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Comparative study of factors influencing tension lap splices in reinforced concrete beams

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Abstract. The practice of splicing reinforcing bars in reinforced concrete structures to manage insufficient bar length is a common approach, which is mainly due to transportation limitations on bar length. The splicing of reinforcing bars side by side offers a simple and economical solution to the problem of continuity. This paper examines the influence of different structural parameters such as concrete cover, lap splice length, shear links confinement and concrete strength on the lap splices based on an extensive experimental database of laps and anchorage. The current study shows that increasing the lap splices beyond 50Ø has no additional benefit for increasing its strength. The results also show that relative to the measured stress, specimens with larger concrete side covers shows higher splice stress compared to the samples with smaller concrete covers.

Keywords: Lap splices; concrete; laps; splicing; cover; reinforcing bars

1. Introduction

The bond between concrete and reinforcement requires enough anchorage of the reinforcing bar in concrete to ensure proper structural interaction. The required lap splices and anchorage length not only relies on the efficiency of the anchorage but also on the bar forces that may be transferred or developed (i.e., the bar yield strength and bar size).

The current Eurocode 2, Design for concrete structures general rules for building (BS EN 1992-1-1 2004), treats anchorage length and lap splices lengths as separate (though related) entities. However, current research has shown that the two are similar and should be addressed with a single design equation TG4.5 (2014). The Eurocode 2 requires a lap splice length that is calculated by multiplying the design anchorage length by a factor, the magnitude of which depends on the “class” to which the splice belongs. Classes depend on i) percentage of bars spliced at the location, and ii) the concrete class considered. The bond efficiency of splice length relies on the confinement given either by the concrete itself or by the shear links, which surrounds the main reinforcement or combination of both (Bournas and Triantafillou 2011). With smaller concrete covers that are ordinarily provided to the deformed reinforcing bars in concrete constructions, bond failure occurs by concrete splitting. The bar deformations on the surrounding concrete cracks cause bursting stresses, so that the concrete splits away from the reinforcement. This bond resistance with splitting failure mode is dependent on the concrete cover provided to the longitudinally spaced bars (Kadoriku 1994, Mabrouk and Mounir 2018). Any shear link that intercepts the splitting cracks is also effective in providing confinement and improving bond resistance. Shear link confinement provides greater strength in addition to greater ductility (Tepfers 1980, Rezansoff and Tsui 1982, Osifala and Akeju 2018). The bond strength of lap splices with surrounding concrete leading to confinement., splitting failure before yielding is less likely. However, with larger confinement, bond failure occurs when the deformed reinforcing bars pull out of the concrete, crushing the concrete in front of the bar deformations (Bournas and Triantafillou 2011). This represents an optimum bond resistance condition. This collaborative study aims to examine the influence of concrete cover, lap splice length, shear links confinement and concrete strength on structural performance of lap splices based on an extensive experimental database of laps and anchorage, which is gathered by the Task Group 2.5.

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2. Previous studies on lap splices

In the past decades, the bond behaviour of spliced reinforced concrete members with lap splices in the maximum moment zone has been extensively studied

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(Chinn *et al*. 1995, Chamberlin 1958, Tepfers 1980); Ferguson and Breen 1965). The aim of these studies was to quantify the strength of lap splices as well as to improve the understanding of the observed splitting failure modes. The analysed parameters include compressive strength, concrete cover, length of splices and spacing, longitudinal rebar diameter, presence, and amount of confining reinforcement. The influence of moment gradient along the lap splice was also studied, and its beneficial effect on the splice performance was recognised. Additional experiments on spliced reinforced concrete beams were conducted by Renzasoff *et al*. (1991), who investigated the effect of confining reinforcement on the bond strength of lap splices. The objective was to investigate the effect of heavy confinement on lap splice performance under static loading, thereby permitting shorter lap splice lengths than currently required. Forty-eight simply supported beams containing tensile lap splices in the constant moment region was tested under four-point bending test. It was observed that beams containing lap splice with heavy confinement performed as well as beams in which the lap splices were lightly confined. Rakhshanimehr *et al.* (2014) investigated the influence of the number of shear links over the lap splices on the ductility behaviour of beams. They found that the ductility and bond strength are not necessarily improved by increasing the lap splice length, especially in the case of high strength concrete beams. On the other hand, they concluded that by providing an appropriate number of shear links, a significant improvement in ductility and bond strength can be achieved.

