

Experimental Results on Staggered Lapped Bars in FRC

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ABSTRACT: The paper presents experimental results on lap splices in fiber reinforced concrete (FRC). Four point bending tests were carried out on several full-scale beams with all or part of the longitudinal reinforcement lap spliced at mid-span. The beams were reinforced with either 16 mm or 20 mm diameter rebars and included various lap splices configurations varying the percentage of lapped bars. The behaviour of lapped bars in FRC with a volume content of steel hooked fibres equal to 0.5% was investigated. The results show that the post-peak behaviour of FRC can enhance the strength of staggered lapped splices as well as it can reduce their brittleness, thus allowing a reduction of lap length when only a portion of bars at a section are lapped. The results show also the benefits on the durability of concrete members due to the capability of the fibres to markedly reduce the splitting cracks along the splice at service loadings.

1 INTRODUCTION

Among the different coupler systems to link the steel rebars in concrete members (loops, welded bars, mechanical splices, splices) the lap splices are the most used in the construction process of Reinforced Concrete (RC) members for their cost-effectiveness, laying speed and simplicity of design. The main building Codes of concrete structures encourage staggering of lap splices since the lapped bars are considered weak joints, which may impair the safety and the ductility of the RC member. When staggered lap splices are used, splice strength may be enhanced by the better confinement from the concrete cover because the bars are widely spaced. Moreover the brittleness of the joint may be reduced because the continuous bars can still guarantee a portion of the flexural strength of the section once the splice failure occurs. On the contrary, staggered laps require a wide beam length with several spliced bars, thus reducing the efficiency of the rebars assembling.

For this reason several codes impose a penalty on the lap length if all the bars are lapped at one section. According to ACI 318-11, when the percentage of bars spliced is greater than 50%, the splice length should be at least 1.3 times the anchorage length (splice of Class B) while Eurocode 2 is more conservative and requires lap lengths to be increased by a factor of up to 1.5 times the anchorage length, depending on the proportion of bars lapped at the section. In Model Code 90 (CEB-FIP, 1993), the required lap length could be up to twice the base anchorage length when all bars are spliced at the same section. The new *fib* Model Code 2010 for concrete structures does not distinguish between anchorages and laps. A lap length depends on the concrete strength, concrete cover, bar diameter, transverse reinforcement and transverse pressure. Moreover, the dependency of the lap length according to the percentage of lapped bars was removed on the basis of results of a wide experimental campaign on staggered lapped bars (Cairns, 2014; Metelli et al., 2015). These results showed a significant reduction of the joint strength of about 25% when the percentage of lapped bars reduces to 50% despite the higher confining contribution of concrete cover due to the larger bar spacing. This phenomenon was called by Metelli et al. (2015) as "*weakening effect*" of staggered laps: the higher

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stiffness of a pair of lapped bars, in comparison with a continuous bar, causes the lap splice to attract a greater share of the total tension force in the reinforcements with respect to the assumption of an equally distributed tensile action among continuous and lapped bars within a joint.

The bond phenomenon allows the variation of the tensile action in a reinforcement to be transferred to the surrounding concrete by means of shear stresses developing along the lateral surface of the bar. The resistance of bond depends mainly on the mechanical interlocking between concrete and bar ribs. This mechanism entails the formation of radial transversal pressure as a result of the wedge action of the crushed concrete between the ribs. This action may cause the onset of longitudinally splitting cracks when the tensile strength is reached in the concrete cover. The propagation of the splitting cracks and thus the brittle failure of the anchorage can be efficiently arrested by the confinement action provided by transversal reinforcements within the concrete cover, by transversal pressure (Eligehausen et al., 1983; Darwin et al., 1992; 1990; Giuriani et al., 1991) or by cohesive stresses between the surfaces of splitting cracks. This last contribution depends mainly on the post-peak behaviour of concrete, which can be significantly enhanced with the addition of fibres to the concrete mixture.

