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Effects of the position of confining transverse links on lap strength

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Abstract

The article presents the results of an experimental campaign to investigate the effect of the position of transverse links on the strength of lap splices in tension. Lap splices with transverse links either adjacent to the lapped bars or at a distance of 4.5 times the bar diameter from the lap were tested. The stirrups index of confinement was similar in all the specimens. The results show a reduction of the lap strength up to 15% when the transverse links are not close to the lapped bars because of the splitting crack propagation which is not adequately counteracted by the confining action of the links. The test results show that the provisions of MC2010 for lap splices, with links relatively far, may be unconservative. Furthermore, an experimental database on the strength of lap splices with different distances of transverse links to the lapped bars is gathered from studies published in literature. This database enables to assess the accuracy of the efficiency factor k_m of confining reinforcement in the fib MC2010 formulation. Based on the statistical analysis of the test results concerning the confining reinforcement, a reduction is proposed for the effectiveness factor (k_m), to be applied whenever the distance of laps to the transverse links exceeds four times the bar diameter.

KEYWORDS

bond, confinement, lap splices, Model Code 2010, splitting crack, transverse reinforcement

1 | INTRODUCTION

Lap splices are the most used system to joint longitudinal steel rebars in concrete elements for their reduced placing time, which makes splices cost-effective in comparison with alternative coupling systems (welded bars, loop joints, and mechanical splices). However, the transfer of the tensile force form one rebar to the other generates a radial transversal pressure due to the wedge action of the crushed concrete between the bar ribs.[1–5] Thus, if the stresses in the cover reach the tensile concrete strength, the development and propagation of longitudinal splitting cracks along the bond length may occur, thus impairing the bearing capacity of the lap splice.[1,2,6-9]

Models for bond resistance first developed by Ferguson and Breen[10] in the US and by Tepfers[1] in Europe take into account the resistance provided by the RC

section to these bursting forces. This resistance depends on the confining action provided by the concrete cover, by the transverse reinforcement crossing the splitting crack,[6–8] and by the transverse pressure[11,12] as well as by the post-cracking behavior of concrete which may become significant when fibers are added to concrete mix.[13,14] All these confining actions are now widely recognized in the main international design Codes (ACI318-19,[15] Eurocode 2,[16] Model Code 2010[17]). Among them, transverse reinforcement plays a significant role in the anchorage capacity after cover splitting in terms of both resistance and ductility. A linear increase of the anchorage strength with the area of transverse reinforcement crossing the splitting crack was observed by Morita and Fujii,[18] Kaku et al.,[19,20] Giuriani et al.,[6] and Maeda et al.[21] These studies also showed the importance of the arrangement of the transverse ties on their capability to delay the splitting crack opening. A markedly different confining action to the corner and inner bars was observed in the work by Maeda et al.,[21] who observed that links close to anchored bars are more efficient than those at a distance to anchored bars 3 to 5 times the bar diameter, thanks to the better control of splitting in the former case. The lower effectiveness of outer ties to resist the bursting forces due to the wedge action of inner bars was already documented by Warren[22] who tested several specimens having up to seven longitudinal anchored bars confined by a single two-legged stirrup.

A bilinear relationship between transverse reinforcement and the anchorage/splice strength was first observed by Orangun et al.[22] and then confirmed by Plizzari et al.[6,8,24] who clearly showed that the enhanced anchorage/splice response provided by the confining reinforcement may be accurately represented by the "*stirrup index of confinement*" that was later adopted in the main international building codes (ACI318-19[15] since 2008; Model Code 2010[17]). The "*stirrup index of confinement*" is defined as[6]:

$$K_{tr} = n_t \, n_{st} \, A_{st} / (n_b \, d_b \, l_b) \tag{1}$$

where A_{st} is the area of the cross section of one leg (mm^2); n_{st} the total number of confining stirrups within the anchorage/lap length; n_t the number of legs of a stirrup crossing the potential splitting failure surface; n_b is the number of anchored bars or pairs of lapped bars; d_b is the diameter of the smaller of a pair of lapped bars [mm] and l_b is the lap/anchorage length (mm).

In Model Code 2010,[17] the basic bond resistance $f_{bd,0}$ in the reference conditions of minimum confinement (minimum cover equal to one bar diameter, clear spacing equal to two bar diameters without confining reinforcement) may be increased by taking into account the effect of confining actions. In fact, in the expression proposed in MC2010, the maximum bar stress f_{stm} carried by

lapped or anchored bars may benefit from the confinement contributions of concrete cover and transverse reinforcement, as expressed by the terms enclosed by square brackets in the following:

$$f_{stm} = 54 \left(\frac{f_{cm}}{25}\right)^{0.25} \left(\frac{25}{d_b}\right)^{0.20} \left(\frac{l_b}{d_b}\right)^{0.55} \left[\left(\frac{c_{min}}{d_b}\right)^{0.25}\right.$$
$$\left. \times \left(\frac{c_{min}}{c_{max}}\right)^{0.10} + k_m K_{tr}\right] \tag{2}$$

where f_{cm} is the concrete strength, c_{max} and c_{min} are the largest and the smallest of: (i) one-half the clear spacing between lapped bars (c_s), (ii) bottom cover (c_y), and (iii) side cover (c_x), respectively (Figure 1a). In Equation (2) k_m is the effectiveness factor of confining reinforcement which depends on bar arrangements. This coefficient is reduced from 12 to 6 when the distance a_l of an anchored/lapped bar from the nearest vertical link (crossing the potential splitting plane) is more than 125 mm or five times bar diameters (Figure 1b). This is due to the fact that the confinement is less effective when face splitting cracks occurs (compared with corner or side-splitting cracks) since the crack would be crossed by a lower amount of confining reinforcement (Figure 1b). The factor k_m is further reduced to 0 when the splitting crack is not intersected by any transverse reinforcement, for example, when the clear spacing between the link and the anchored/lapped bar is lower than 8 c_y (Figure 1b) (*fib* Bulletin 72[24]).

According to Eurocode 2,[16] the basic anchorage length may be reduced by a factor α_3 ($0.7 \le \alpha_3 \le 1.0$) which represents the influence of the confining reinforcement on the lapped/anchored bars in excess of the minimum required area, defined as:

$$\alpha_3 = 1 - k\,\lambda \tag{3}$$

where $\lambda = (\sum A_{st} - \sum A_{st,min})/A_s$, A_s the area of a single anchored bar, $\sum A_{st}$ is the cross-sectional area of the transverse reinforcement along the anchorage length, $\sum A_{st,min}$ is the cross-sectional area of the minimum transverse reinforcement, while k is a coefficient varying between 0.1 and 0 and depends on the position of the lapped bar with respect to the confining links (Figure 1c). Thus, the confining transverse reinforcement is fully effective only for bars close to corner links while the effectiveness of confining reinforcement for an anchored or spliced bar in a face location is reduced by 50% (Figure 1b,c).