Micallef and Vollum (2017) investigated the effect of lap splice length on ductility and strength where the failure modes of beams with different lap splice length were compared. The outcomes of their studies indicated that an increase in splice length results in an improvement in ductility with decrease in lap splice strength. In addition, the result of the average bond stresses between strain gauges at the ends of laps and the length of longitudinal splitting cracks lap were almost independent of the lap length. The results obtained by Micallef and Vollum (2018) correspond to that of Rakhshanimehr *et al.* (2014), in which they studied the influence of number of shear links over the lap joint on the ductility behaviour of beams. Pandurangan *et al*. (2010) conducted seventeen tests on high strength concrete beams to investigate the influence of shear links in the tension zone. The parameters investigated include the lap splice length, compressive strength, and the shape of the shear links around the spliced length and the number of shear links within the splice region. The results of their studies indicated that when the amount of shear link in the splice length increased, the mode of failure changed from a splitting bond failure to a flexural failure. Furthermore, their results also showed that the presence of shear links along the splice length had a pronounced influence on improving the displacement ductility and ultimate deflection. Moreover, the result of their experiments further suggested that decreases of shear links in the lap splice length lead to reduction of ultimate load and failure mode became splitting without any ductility. The findings of their experiments are the same to that of Pandurangan *et al*. (2010), Osifala *et al*. (2017), Rakhshanimehr *et al.* (2014), Mabrouk *et al*. (2018).

Wu *et al*. (2018) investigated the bond strength of tension lap splices in the self-compacted concrete beam and ordinary concrete beam. Six beams were tested with lap splices at the maximum moment region. It was observed that both the ordinary concrete beam and self-compacted concrete beam present a similar bond strength. Mabrouk *et al*. (2018) carried out an experimental program that consisted of sixteen reinforced concrete beams. The parameters under study were the diameter of the transverse reinforcement as well as its shape and distribution while using three different types of concrete, namely normal strength concrete, high strength concrete and self-compacting concrete. The targeted compressive strength after 28 days for the normal and high strength concrete is 30 MPa, and 90 MPa for self-compacting concrete. The normal strength concrete did not contain any type of admixture, while both the high strength and self-compacting concrete contained admixtures. In the three mixes, ordinary Portland cement CEM 1 42.5R was used that complies with ASTM C150 type 1 cement. The beams were all simply supported with 1800 mm span and 150×250 mm cross-section. The main reinforcement comprised of two high grades (400/600) steel reinforcing bars with diameter 10 mm. The tensile steel was spliced in the constant moment zone. Their study showed that decreasing shear links in the lap splice length lead to the reduction of ultimate load capacity and failure mode became splitting without any ductility.

3 Database evaluation and design models

The current study in this paper compared Eq. (9) and Eq. (10) for estimating mean tension bar stress with the experimental results for a tension splice database to evaluate the applicability of the design equations. The authors evaluate fib database of a large-scale experimental study for lap and anchorage, which was compiled by Fib Task Group 4.5 and Concrete Centre. The database comprises the results of laboratory tests on laps and anchorages conducted by ACI (for casted beams at tension only), and some additional data from the Asian and European investigations. In this database, a wide range of cross-sections, lap splice length, bar spacing, concrete cover, yield strength, bar diameter, confinement, and compressive strength are studied by the various researchers; (Darwin *et al*. 1995, Zuo and Darwin 1998, Azizinamini *et al*. 1993, 1995, Rezansoff *et al*. 1991, 1993, Hester *et al*. 1991, 1993, DeVries *et al*. 1991, Choi *et al*. 1990, 1991, Zekany *et al*. 1981, Thompson *et al*. 1975, Ferguson and Breen 1965, Ferguson and Thompson 1965, Mathey and Watstein 1961, Chamberlin 1956, 1958, Chinn *et al*. 1955, Micallef and Vollum 2017, 2018). The number of bars that were spliced varied from 1 to 6, and the lap length is ranged from $5\emptyset$ to $80\emptyset$, while the concrete strengths and bar diameter are within the range of 111 N/mm^2 to 14 N/mm^2 and 8mm to 38.9 mm. A total number of 824 tests are in the database, including 397 Lap and anchorage specimens in

Table 1 Summary of filtered specimens considered in this study

	Total number of results	Test discarded	Test with links	Test without links
Overall number of tests	828	32	48	397
Filtered data	24	-	8	20

which the bars are not confined by shear links and 418 specimens in which the bars are confined by shear links. Of these, 824, specimens (see Table 1 for the summary of data included in this study) remained after filtering the database.

The proposed filtering limits are in accordance with fib bulletin 72 (fib TG4.5 2014) recommendations for laps and anchorages.

In this respect, the proposed filter for this study contains only test specimens where:

$$k_{tr} \leq 0.005;$$
$$15\ MPA \leq f_{cm} \leq 110\ MPa$$
$$0.5 \leq \frac{c_{min}}{\emptyset} \leq 3.5 \quad \text{and} \quad \frac{c_{max}}{c_{min}} < 5$$
$$l_b \geq 17\emptyset;$$

The current study considers six experiments with shear links and sixteen experiments without them (as shown in Table 1).