Several studies (Harajli et al., 1997; Plizzari, 1999; Jansson et al., 2012) showed a significant increase of the bond strength and of its residual capacity with an increase of the dosage of fibres in particular when twisted steel fibres were used with volume content greater than 1%. The addition of fibres increases the confinement effect of concrete cover, which allows for a delay of the onset and propagation of splitting cracks. The research of Chao (2009) regarding pull-out tests in strain hardening FRC composites proved the higher efficiency of twisted steel fibres with a volume content of 2% in providing confinement action and crack control in comparison to an equivalent amount of transversal reinforcement. Other studies showed an opposite trend due to a workability problem of FRC near the bar ribs (Dancygier and Katz, 2010). While many studies are available in the literature on the effect of types and dosage of fibres on bond strength, few experimental results have been published so far on the behaviour of lap splices in conventional FRC and with a content of fibres lower than 1%.

Lee (2015) investigates the behaviour of lap-spliced reinforcements with a concrete cover equal to 2.5 or 3.3 times the bar diameter in UHPFRC with a compressive strength of 130 MPa and varying the volume of steel fibres from 0 to 2%. The results of four point bending tests on seven beams showed that the lap-splice is able to develop the bar yield strength if the volume content of fibres is greater than 1% or 2% for a lap length $l_b=10d_b$ or $5d_b$, respectively. Lageir et al. (2015) carried out direct tensile tests on tensile lap splices of large reinforcing bars ($d_b=25$ or 33 mm) having a small concrete cover $c=1.2d_b$ in UHPFRC ($f_{cm}=104\div 167$ MPa) with volume content of straight steel fibres up to 4%. The strain hardening of UHPFRC led to a significant enhancement in lap strength, equal to 53%, if the fibre content increases from 1% to 4%, for a given splice length of $10d_b$. The yield stress of 400 MPa can be ensured in short lap ($l_b=12d_b$) for a fibre content of 4%. With regard of HPFRC, in the research of Hamad et al. (2001) test results on full-scale beams with lapped ribbed bars over a length of 305 mm were presented with the aim to investigate the effect of bar diameter ($d_b=20, 25,$ or 32 mm) and the fibre content of hooked steel fibre on the lap strength. The results showed an increase of bond strength of about 50% for $V_f=2\%$ in comparison with plain concrete, and the remarkable capability of fibres in mitigating the size effect of bond. For a 0.5% fibre content only, tests on 32 mm and 20 mm lapped bars averaged 33% and 10% stronger respectively than the reference specimens with plain concrete. This study pointed out pull-out tests underestimate the effects of fibres on the bond strength of bars in tension.

Harajili et al. (2002) investigated the behaviour of short lap splices ($l_b=5d_b$) having a small cover ($c<2.1 d_b$) for a steel fibre dosage ranging from 0.5 to 2% and varying the bar diameter from 16 to 32 mm. Tests on beam specimens in normal strength concrete ($f_{cm}\cong 30$ MPa) showed a 26% and 33% increase of the splitting bond strength for a fibre dosage of 1 and 2%, respectively. A 0.5% volume fraction of fibres had a beneficial ef-

fect on the splitting strength of large bars (32 mm) only. A significant improvement in the post-peak behaviour in comparison to plain unconfined concrete was also showed. Finally, a recent work of Bandedet and Billington (2016) dealt with experimental results of lap-splices ($l_b=10d_b$) tested in four-point bending to investigate the overall bond-slip behaviour in three different HPFRCC mixtures with fibre volume of 1.5% or 2%. The results confirmed the trend observed by Lageir et al. (2015) with an increase in the normalized bond strength varying between 20 and 55% depending on the concrete cover dimension and to the simultaneous presence of stirrups. The strain hardening of the materials markedly increased the bond toughness in comparison with plain concrete specimens. This research confirmed also the effectiveness of the bond model proposed by Harajli (2009) in predicting the lap-splice strength HPFRCC mixtures. This paper deals with experimental results on lap-splices in conventional FRC with a low volume fraction of fibre. Beam specimens were designed so that the lap-splice behaviour could be investigated varying the percentage of lapped bars at a section with the aim at understanding the potential capability of the softening behaviour of conventional FRC to mitigate the "weakening effect" of staggered laps.

