Received: 9 September 2020 | Revised: 5 February 2021 | Accepted: 8 March 2021

DOI: 10.1002/suco.202000576

TECHNICAL PAPER

fib CEB-FIP WILEY

Local bond behavior of bundled bars: Experimental investigation

Giovanni Metelli[1] | John Cairns[2] | Antonio Conforti[1] | Giovanni A. Plizzari[1]

[1]Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Brescia, Italy

[2]School of Energy, Geoscience, Infrastructure and Society, Heriot Watt University, Edinburgh, UK

Correspondence
Giovanni Metelli, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Brescia, Italy.
Email: giovanni.metelli@unibs.it

Abstract

The use of bundled bars in highly loaded concrete members instead of individual bars can reduce or even avoid reinforcement congestion, allowing easier placing and compaction of concrete, since bundles (with two or more side-by-side bars) are less obstructive to fresh-concrete flow. However, there is still a lack in knowledge of the fundamental phenomena related to the bond behavior of bars in bundles. Therefore, design code rules for anchorages and splices differ significantly among International Standards (Eurocode 2, *fib* Model Code 2010, and ACI 318–19). The present paper reports the results of more than 100 pullout tests with short embedded length with the aim of comparing the local bond behavior of bundles with that of corresponding notional individual bars. Among the three criteria usually introduced to compare bundled and individual bars, based on the concepts of "equivalent sectional area," and "minimum or maximum sectional perimeter," the first and the second are introduced in this paper. Experimental results show that both criteria are suitable methods for evaluating the bearing capacity of bundled bar anchorages, even if equivalent area criterion seems to be slightly more conservative. The experimental results provide also information on the bursting forces generated by the wedge action of the ribs which clearly increases with bar diameter. Finally, experimental results are compared with design rules for anchorage strength of bundled bars as prescribed by *fib*-Model Code 2010.

KEYWORDS

anchorages, bond strength, bundled bars, local bond-slip law, pullout test

1 | INTRODUCTION

The placement of bars in bundles may be beneficial—or even unavoidable—in some circumstances to reduce congestion of reinforcement, for example when large bars are unavailable ($\varnothing > 40$ mm)[1] or where large diameters are not

Discussion on this paper must be submitted within two months of the print publication. The discussion will then be published in print, along with the authors' closure, if any, approximately nine months after the print publication.

allowed by the codes. Bundles of smaller diameter bars also allow easier manual handling on site and a more efficient construction process when compared to placing each bar individually in single layers. Furthermore, the placing and compaction of concrete may be facilitated by the use of bundled bars because of larger clear spacing between reinforcements. The effective depth of longitudinal rebars may be increased by avoiding more bars in layers, thus allowing a reduction of the total amount of reinforcement. Another benefit of bundled bars is the significant reduction of mandrel diameter for bending of the smaller bars. The recommended minimum value in *fib* Model Code 2010[2] and Eurocode 2[3] is either four times the bar diameter for a bar diameter not greater 16 mm, or seven times the diameter for larger sizes. As an example, in a bundle with two 12 mm diameter bars the minimum recommended mandrel diameter would be 48 mm, while for a single bar having the same area as that of the bundle ($\varnothing_{n,A}=17\ mm$) the mandrel diameter significantly increases to 119 mm.

Bundling of bars does, however, require some adjustments in the way laps and anchorages are treated when detailing structural concrete. Four different cases may arise, as shown in Figure :

i. anchorages where all bars are pulled in the same direction and terminate at the same location (Figure 1(a));
ii. anchorages where all bars are pulled in the same direction, but cut-off points are staggered (by an anchorage length or more) (Figure 1(b));
iii. laps where pairs of bars overlap at the same section and are pulled in opposite directions (Figure 1(c));
iv. laps where only one bar within the bundle is lapped at any section, bars are pulled in opposite directions, and lap zones are staggered (Figure 1(d)).

This paper addresses the first of these cases.

Bond between ribbed bars and concrete is governed by the confinement available to resist radial pressure exerted by the wedging action of the crushed concrete between ribs. This pressure can cause the onset of longitudinal splitting cracks along the bar if the tensile strength of the concrete cover is reached ([4–7]; Chapter 1 of *fib* Bulletin n.10, 2000[8]). The confinement provided by external pressure or by transverse reinforcement can efficiently prevent the propagation of the splitting cracks, which impair the bearing capacity of anchorages and lap splices, and thus enhance capacity.[7,9-11] As a result, bond failure may change from brittle to a more ductile mechanism being characterized by bar pull-out owing to the shearing-off of the concrete keys between the ribs (Chapter 1 of *fib* Bulletin n.10, 2000[8]). Therefore, the strength of an anchorage depends on many factors, such as the size of the concrete cover, the tensile strength of concrete, the anchorage length, the bar diameter and the amount of secondary reinforcement crossing the potential splitting crack, as well as the transverse pressure. All these factors are now included in the bond models of the main international design Codes (*fib* Model Code 2010,[2] Eurocode 2[3]; ACI 318-19).[12]

Fib Model Code 2010[2] formulations for the design anchorage (or lap) length have been validated against a large quantity of physical test results on anchorages of individual bars. There is, however, little experimental evidence for anchorage of bars in a bundle. CEB Bulletin 151[13] noted the various alternatives for dealing with bundles and considered the equivalent bar diameter approach "to be sufficient from a practical point of view," but no supporting experimental evidence was cited. Although it is known that a number of studies of anchorage of bundled bars were conducted, probably in the 1960s and 70s, it has proved difficult to track these down. One study by Jirsa et al.[13] investigated

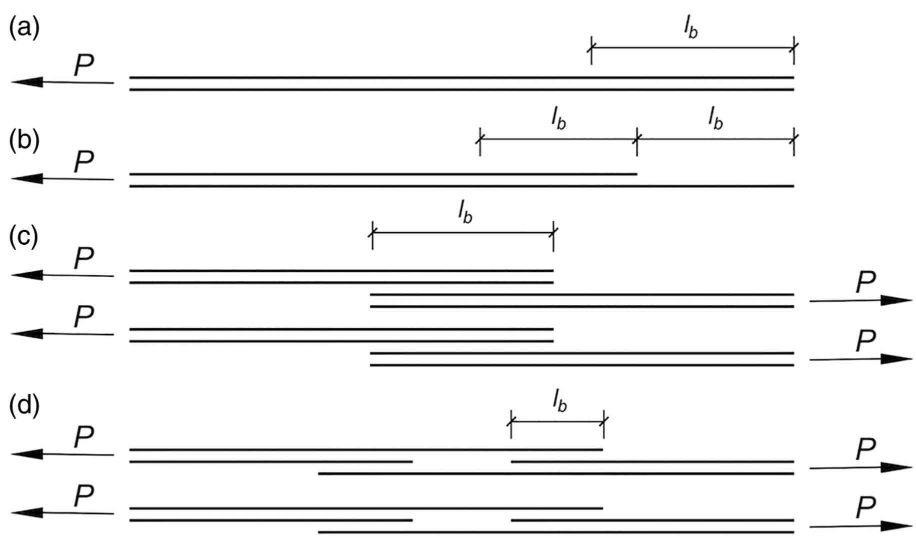

FIGURE 1 Configuration of anchorages (a and b) and lap splices (c and d) of bars in bundles

bond strength of bundles arranged in one or two layers, with some bars top cast and some bottom cast. The experimental plan makes comparisons somewhat indirect, and the scatter between the test results and the predictions yielded by the two criteria means that it is not possible to obtain a clear verdict in favor of any of the three criteria usually adopted to relate bundled bars to individual bars with reference to reinforcement-concrete bond (equivalent area and maximum-/minimum-perimeter criteria, Figure 2). In literature, a few tests of laps of bars within a bundle can be also found. Bashandy[14] demonstrated that, for simultaneous laps of up two bar bundles (as in Figure 1 (c)), lap length may be determined by using a "notional bar" having the diameter of an equivalent bar with the same cross-sectional area as that of the bundle. This approach is consistent with Eurocode 2 (CEN-EN 1992-1-1:2004)[3] provisions. Cairns[15] has shown that where only a single bar within a bundle is lapped at a section (as in Figure 1(d)), it is reasonable to determine lap length as for an individual bar. These findings indicate that lap capacity is not a function of bar perimeter in contact with concrete when splitting failure governs the anchorage or lap strength.

The international design codes (CEN-EN 1992-1-1:2004,[3] *fib* Model Code 2010[2]; ACI 318-19) use the "notional bar" procedure for anchorage of a bundle, in which the whole bundle is substituted by a notional single bar. As shown in Figure 2(a), three different criteria may be adopted for defining the diameter ($\varnothing_n$) of a notional bar corresponding to a bundle with a number (n_b) of individual bars having the same diameter ($\varnothing_i$):

1. the equivalent area criterion, for which the bundles can be treated as a single bar of equivalent cross-sectional area, as given by:

$$\varnothing_{n,A} = \sqrt{n_b} \cdot \varnothing_i \tag{1}$$

or more generally

$$\varnothing_{n,A} = \sqrt{\frac{4}{\pi} A_{s,tot}} \tag{1a}$$

when bars having different diameter and a total area $A_{s,tot}$ are bundled.

