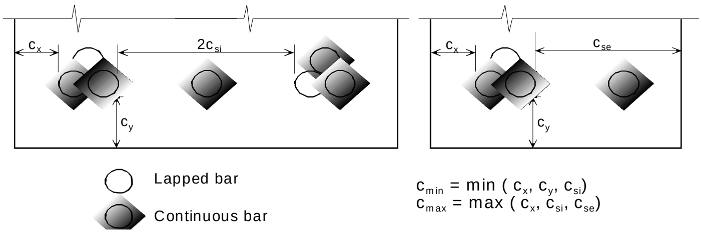

Figure 7. Definition of cover dimensions.

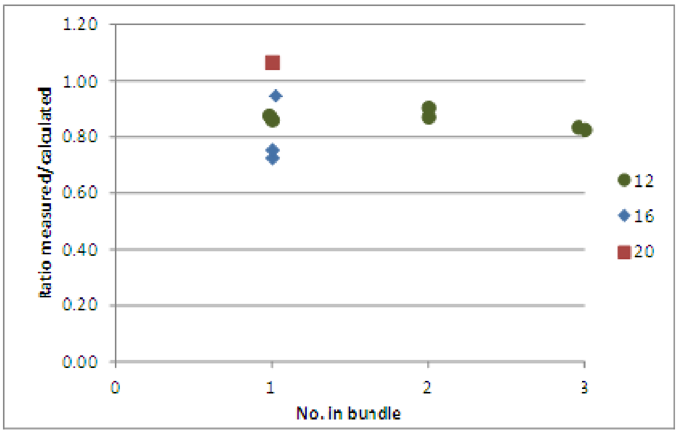

Figure 8. Variation in ratio of measured/calculated bond strength with bundle size.

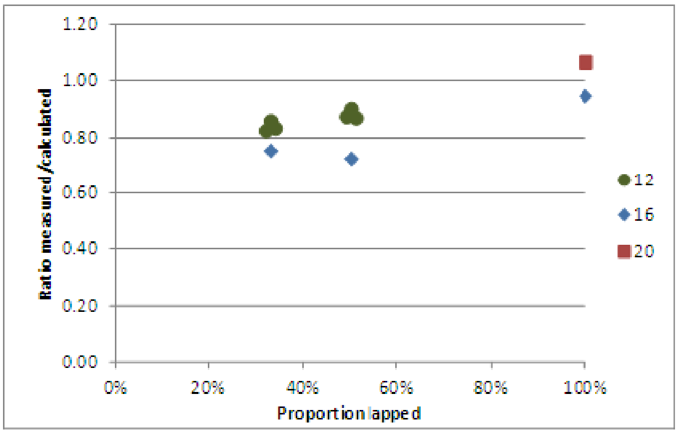

Figure 9. Variation in ratio of measured/calculated bond strength with proportion lapped.

The ratio of measured/calculated bond strength for CR2 and CR3, the two results for 100% laps of individual bars confined by links, the condition for which Equation 3 was calibrated, are 0.95 and 1.07, an average of 1.01, and provide confirmation that Equation 2 gives a reasonable estimate of lap strength. Average ratios for 50% and 33% lapped are lower, at 0.88 and 0.84 respectively. There is less variation in ratio with the number of bars in the bundle, with averages of 0.90, 0.89 and 0.83 for bundles of 1, 2 and 3 bars respectively.

The comparison for CR and CE specimens is of particular significance. These laps were almost identical except that bars were all lapped at the same section in CR specimens and staggered in CE specimens (there were minor differences in links).

Table 2. Test results.

Beam Ref.	Bond strength			Ratio measured/ estimated		
	$f_{b,meas}$	$f_{b,est}$	$f_{b,EC2}$	$f_{b,meas}/f_{b,est}$	$f_{b,meas}/f_{b,EC2}$	D_{res}
	MPa	MPa	MPa			
A1	4.34	4.76	3.35	0.91	1.29	-
A2	4.16	6.18	3.72	0.67	1.12	-
A2L	3.42	5.10	3.33	0.67	1.03	-
B11	4.01	4.77	3.06	0.84	1.31	-
B12	4.33	5.67	3.72	0.76	1.16	-
B13	4.48	4.93	3.18	0.91	1.41	-
B21	3.48	5.83	4.87	0.60	0.71	-
B22L	3.46	5.58	4.87	0.62	0.71	-
B23	4.24	4.77	3.75	0.89	1.13	-
CB3a	5.55	6.65	4.65	0.83	1.19	0.76
CB3b	5.49	6.65	4.65	0.82	1.18	0.70
CB2a	5.59	6.19	4.15	0.90	1.35	0.43
CB2b	5.39	6.19	4.15	0.87	1.30	0.28
CS3	5.47	6.37	4.65	0.86	1.18	0.83
CS2	5.18	5.92	4.15	0.87	1.25	0.27
CR3	5.64	5.28	3.33	1.07	1.70	0.23
CR2	5.13	5.41	3.63	0.95	1.41	0.20
CE3	4.19	5.78	3.28	0.68	1.19	0.55
CE2	4.95	6.56	4.53	0.75	1.09	0.75

Bond strength of CE laps averaged 15% weaker than companion CR specimens. If allowance is made for differences in confinement according to Equation 2, CE laps area apparently 27% weaker than companion CR specimens.