2 EXPERIMENTAL PROGRAMME

2.1 Specimens details and materials

Two test series were carried out on ten beams designed with lap-splice at mid-span to be tested under constant bending moment over the joint length. The beams were 4.5 m long, 0.35 m deep and 0.30 m wide. The first series consisted of four beams with four longitudinal bars having a 20 mm diameter while in the second series six beams were reinforced with three bars with 16 mm diameter. As depicted in Figure 1, each series comprised a reference beam with continuous reinforcements and a beam with all bars lapped at the mid-span embedded in plain concrete while in FRC the laps were tested varying the percentage of bars lapped at a section. In the first series the specimens were tested with either one or all three 20 mm bars lapped, corresponding to 33% or 100% of bars lapped at a section, respectively. When using 16 mm rebars (series 2), specimens were made with one, two or all four bars lapped, corresponding to a proportion of the bars spliced at a section equal to 25%, 50% or 100%. Figure 1 shows the details of each specimen. In the case of two 16 mm bars lapped, beams were designed with splices positioned both internally and externally (in the section) which provide results on the role of stirrup positioning on the anchorage's confinement.

All beams were designed with a normal concrete strength with an expected mean strength $f_{cm} = 28$ MPa. Assuming the expected concrete strength and the steel yield strength ($f_{ym} = 550$ MPa), a splice length (l_b) of 25 bar diameters (d_b) provides a maximum bar stress (f_{stm}) which approaches the yield stress and a splitting-failure mode according to the new fib MC2010 expression for bond strength.

The beams were realized with similar vertical concrete cover (c_y) of 28 mm and 30 mm to 16 mm and 20 mm lapped bars, respectively (Fig. 1). As a result, the minimum concrete cover/bar diameter ratio (c_{min}/d_b) varied from 1.04 to 1.75 depending on the spacing between the lapped bars which increased with a reduction of the percentage of bars lapped bars. The bars were arranged with the ribs pointing in the vertical direction.

In the specimen with 33% or 50% of lapped bars a 20% reduction of the lap length was applied according to the Eurocode 2 provisions while if the percentage of bars lapped at a section was 25% the lap length was reduced by 40%. It should be noted that this specimens were tested with FRC only.

The same mix design was used for the two concrete mixtures (Table 1), the reference plain concrete and FRC, both having a target concrete class C20/25. The concrete was supplied by local-ready mix company. It had a high workability (according to EN 12350) since for the plain concrete the measured slump was 220 mm, while for FRC, in spite of the higher content of superplasticizer, its value was slightly less and equal to about 170 mm, because of addition of fibres. Hooked-end steel fibres ($L_f=35$ mm,

$d_f=0.75$ mm with a tensile strength of 1200 MPa) were used with a volume fraction of 0.5% (corresponding to 40 kg/m³).