Therefore, MC2010 provision is broadly consistent with the current EC2 where the efficiency of confining reinforcement for inner bars characterized by a face splitting failure is reduced by 50%, with respect to the case
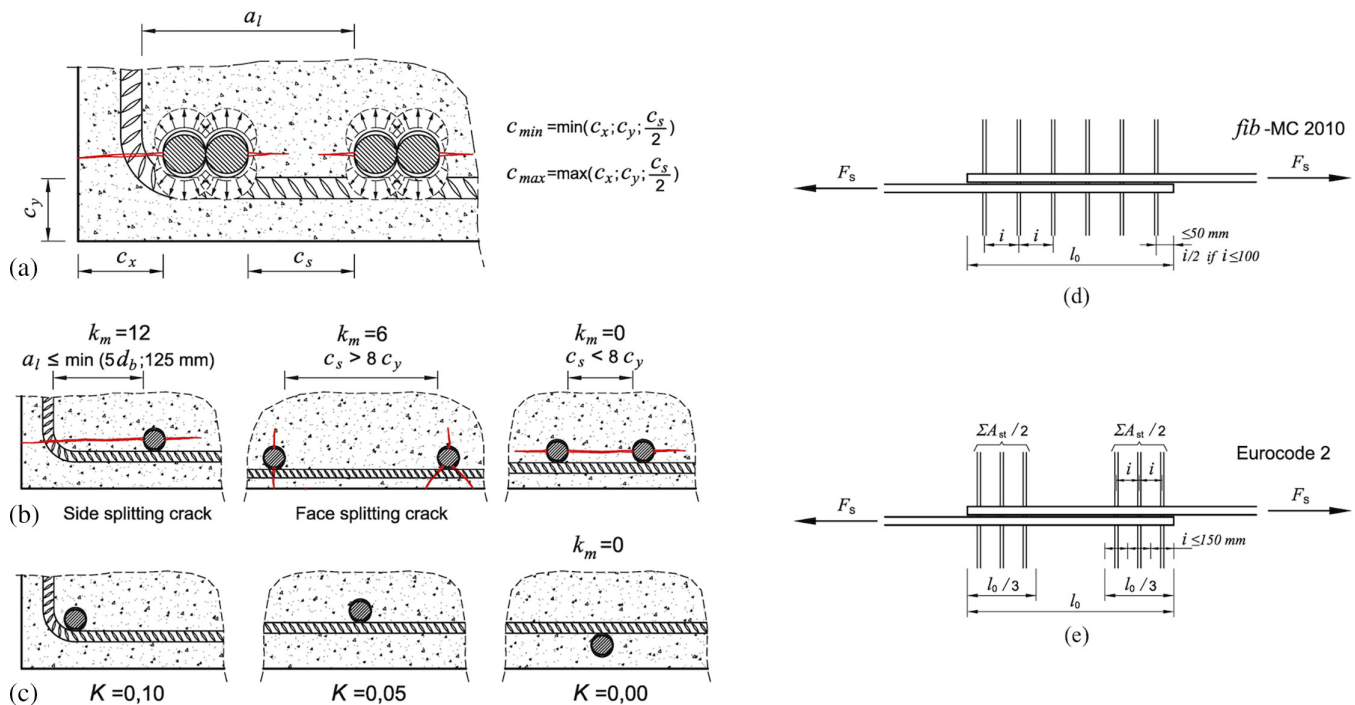
FIGURE 1 Arrangement of confining reinforcement in (a) MC2010 and definition of its effectiveness factor according to (b) MC2010 and (c) EC2; (d, e) possible distribution of transverse reinforcement

where the bar is close to the corner link. However, while MC2010[17] allows the transverse reinforcement to be evenly distributed along the lap length (Figure 1d), Eurocode 2[16] requires the links to be located at the joint ends within one-third of lap length (Figure 1e).

As pointed out in the *fib* Bulletin 72,[25] the proposed values of the k_m factor were set to improve the statistical fit of the semi-empirical formulation with the test results, despite the fact that in the literature there is an evident lack of experimental data to allow a precise definition of the effectiveness of the confining legs of links relatively far from the anchored bar. To this aim, the article presents the experimental results from 10 full scale beams that were tested to shed some new lights on the behavior of lap splices embedded in normal-strength concrete with different arrangements of transverse reinforcement. Finally, the experimental results are compared with the formulation of fib-MC2010 in order to improve the accuracy of the definition of the k_m factor for transverse reinforcement efficiency.

2 | EXPERIMENTAL PROGRAMME

2.1 | Details of specimens and material properties

Two series of full-scale beams were designed with lap-splices at mid-span to be tested under constant bending

moment. The beams had a length of 3.5 m, a depth of 0.35 m and a width of 0.30 m. Each series consisted of five beams reinforced with either four longitudinal bars of a diameter (d_b) of 20 mm or with three 16 mm diameter bars. Both series comprise a reference beam with continuous reinforcements (20C or 16C) while the other four beams have longitudinal spliced rebars at mid-span (Figure 2).

In each series four different configurations of transverse reinforcement were investigated: (i) stirrups with two outer legs uniformly spaced along the lap length; (ii) stirrups with two outer legs concentrated at the lap ends; (iii) stirrups with two outer legs and two inner legs uniformly distributed along the lap length; and (iv) stirrups with two outer legs and two inner legs concentrated at the lap ends. It should be noted that in the first two arrangements the inner laps were relatively far from the vertical links, at a distance of 100 mm (corresponding to 5.0 times the bar diameter) and 72 mm (4.5 times the bar diameter) for 20 and 16 mm bars, respectively.