Variations in bond strength of bars lapped within a bundle are appear to be more closely linked to the proportion of bars lapped than to the number of bars in a bundle.

Although bond strength of laps confined by links in Series C is reduced when laps are staggered, post-peak behaviour became less brittle, Figure 10. Even so, residual bond strength still reduced immediately after peak load was reached, and dropped by 20% shortly thereafter where only one in three bars were lapped at a section.

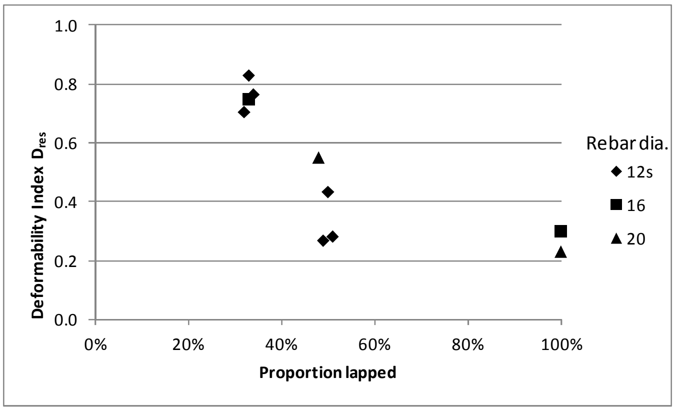

Figure 10. Variation in post peak ductility with proportion lapped.

The change is similar for individual lapped bars and for bars within a bundle. Metelli et al(2010) have similarly observed less brittle behaviour where a proportion of reinforcement is continuous through a lapped joint. Bundle size does not appear to influence ductility.

5 COMPARISON WITH EC2 PROVISIONS

The results presented in Figures 6 and 8 support the approach in EC2 which uses the same lap length whether a bar forms part of a bundle or is lapped individually. It is not necessary to increase lap length on account of a reduced effective perimeter as in ACI318.

Both codes permit shorter lap lengths where only a portion of bars are lapped at a section in certain circumstances. Results presented above suggest that such reductions are unreasonable.

In Figure 11 the ratio of measured bond strength to the characteristic bond strength assessed according to the provisions of EC2 is plotted for each specimen. EC2 calculates a characteristic ultimate bond strength f_{bk} based on the tensile strength of the concrete and casting position, and which may be modified for bars > 32mm. The characteristic stress developed in a bar is given by Equation 3.

$$\sigma_{s,EC} = f_{bk}\,{}^{4.l_b}/_{\phi}.(\alpha_2.\alpha_3.\alpha_6)^{-1} \tag{3}$$

where $f_{bk} = 2.25\eta_2.f_{ctk,0.05}$

Coefficients α_2, α_3, α_6 andη_2 represent the effects of confinement from concrete cover, of confinement from secondary reinforcement, of the proportion of bars lapped at a section, and of bar diameter respecttively. Other α and η coefficients for bond in EC2 take a value of 1.0 for all specimens considered here. Coefficient α_6 takes values of 1.5, 1.4 and 1.15 for 100%, 50% and 33% laps respectively.

Figure 11 shows a marked influence of the proportion of bars lapped on the ratio of measured bond strength to that estimated by Equation 3. This variation arises from two sources, namely the measured variation in bond strength and the influence of the proportion lapped factor α_6.

As previously mentioned, the laps tested in this investigation did not comply with EC2 requirements for spacing between lap zones. Tests reported by Metelli et al(2010) on specimens containing laps of individual bars in which the proportion lapped was varied show a similar trend to those observed in this investigation. In Metelli et al's tests all laps were at the same section while non-lapped bars were continuous throughout the whole span. It is therefore considered unlikely that the absence of a gap of $0.3l_o$ between lap zones was responsible for the lower bond strength of staggered laps.