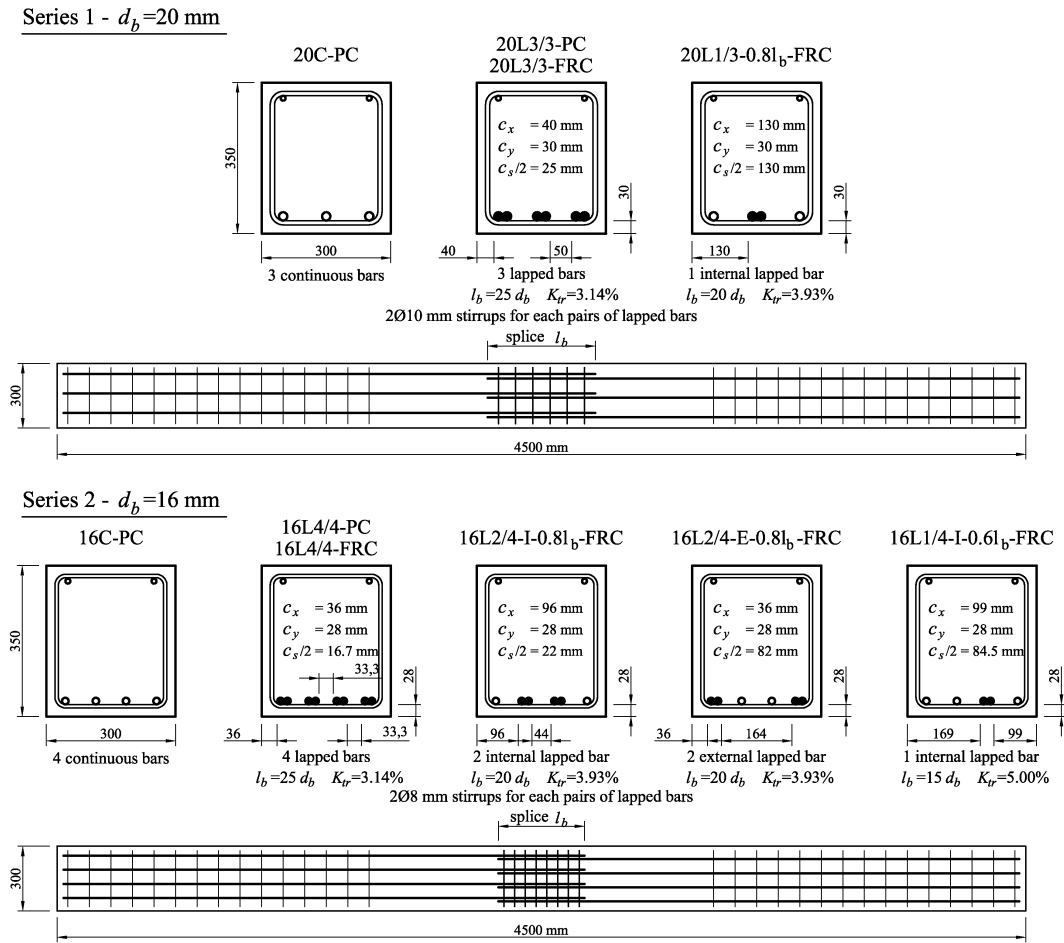


Figure 1. Details of the beams.

Ten standard 150 mm cube control specimens and five cylinders were used for each mixture to evaluate the concrete compressive strength and the modulus of elasticity respectively of both plain and fibre reinforced concrete. The cubes were cast and cured in the same condition as the beams and tested at the same age as the beam specimens. At the time of the tests, the specimens had an average compressive strength (f_{cm}) of about 28.4 MPa for plain concrete, lower than expected, and of 34.5 MPa for FRC (Tab. 3). Finally, the FRC post-cracking properties were characterized by means of seven three point bending test (3PBT) on notched beams (150x150x550 mm), according to EN 14651. The same test on three notched beams allowed the evaluation of the tensile resistance of plain concrete. The tests were carried out with a closed-loop hydraulic testing machine by using the Crack Mouth Opening Displacement (CMOD) as control parameter that was measured by means of a clip gauge crossing a notch having a depth of 25 mm at mid-span. The limit of proportionality (f_{Lm}) and the values of the average residual flexural strength (f_{R1m} , f_{R2m} , f_{R3m} , f_{R4m} , corresponding to CMOD values of 0.5, 1.5, 2.5 and 3.5 mm, respectively) are listed in Table 2. Moreover, by evaluating the characteristic values of the residual strengths according to fib Model Code 2010, FRC can be classified as class “2a”.

To comply with Model Code 2010 provisions, the total amount of the transverse reinforcement (A_{st}) was chosen as a percentage of the area (A_s) of the bars lapped (50% in the present research work). Two stirrups having a diameter of 10 mm and 8 mm were placed for each pair of 20 mm and 16 mm lapped bars, respectively. The shear failure of the beam was prevented by additional stirrups with a diameter of 10 mm placed at 100 mm spacing throughout the shear span (Fig. 2). In the present experimental program, the “stirrup index of confinement” (K_{tr}) associated to the transversal steel reinforcement only without taking into account the contribution of fibre reinforcements (Model Code 2010) ranged between 3.1% and 5.0% (Fig. 1), higher values being associated with shorter lap lengths. It should be noted that this index does not take into account the confining effect of steel fibres.

Steel grade B500C (in accordance to EN 10080) was used for longitudinal reinforcements, whose measured mean yield strength ($f_{ym,ex}$) was 545 MPa and 523 MPa for 16 and 20 mm diameter rebars respectively. The relative rib area averaged 0.060 and 0.086 for 16 and 20 mm bar diameter, respectively.