In all arrangements, *fib* Model Code 2010 considers a fully effective contribution of transverse reinforcement since the distance between the link and the laps is not >5 times the bar diameter and 125 mm. Thus, in all configurations the effectiveness factor k_m of MC2020 formulation for confining reinforcement is always set equal to maximum value ($k_m = 12$).
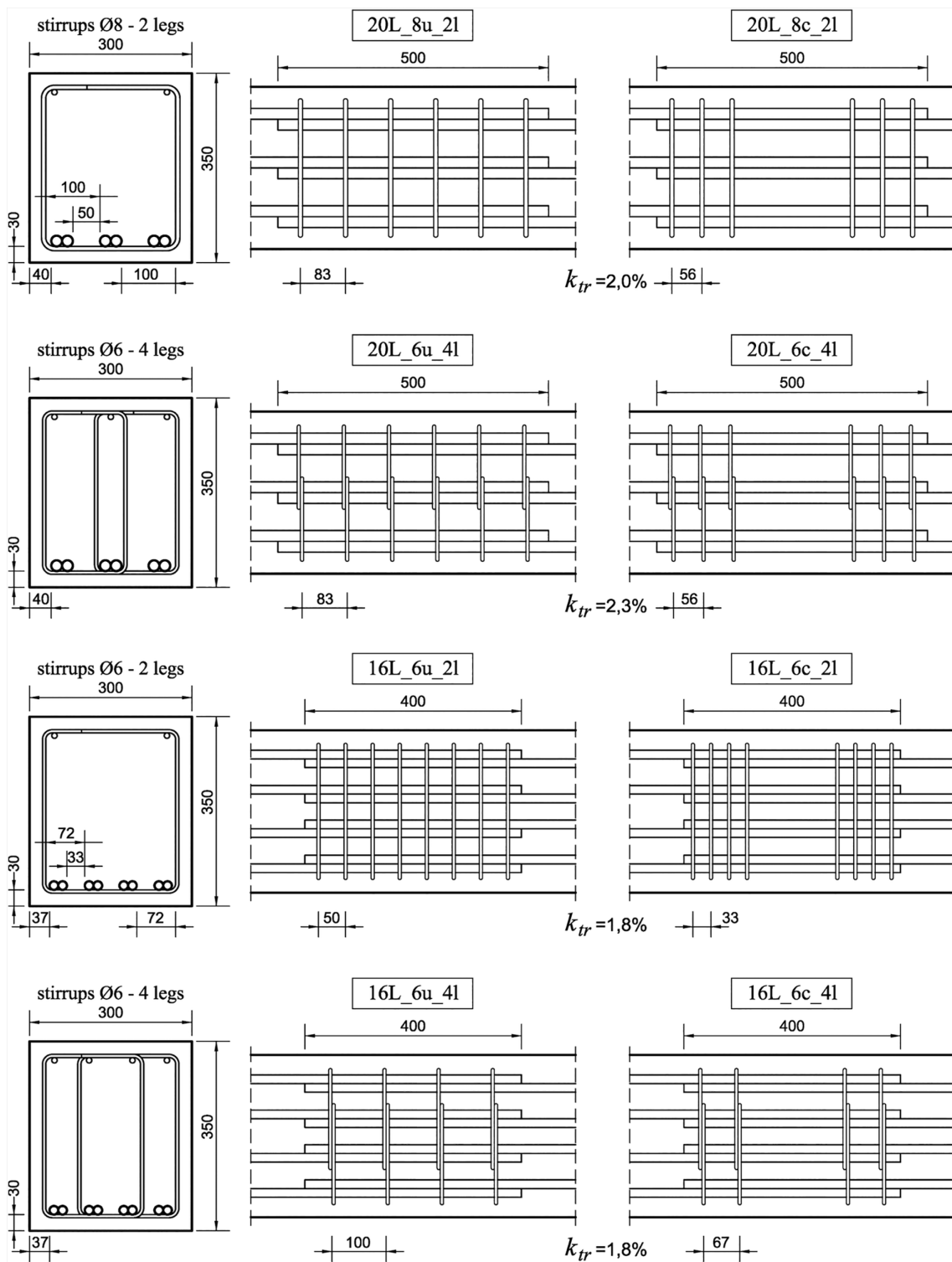
FIGURE 2   Geometrical details of the beams and transverse reinforcement arrangement along the splice length

A splice length (l_b) of 25 times the bar diameters (d_b) was used in such a way as to reach a maximum stress (f_{stm}) in the lapped bars approaching the average yield stress (f_{ym} = 550 MPa for B500 steel grade) and showing a splitting-failure mode. Therefore, the maximum bar stress in the joint was calculated by means of the *fib*-MC2010 formulation (Equation 2) for lap strength assuming a compressive strength of concrete equal to f_{cm} = 35 MPa (representative of a C25/30 concrete class). The calculation of the lap strength is shown in Table 1 for each configuration.

The rebars had a bottom concrete cover (c_y) of 30 mm while the lapped bars spacing (c_s) was set equal to 50 and

TABLE 1 Geometrical and mechanical properties of the tested lap slices

	Specimen	l_b/d_b	c_x (mm)	c_y (mm)	$c_s/2$ (mm)	c_{min} (mm)	c_{max} (mm)	α_2	d_{sw} (mm)	n_t	n_b	n_{st}	K_{tr} (%)	f_{stm} (MPa)	$\frac{f_{stm}}{f_{ym}}$
Series 1	20L_8u_2l	25	40	30	25	25	40	1.11	8	2	3	6	2.01	518	0.99
d_b = 20 mm	20L_8c_2l														
f_{ym} = 522 MPa	20L_6u_4l	25	40	30	25	25	40	1.11	6	4	3	6	2.26	530	1.01
f_{cm} = 45 MPa	20L_6c_4l														
Series 2	16L_6u_2l	25	37	30	16.5	17	37	1.09	6	2	4	8	1.77	492	0.94
d_b = 16 mm	16L_6c_2l														
f_{ym} = 525 MPa	16L_6u_4l	25	37	30	16.5	17	37	1.09	6	4	4	4	1.77	492	0.94
f_{cm} = 35 MPa	16L_6u_4l														

Note: c_x, c_y, side and vertical concrete cover; c_s, spacing of lapped bars; $\alpha_2 = (c_{min}/d_b)^{0.25} (c_{min}/c_{max})^{0.1}$, confinement coefficient provided by concrete cover (as expressed by MC2010); d_{sw}, stirrup diameter; n_t, n_b, n_{st}, number of transversal legs, lapped bars and transversal reinforcement; K_{tr}, stirrup index of confinement; f_{stm}, bar stress in the lap estimated with MC2010 formulation (Equation 2).

33 mm for 20 and 16 mm bars, respectively (Figure 2 and Table 1). Figure 1a also shows the orientation of the bar ribs provoking the wedge action towards the vertical direction.

Each beam is tagged with the bar diameter first; the second character (C or L) refers to continuous and lapped bars, respectively; the next figure indicates the diameter of the stirrups (6 or 8 mm) which confine the laps; the following letter refers to arrangement of stirrups along the lap length (u: uniformly distributed along the splice; c: concentrated at the lap ends); finally, the last number indicates the links crossing the potential splitting surface (two links placed in the corners only, or four links each of them is adjacent to the lapped bars). The arrangement and the diameter of the transverse reinforcement were set to provide a rather constant *stirrup index of confinement K_{tr}* (ranging between 1.8% and 2.3%) among the eight beams (see Figure 2 and Table 1). Steel grade B500C (in accordance with EN 10080[26]) was used for longitudinal rebars, whose measured mechanical properties are listed in Table 2. The concrete, with a target class C25/30, was supplied by a local-ready-mix company. Cement CEM II/A-LL 42.5R, natural sand and river gravel with a maximum size of 14 mm and a water/cement ratio of 0.51 were chosen to obtain a normal strength concrete with consistency S4 (slump: 170 mm).[28]

Ten standard cylinders were taken from both series (for the beams with 16 and 20 mm rebars, respectively) to assess the compressive strength and the modulus of elasticity of concrete. The specimens were cast and cured under laboratory conditions. At the onset of testing, concrete mean compressive strength ($f_{cm,ex}$) was close to 45 and 35 MPa for the beams with 20 and 16 mm rebars, respectively.

2.2 | Test setup

The beam specimens were tested in four-point bending with a span of 3.2 m. The lapped joints were located within the constant moment region of 1.6 m (Figure 3a). The loading points were about 0.55 m (>1.5 times the beam depth) away from the lap to limit any disturbance effect on the behavior of lap splices. The specimens were tested by means of an electro-mechanical screw-jack acting on a steel beam distributing the load in two points. The test ended when the deflection at mid-span was about 60 mm or at the splice failure. The displacement rate was similar to that already used in many tests on lap splices carried out by the authors[9,14]; in particular, it was 0.5 mm/min up to the peak load and, then, 2 mm/min up to the maximum applied displacement. Two load cells were set at the ends of two tying steel bars pulled by the jack to measure the load applied to the specimen.