2. the minimum perimeter criterion, for which the bundles can be treated as a single bar of equivalent minimum perimeter:

$$\varnothing_{n,P} = \left(\frac{n_b}{\pi} + 1\right) \cdot \varnothing_i \tag{2}$$

3. and the maximum perimeter criterion, for which the equivalent notional bar has the maximum perimeter of the bundle in direct contact with concrete:

$$\varnothing_{n,Peff} = \left(\frac{n_b}{2} + 1\right) \cdot \varnothing_i \tag{3}$$

As an example, a bundle with two 12 mm diameter bars corresponds to a single bar of 16.97, 19.64, and 24 mm diameter for equivalent area, minimum and maximum perimeter criteria, respectively. Consequently, the criterion adopted is important since the minimum and the maximum perimeter criteria lead to an equivalent diameter for bond 15%–45% greater than the equivalent area criterion (Figure 2(b)).

Eurocode 2,[3] *fib*-Model Code 2010,[2] and ACI 318–19[11] limit to four the number of bars in a bundle for both

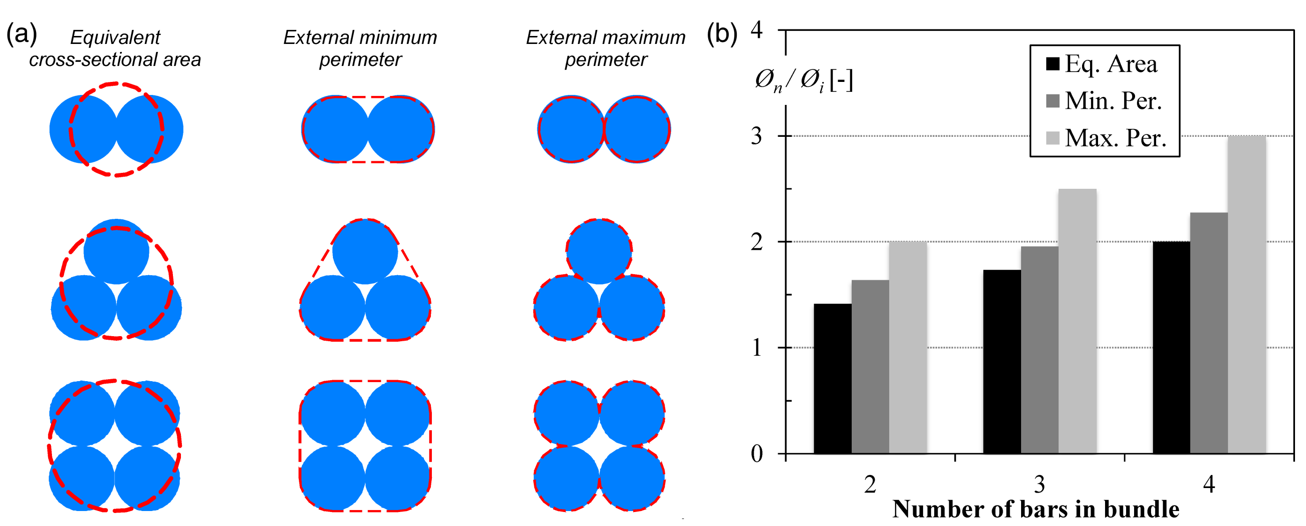

FIGURE 2 (a) Definition of notional bar of bundled bars and (b) ratio of notional bar and individual bar size within a bundle against the number of bars in a bundle anchorages and splices. However, the provisions of Eurocode 2[3] and *fib* MC2010[2] are markedly different from those of ACI. In fact, according to Eurocode 2[3] and *fib* Model Code 2010,[2] the anchorage length of a whole bundle is calculated with the rules for a bar by substituting the entire bundle with a single notional bar having the same cross-sectional area (see Equation (1)). According to these codes, a bundle with two bars only (having a diameter $Ø_n < 32$ mm) may be spliced at the same section and the notional bar size has to be used to calculate the lap length. Otherwise, only individual bars may be lapped at the section and splices should be staggered by at least 1.3 times the lap length calculated with the diameter of the individual bar.

ACI 318–19[11] does not permit all the bars of a bundle to be anchored or spliced at the same section and, therefore, the cut-off point of each individual bar should be staggered. Furthermore, ACI 318–19[11] requires bond length of an individual bar within a bundle of 3 and 4 bars to be increased by 20% and 33% respectively. This increase is based on the reduction in the perimeter of the bars in contact with concrete with respect to that of the same number of bars considered individually, corresponding approximately to the criterion of the maximum perimeter (see Equation (3) and Figure 2). However, Jirsa et al.[13] have questioned whether a minimum perimeter would be more appropriate.

In summary, Eurocode 2[3] and *fib* MC2010[2], when all bars are anchored at the same location, require a longer anchorage length for bundles (typically between 15% and 25%) than ACI 318–19. On the other hand, ACI requires a longer splice length for individual bars within a lap than Eurocode 2. Figure 3 compares the increases in anchorage length for various bundle as required by Eurocode 2, *fib* Model Code 2010, and ACI 318-19. However, it should be underlined that the calculation of

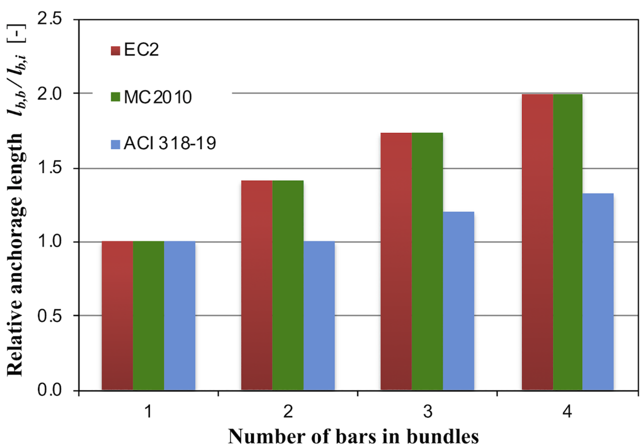

FIGURE 3 Comparison of provisions for bundled bars (the same design bond strength for bundle and individual bar is assumed)

confinement effects is based on the notional bar and not on the individual bar diameter, which mitigates the difference between the approaches of different codes.

The main aim of this paper is to evaluate the bond behavior of short anchorages where several bars in a bundle terminate at the same point, as proposed by Eurocode 2[3] and *fib* Model Code 2010[2].

The experimental investigation concerns 135 pull-out tests on short anchorages of bundled ribbed bars and of individual bars matching either the equivalent cross-sectional area or the minimum perimeter of the bundle. Experimental results provide the bond strength, the bond-slip behavior, and information on bursting force due to the rib wedge action of bundled bars.

2 | EXPERIMENTAL PROGRAM

2.1 | Specimen geometry and materials

Two main series of tests were conducted, one (Series A) tailored to evaluate the accuracy of the equivalent cross-sectional approach (Equation (1)), the other (Series P) to evaluate the accuracy of the minimum perimeter approach (Equation (2)).

Series A comprised 24 groups of pull-out specimens including bundles of 2, 3, or 4 bars together with companion specimens concerning a single commercial bar ($Ø$) matching as closely as possible the cross sectional area of the corresponding bundle. Similarly, Series P contained bundles of 2, 3, or 4 bars together with a single commercial bar ($Ø$) matching as closely as possible the minimum perimeter of the bundle. Two nominal concrete covers were considered, equal to 2.5 and 4.5 times the equivalent bar diameter. Test specimens are shown in Figure 4.

As summarized in Table 1, each series was labeled with the batch order number; the following character refers to the adopted criterion (A = equivalent area) while the subsequent figure to the number of bundled bars; the next characters refers to the bar diameter, followed by the concrete cover thickness ($c = 2.5Ø$ or $c = 4.5Ø$) and the embedment length ($l_b = 5Ø$). As an example, the designation 2A-3d12/c2.5/l_b5 refers to a group with order number 2 tested to evaluate the equivalent area criterion (A) and to a bundle of three 12 mm diameter bars (3d12; having an area A_s of 339 mm^2) with $c = 2.5Ø$ and $l_b = 5Ø$. In the same way, 10A-1d20/c2.5/l_b5 refers to series n.10 comprising a single bar with a diameter of 20 mm (1d20 having an area A_s of 314 mm^2) with $c = 2.5Ø$ and $l_b = 5Ø$, tested to evaluate the equivalent area criterion. Table 1 also shows the equivalent notional diameter ($Ø_{n,A}$) of the bundle, the diameter of the equivalent commercial bar ($Ø$), the cross-section dimensions of the specimen (a and b), the concrete