Table 1. Mixture proportion of fibre reinforced concrete

Cement type		CEM I-32-5R
Cement content	[kg/m ³]	320
Water	[l/m ³]	164
Water/cement ratio	[-]	0.51
Sand (0/6 mm)	[kg/m ³]	1174
Coarse aggregate (6/14mm)	[kg/m ³]	754
Maximum aggregate	[mm]	14
Fibres	[kg/m ³]	40
V _f	[%]	0.5
Superplasticizer	[l/m ³]	3.02

Table 2. Mean mechanical properties of concrete

Type	f_{cm} [MPa]	$f_{cm,cube}$ [MPa]	E_{cm} [MPa]	ρ_c [kg/m ³]	f_L [MPa]	f_{R1} [MPa]	f_{R2} [MPa]	f_{R3} [MPa]	f_{R4} [MPa]
PC	28.4	31.3	28.0	2340	3.81	0.37	-	-	-
FRC	34.5	39.8	29.0	2360	5.04	3.68	3.68	3.42	2.93

$f_{cm}, f_{cm,cube}$: compressive strength of cylinder or cube specimens; f_L peak tensile strength for CMOD less than 0.05 mm; $f_{R1}, f_{R2}, f_{R3}, f_{R4}$ tensile strength for CMOD equal to 0.5-1.5-2.5-3.5 mm respectively

2.2 Test set up

The ten beams were loaded by a four point bending test having a span of 4.0 and a constant moment region of 2.0 m where the beam splice was located (Fig. 2). The tests were carried out under displacement control by means of an electro-mechanical up to the splice failure or a mid-span deflection of 80 mm. The mean displacement rate was equal to 0.5 mm/min but beyond the peak beam resistance it was increased to 2 mm/mm up to the maximum applied displacement. The load was measured by two load cells placed at the ends of two tying bars connected to the jack.