The beam deflection was recorded at mid-span by two Linear Variable Differential Transformers (LVDTs) pointing on the bottom surface of the beam (pos. 1 and pos. 2 in Figure 3b). Moreover, several potentiometric transducers were used to record the crack pattern development along the splice length. In particular, seven devices (pos. 3 to 9 in Figure 3c,d) recorded the onset and the opening of both face splitting cracks (spreading towards the bottom surface of the beam) and the side-splitting cracks (developing at the rebar plane). Two additional longitudinal transducers were placed on one beam side to record the width of flexural cracks developing along the splice length (pos. 10 to 11 in Figure 3b).

Besides the potentiometric transducers, Digital Image Correlation (DIC) was used to measure the strain fields on the back side of the beams of series 1 only. This system enabled a clear quantification and evolution of the flexural and side-splitting cracks caused by the lap splices. The DIC system consisted of two high sensitivity cameras (with 35.9 mm × 24.0 mm sensor CMOS) with a resolution of 36 Mpixels. Before testing, the back lateral surface of the specimen was painted in white and speckled with 0.5–2.0 mm black dots to make a black-white pattern along the lap length. The frequency of data acquirement was 1.0 Hz up to the service load (corresponding to a bar stress of 250 MPa) and then

TABLE 2 Geometrical and mechanical properties of the reinforcement (EN ISO 15630-1[27])

d_b (mm)	f_R (−)	f_{ym} (MPa)	f_{um} (MPa)	A_{gt} (%)
20	0.086	522	621	13.7
16	0.081	525	610	11.0

Abbreviations: A_{gt}, elongation at maximum force; f_R, relative rib area; f_{um}, tensile strength; f_{ym}, yielding strength.
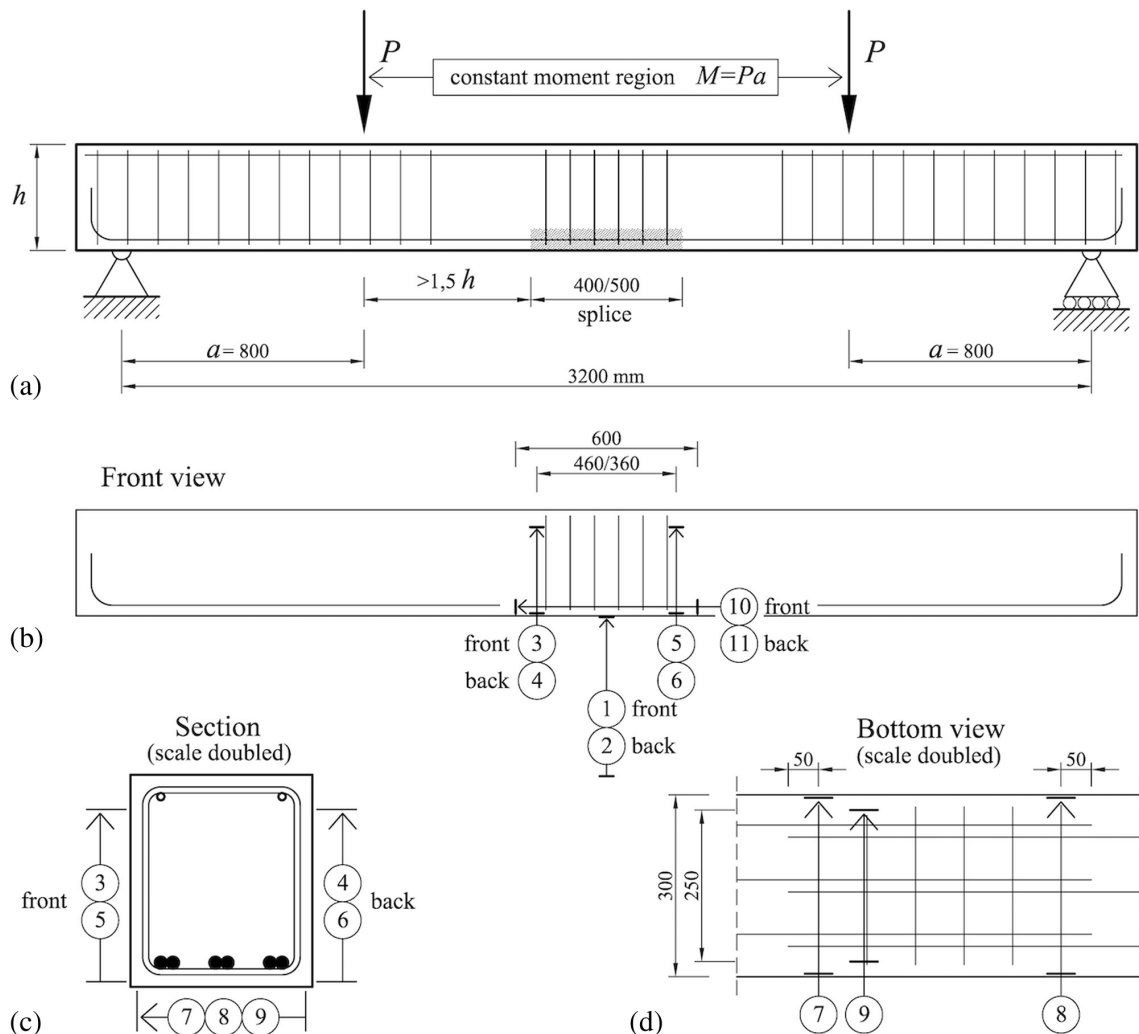

FIGURE 3 (a) Test set up and (b, c, d) positions of linear variable differential transformers (LVDTs) for the measurement of the beam deflection and cracks width

reduced to 0.5 Hz up to lap splice failure. After testing, the DIC data was postprocessed with GOM software[29] to obtain the strain vector fields. The obtained side deformations were assessed by means of the measurements recorded by the potential transducers.

3 | ANALYSIS OF TEST RESULTS: LAP STRENGTH AND CRACKS DEVELOPMENT

The applied load (P) – beam deflection (δ) curves for each series are shown in Figure 4 where the plots are labeled by a sketch depicting the transverse links arrangements used to confine the lap splice. The curves enable, therefore, the comparison among beams with different arrangements of the transverse reinforcement along the lapped bars. First, it should be noted that a 10% stiffer elastic response of the beams with lapped bars was measured due to the higher reinforcement ratio at midspan with the lap splices. Reference beams with continuous rebars (20C or 16C) exhibited a ductile failure with large flexural cracks due to yielding of rebars, while in the specimens with lapped bars a brittle failure was observed because of the formation of longitudinal splitting cracks along lap splices. These results confirmed the assumed design criteria of laps. Two different failure modes of the splices were observed due to concrete-cover splitting: (i) side splitting failure characterized by cracks developing in the plane of longitudinal rebars towards the beam sides (Figure 1a) and (ii) face splitting failure with vertical and longitudinal cracks that occurred on the bottom surface of the beam (Figure 1b).