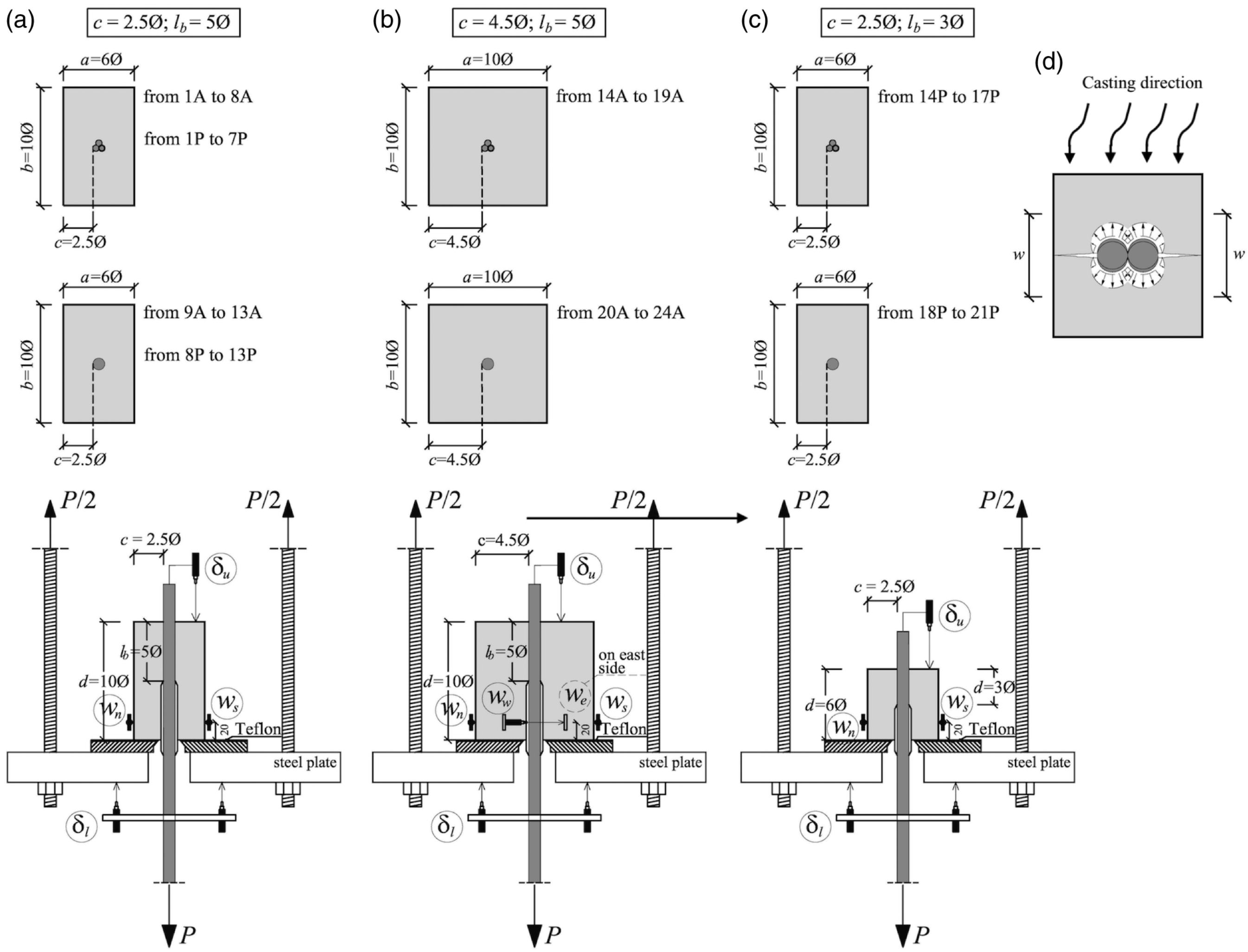

FIGURE 4 Specimen geometry, test set-up, and its instrumentation

cover (c), the bond length (l_b) as well as the order number of the series having the corresponding equivalent area to the bundle. The first eight series (from 1A to 8A) containing bundled bars (number of bars in bundle varying between 2 and 4 with diameter ranging from 12 to 16 mm) and their related five equivalent series (from 9A to 13A with $16 \leq Ø \leq 28$) were characterized by a concrete cover $c = 2.5Ø$ (Figure 4(a)). The last six series (from 14A to 19A) with either 2 or 3 bars in the bundle (with diameter ranging from 12 to 16 mm) and their five corresponding equivalent series (from 20A to 24A with $16 \leq Ø \leq 28$) were tested with a higher concrete cover $c = 4.5Ø$ (Figure 4(b)), as required by the standard RILEM pull-out test. It should be noted that the series 14A–19A have a corresponding series with $c = 2.5Ø$ in 1A–13A.

Table 2 reports the further 21 experimental series which were tested to evaluate the minimum perimeter criterion. Keeping concrete cover ($c = 2.5Ø$) and the specimen cross section ($a = 6Ø$, $b = 10Ø$, Figure 4(a)) constant, behavior of bundled bars was studied by considering two different embedded lengths.

In particular, from series 1P to 13P (Figure 4(a)), the same number and type of bars in bundle previously studied for the equivalent area criterion (with the exception of series 4A characterized by 3Ø14) were considered with an embedded length (l_b) equal to 5Ø. In addition, in series from 14P to 21P, a shorter bond length $l_b = 3Ø$ was adopted (Figure 4(c)). In this case four series of both bundled bars (number of bars in a bundle varying between 2 and 3 with diameter ranging from 12 to 16 mm) and their corresponding single equivalent bar (20 mm $\leq Ø \leq$ 32 mm) were studied. Their series designation differs from that adopted for the equivalent area criterion series only in the character after the order number. For instance, 2P-3d12/c2.5/l_b5 refers to series with number 2 for minimum perimeter criterion (P) and to a bundle of three 12 mm diameter bars (3d12) with $c = 2.5Ø$ and $l_b = 5Ø$.

Three samples for each series were produced and tested to failure, for a total of 135 individual specimens. Six concrete batches with composition as detailed in Table 3 were used in the program. Cement CEM II/A-LL 42.5R, a water/cement ratio of 0.51, natural sand and

TABLE 1 Equivalent area criterion (series A): geometrical characteristics of specimens

Series		Bars (–)	$Ø_{n,A}$ (mm)	Ø (mm)	Eq. series	*a* (mm)	*b* (mm)	*c* (mm)	*c*/Ø (–)	l_b (mm)	l_b/Ø (–)
Bundles	1A-2d12/c2.5/l_b5	2$Ø_i$12	16.97	16	9A	100	160	38	2.4	80	5.0
	2A-3d12/c2.5/l_b5	3$Ø_i$12	20.78	20	10A	125	200	51	2.5	100	5.0
	3A-2d14/c2.5/l_b5	2$Ø_i$14	19.80	20	10A	125	200	49	2.5	100	5.0
	4A-3d14/c2.5/l_b5	3$Ø_i$14	24.25	24	12A	150	240	61	2.5	120	5.0
	5A-2d16/c2.5/l_b5	2$Ø_i$16	22.63	22	11A	150	220	59	2.7	110	5.0
	6A-3d16/c2.5/l_b5	3$Ø_i$16	27.71	28	13A	175	280	72	2.6	140	5.0
	7A-4d12/c2.5/l_b5	4$Ø_i$12	24.00	24	12A	145	240	61	2.5	120	5.0
	8A-4d14/c2.5/l_b5	4$Ø_i$14	28.00	28	13A	170	280	71	2.5	140	5.0
Equivalent bar	9A-1d16/c2.5/l_b5	1Ø16	–	–	–	90	160	37	2.3	80	5.0
	10A-1d20/c2.5/l_b5	1Ø20	–	–	–	120	200	50	2.5	100	5.0
	11A-1d22/c2.5/l_b5	1Ø22	–	–	–	140	220	59	2.7	110	5.0
	12A-1d24/c2.5/l_b5	1Ø24	–	–	–	145	240	61	2.5	120	5.0
	13A-1d28/c2.5/l_b5	1Ø28	–	–	–	170	280	71	2.5	140	5.0
Bundles	14A-2d12/c4.5/l_b5	2$Ø_i$12	16.97	16	20A	160	160	68	4.2	80	5.0
	15A-2d14/c4.5/l_b5	2$Ø_i$14	19.80	20	21A	200	200	86	4.3	100	5.0
	16A-3d12/c4.5/l_b5	3$Ø_i$12	20.78	20	21A	200	200	88	4.4	100	5.0
	17A-2d16/c4.5/l_b5	2$Ø_i$16	22.63	22	22A	220	220	94	4.3	110	5.0
	18A-3d14/c4.5/l_b5	3$Ø_i$14	24.25	24	23A	240	240	106	4.4	120	5.0
	19A-3d16/c4.5/l_b5	3$Ø_i$16	27.71	28	24A	300	300	134	4.8	150	5.0
Equivalent bar	20A-1d16/c4.5/l_b5	1Ø16	–	–	–	160	160	72	4.5	80	5.0
	21A-1d20/c4.5/l_b5	1Ø20	–	–	–	200	200	90	4.5	100	5.0
	22A-1d22/c4.5/l_b5	1Ø22	–	–	–	220	220	99	4.5	110	5.0
	23A-1d24/c4.5/l_b5	1Ø24	–	–	–	240	240	108	4.5	120	5.0
	24A-1d28/c4.5/l_b5	1Ø28	–	–	–	280	280	126	4.5	140	5.0

river gravel having a maximum size of 15 mm were used to obtain a normal strength concrete with a target concrete class C30/37. A polycarboxylate-based superplasticizer (1.07% by weight of the total binder content) was also added to obtain a concrete with consistency S4 (slump of about 160 mm). In any concrete batch, nine 150 mm cubes were cast to monitor concrete compressive strength. Series with bundled bars and their corresponding series with a single equivalent bar were always manufactured from the same batch to permit comparisons free from variations in concrete strength. More details on concrete compressive strength will be given in Section 3.

Wooden molds were adopted with bars cast in a horizontal position to guarantee homogeneous bond conditions along the bond length (l_b). Bars were arranged with ribs pointing vertically (Figure 4(d)). The embedment length (l_b) was obtained by placing a plastic sleeve over half the sample depth (*d*) (Figure 4). After casting, the specimens were protected by plastic sheets to avoid water evaporation and demoulded after 24 h. Specimens were stored in a controlled environment room (with relative humidity >95% and temperature of 20 ± 2°C) until testing after 30–40 days.