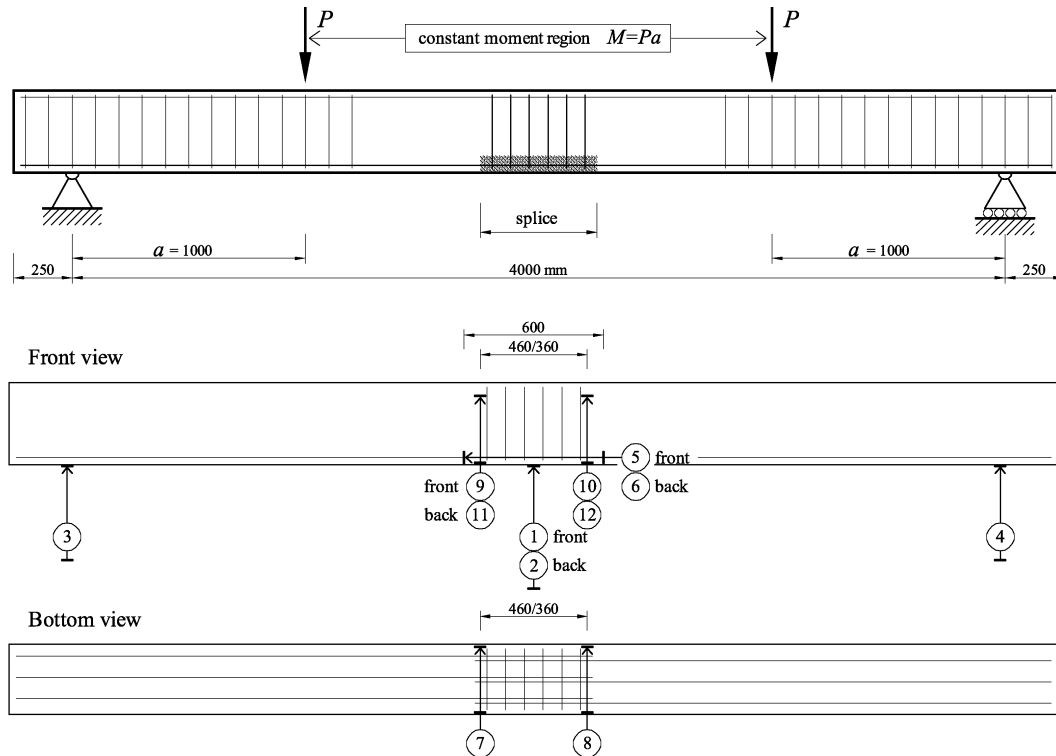


Figure 2. Test set up with the position of the devices

Linear Variable Differential Transformers (LVDTs) were placed against the bottom surface of the beam to measure the deflections at mid-span and at the supports (pos. 1 to 4 in Fig. 2). Furthermore, potentiometric transducers having a gauge length of 600 mm were set on each side of the beam to measure the flexural crack widths within the splice region (pos. 5 and 6 in Fig 2). Two devices (pos. 7 to 8) recorded the face splitting cracks developing on the beam's bottom surface. Additional two vertical potentiometric transducers were placed on the sides of the beam (pos. 9 to 12) at the lap ends to monitor the onset and the opening of the longitudinal side splitting cracks occurring in the bar plane. In order to measure the bar strain the continuous and lapped bars of the specimens 16L2/4-E-0.8lb-FRC and 20L1/3-I-0.8lb-FRC were instrumented with strain gauges placed 20 mm outside the splice length.

3 TEST RESULTS

The behaviour of the tested beams is described by Figure 3 where the applied load (P) is plotted against the beam deflection (f). It can be noted a slightly non-linear behaviour of FRC beams during the transition from the un-cracked stage to the cracked one because of the beneficial effect of fibres on tension stiffening. Initially, several vertical cracks formed within the constant-moment region, followed by shear cracks close to the supports. A typical crack pattern of FRC beams characterized by more distributed and smaller cracks than the plain concrete specimens was observed. A 0.5% volume fraction of fibre enhanced the post-cracking stiffness flexural stiffness of the beams, resulting in reduction of beam deflection at Serviceability Limit State ranging between 15 and 25%. This confirms the capability of the fibres to reduce the flexural crack propagation, thus improving the tension stiffening.

Furthermore, it should be noted that the beam stiffness also increases with the percentage of lapped bars lapped. This result supports the assumption that laps may be stiffer

than continuous bars and so they can attract a greater share of the total tension load. The reference beams (16C or 20C) with continuous reinforcements failed in a ductile manner due to yielding of rebars, whereas in the splices the bars did not reach the yielding, which confirms the design criteria of laps. The failure of the beam was governed by the formation of longitudinal splitting cracks along the splices before bar yielding. In PC specimens both side and face splitting cracks developed, while the splices in FRC showed mainly diffuse face side splitting cracks with narrow and less evident side splitting cracks which occurred only when all bars were lapped.

First, unlike the results of previous research on staggered lap splices in plain concrete (Metelli et al., 2015), in both series it should be noted the higher peak load of the FRC beams with a portion of bars lapped and a shorter splice length in comparison with PC beams with all bars lapped.

Furthermore, when all bars were lapped at a section, the splice strength in normal strength FRC was 30% greater than in plain concrete. A volume fraction of fibre equal to only 0.5% seems to be sufficient to provide the concrete cover with the capability to withstand the bursting wedge action of ribbed bars along a lap-splice. The softening-behaviour of a conventional FRC is able to arrest the splitting crack propagation within the concrete cover. As a result, the bond stresses can be more uniformly distributed along the lap length than in plain concrete, thus guaranteeing higher lap strength, despite the development of longitudinal splitting cracks. With regard to this issue, it should be also noted that the former experimental campaign evidenced that and a percentage equal to 50% of the lapped bars as transversal reinforcements (the same was used in this research) was not able to arrest the splitting crack propagation in PC specimens.