The main test results are summarized in Table 3, where the peak load (P_u), the ultimate displacement (δ_u), and the maximum nominal bar stress ($f_{s,ex}$) are listed. The latter was calculated, by using material and geometrical properties of each beam (Figure 2 and Table 1), as:

$$f_{s,ex} = \frac{P_u a}{z A_{s,tot}} \quad (4)$$

where $A_{s,tot}$ is the cross sectional area of longitudinal reinforcement, z is the inner lever arm of the cross section (around 0.88 d); a is the shear span (equal to 0.8 m) and d is the effective depth of the cross section (Figure 2). The maximum nominal bar stress ($f_{s,ex}$) is also normalized with the maximum bar stress expected by the MC2010 formulation (Equation 2), in order to provide a better comparison among specimens having different concrete strength and confinement from stirrups and concrete cover. To this aim, the value of the Bond Strength ratio ($BS = f_{s,ex}/f_{stm}$) is reported for each beam in Table 3.
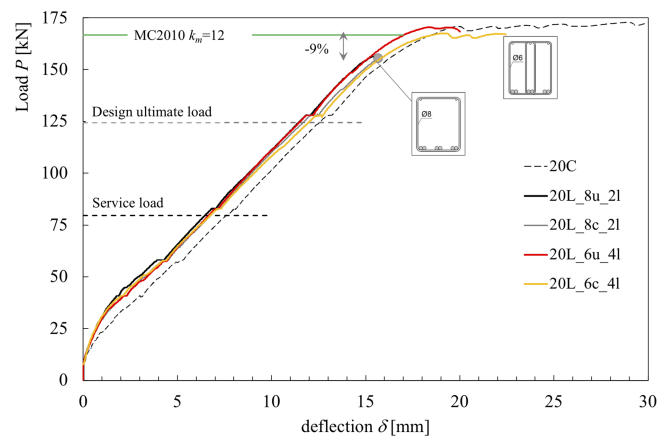
(a)
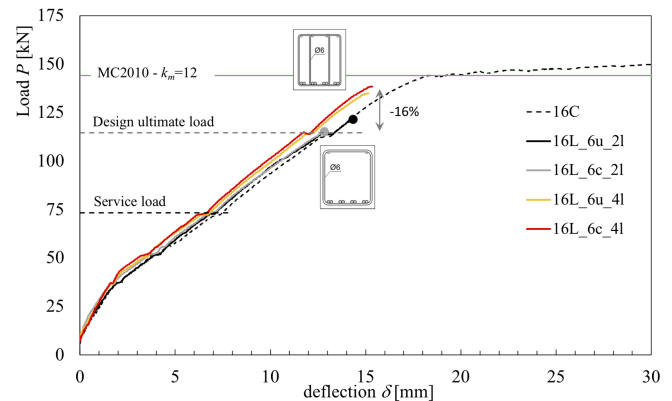
(b)

FIGURE 4 Load (P) vs. deflection (δ) experimental curves of beams in (a) series 1 and (b) series 2

From Figure 4, it should be noted that, in both series, the beams with a transverse link adjacent to each lap splice (Series 1: 20L_6u_4l, 20L_6c_4l; Series 2: 16L_6u_4l; 16L_6c_4l) exhibited a higher peak load than the specimens with corner links only, although the stirrup index of confinement K_{tr} (2.3% and 1.8% in series 1 and 2, respectively) was similar for all lap splices. The specimens with external links only, exhibited a decrease of the peak load of about 10–15% when compared to the beams with links adjacent to each lap splice. In series 1, the inner links also enabled the laps to develop a modest ductility (Figure 4a). These results point out a significant influence of the stirrup arrangements with a better efficiency of the confining links close to the lap splices; stirrup efficiency seems vanishing when the distance from the laps is larger than four times the bar diameter.

This result suggests that the Model Code limits on the efficiency of confining reinforcement may be improved, as demonstrated by the *Bond Strength* ratio (*BS*) reported in Table 3 and shown in Figure 5. The *BS* ratio ranges from about 1.0 when the lapped bars are confined by adjacent transverse links to a minimum of 0.85 when

TABLE 3   Main test results

	Specimen	$f_{cm,ex}$ (MPa)	P_u (kN)	δ_u (mm)	$f_{s,ex}$ (MPa)	$\frac{f_{s,ex}}{f_{ym,ex}}$	$BS = \frac{f_{s,ex}}{f_{stm}}$	Failure mode	Number of face splitting cracks
Series 1	20C	45	170.7	80	522	1.00		Y	–
	20L_8u_2l	45	156.5	16	479	0.92	0.93	SP-f-s	3
	20L_8c_2l	45	155.8	15	476	0.91	0.92	SP-f-s	3
	20L_6u_4l	45	170.5	20	521	1.00	0.98	SP-f-s	2
	20L_6c_4l	45	167.6	22	513	0.98	0.96	SP-f-s	2
Series 2	16C	35	143.4	80	525	1.00		Y	–
	16L_6u_2l	35	120.7	14	442	0.84	0.90	SP-f-s	4
	16L_6c_2l	35	114.3	13	418	0.79	0.85	SP-f-s	4
	16L_6u_4l	35	133.8	15	490	0.93	0.99	SP-f	2
	16L_6c_4l	35	137.8	15	504	0.96	1.02	SP-f	2

Note: *f*, *s*, Face and side splitting crack; SP, Splitting of concrete cover; Y, Bar yielding.

outer legs only are used. Thus, while in the former case the MC2010 formulation predicts accurately the lap strength, in the latter configuration it tends to overestimate the lap strength of about 10–15% when only outer legs are used. A better prediction could be obtained by assuming $k_m = 0$ when the distance between the link and the lap splice is equal or larger than four times the bar diameter.

Furthermore, experimental results show that the arrangement of the stirrups (evenly distributed along the lap length or concentrated at the lap ends) affects neither the strength nor the ductility of the lap splice, as the specimens exhibit similar peak loads (Figure 4). These results are consistent with those observed in the tests carried out by Maeda et al.[21] on lap splices with either corner bars supported by hoops and inner bars unsupported by subties, with a distance of about three times the longitudinal bar diameter with respect to the outer link. However, in the research of Maeda et al.[21] a direct comparison of the test results is possible only for two specimens having the same stirrups index of confinement (equal to 1.2%) but a different links' arrangements.