3.1 BS EN 1992-1-1 (2004)

The current EN 1990 (2004) design for laps and anchorage is based on the CIB-FIP (1991). The design lap length l_{bd} includes the basic required anchorage length and the coefficients which is given by

$$l_{bd} = \alpha_1\alpha_2\alpha_3\alpha_5\alpha_6 l_{b,rqd} \tag{1}$$

Where,

α_1 is coefficient of bar shape (1.0 for straight bars)

α_2 is coefficient of concrete cover with 1.0-0.15 $(c_{min} - \emptyset)/\emptyset \geq 0.78 \leq 1.0$

α_3 is coefficient for transverse reinforcement with $1.0 - k\lambda \geq 0.78 \leq 1.0$

α_5 is coefficient for transverse pressure with 1.0 for no confining pressure

α_6 is coefficient for the percentage of bars lapped at a section determined as $1.0 \geq \alpha_6 = (\rho_1/25)^{0.5} \leq 1.5$

In which

$c_{\min}$ =min (clear bar spacing/2, bottom cover, side cover)

$\rho_1 =$ percentage of bars lapped at a section with 1.5 for > 50% lapped

λ is the difference between the cross-section area of transverse reinforcement provided along the anchorage length (A_{st}) and cross-sectional area of the minimum transverse reinforcement $(A_{st,\min})$ with $\Sigma A_{st,\min} = 1.0 \times A_s(\sigma_{sd}/f_{yd}) \geq 1.0 \times A_s$ for laps and $\Sigma A_{st,\min} = 0.25 A_s$ for beams.

A_s area of single anchored bar with maximum diameter

K is the efficiency of transverse reinforcement depending on the location of the section considered (see Fig. 1).

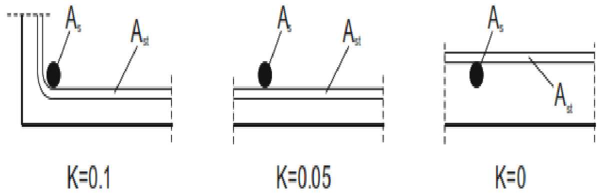


Fig. 1 Efficiency of K factor depending on the location of the shear links (adapted from BS EN 1992-1-1 2004)

$$l_{b,rqd} = \frac{\emptyset}{4}\frac{\sigma_{sd}}{f_{bd}} \tag{2}$$

Where,

$\sigma_{sd} =$ design reinforcement stress

$\emptyset$ is the bar diameter

$$f_{bd} = 2.25\eta_1\eta_2 f_{ctk}/\gamma_c \tag{3}$$

Where,

The coefficient η_1 take the bond condition (1.0 for good bond conditions)

η_2=Min $(1.0(132 - \emptyset)/100)$

$f_{ctk} = 0.21 f_{ck}{}^{2/3} for \ \leq C50/6$ concrete (f_{ck} characteristic concrete compressive strength, f_{ctk} lower characteristic concrete tensile strength**.**

3.2 Fib model code for concrete structures (2010)

According to the MC2010, the lap length l_o is given as

$$l_o = \alpha_{4,MC}\frac{\theta f_{yd}}{4 f_{bd}} \tag{4}$$

In which f_{bd} is the design bond strength given as

$$f_{bd} = (\alpha_{2,MC} + \alpha_{3,MC}) f_{bd,0} - \frac{2p_{tr}}{\gamma_c} < 2.0 f_{bd,0} - \frac{0.4p_{tr}}{\gamma_c} < \frac{1.5\sqrt{f_{ck}}}{\gamma_c} \tag{5}$$

Where

$$f_{bd,0} = \eta_1\eta_2\eta_3\eta_4\left(\frac{f_{ck}}{25}\right)^{0.5}/\gamma_c \tag{6}$$

$$\alpha_{2MC} = \left(\frac{c_{min}}{\emptyset}\right)^{0.5}\left(\frac{c_{max}}{2.c_{min}}\right)^{0.15} \tag{7}$$

$$\alpha_{3,MC} = k_d.(k_{tr} - \alpha_t/50) \tag{8}$$

with

$p_{tr} =$ mean compression stress perpendicular to the potential splitting at failure surface at ultimate limit state

$\eta_1 = 1.75$ for ribbed bars

γ_c partial safety factor for bond ($\gamma_c = 1.5$)

f_{yd} design yield strength of reinforcing bars

$\eta_2 = 1.0$ for good bond condition

$\eta_3 =$ Coefficient effect for bar diameter $\eta_3 =$ Max (1.00, $(25/\emptyset)^{0.5}/\gamma_c$

$\eta_4 =$ coefficient for characteristic strength of steel being lapped ($\eta_4 = 1.0$ for $f_{yk} = 500$ MPA

k_{tr} confining effect provided by the transverse reinforcement along the lap length.

c_{max} maximum concrete cover

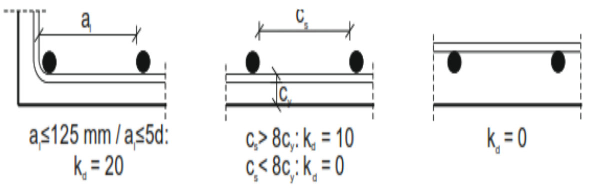


Fig. 2 Coefficient k_d for efficiency of transverse reinforcement adapted from MC (2010)

α_t coefficient for bar diameter $\alpha_t = 0.5$ for $\emptyset \leq 25$ mm or 1.0 for $\emptyset = 50$ mm

k_d efficiency of transverse reinforcement (see Fig. 2)

The factor K_d accounts for the nonlinear relationship between lap length and the stress developed in the bar.