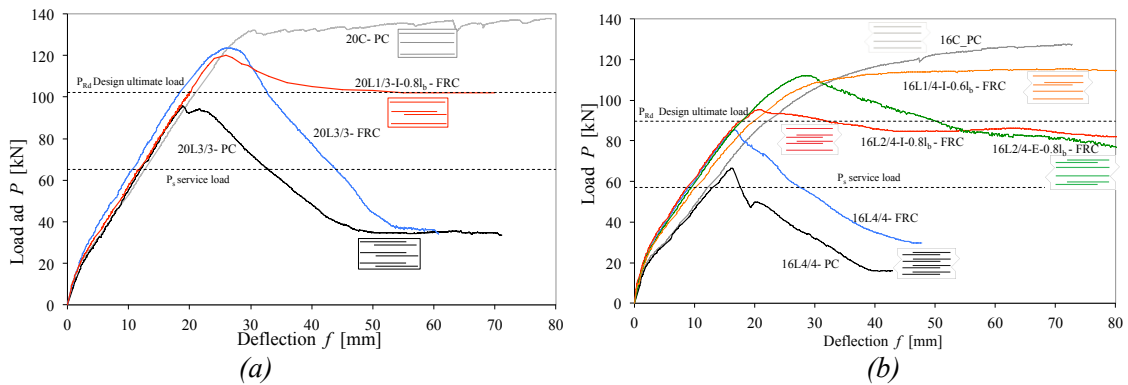


Figure 3. Test results: normalized load P vs. deflection f ; series 1 (a) and series 2 (b)

The better performance of lap-splices in FRC might be due the higher tensile resistance of FRC in comparison with plain concrete (see Table 2). For this reason, Table 3 and Figure 4a show also the "bond strength ratio" (BS), defined as the ratio of the maximum average measured bar stress at peak load ($f_{s,ex}$) to that estimated (f_{stm}) by means of *fib*-MC2010 expression. The bar stress was calculated by means of a cracked sectional analysis at failure and by assuming that the tensile force within the joint is equally distributed between continuous and lapped bars (Metelli et al. 2015). The value of the maximum bar stresses were confirmed by the strain measurement of the strain gauges thus proving the negligible effect of FRC in tension at beam's failure. By means of the BS ratio the lap strength of each specimen can be normalized with respect to the concrete strength, concrete cover, as well as to the confinement from stirrups since all these pa-

rameters differ among the specimens by varying the percentage of lapped bars and the concrete mixtures. Thus, the bond strength ratio allows examining the only effects of fibre content and percentage of lapped bars on the bond strength of the tested lap splices. While previous experimental results on staggered laps in plain concrete (Metelli et al., 2015; Cairns, 2014) showed that bond strength ratio decreased by about 25% when only a portion of bars were lapped, Figure 4a shows that the lap splices in FRC had an opposite trend without any reduction on strength with the decrease of percentage of bars lapped at the section. Therefore, the bond behaviour benefits from the effectiveness of the post-cracking behaviour of concrete cover reinforced with fibres which is able to mitigate the weakening effect of staggered laps, thus allowing a reduction of the lap length up to 40% if only a 25% of bars is lapped at a section.

The tested beams showed a different post-peak behaviour which can be clearly expressed by the joint post-peak strength ratio ($JPPS$), defined as the ratio between the post-peak load (P_{40}) and the load of the reference beam with continuous bar at the same deflection ($P_{40,ref}$). As shown in Figure 4b, the degrees of beam brittleness depended on the number of continuous bars and on the post-peak toughness of bond behaviour provided by the confining effect of FRC cover: $JPPS$ increased from a mean value of 0.4 when all bars were lapped to 0.97 when 25% of bars were spliced. Furthermore, in FRC specimens the $JPPS$ ratio is 20% higher than in PC beams with the same lap splice configuration.

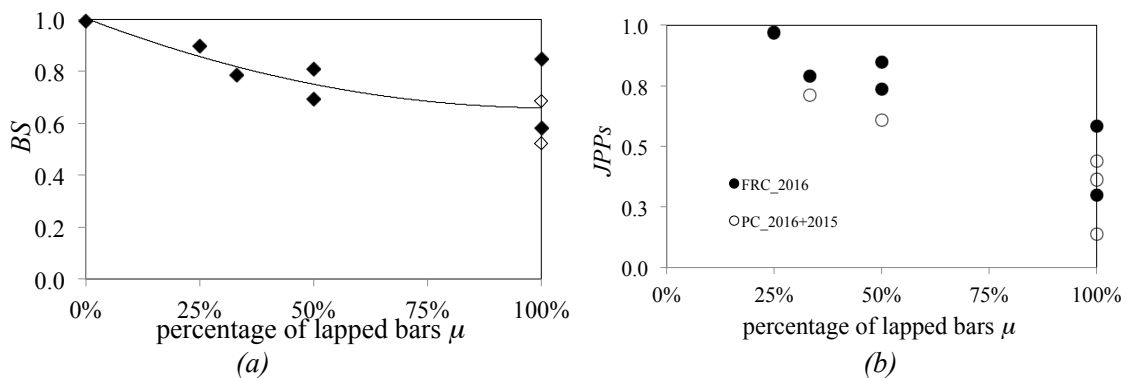


Figure 4. Influence of lapped bars proportion on bond strength (a) and on joint post-peak strength ($JPPS$) (P_{40} : post-peak load for a mid-span deflection of 40 mm; $P_{40,ref}$