Steel grade B450C (in accordance to EN 10080)[16] was used for all series (both bundles and individual ones), having a mean yield strength ranging between 500 and 567 MPa. The mean relative rib area (f_{Rm}) of the rebars varied from 0.068 to 0.098 (Table 4).

2.2 | Test set-up and instrumentation

Figure 4 shows the test equipment adopted for the different series of pull-out tests. A servo-hydraulic machine with a capacity of 500 kN (INSTRON 1274–8500) was used under displacement control. The displacement rate of the loaded end of the bar (for all specimens) was 0.1 mm/min

TABLE 2 Minimum perimeter criterion (series P): geometrical characteristics of specimens

	Series	Bars (–)	$Ø_{n,P}$ (mm)	Ø (mm)	Eq. series	*a* (mm)	*b* (mm)	*c* (mm)	*c/Ø* (–)	l_b (mm)	$l_b/Ø$ (–)
Bundles	1P-2d12/c2.5/l_b5	2$Ø_i$12	19.64	20	8P	120	200	48	2.5	100	5.0
	2P-3d12/c2.5/l_b5	3$Ø_i$12	23.46	24	10P	145	240	61	2.6	120	5.0
	3P-2d14/c2.5/l_b5	2$Ø_i$14	22.91	22	9P	135	220	54	2.4	110	5.0
	4P-2d16/c2.5/l_b5	2$Ø_i$16	26.19	26	11P	170	260	69	2.6	130	5.0
	5P-3d16/c2.5/l_b5	3$Ø_i$16	31.28	32	13P	185	320	77	2.5	160	5.0
	6P-4d12/c2.5/l_b5	4$Ø_i$12	27.28	28	12P	170	280	73	2.7	140	5.0
	7P-4d14/c2.5/l_b5	4$Ø_i$14	31.83	32	13P	180	320	76	2.4	160	5.0
Equivalent bar	8P-1d20/c2.5/l_b5	1Ø20	–	–	–	115	200	48	2.4	100	5.0
	9P-1d22/c2.5/l_b5	1Ø22	–	–	–	130	220	54	2.5	110	5.0
	10P-1d24/c2.5/l_b5	1Ø24	–	–	= 12A (see Table 1)						
	11P-1d26/c2.5/l_b5	1Ø26	–	–	–	165	260	70	2.7	130	5.0
	12P-1d28/c2.5/l_b5	1Ø28	–	–	= 13A (see Table 1)						
	13P-1d32/c2.5/l_b5	1Ø32	–	–	–	185	320	77	2.4	160	5.0
Bundles	14P-2d12/c2.5/l_b3	2$Ø_i$12	19.64	20	18P	120	200	48	2.4	60	3.0
	15P-3d12/c2.5/l_b3	3$Ø_i$12	23.46	24	19P	145	240	61	2.6	72.5	3.0
	16P-2d16/c2.5/l_b3	2$Ø_i$16	26.19	26	20P	170	260	69	2.6	85	3.0
	17P-3d16/c2.5/l_b3	3$Ø_i$16	31.28	32	21P	185	320	77	2.4	92.5	3.0
Eq. bar	18P-1d20/c2.5/l_b3	1Ø20	–	–	–	115	200	48	2.4	57.5	3.0
	19P-1d24/c2.5/l_b3	1Ø24	–	–	–	145	240	61	2.5	72.5	3.0
	20P-1d26/c2.5/l_b3	1Ø26	–	–	–	165	260	70	2.6	82.5	3.0
	21P-1d32/c2.5/l_b3	1Ø32	–	–	–	185	320	77	2.4	92.5	3.0

TABLE 3 Concrete mix-design

Cement type	CEM II/A-LL 42.5R
Cement content (kg/m^3)	350
Sand 0/4 (kg/m^3)	890
Coarse aggregate 4/15 (kg/m^3)	925
Maximum aggregate size (mm)	15
Water-cement ratio[a]	0.51
Superplasticizer (% on cement content)	1.07

[a]Aggregates in saturated-surface-dry condition.

TABLE 4 Main properties of reinforcing bars (nominal values)[16]

Ø (mm)	f_{Rm} (–)	f_y (MPa)	f_u (MPa)	A_{gt} (%)
12	0.093	531.9	627.3	14.9
14	0.090	536.3	622.6	11.4
16	0.094	538.8	613.4	13.1
20	0.098	567.4	653.7	10.0
22	0.090	535.5	631.8	12.4
24	0.084	547.7	652.0	13.4
26	0.075	521.3	620.8	11.9
28	0.080	530.3	626.5	12.3
32	0.068	500.3	635.0	15.1

and was kept constant up to failure (each test took about 2 h). All specimens were accurately aligned in the hydraulic machine in order to avoid any eccentricity. Friction between concrete and steel plate was reduced by a layer of polytetrafluoroethylene (Teflon) 2 mm thick.

A linear variable differential transformer (LVDT) was installed to measure the unloaded-end slip (δ_u), while two LVDTs were placed on the opposite side of the bar to capture the loaded end slip (δ_l). Transverse deformation (*w*) due to bursting forces generated by bond actions (Figure 4(d)) was measured by LVDTs on the north (w_n) and south side (w_s) in specimens of rectangular cross-section;

TABLE 5 Equivalent area criterion: summary of test results (in brackets the coefficient of variation of the test results is listed for each series)

	Series	f_{cm} (MPa)	P_{max} (kN)	τ_{max} (MPa)	$\frac{\tau_{max}}{(f_{cm}/39)^{0.25}}$ (MPa)	$\delta_{u,peak}$ (mm)	$P_{0.1}$ (kN)	$\tau_{0.1}$ (MPa)	$w_{m,0.1}$ (mm)
Bundles	1A-2d12/c2.5/l_b5	39.7 (0.04)	63.9 (0.02)	10.60	10.56	0.210 (0.54)	42.2 (0.44)	7.00	0.027 (0.12)
	2A-3d12/c2.5/l_b5	39.7 (0.04)	96.4 (0.05)	10.23	10.19	0.203 (0.35)	79.6 (0.10)	8.44	0.022 (0.25)
	3A-2d14/c2.5/l_b5	39.7 (0.04)	105.5 (0.05)	11.99	11.94	0.215 (0.59)	59.5 (0.11)	6.76	0.012 (0.09)
	4A-3d14/c2.5/l_b5	39.7 (0.04)	149.0 (0.16)	11.29	11.25	0.149 (0.33)	132.0 (0.08)	10.00	0.054 (0.57)
	5A-2d16/c2.5/l_b5	33.8 (0.02)	103.9 (0.14)	9.39	9.74	0.255 (0.34)	56.2 (0.13)	5.08	–
	6A-3d16/c2.5/l_b5	33.8 (0.02)	162.3 (0.01)	9.23	9.57	0.190 (0.52)	72.0 (0.28)	4.09	–
	7A-4d12/c2.5/l_b5	39.7 (0.04)	123.5 (0.21)	9.10	9.07	0.076 (0.06)	–	–	–
	8A-4d14/c2.5/l_b5	39.7 (0.04)	180.0 (0.09)	9.75	9.71	0.077 (0.56)	–	–	–
Equivalent bar	9A-1d16/c2.5/l_b5	39.7 (0.04)	65.3 (0.26)	16.24	16.18	0.346 (0.71)	28.4 (0.20)	7.06	0.007 (0.33)
	10A-1d20/c2.5/l_b5	39.7 (0.04)	100.9 (0.03)	16.05	15.99	0.445 (0.27)	40.6 (0.19)	6.46	0.012 (0.32)
	11A-1d22/c2.5/l_b5	33.8 (0.02)	99.4 (0.12)	13.07	13.55	0.350 (0.48)	62.4 (0.13)	8.21	0.012 (0.82)
	12A-1d24/c2.5/l_b5	37.4 (0.09)	128.8 (0.02)	14.24	14.40	0.843 (0.26)	69.4 (0.24)	7.67	0.052 (0.34)
	13A-1d28/c2.5/l_b5	37.4 (0.09)	168.1 (0.03)	13.65	13.80	0.597 (0.14)	89.5 (0.10)	7.26	0.020 (0.35)
Bundles	14A-2d12/c4.5/l_b5	37.6 (0.05)	99.8 (0.17)	16.54	16.70	0.445 (0.78)	64.0 (0.12)	10.61	0.035 (0.52)
	15A-2d14/c4.5/l_b5	37.6 (0.05)	117.9 (0.07)	13.40	13.53	0.575 (0.41)	69.9 (0.28)	7.95	0.033 (0.98)
	16A-3d12/c4.5/l_b5	37.6 (0.05)	117.2 (0.06)	12.44	12.56	0.514 (0.54)	63.2 (0.06)	6.70	0.039 (0.04)
	17A-2d16/c4.5/l_b5	35.7 (0.09)	142.2 (0.05)	12.86	13.16	0.804 (0.26)	92.8 (0.05)	8.39	0.039 (0.03)
	18A-3d14/c4.5/l_b5	39.0 (0.04)	176.6 (0.24)	13.38	13.39	0.303 (0.48)	101.1 (0.11)	7.66	0.026 (0.62)
	19A-3d16/c4.5/l_b5	39.0 (0.04)	177.8 (0.11)	9.43	9.44	0.170 (0.17)	140.4 (0.02)	7.45	0.041 (0.62)
Equivalent bar	20A-1d16/c4.5/l_b5	37.6 (0.05)	65.0 (0.09)	16.07	16.23	0.557 (0.59)	41.8 (0.17)	10.38	0.022 (0.13)
	21A-1d20/c4.5/l_b5	37.6 (0.05)	102.8 (0.14)	16.36	16.52	1.014 (0.32)	50.8 (0.34)	8.08	0.026 (0.25)
	22A-1d22/c4.5/l_b5	35.7 (0.09)	120.0 (0.11)	15.78	16.14	0.791 (0.64)	55.5 (0.07)	7.29	0.027 (0.11)
	23A-1d24/c4.5/l_b5	39.0 (0.04)	130.4 (0.31)	14.41	14.42	0.650 (0.76)	68.5 (0.14)	7.57	0.025 (0.87)
	24A-1d28/c4.5/l_b5	39.0 (0.04)	158.9 (0.04)	12.05	12.06	0.453 (0.27)	84.0 (0.11)	6.37	0.026 (0.25)

in specimens having a square section one LVDT was applied on all sides of the specimen (Figure 4(b)).