The stress developed in a lap according to the (Model Code 2010) may be taken as

$$\sigma_{sd} = \frac{l_o}{\emptyset}\frac{4}{\alpha_4 MC}$$
$$\left[(\alpha_{2,MC} + \alpha_{3,MC})1.75\left(\frac{25}{\emptyset}\right)^{0.3}\left(\frac{f_{ck}}{25}\right)^{0.5} - 2p_{tr}\right]/\gamma_c \quad (9)$$

3.3 Fib bulletin 72 (fib TG4.5, 2014)

The design equation for estimating the average bar stress in lapped bars was derived from a database of around 775 tension lap tests conducted in the United States, Asia, and Europe. Fib bulletin 72 (fib TG4.5 2014) recommends the following equation for estimating mean stress developed in the bar under tension as

$$f_{stm} = 54\left(\frac{f_{cm}}{25}\right)^{0.25}\left(\frac{25}{\emptyset}\right)^{0.2}\left(\frac{l_b}{\emptyset}\right)^{0.55}$$
$$\left[\left(\frac{c_{min}}{\emptyset}\right)^{0.25}\left(\frac{c_{max}}{c_{min}}\right)^{0.1} + k_m k_{tr}\right] \quad (10)$$

Where f_{cm} is the measured concrete cylinder compressive strength; l_b and $\emptyset$ are the bond length and diameter of the lapped or anchored bar; k_{tr} is the confining effect provided by the transverse reinforcement and shear links located along the anchorage or lap given by

$$k_{tr} = \eta_1 \eta_g A_{sv} / (l_b \emptyset \eta_b) \quad (11)$$

The definition of the concrete cover $c_{\min}$, $c_{\max}$ and coefficient k_m is explained in Figs. 3 and 4, respectively.

The limits set by fib bulletin 72 Eq. (3-2) (here Eq. (10) are as follows:

$k_{tr} \leq 0.005$;

$15\ MPA \leq f\_cm \leq 110\ MPa$

$0.5 \leq c_{min}/\emptyset \leq 3.5$ and $c_{max}/c_{min} < 5$

$l_b \geq 10\emptyset$;

$25/\emptyset \geq 2$;

The expression of Eq. (10) (Eq. (3-2) in Fib bulletin 72) has been calibrated taking into consideration the nonlinear effect of lap strength, and the main variables that may influence the lap resistance such as f_{stm} and $l_b/\emptyset$.

Similarly, the equation for predicting the effective bond length in lap splices is given by Fib bulletin 72 fib bulletin equation as

$$l_b^* = l_b[20/(l_b/\emptyset)]^{0.45}[25/f_{cm}]^{0.42} \leq l_b \quad (12)$$

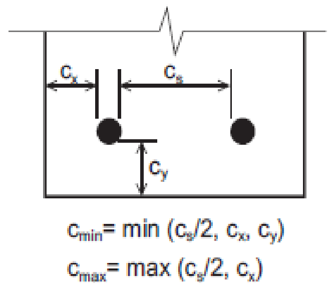


Fig. 3 Definition of concrete cover adapted from fib TG4.5 (2014)

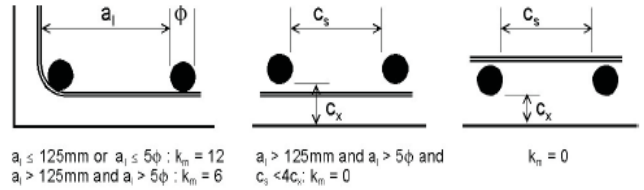


Fig. 4 Reduced effectiveness of transverse reinforcement adapted from fib TG4.5 (2014)

Where l_b is the actual bond length (mm) and $\emptyset$ is the diameter (mm), the constant of 20 within the first bracket represents the medium ratio of $l_b/\emptyset$, while the constant of 25 in the second bracket represent the weakest grade of concrete.

4. Results and discussion

The test results are provided in A1-A5 in the appendix. The strength of the specimens is presented as the ratio of the stress measured in the test to that estimated by fib bulletin 72 Eq. (10) for mean lap stress.

4.1 Effect of lap-length to bar-diameter ratio on lap strength

The splice lengths ranged from 570 mm to 950 mm (30Ø to 50Ø) were used to examine the influence of lap-length to bar-diameter ratio on the maximum measured bar stress in the test. The measured lap stress indicates the stress developed on the lap length. Although the lap stress measured in the test decreases as the lap-length to bar-diameter ratio is increased, the measured lap stress does increase with an increase in the lap length to bar-diameter ratio. Fig. 5 shows the plot of the maximum bar stress measured in the test σ_{test} against the lap-length to bar-diameter ratio. Fig. 5 shows the plot of the maximum bar stress measured in the test σ_{test} against the lap-length to bar-diameter ratio. Increasing the lap-length to bar-diameter ratio by 33% from 30Ø to 40Ø (570 mm to 760 mm) resulted in a 22% increase in lap stress. A further 20% increase in lap-length to bar-diameter ratio from 40Ø to 50Ø (760 to 950 mm) amplified the lap stress by 26%. While the measured stress of 750MPa in this experiment is very high, it is worth mentioning that the reinforcement used in this experiment is Japan steel with a yield strength of 708 MPa, which is very high compared to the UK