The different arrangement of transverse reinforcement (without inner links or with inner links) also affected the cracking development along the lap length. In fact, all beams failed with both side and face splitting cracks (Figure 6); however, while the specimens without inner links developed a number of face splitting cracks equal to the pairs of lapped bars (three in series 1 and four in series 2), the specimens with inner links developed only two larger splitting face cracks under the outer splices, because of the larger confinement provided by the horizontal links under the internal laps. As an example, the crack pattern of two specimens is shown in Figure 6 where both the side and the face splitting cracks can be observed.
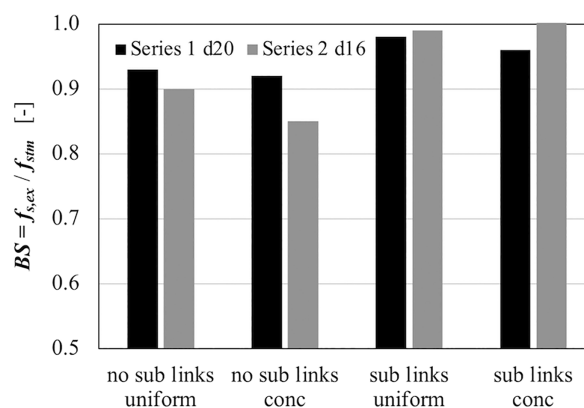

FIGURE 5   Effect of links arrangement on the assessment of lap strength (*BS* ratio)

The capability of the inner transverse links to better control the lap splitting failure is also shown in Figure 7 where the load (*P*) versus side (w_{ss}) and face splitting crack width (w_{fs}) is plotted. It can be noticed that the lap splices with only links having outer legs exhibited a sudden splice failure with both side or face spitting cracks width <0.2 mm, while the specimens with inner ties showed a more stable splitting crack development up to a width close to 0.8 mm at failure. Once again, the experimental evidence supports the idea that outer links of transverse reinforcement may not be effective in confining the wedge action of internal lapped bars when the link is placed at a distance larger than four times the bar diameter. It should also be observed that the splitting crack width was always smaller than 0.1 mm at service load.

The measurement of the full displacement and strain field along the lap length with DIC system confirmed the major role played by the arrangement of the confining
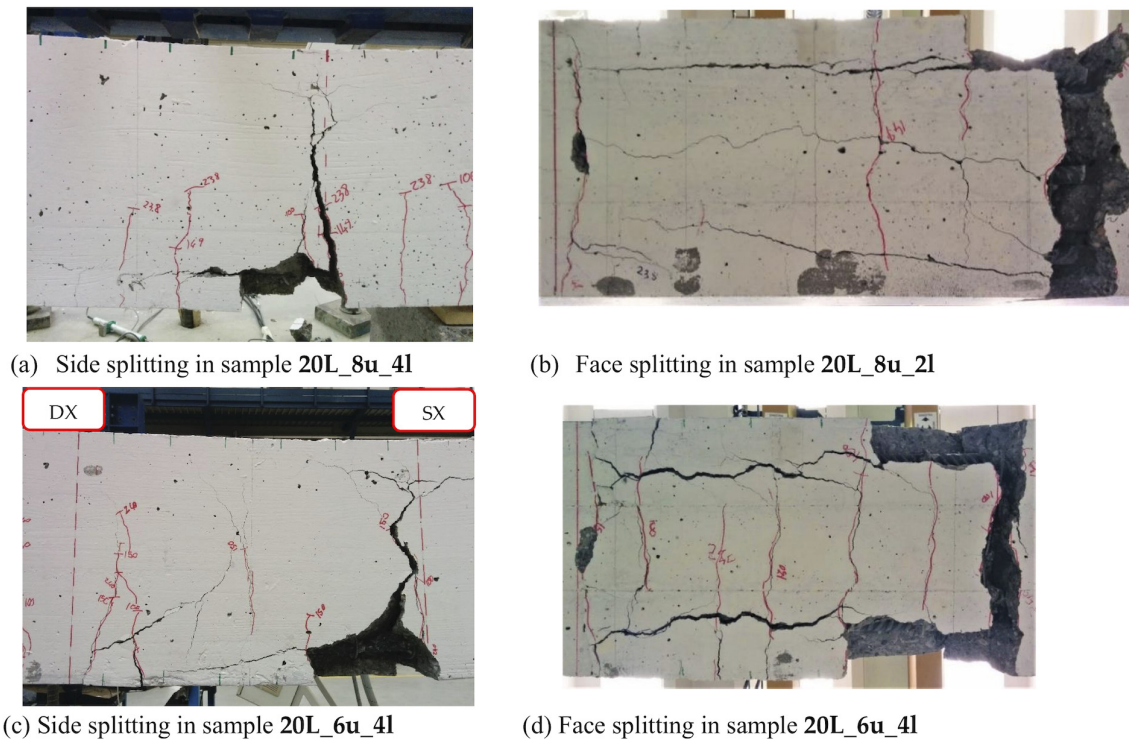
(a) Side splitting in sample **20L_8u_4l**

(b) Face splitting in sample **20L_8u_2l**

(c) Side splitting in sample **20L_6u_4l**

(d) Face splitting in sample **20L_6u_4l**

FIGURE 6 (a, b) Crack pattern: Side splitting crack and face splitting cracks along the lap length in specimens 20L_8u_2l with inner lapped bars unsupported by sub-ties and (c, d) 20L_6u_4l inner lapped bars supported by sub-ties
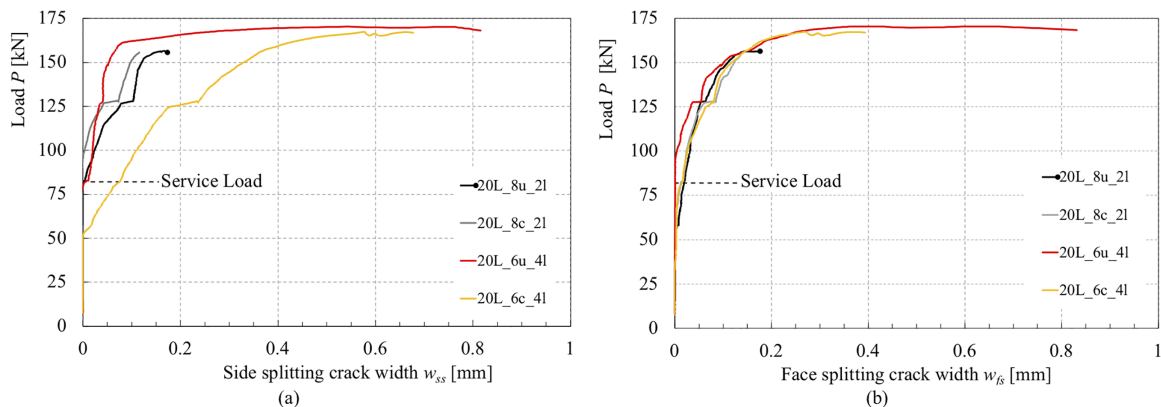

FIGURE 7 Development of splitting cracks: Load P versus width of side (a) w_{ss} or (b) face w_{fs} splitting crack in specimens of series 1

transverse links on the development and propagation of the side-splitting crack. In fact, in specimen 20L_8u_2l, without inner links, no horizontal side cracks were observed up to 99% of the peak load (Figure 8a). At the peak load (156.5 kN) the side-splitting crack developed suddenly along the lap length (Figure 8b) and the bearing capacity of the beam sharply decreased (brittle failure) because the outer links were not efficient in controlling the propagation of the splitting crack developed from the internal laps.