3 | EXPERIMENTAL RESULTS AND DISCUSSION

All specimens with either single or bundled bars exhibited a splitting failure with a splitting crack developing along the embedded length. In fact, it is well known that bond action generates radial transversal pressure as a result of the wedge action of the crushed concrete between the bar ribs ([4,5,7]; Chapter 1 of *fib* Bulletin n.10, 2000[8]) which may generate longitudinal splitting cracks along the bond length when the tensile strength of the concrete cover is reached.[7,10,17]

Tables 5 and 6 summarize the mean experimental results (the coefficient of variation [CV] is also provided in brackets) of each series for equivalent area and minimum perimeter criteria, respectively. These two tables report:

- the cylinder compressive concrete strength (f_{cm}, here conventionally assumed as 83% of the cubic one);
- the maximum load (P_{max});
- the bond stress at P_{max} (τ_{max}; i.e., bond strength);
- the normalized bond strength $[\tau_{max}/(f_{cm}/39)]^{0.25}$, 39 MPa being the mean compressive concrete strength as determined from all specimens;
- the unloaded-end slip at P_{max} ($\delta_{u,peak}$);
- the load at $\delta_u = 0.1$ mm ($P_{0.1}$);
- the bond stress at $P_{0.1}$ ($\tau_{0.1}$) and
- the transverse deformation at $\delta_u = 0.1$ mm ($w_{m,0.1}$).

Bond stresses were calculated by considering the effective surface area ($l_b \times u_{eff}$) in contact with concrete,

TABLE 6 Minimum perimeter criterion: summary of test results (in brackets the coefficient of variation of the test results is listed for each series)

	Series	f_{cm} (MPa)	P_{max} (kN)	τ_{max} (MPa)	$\frac{\tau_{max}}{(f_{cm}/39)^{0.25}}$ (MPa)	$\delta_{u,peak}$ (mm)	$P_{0.1}$ (kN)	$\tau_{0.1}$ (MPa)	$w_{m,0.1}$ (mm)
Bundles	1P-2d12/c2.5/l_b5	37.4 (0.09)	72.9 (0.08)	9.67	9.78	0.590 (0.41)	49.0 (0.09)	6.49	0.020 (0.57)
	2P-3d12/c2.5/l_b5	37.4 (0.09)	136.1 (0.09)	12.04	12.17	0.180 (0.16)	116.3 (0.04)	10.28	0.018 (0.53)
	3P-2d14/c2.5/l_b5	37.4 (0.09)	101.4 (0.07)	10.48	10.60	0.200 (0.13)	82.7 (0.02)	8.54	0.034 (0.25)
	4P-2d16/c2.5/l_b5	43.4 (0.03)	134.8 (0.06)	10.31	10.04	0.310 (0.18)	69.7 (0.18)	5.33	0.046 (0.33)
	5P-3d16/c2.5/l_b5	43.4 (0.03)	150.1 (0.30)	7.47	7.28	0.087 (0.55)	–	–	–
	6P-4d12/c2.5/l_b5	43.4 (0.03)	184.3 (0.07)	11.64	11.34	0.202 (0.19)	72.8 (0.28)	4.60	0.050 (0.36)
	7P-4d14/c2.5/l_b5	43.4 (0.03)	159.3 (0.44)	7.55	7.36	0.083 (0.68)		–	–
Equivalent bar	8P-1d20/c2.5/l_b5	37.4 (0.09)	82.2 (0.08)	13.08	13.23	0.410 (0.08)	52.5 (0.19)	8.36	0.011 (0.33)
	9P-1d22/c2.5/l_b5	37.4 (0.09)	105.9 (0.01)	13.93	14.09	0.780 (0.07)	46.3 (0.27)	6.08	0.023 (0.79)
	11P-1d26/c2.5/lb5	43.4 (0.03)	156.6 (0.06)	14.74	14.36	0.607 (0.22)	66.0 (0.29)	6.22	0.040 (0.10)
	13P-1d32/c2.5/l_b5	43.4 (0.03)	156.4 (0.06)	9.73	9.48	0.163 (0.52)	80.7 (0.14)	5.01	0.070 (0.20)
Bundles	14P-2d12/c2.5/l_b3	37.4 (0.09)	47.3 (0.10)	10.45	10.57	0.020 (0.50)	–	–	–
	15P-3d12/c2.5/l_b3	37.4 (0.09)	76.1 (0.19)	11.14	11.26	0.213 (0.26)	57.2 (0.10)	8.37	0.043 (0.18)
	16P-2d16/c2.5/l_b3	43.4 (0.03)	96.6 (0.08)	11.31	11.02	0.267 (0.22)	58.0 (0.08)	6.79	0.063 (0.07)
	17P-3d16/c2.5/l_b3	43.4 (0.03)	104.8 (0.06)	9.02	8.79	0.110 (0.09)	100.6 (0.06)	8.65	0.042 (0.18)
Equivalent bar	18P-1d20/c2.5/l_b3	37.4 (0.09)	52.5 (0.26)	14.53	14.69	0.290 (0.63)	36.4 (0.25)	10.08	0.028 (0.13)
	19P-1d24/c2.5/l_b3	37.4 (0.09)	78.7 (0.10)	14.40	14.56	0.550 (0.31)	41.5 (0.09)	7.58	0.023 (0.30)
	20P-1d26/c2.5/l_b3	43.4 (0.03)	78.2 (0.42)	11.61	11.31	0.270 (0.52)	41.8 (0.08)	6.20	0.053 (0.34)
	21P-1d32/c2.5/l_b3	43.4 (0.03)	93.2 (0.16)	10.02	9.76	0.307 (0.23)	42.1 (0.05)	4.53	0.035 (0.32)

where u_{eff} corresponds to the maximum perimeter (Equation (4) and Figure 2(a)). Therefore, in case of bars in a bundle, the bar surface not exposed to concrete was not considered for the calculation of the bond stress.

$$\tau = \frac{P}{u_{eff}.l_b} \tag{4}$$

$$u_{eff} = \pi \varnothing_{n,Peff} \tag{5}$$

Consequently, Equations (4) and (5) allow the bond stress in a bundle to be evaluated, making possible a comparison against corresponding single equivalent bars. It can be observed that the loads reached by bundles and