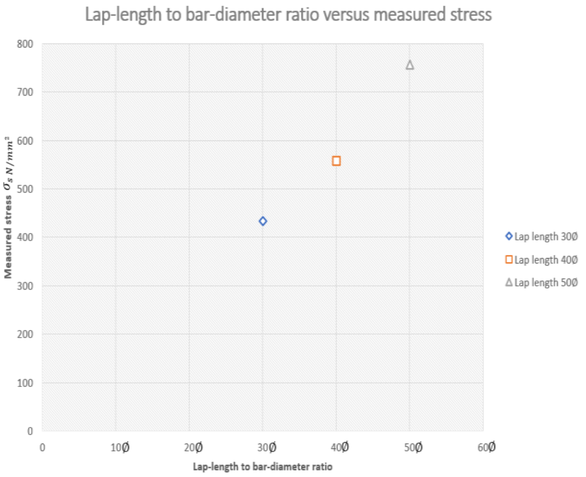


Fig. 5 Influence of lap length to bar diameter ratio on maximum bar stress measured in the test

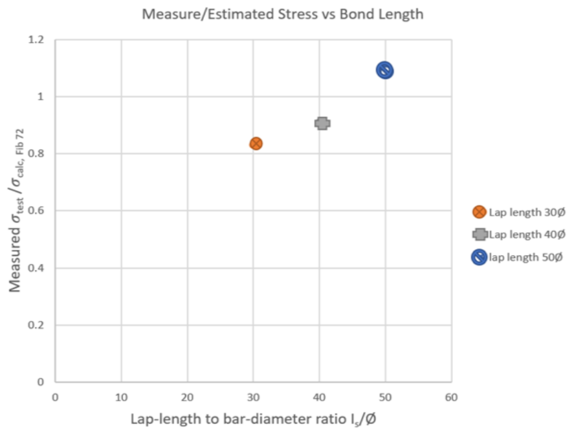
reinforcement which has mean strength of about 560 MPa.

4.2 Influence of design models on estimating bar stress

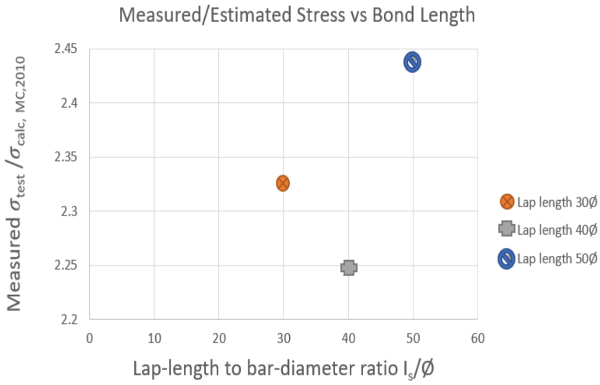
Fig. 6 shows a plot of lap-length to bar-diameter ratio against the ratio of maximum mean bar stress over the lap length measured in test σ_{test} to the calculated average lap stress according to fib bulletin 72 (Fig. 9(a)) and Model Code (2010) (Fig. 9(b)). As shown in Fig. 6 (Fig. 9(a)), the bar stress predicted by fib bulletin 72 (2014) equation increases as a rate that is less than proportional to lap-length to bar-diameter ratio. It is observed that the ratio of measured stress to estimated stress increases with lap length. This comparison indicates that the design Eq. (10) for estimating the average bar stress in lapped bars according to Fib bulletin 72 (2014) overestimates the effect of lap length on the measured lap stress in the test (σ_{test}) in comparison to Model Code's (2010) design Eq. (9) for mean bar stress. Increasing the lap-length to bar-diameter ratio from 30Ø to 40Ø (570 mm to 760mm) resulted in an 8% increase in the ratio of measured to estimated strength. However, it appears that a further increase in lap-length to bar diameter ratio from 40Ø to 50Ø increased the ratio of measured to estimated lap strength by 17%. In comparison to the mean bar stress calculated according to the Model code (2010), it appears there is a reduction of 64%, 60% and 55% for lap-length to bar-diameter of 30Ø, 40Ø and 50Ø. This means Fib bulletin Eq. (10) is less conservative than the recommended (Model Code 2010) Eq. (9) for mean bar stress design Eq. (9) recommended by Model Code (2010).