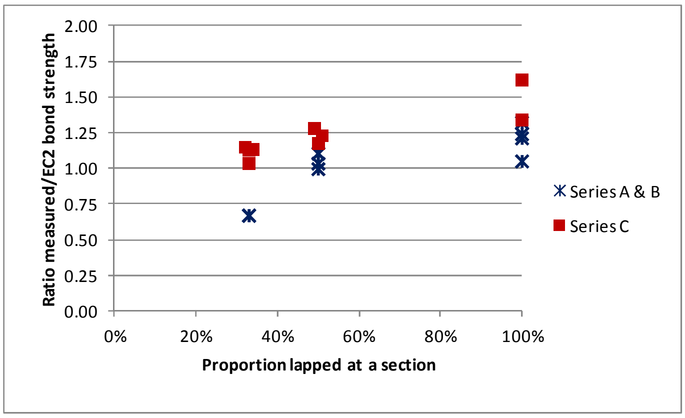

Figure 11 Comparison with provisions of EC2

While measured bond strength exceeded EC2 characteristic strength in all but one test, it should be remembered a) that lap lengths tested in this investigation were, at around 20φ, less than required to develop design strength of reinforcement, and that average bond strength reduces with bond length, Equation 2, and similar 'best fit' expressions by others. Average bond strength for a 50φ bond length will be reduced by between 20% and 30% relative to that for a 20φ length, depending on circumstances and the particular best fit expression consulted. Bars used in bundles within the study were of size 12, and larger diameters are weaker in bond. The margin of safety for design is therefore less than might be thought from the Figure.

These results thus raise questions over the validity of the α_6 factor in EC2, as they indicate that staggering of laps does not lead to increased bond strength. While the observed reduction in brittleness might be associated with a reduction in scatter of individual results and thus justify an increased characteristic strength, this study does not provided sufficient data to evaluate such a justification. The reduction in brittleness where laps are staggered does not provide sufficient ductility to justify a reduction in lap length, particularly in determinate structures where no alternative load path exists.

6 DISCUSSION

The trends observed in this investigation tend to confirm raise doubts about the validity of α_6 values in EC2 and the equivalent rules in ACI318. The causes of the observed influence of proportion lapped at a section on lap strength are now briefly considered.

Where all bars are lapped at the same section, the force in tension reinforcement will be evenly shared, at least until longitudinal cracks form close to failure.

The overall elongation of a pair of lapped bars over the lap length is taken as the sum of two components, a) the elongation of a lapped bar over the lap length, plus b) the loaded end slip s_b of the lapped bars. Stress in lapped bars reduces from a maximum at the loaded end to zero at the unloaded end, and consequently elongation of a lapped bar over the lap length will be less than that of a continuous bar. The difference between the two will be mitigated to some extent by bond slip, but preliminary estimates indicate that over practical lap lengths elongation of lapped bars will be lower than that of an equivalent continuous bar. Lapped bars will therefore be stiffer than an equivalent continuous bar, and will therefore attract a greater share of tension force in reinforcement. Even if the bond resistance is identical, lap strength will appear to be reduced where only a portion of the bars are lapped as continuous bars will be less highly stressed at failure.

A second factor concerns the distribution of bond stress throughout a lap length. Consider a lap zone situated within a constant moment zone, stressed within the elastic range, and of sufficient length to allow all bars in the section, whether lapped or not, to be under the same strain at midlength. If all bars are lapped at the same section, the total cross sectional area of reinforcement within the splice length is double that outside, and as the force is divided equally then bar stress, and therefore strain, at midlength tends towards a value half that outside the lap zone. If only a portion of bars in the section are spliced, the total cross sectional area of reinforcement within the splice length is less than double that outside, and therefore the strain at midlength will exceed half of that outside, Equation 1.

$$\varepsilon_{ml} = \varepsilon_{so}\frac{\Sigma A_{so}}{\Sigma A_{ml}} = \varepsilon_{so}\frac{1}{(1+\rho_l)} \qquad (1)$$

where: ε_{ml} and ε_{so} are the bar strains at midlength and outside of the long splice respectively, ΣA_{ml} and ΣA_{so} are the areas of reinforcement at within and outside of the long splice respectively and ρ_l is the proportion of reinforcement lapped at the section

While Equation 1 makes considerable simplifications about load sharing and bar/concrete slip, it does demonstrate that the force to be transferred over the end half of a lap length will tend to be higher when only a portion of the bars are spliced. Splitting bond failure in a long splice is initiated by the peak bond stress near the ends of the lap, hence the average bond strength over the whole lap length at failure tends to reduce as the proportion of lapped bars ρ_l increases.

7 CONCLUSIONS

This investigation set out to assess whether bond strength was reduced where a single bar within a bundle of two or three was lapped. In the course of the investigation it became necessary to also examine the effect of staggering laps longitudinally, whether as part of a bundle or as a lap of an individual bar. Within the scope of the investigation, it is concluded that:

1. Bond strength is not reduced where an individual bar within a pair or bundle of three bars is lap jointed.
2. Less brittle failures are observed where lap joints are confined by links and staggered longitudinally, whether the lap is between individual bars or is of one bar in a pair or bundle.
3. The practice in EC2 of permitting a reduction in lap length where only a portion of the bars is lapped at a section could be unsafe in some circumstances, whether the lap is between individual bars or is of one bar in a pair or bundle

The conclusions should be treated with caution, as only small diameters have been tested to date due to resource limitations, and as specimens did not fully comply with EC2 provisions for staggered laps. Nonetheless, it would be prudent to set the α_6 factor at its maximum of 1.5 in all situations pending more thorough investigation.

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