The face splitting crack width (w_{fs}) measured by the devices 7 and 8 (Fig. 2) is plotted against the beam deflection (f) or the applied load (P) in Figure 5a and 5b, respectively, for series 2 with lap-splices of 16 mm diameter bars. First, in the two specimens with all bars lapped (16L_4/4_PC and 16L_4/4_FRC) a sharp increase of the transversal deformation can be noted when the face splitting cracks occurred at the bottom surface of the beam. Furthermore, the addition of steel hooked-end fibres allowed reducing the rate of the crack opening because of the softening behaviour of the concrete cover in tension. When the percentage of bars lapped at the section was not greater than 50%, the face cracks developed for a larger beam deflection and they widened more progressively, which denoted the capability of the bridging effect of fibres to limit the crack propagation and opening. As a result, the bond stress could be more uniformly distributed over the lap splice, which could achieve a higher bond stress. Lower crack widths were measured in the case of external splices (16L_2/4_E_0.8lb_FRC) with respect to internal splices (16L_2/4_I_0.8lb_FRC) thus confirming the importance of the position of the stirrups on the splice strength.

Finally, in Figure 5b it should be observed that, at service load (P_s), the splitting crack widths in FRC beams were half of the crack widths in plain concrete, with the exception of the beam with one pair of internal spliced bars with a reduced lap length, which showed a larger crack width close to 0.05 mm. These results point out the remarkable behaviour of lap splices in conventional FRC at service condition which can be characterized with a high durability class.

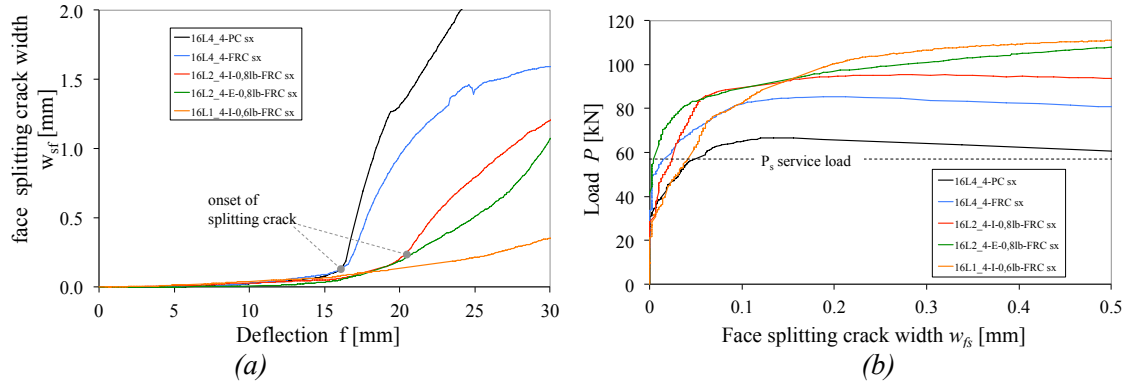


Fig. 5. Series 2: face splitting crack widths (w_{fs}) vs. beam deflection (a); load (P) vs. face splitting crack width (w_{fs}) (b).

4 FINAL REMARKS

This research examined the behaviour of lap-splices in conventional fibre reinforced concrete with a fibre volume content of 0.5%. The influence of two parameter was evaluated, namely the volume fraction of steel fibres and the percentage of bars lapped at the section. On the basis of the test results, the following outcomes can be drawn: (i) when all bars were spliced, the addition of fibres allowed the lap strength to be increased by about 23% and 11%, for 20 and 16 diameter rebars, respectively; (ii) in FRC if only a portion of bars is lapped a section, no weakening effects was observed in the joint so that a reduction of the lap length can be used which allows to minimise the dimension of joints with staggered laps; (iii) the durability of the concrete member can benefit from to the capability of the fibres to markedly reduce the splitting cracks over the splice length at service loadings.

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