4.3 Effect of effective bond length on splice strength

Similarly, the effective bond length $l_b{}^*$ is plotted against the ratio of measured stress to estimated stress (σ_{test}/f_{stm}). As evidenced by the data trend shown in Fig. 7, for 30Ø to 50Ø lap length, the effectiveness of increasing the lap length reduced as splice length increased. Increasing the lap length by 25% from 30Ø to 40Ø (570 to 760 mm)



(a) Fib bulletin 72



(b) Model code (2010)

Fig. 6 Comparison of maximum bar stress in test to the calculated bar stress according to Fib bulletin 72 (a) and Model code (2010) (b)

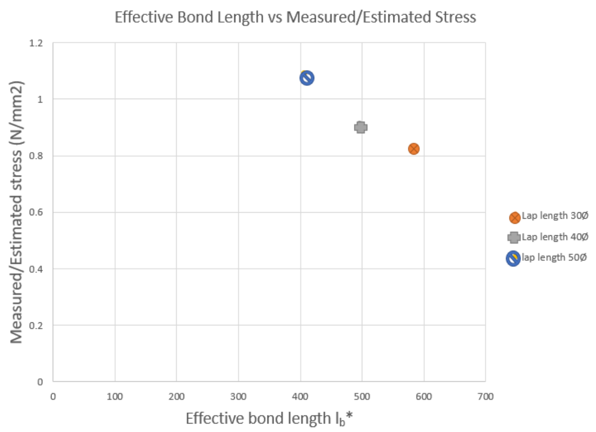


Fig. 7 Effective bond length against splice strength

resulted in a 14% decrease in effective bond length. A similar increase in the lap length by 20% from 40Ø to 50Ø (760 to 950 mm) decreased the effective bond length by around 18%. Overall, the effective bond length did not seem to be linearly proportioned to the lap length.

4.4 Effect of bar spacing on splice strength

The concrete cover dimensions determine the splitting failure modes. While the small side cover C_x and small bar

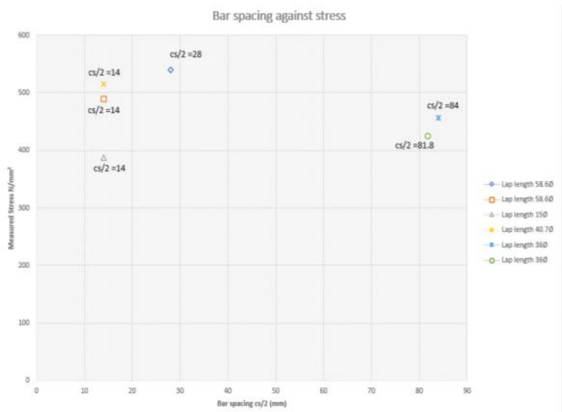


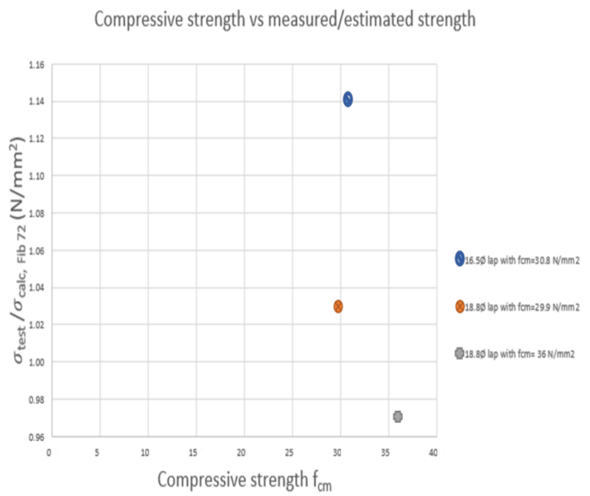
Fig. 8 Effect bar spacing on the splice strength

spacing C_s cause side-splitting, the small bottom cover C_y induces face splitting. Since bar spacing contributes to the load transfer between bars, the spacing is accounted for by $C_s/2$. Therefore, numerous design models (Fib bulletin 72 2014, Model code 2010, EN 1990 2004) only regard a minimum $C_{\min} = \min\{\text{cy; cx; cs}/2\}$. The concrete cover and the lap-length to bar diameter are classified according to table A6 in the appendix. Figure 8 shows the effect of bar spacing on the maximum bar stress for the filtered database test with transverse reinforcement. Increasing the splice length from 210 mm to 570 mm resulted in a 24% decrease in lap stress. Furthermore, for the same 58Ø lap length, decreasing the bar spacing from 29 mm to 14 mm resulted in 10% decrease in lap stress. Likewise, for similar lap length of 30Ø, increasing the bar spacing from 81.8mm to 84 mm resulted in 8% increase in lap stress.

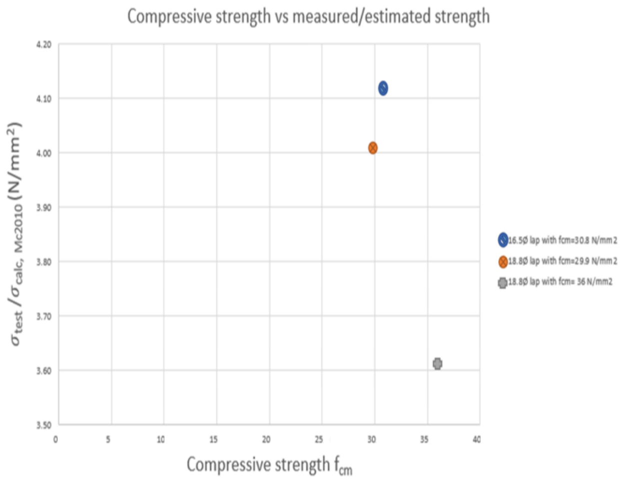
4.5 Effect of concrete strength on lap splice strength