Furthermore, the strains perpendicular (ε_y) to lapped bars, measured by DIC over a beam depth of 150 mm (from the bottom), which comprises all possible side-splitting cracks, are plotted in Figure 9. The DIC strain fields indicate values of vertical deformation in specimen with inner links (20L_6u_4l) as twice as those of the specimen without inner links (20L_8u_2l) demonstrating, once again, the better spitting crack control provided by inner links. Furthermore, in the former specimen the vertical strains resulted mainly distributed along a length
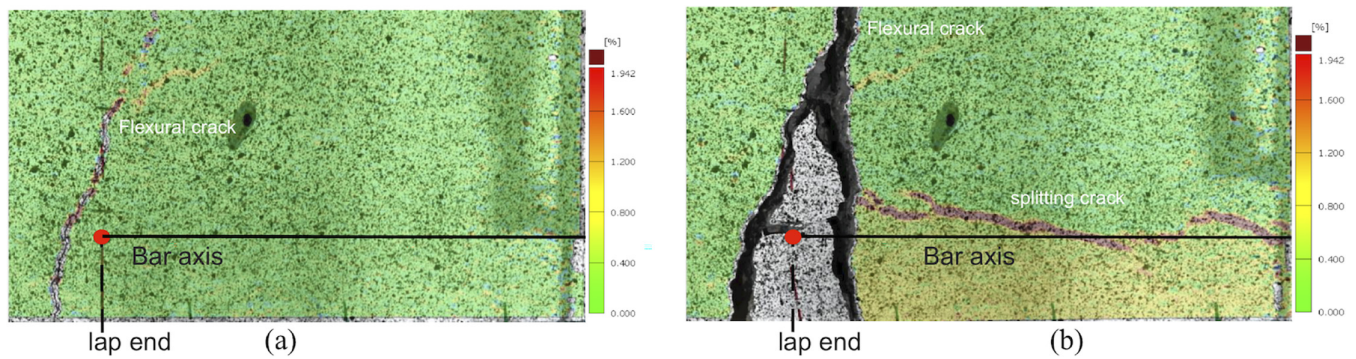
FIGURE 8   Crack patterns along half lap length of specimen without inner transverse links (20L_8u_2) for (a) a load equal to 99% of the peak load and (b) after lap failure
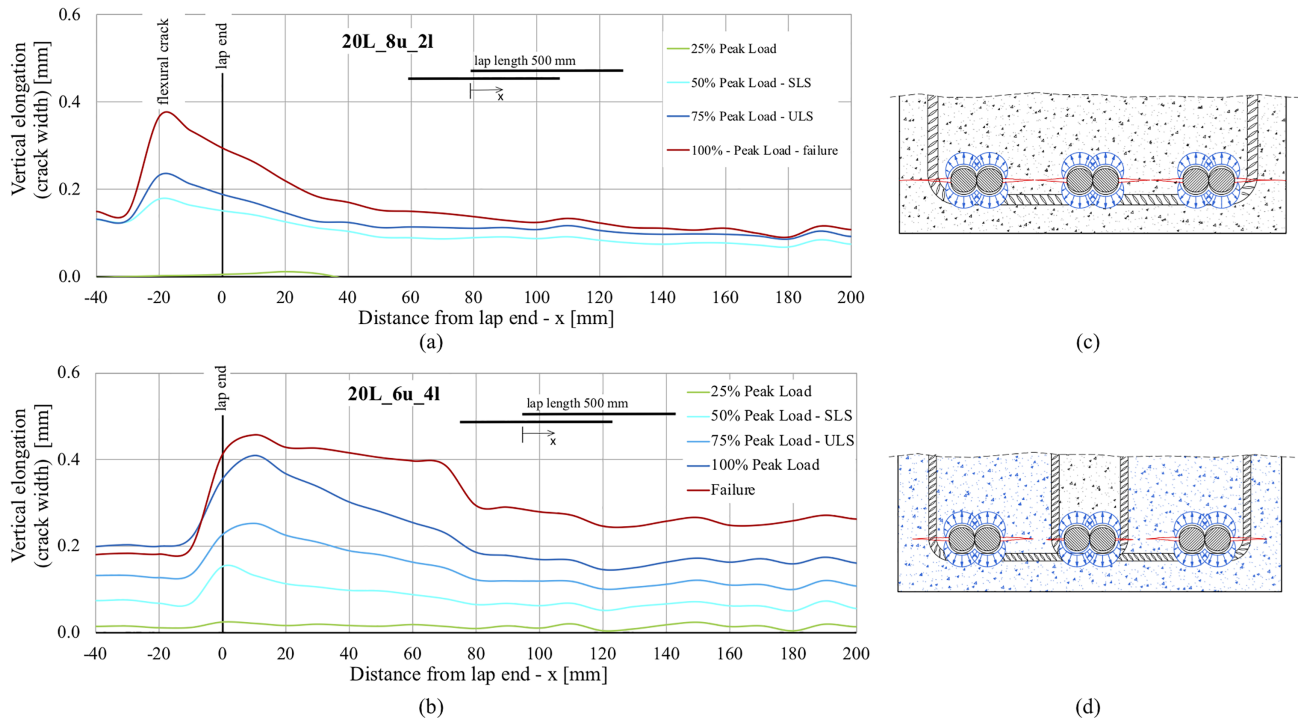

FIGURE 9   Vertical deformation of concrete cover along the lap length between the bottom surface and a directrix having a distance of 150 mm for (a) the specimen 20L_8u_2l and (b) the specimen 20L_6u_4l; outer links not efficient in controlling the propagation of the splitting crack from the inner lap (c) and splitting crack controlled by the inner transverse links (d)

of 80 mm whilst in the latter specimen (without inner links) they were concentrated at the lap end and close to the vertical flexural crack (as also shown in Figure 8b).

4 | ANALYSIS OF A DATABASE ON LAP STRENGTH IN TENSION AND COMPARISON WITH THE PREDICTION OF MC2010 FORMULATION

An experimental database on the strength of lap splices with different distance of transverse links to the lapped

bars is gathered from studies published in literature. This database enables to evaluate the accuracy of the efficiency factor k_m of confining reinforcement in the aforementioned *fib* MC2010 formulation (Equation 2). While the complete database used to calibrate MC2010 formulation includes about 380 test results on laps confined by links (90% of them are adjacent to the laps; Fib Bulletin 72[25]), this survey is only limited to 47 tests because of the scanty tests with a distance (a_l) of lapped bars to the legs >2 times the bar diameter. Furthermore, the test results found in literature were filtered in order to exclude results of specimens with low concrete cover, lap lengths shorter than the EC2 permitted minimum, and measured

TABLE 4 Experimental database: Number of test specimens for varying distance a_l of transverse link to the lapped bars and authors

		MC2010 provision $k_m = 12$ for $a_l \leq 5\,d_b$ and $a_l \leq 125$ mm			Proposal $k_m = 0$
		$2 < a_l/d_b \leq 3$	$3 < a_l/d_b \leq 4$	$4 < a_l/d_b \leq 5$	$4 < a_l/d_b \leq 5$
Rezansoff et al. (1993)[30]		–	3	–	
Darwin et al. (1996)[31]		–	3	2	2
Zuo & Darwin (1998)[32]		4	8	–	–
Hegger & Burkhardt (1998)[33]		–	1	–	–
Rehm & Elighausen (1978)[34]		–	1	–	–
Metelli et al. (2015)[9]		–	–	4	4
Presented results (Metelli et al.)		–	–	4	4
Hamad et al. (2003)[35]		–	4	–	–
Hamad & Jirsa (1993)[36]		1	2	–	–
Number of tests	47	5	22	10	10
BS ratio ($f_{s,ex}/f_{stm}$)	Mean	1.01	1.05	0.88	1.13
	CoV	0.17	0.14	0.08	0.10
	Not conservative results (%)	40	23	100	10