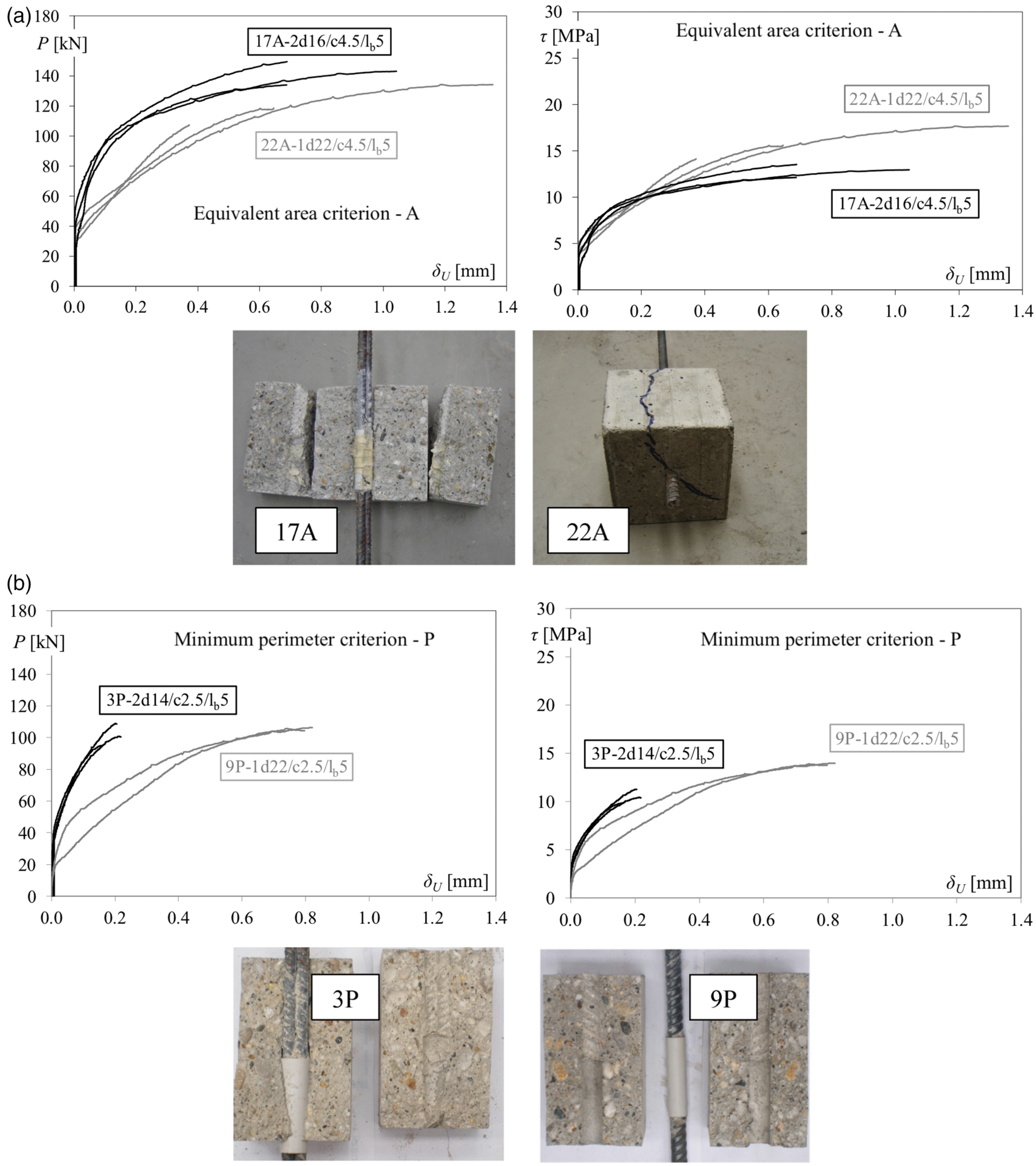

FIGURE 5 Load and stress versus unloaded-end slip curves and typical splitting failure for the series (a) 17A-2d16/c4.5/l_b5 and 22A-1d22/c4.5/l_b5; (b) 3P-2d14/c2.5/l_b5 and 9P-1d22/c2.5/l_b5

corresponding single bars are generally comparable (using either equivalent area or minimum perimeter criteria), even if the bond strength (τ_{max}) is generally lower in bundled series (because of the larger surface in contact with concrete) (Figure 5, Tables 7 and 8). A similar experimental scatter was observed for series with individual and bundled bars.

In particular, $P_{\max}$ was characterized by small values of CV (around 0.12), while the values of both slips at peak load and transverse deformations (i.e., $\delta_{u,peak}$ and $w_{m,0.1}$) were more variable (CV of about 0.40). It should be also noticed that the bundle series were generally characterized by both higher values of $P_{0.1}$ and lower values of $\delta_{u,peak}$, compared to equivalent single bars, thus

TABLE 7 Equivalent area criterion: comparison between bundle and equivalent bar

Series of bundled bars	Number of bars in bundle	Eq. series	$\frac{u_{eff}}{u_{eq}}$ (−)	$\frac{P_{max,b}}{P_{max,eq}}$ (−)	$\frac{\tau_{max,b}}{\tau_{max,eq}}$ (−)
$c = 2.5Ø$; $l_b = 5Ø$					
1A-2d12/c2.5/l_b5	2	9A	1.41	0.98	0.65
2A-3d12/c2.5/l_b5	3	10A	1.44	0.96	0.64
3A-2d14/c2.5/l_b5	2	10A	1.41	1.05	0.75
4A-3d14/c2.5/l_b5	3	12A	1.44	1.16	0.79
5A-2d16/c2.5/l_b5	2	11A	1.41	1.05	0.72
6A-3d16/c2.5/l_b5	3	13A	1.44	0.97	0.68
7A-4d12/c2.5/l_b5	4	12A	1.50	0.96	0.64
8A-4d14/c2.5/l_b5	4	13A	1.50	1.07	0.71
Mean (CV)	–	–		1.03 (0.07)	0.70 (0.08)
$c = 4.5Ø$; $l_b = 5Ø$					
14A-2d12/c4.5/l_b5	2	20A	1.41	1.53	1.02
15A-2d14/c4.5/l_b5	2	21A	1.41	1.15	0.82
16A-3d12/c4.5/l_b5	3	21A	1.44	1.14	0.76
17A-2d16/c4.5/l_b5	2	22A	1.41	1.19	0.81
18A-3d14/c4.5/l_b5	3	23A	1.44	1.35	0.93
19A-3d16/c4.5/l_b5	3	24A	1.44	1.12	0.78
Mean (CV)	–	–		1.25 (0.13)	0.85 (0.12)

Abbreviation: CV, coefficient of variation.

TABLE 8 Minimum perimeter criterion: comparison between bundle and equivalent bar

Series of bundled bars	Number of bars in bundle	Eq. series	$\frac{u_{eff}}{u_{eq}}$ (−)	$\frac{P_{max,b}}{P_{max,eq}}$ (−)	$\frac{\tau_{max,b}}{\tau_{max,eq}}$ (−)
$c = 2.5Ø$; $l_b = 5Ø$					
1P-2d12/c2.5/l_b5	2	08P	1.21	0.89	0.74
2P-3d12/c2.5/l_b5	3	10P	1.28	1.05	0.85
3P-2d14/c2.5/l_b5	2	09P	1.21	0.96	0.75
4P-2d16/c2.5/l_b5	2	11P	1.21	0.86	0.69
5P-3d16/c2.5/l_b5	3	13P	1.28	0.96	0.77
6P-4d12/c2.5/l_b5	4	12P	1.32	1.09	0.85
7P-4d14/c2.5/l_b5	4	13P	1.32	1.02	0.77
Mean (CV)	–	–		0.97 (0.09)	0.77 (0.08)
$c = 2.5Ø$; $l_b = 3Ø$					
14P-2d12/c2.5/l_b3	2	18P	1.21	0.90	0.72
15P-3d12/c2.5/l_b3	3	19P	1.28	0.97	0.77
16P-2d16/c2.5/l_b3	2	20P	1.21	1.24	0.97
17P-3d16/c2.5/l_b3	3	21P	1.28	1.12	0.90
Mean (CV)	–	–		1.06 (0.14)	0.84 (0.14)

Abbreviation: CV, coefficient of variation.

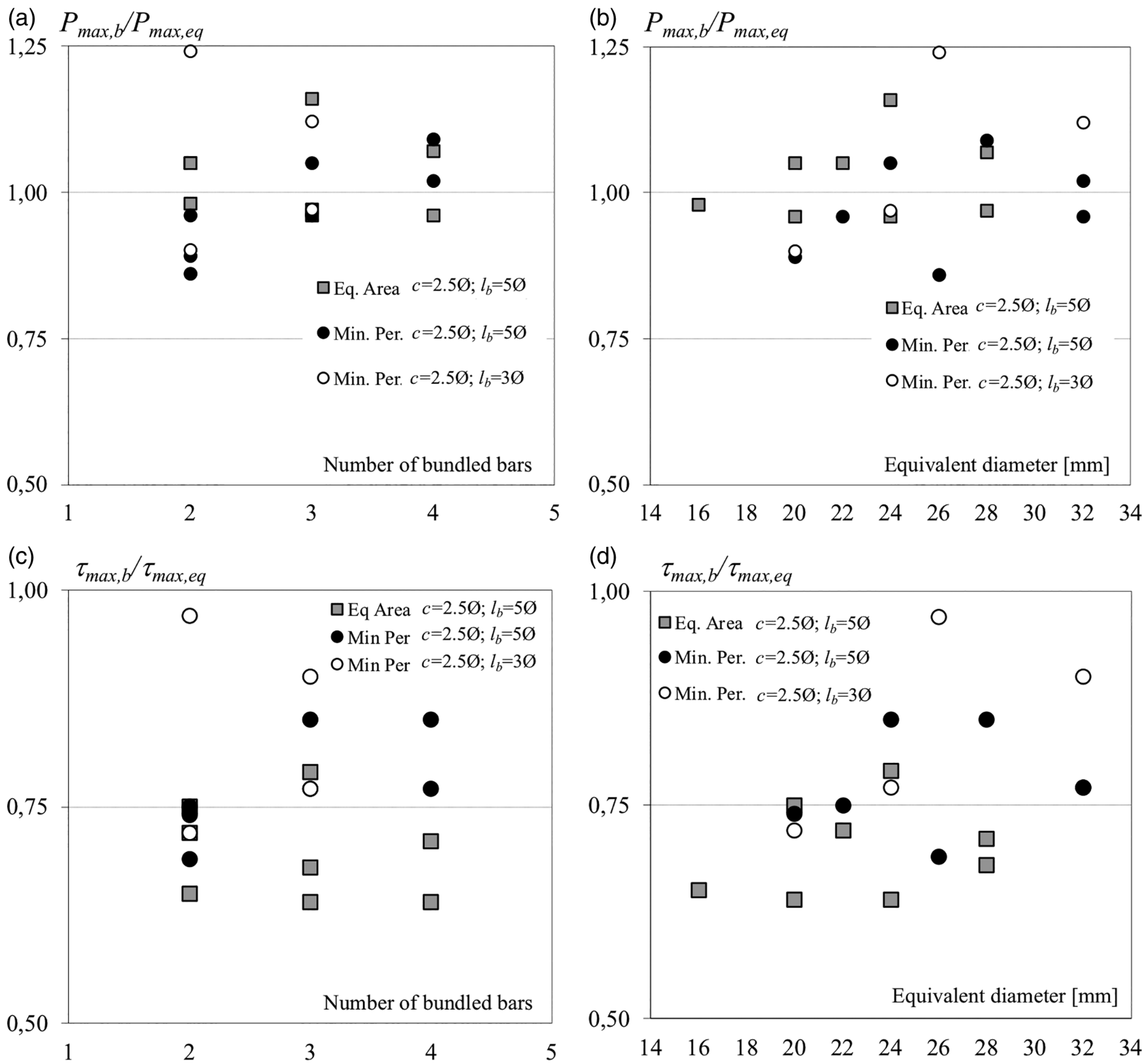

FIGURE 6 Influence of number of bars in bundle (a and c) and of equivalent diameter (b and d) on the ratio $P_{max,b}/P_{max,eq}$ and on the ratio $\tau_{max,b}/\tau_{max,eq}$

showing a higher load-slip stiffness. However, when bond stresses are considered ($\tau_{0.1}$), up to $\delta_u = 0.1$ mm, the initial response of bundled series was comparable to that of equivalent bars.