When examining the influence of concrete strength on the lap strength, the ratio of lap length to bar diameter as well as the concrete cover must be considered as it is an influential factor (Micallef and Vollum 2018). Fig. 9 shows a plot of compressive strength against the ratio of maximum mean bar stress over the lap length measured in test σ_{test} to the estimated mean lap stress according to equation (10) of fib bulletin 72 (2014) (Fig. 9(a)) and Eq. (9) of Model Code (2010) (Fig. 9(b)). The estimated bar stress calculated according to fib bulletin 72 (2014) in the splice region with increasing concrete strength is much higher than the values estimated according to Model Code (2010). For the same concrete cover, confinement and lap-length to bar-diameter ratio, a better performance with decrease in concrete strength is observed. It appears that a small reduction in the splice strength, relative to the predicted strength, occurs when the concrete strength is decreased from 36 to 29.9 N/mm^2 (Fig. 9(a)). However, reducing the lap splice by 13% (18.8Øto16.5Ø) and the concrete strength from 36 to 30.8 N/mm^2 resulted in a 5% decrease in the lap measured stress.

4.6 Effect of stirrup confinement on lap splices strength



(a) Fib bulletin 72



(b) Model code (2010)

Fig. 9 Influence of compressive strength on the splice strength

It is believed that providing adequate stirrups can not only change the failure mode and bond-slip relationship, but it can also delay the initiation of splitting cracks (ACI Committee 408 2003, Tepfers 1973). In this paper, the influence of the confinement provided by the stirrups was examined by comparing the splice strength of three specimens with different stirrup confinement. The direct comparison between the specimen with three different stirrup confinement levels shows the positive influence of stirrup confinement. In this regard, Fig. 10 plots the ratio of measured to predicted strength against the confining effect kt_r. As depicted, an increase in the number of stirrups could effectively improve the lap splice strength. The test specimens containing lap splices with more confinement performed as well as beams in which the lap splices were less confined. Increasing the confinement level from for shorter lap length (18.8Ø) by 44% resulted in a 28% increase in splice stress length compared to longer lap length (26.3Ø). For the same splice length of 28.4Ø, increasing the shear link confinement from 5 to 8 resulted in a 4 % increase in lap stress. Overall, the effectiveness of lap splices increases, with an increase in confinement level.

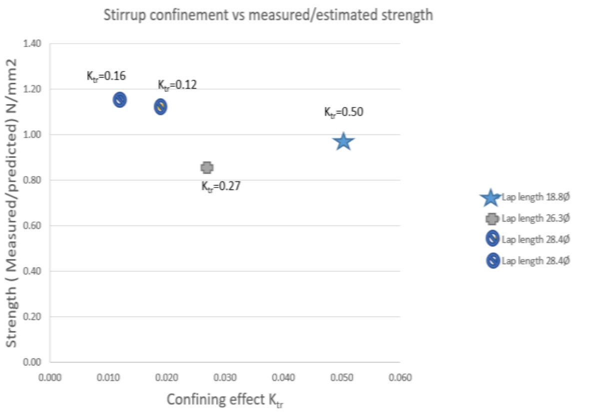


Fig. 10 Influence stirrup confinement on the splice strength

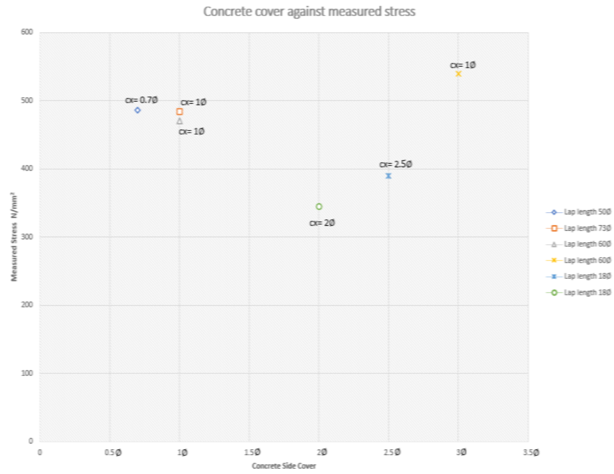


Fig. 11 Effect of side cover on splice strength

However, improving the splice strength by increasing the number of shear links is not sustainable and economical as more steel will be used.

4.7 Effect of side cover on lap splice strength

The effect of side cover on the performance of lap splice on a reinforced concrete beam is shown in Fig. 11. For the same splice length of 60Ø, increasing the side cover from 1Ø to 3Ø (26 mm to 78mm) resulted in a 15% increase in lap stress. Likewise, for similar splice length of 18Ø, increasing the concrete cover from 2Ø to 2.5Ø resulted in a 13% increase in lap stress. Furthermore, for similar side cover (1Ø), increasing the lap to bar diameter ratio from 60Ø to 73.1Ø resulted in 3% increase in lap stress. However, a 3% increase in lap stress were observed when the splice length and concrete cover were increased by 20% and 44%.