Note: $l_b/d_b > 15$; $f_{cm} > 20$ MPa; $c_{min} > 0.5d_b$; $f_{s,ex}$ and $f_{stm} < 1.1f_{ym}$.
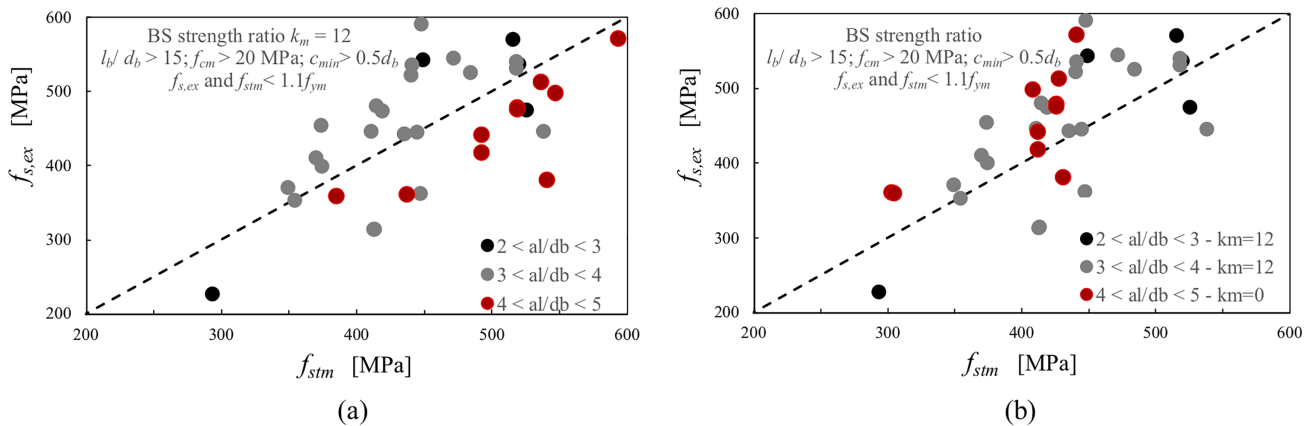
FIGURE 10 (a) Measured ($f_{s,ex}$) versus predicted (f_{stm}) lap strength according to MC2010 and (b) with the modified $k_m = 0$ if $a_l > 4d_b$

lap strengths exceeding 1.1 times the yield strength of the reinforcements ($l_b/d_b > 15$; $f_{cm} > 20$ MPa; $c_{min} > 0.5d_b$; $f_{s,ex}$ and $f_{stm} < 1.1\,f_{ym}$; $a_l \leq 5d_b$ and $a_l \leq 125$ mm), as listed in Table 4.

The statistical analysis of the selected test results shows that MC2010 provides an accurate evaluation of the lap strength only if the distance of confining legs of links to the lap splices is up to four times the bar diameter; in this case the Bond Strength ratio (BS) ranges between 1.01 and 1.05 (Table 4 and Figure 10). However, for larger distance (>4 d_b) the MC2010 formulation overrates the lap strength of

about 15% and it is unconservative for all the selected specimens with the statistical calibration of Equation (2) that considers the full efficiency of confining transverse reinforcement ($k_m = 12$) placed up to five times the bar diameter (Figure 10). As shown in the last column of Table 4 and in Figure 10b, by considering k_m equal to 0 for a distance of links >4 d_b, the mean value of the bond strength ratio would be equal to 1.13 with a Cov of 0.10 and 10% of unconservative results, in line with the statistical reliability of MC2010 formulation for links closer to the lapped bars (fib Bulletin 72[25]).

5 | CONCLUDING REMARKS

Aim of this article is the experimental investigation of the influence of transverse links arrangement on the behavior of lap-splices in normal-strength concrete. Eight beams were tested with four different arrangements of confining reinforcement, namely with links either evenly spaced along the lap length or concentrated at its end, and with either outer-corner links or links close to each lap splice.

Based on the test results and on the statistical treatment of literature results, the following remarks can be made:

- The splice strength of the beams merely provided with outer links only is about 10–15% lower than that of the beams having also inner links confining each lap splice. Hence, the transverse link is not efficient against the propagation of the splitting crack generated by the wedge action of lapped bars placed at a distance larger than four times the bar diameter.
- The arrangement of the stirrups (either evenly distributed along the lap length or concentrated at the lap ends) hardly affects either the strength or the ductility of lap splices in tension, thus confirming the validity of MC2010 provisions on the distribution of transverse reinforcement along the lap length.
- The analysis of the test results on lap splices shows that the MC2010 provisions may be unconservative (up to +14% overestimation of the strength) with relatively far confining links. This trend is also confirmed by the statistical analysis of the experimental results found in literature on lapped splices with not-adjacent confining links. This outcome suggests that the efficiency factor (k_m) of transverse links considered in MC 2010 should be further investigated.
- Finally, in the authors' opinion MC 2010 design provisions could be improved by reducing to 0 the effectiveness factor (k_m), when the distance of the ties to the lap splice is larger than four times the bar diameter.

NOTATION

a	shear span
a_l	distance of lapped bars to the confining link
A_s	cross sectional area of a single anchored/lapped bar
$A_{s,tot}$	total cross sectional area of longitudinal reinforcement
A_{st}	cross sectional area of one leg
A_{gt}	steel rebar strain at maximum force
BS	bond strength ratio
c_x	side concrete cover
c_y	bottom concrete cover
c_s	clear spacing between lapped bars
d	effective depth of the beam cross section
d_b	diameter of the smaller of a pair of lapped bars
d_{sw}	stirrup diameter
$f_{bd,0}$	basic bond resistance
f_{cm}	concrete strength
f_R	relative rib area (bond index)
f_{um}	mean tensile strength of steel rebars
f_{ym}	mean yield strength steel rebars
$f_{ym,ex}$	measured mean yield strength steel rebars
f_{stm}	maximum lapped bar stress according to fib-MC20101 formulation
$f_{s,ex}$	nominal bar stress at peak load
K_{tr}	stirrup index of confinement
k_m	effectiveness factor of confining reinforcement
l_b	lap/anchorage length
n_b	number of anchored bars or pairs of lapped bars
n_{st}	total number of confining stirrups along the anchorage/lap length
n_t	number of stirrup's legs crossing the splitting failure surface
P, P_u	applied load, ultimate load
w_{ss}	width of side-splitting crack
w_{fs}	width of face-splitting crack
z	inner lever arm of the cross section
α_3	confinement coefficient provided by transverse reinforcement (as expressed by EC2)
α_2	confinement coefficient provided concrete cover (as expressed by MC2010)
δ, δ_u	beam deflection, ultimate deflection

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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