The experimental evidences described above can clearly be observed in Figure 5 where both load and stress versus unloaded-end slip curves of samples with bars in a bundle (series 17A-2d16/c4.5/l_b5 and 3P-2d14/c2.5/l_b5) are plotted along with the curves of their equivalent series (22A-1d22/c4.5/l_b5 and 9P-1d22/c2.5/l_b5). The markedly stiffer response of bundled bars can be observed, as well as the smaller value of δ_u at splitting failure in samples with reinforcing bars within a bundle (as compared to the equivalent single bar). This behavior could be related to the different splitting crack development in specimens with the notional equivalent bars, characterized by larger diameters and higher ribs provoking greater wedge actions even though the relative rib area of large diameter bars was lower than that of small diameter bars[4,5,18] (see Table 4).

Furthermore, Figure 5 shows that even if the bearing capacity of the anchorages seems to be similar (using both equivalent area and minimum perimeter criteria), a different bond stress occurs in a bundle (as compared to the corresponding individual bars) due to the higher surface area in contact with concrete. Figure 5 shows also the final crack patterns of samples 17A, 22A, 3P, and 9P. As expected, failure due to the development of a

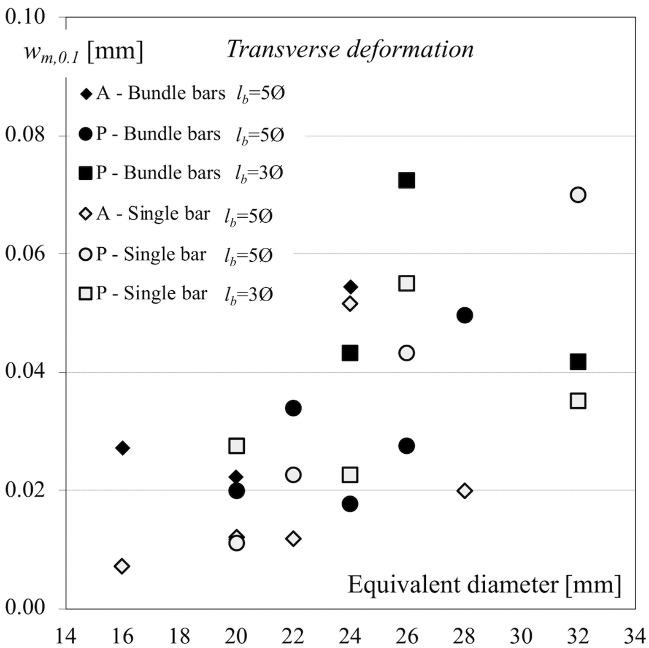

FIGURE 7 Mean transverse deformation at $\delta_u = 0.1$ mm for specimens with cover c = 2.5ϕ

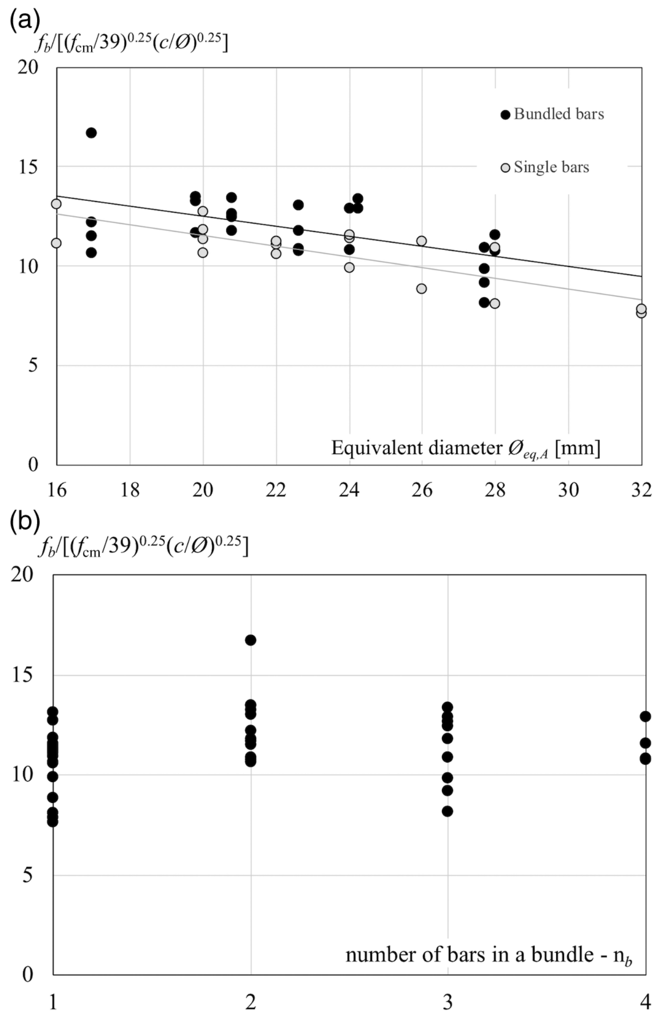

FIGURE 8 (a) Normalized bond strength as a function of the equivalent diameter and (b) of number of bars in a bundle

splitting crack along two orthogonal planes was observed in the series with cube specimens (from 14A to 24A, Figure 5(a)) while a single splitting crack parallel to the shorter side formed in all prism specimens (Figure 5(b)).

In Tables 7 and 8 the results of each series are compared to those of the related equivalent series for equivalent area and minimum perimeter criteria, respectively, both in term of maximum load ($P_{max,b}/P_{max,eq}$) and bond strength ($\tau_{max,b}/\tau_{max,eq}$). These tables also report the ratio between the maximum perimeter (u_{eff}) of a bundle in contact with concrete and the perimeter of the corresponding equivalent bar (u_{eq}); it should be observed that this ratio (u_{eff}/u_{eq}) increases with the number of bars in a bundle and it is greater when the equivalent area criterion is adopted.

Figure 6 shows the influence of equivalent diameter and number of bars in bundle on the ratio $P_{max,b}/P_{max,eq}$. It should be noticed that the equivalent area criterion seems to be slightly more conservative with respect to the minimum perimeter one, regardless of bar size (Figure 6(a)). In fact, with a concrete cover of 2.5ϕ, the mean value of $P_{max,b}/P_{max,eq}$ was slightly higher than 1 for equivalent area criterion (1.03) but slightly lower (0.97) in case of minimum perimeter criterion. Similar low CVs were observed in both criteria, thus underlining the reliability of the obtained results. It can be also observed (from Table 7) that the equivalent area criterion becomes more conservative with increasing concrete cover; in fact, the mean value of the ratio $P_{max,b}/P_{max,eq}$ increased from 1.03 to 1.25 for a concrete cover of 2.5 and 4.5 times bar diameter, respectively.

Concerning the possible influence of the embedded length, Table 8 shows that comparable results were obtained with series having an anchorage length of either 3Ø or 5Ø when equivalent minimum perimeter criterion is considered. This underlines that, in the considered range, the bond length does not significantly influence the accuracy of criteria for short anchorages. However, it should be noticed that, as expected, anchorages of 3Ø led to slightly greater bond strength (+10%) as compared to 5Ø ones (Table 6).

The different level of bond stress that takes place in a bundle, as compared to the equivalent bar, is well represented by the ratio $\tau_{max,b}/\tau_{max,eq}$. In bundles the bond strength was always lower than in equivalent series (Figure 6(c),(d)). In particular, a reduction of 30% and 23% was observed (for bundled series with $c = 2.5Ø - l_b = 5Ø$) for the equivalent area and the minimum perimeter criteria, respectively (Tables 7 and 8). As mentioned above, the bond strength depends on the reference area adopted that, in the present work, concerns the contact area between steel and concrete. However, the bearing capacity of the bundle is mainly related to the maximum load transmitted by the bundle to the concrete without having anchorage (or lap) failure. Therefore, the bond strength is not a representative parameter for evaluating anchorage and lap behavior of bundled bars.

Figure 7 shows the mean crack opening ($w_{m,0.1}$) at unloaded-end slip $\delta_u = 0.1$ mm as a function of the equivalent diameter; a clear increase of the wedge action with bar diameter can be noted, confirming the influence of the size effect on bond when splitting failure occurs.