5. Conclusions

This study investigated performance of the tension laps in the concrete beam using combination of experimental works in conjunction with the Model code 2010 and Fib bulletin 72 recommendations for laps in reinforced concrete structures. Based on the limited number of data analysed, the following conclusion can be drawn:

- The reinforced concrete beams containing lap splices with more confinement performed as well as, beams in which the lap splices were lightly confined. Increasing confinement increases the effectiveness of the lap, however, there is a trade-off between steel used for longer laps and steel used for increasing the number of shear links.
- The bond stress increases with increased in concrete side cover and lap-length to bar-diameter ratio. For similar lap-length to bar-diameter ratio, a 15% increase in lap stress was observed when the side cover is increased from 1Ø to 3Ø (26 mm to 78 mm). Similarly, at constant side cover, increasing the lap-length to bar diameter ratio from 60Ø to 73.1Ø resulted in 3% increase in lap stress.
- Fib bulletin Eq. (10) for estimating mean bar stress in laps is less conservative compared to the Eq. (9) recommended by MC (2010).
- Increasing the lap splices beyond 50Ø has no additional benefit for increasing its strength.

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Appendix

Table 1 Effect of lap length to bar diameter ratio

Test No.	I_s	d_s	I_s/d_s	b	h	d	C_x	a	C_y	n_s	f_y	Measured stress	Estimated stress Fib 72. fstm (N.mm^2)	Estimated stress MC210 N/mm^2
PB06***	950.0	19.0	50.0	300.0	250.0	212.0	36.1	151.8	28.5	2	708.0	757	692	310
PB05	760.0	19.0	40.0	300.0	250.0	212.0	36.1	151.8	28.5	2	708.0	558	612	248
PB04	570.0	19.0	30.0	300.0	250.0	212.0	36.1	151.8	28.5	2	708.0	433	523	186

Table 2 Effect of spacing

Test ID	d_s	I_s/d_s	C_x	a	C_y	n_s	d_{ws}	Leg of links	S_w	A_{sw}	Measured stress
S1.11	14.0	15.0	29.0	28.0	18.0	5	8.0	2	153.9	50.3	393
S1.5	14.0	58.6	29.0	56.0	18.0	5	8.0	2	153.9	50.3	544
S1.6	14.0	58.6	29.0	28.0	18.0	5	8.0	2	153.9	50.3	492
S1.7	14.0	40.7	29.0	28.0	18.0	5	8.0	2	153.9	50.3	515

Table 3 Effect of concrete strength

Test No.	I_s	d_s	I_s/d_s	c_s	a	a/c_x	C_x/c_y	n_b	No of legs	f_{cm}	f_y	Measured stress	Estimated stress Fib 72. fstm	Estimated stress MC2010
	475.0	25.2	18.8	25.4	128.5	5.1	1	2	2	36.0	451.9	490	505	209
	475.0	25.2	18.8	25.4	128.5	5.1	1	2	2	29.9	451.9	496	482	221
	415.0	25.2	18.8	25.4	128.5	5.1	1	2	2	30.8	451.9	517	451	212

Table 4 effect of shear link

Test No.	I_s	d_s	I_s/d_s	b	h	d	n_b	No o legs	No of legs	f_{cm}	f_y	Measured stress	Estimated stress Fib 72. fstm	Estimated stress MC2010
	475.0	25.2	18.8	279	330.1	292.1	2	13	2	36.0	451.9	490	505	209
	533	25.2	29.9	279	330.1	292.1	2	11	2	39.6	451.9	449	519	215
	663	25.2	26.3	279	330.1	292.1	2	9	2	30.8	451.9	443	513	222

Table 5 Effect of side cover

Test ID	d_s	I_s/d_s	C_x	a	C_y	n_s	d_{ws}	A_s	A_{sw}	f_y	Measured stress MPa
II7	26.0	50.0	18.0	52.0	23.0	2	115	530.9	50.3	465.0	485
IV17	26.0	60.0	78.0	52.0	23.0	2	115	530.9	50.3	465.0	540
IV18	26.0	60.0	26.0	52.0	23.0	2	115	530.9	50.3	465.0	470
III13	26	73.1	26	52	23	2	115	530.9	50.3	465	485

Table 6 Effect of concrete strength

Test No.	I_s	d_s	I_s/d_s	c_s	a	a/c_x	C_x/C_y	n_b	No of legs	f_{cm}	f_y	Measured stress	Estimated stress Fib 72. fstm	Estimated stress MC2010
	475.0	25.2	18.8	25.4	128.5	5.1	1	2	2	36.0	451.9	490	505	209
	475.0	25.2	18.8	25.4	128.5	5.1	1	2	2	29.9	451.9	496	482	221
	415.0	25.2	18.8	25.4	128.5	5.1	1	2	2	30.8	451.9	517	451	212