For a comparison with the formulation of *fib* Model Code 2010,[2] the bond strength (f_b) of each series is calculated with reference to the lateral surface in contact with concrete (bonded area) of the notional bar provided by the equivalent area criterion. The bond strength (f_b) is normalized to the power of 1/4 of the compressive strength (divided by the mean compressive resistance of concrete at the time of the tests, equal to 39.1 MPa) and to the power of 1/4 of the concrete cover over bar diameter, as suggested by the MC2010 formulation for bond, thus allowing a better comparison between specimens made of different materials and cover thickness. Normalized bond strength is plotted as a function of equivalent diameter in Figure 8(a) for both individual and bundled bars. The trend of test results confirms a clear size effect in the case of splitting-controlled bond failures, as occurred in all tests conducted in this study, as previously reported in pull-out tests (no splitting) of single smooth and ribbed/deformed bars.[19] Size effect means that an increment in equivalent diameter leads to, as expected, a reduction in bond strength of about 30% from a diameter of 16–32 mm. This reduction seems to have a linear trend and it is similar in both individual and bundled bars. By means of linear regressions of test results shown in Figure 8(a), it may also observed that bundled bars showed a 10% higher bond strength compared to that of single equivalent bars. As mentioned above, these results may be affected by the higher ribs of large bars, which exert a greater wedge action on the surrounding concrete; however, as mentioned above, the bond index (f_r) was smaller in larger diameter bars (Table 4). In fact, the smaller bars used in the test of bundles (ϕ_i up to 22 mm) had a relative rib area greater than 0.09 whereas all larger bars (ϕ_i from to 24 to 32 mm) had a lower f_r varying between 0.068 and 0.084.

Finally, the influence of the number of bars in a bundle on bond strength is shown in Figure 8(b), where f_b is normalized to compressive strength, concrete cover and equivalent diameter. It should be also noted that the normalized bond strength shows a fairly constant trend with the number of bars in a bundle, thus confirming that the equivalent area criterion proposed by Eurocode 2[3] and *fib* Model Code 2010[2] can be applied for up to four bars in a bundle.

4 | CONCLUDING REMARKS

Local bond behavior of bundled bars has been investigated by means of pull-out tests within a broad experimental program on 45 series of pull-out tests. The behavior of a bundle was compared to that of the equivalent single notional bar characterized by either the equivalent area or the minimum perimeter criteria.

Based on this wide experimental study, the following conclusions can be drawn:

- Both equivalent area criterion and minimum perimeter criterion are suitable methods for determining the anchorage strength of a bundle; however, the equivalent area criterion seems to be slightly more conservative with respect to the minimum perimeter one.
- A larger stiffness was observed in bundled bars relative to the equivalent notional bar; a clear increase of the wedge action with bar diameter can be also noted, confirming the influence of the size effect on bond when splitting failures occur.
- The bond strength of a bundle should be calculated with reference to the circumferential area of a notional bar having the same cross-sectional area and bond length. With this approach, the bond strength does not depend on the number of bars in a bundle, thus confirming that the equivalent area criterion of Eurocode 2[3] and *fib* Model Code 2010[2] can be used in the design of anchorages of bundles with up to four bars.
- Finally, the *fib* Model Code 2010[2] formulation for bond strength of bundled bars based on the equivalent area criterion is always conservative for bundled bars, regardless of the number of bars in a bundle (up to the maximum permitted number of 4).

ACKNOWLEDGMENTS

The authors are grateful to Engineers Craig Howie, Jerome Girodet, Daniele Monfredini, Andrea Tortelli and Gelmi Alberto for the assistance in performing the experimental program. A special acknowledgement goes also to the technicians Luca Martinelli, Augusto Botturi, Domenico Caravaggi and Andrea Delbarba of the Laboratory P. Pisa of the University of Brescia for their technical support. Research was supported by the University of Brescia and by Alfacciai Group, which provided the steel bars.

DATA AVAILABILITY STATEMENT

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

LIST OF SYMBOLS

a, b	section sides of pull-out specimen
A_s	cross-sectional area of reinforcement
$A_{s,tot}$	total cross sectional area of bundled bars
A_{gt}	percentage total elongation of steel bar
c	concrete cover
d	depth of specimens
f_{cm}	mean value of the cylinder compressive concrete strength
$f_{cm,\mathrm{cube}}$	mean value of the cubic compressive concrete strength
f_{Rm}	mean bond index
f_u	ultimate strength of steel bars
f_y	yield strength of steel bars
l_b	bond length
n_b	number of bars in bundles
$Ø$	nominal diameter of reinforcing bar
$Ø_i$	diameter of individual bar within a bundle
$Ø_n$	equivalent diameter of notional bar
$Ø_{n,A}$	equivalent diameter of notional bar according to equivalent area criterion
$Ø_{n,P}$	equivalent diameter of notional bar according to minimum perimeter criterion
$Ø_{n,\mathrm{Peff}}$	equivalent diameter of notional bar according to maximum perimeter criterion
P	load
$P_{0.1}$	load at $\delta_u = 0.1$ mm
P_{max}	maximum load
$P_{max,b}$	maximum load of a specimen with bundled bars
$P_{max,\mathrm{eq}}$	maximum load of a specimen with an equivalent bar
SPL	splitting failure
w_e	transverse deformation on specimen east side
w_m	mean transverse deformation
$w_{m,0.1}$	mean transverse deformation at $\delta_u = 0.1$ mm
w_n	transverse deformation on specimen north side
w_s	transverse deformation on specimen south side
δ_l	loaded-end slip
δ_u	unloaded-end slip
$\delta_{u,peak}$	unloaded-end slip at $P_{\max}$
τ	bond stress
$\tau_{0.1}$	bond stress at $P_{0.1}$
τ_{max}	bond stress at $P_{\max}$, that is, bond strength
$\tau_{max,b}$	bond strength of a bundle
$\tau_{max,eq}$	bond strength of an equivalent bar
u	perimeter of a single bar
u_{eff}	effective surface area in contact with concrete
f_b	bond strength evaluated with the lateral surface of the notional bar having the same area of a bundle

ORCID

Giovanni Metelli https://orcid.org/0000-0002-4334-4108
John Cairns https://orcid.org/0000-0001-9886-3661
Antonio Conforti https://orcid.org/0000-0003-2796-7409
Giovanni A. Plizzari https://orcid.org/0000-0003-2897-4969

REFERENCES

1. Institution of Structural Engineers/Concrete Society. Standard method of detailing structural concrete: a manual for best practice. 3rd ed. London; The Institution of Structural Engineers; 2006. p. 188. ISBN 978 0 901297 41 9.
2. fib - International Federation for Structural Concrete. Model code for concrete structures 2010. Berlin, Germany: Ernst & Sohn; 2013.p. 434 ISBN 978-3-433-03061-5.
3. CEN Eurocode 2. Design of concrete structures—part 1–1: General rules and rules for buildings, EN 1992-1-1:2004. Brussels: European Committee for Standardization; 2004. p. 225.
4. Cairns J, Jones K. The splitting forces generated by bond. Mag Concr Res. 1995;47(171):153–6.
5. Cairns J, Jones K. Influence of rib geometry on strength of lapped joints: an experimental and analytical study. Mag Concr Res. 1995;47(172):253–62.
6. Ferguson PM, Breen J. Lapped splices for high strength reinforcing bars. Proc ACI. 1965;62(9):1063–78.
7. Tepfers R. A theory of bond applied to overlapped tensile reinforcement splices for deformed bars. Goteborg, Publ. 73/2: Chalmers University of Technology; 1973.p. 328.
8. fib (2000). Bond of Reinforcement in Concrete, Bulletin N.10, State-of-Art Report, T.G. "Bond Models", Convener Ralejs Tepfers 427 pp., ISBN 978–2–88394-050-5
9. Gambarova PG, Rosati GP. Bond and splitting in bar pull-out: behavioral laws and concrete-cover role. Mag Concr Res. 1997; 49(179):99–110.
10. Giuriani E, Plizzari GA, Schumm C. Role of stirrups and residual tensile strength of cracker concrete on bond. J Struct Eng ASCE. 1991;117(1):1–18.
11. Plizzari GA, Deldossi MA, Massimo S. Transverse reinforcement effects on anchored deformed bars. Magazine of Concrete Research. 1998;50:161–177. http://dx.doi.org/10.1680/macr.1998.50.2.161.
12. ACI 318-19. (2019). Building Code Requirements for Structural Concrete
13. CEB Bulletin No. 151. (1982). Bond action and bond behavior of reinforcement, Paris, 153pp.

14. Jirsa JO, Chen W. Grant DB, Elisondo R. (1995). R. Development of bundled reinforcing steel, Rsearch Report. No. 1363, Centre for Transportation Research, University of Texas at Austin
15. Bashandy TR. Evaluation of bundled bar lap splices. ACI Struct J. 2009;106(2):215–21.
16. Cairns J. Lap splices of bars in bundles. ACI Struct J. 2013;110 (2):183–91.
17. EN 10080. Steel for reinforcement of concrete–weldable reinforcing steel–general. Brussels: European Committee for Standardization; 2005.
18. Metelli G, Cairns J, Plizzari G. The influence of percentage of bars lapped on performance of splices. Mater Struct. 2015;48 (9):2983–96. https://doi.org/10.1617/s11527-014-0371-y.
19. Metelli G, Plizzari GA. Influence of the relative rib area on bond behavior. Mag Concr Res. 2014;66(6):277–94. https://doi.org/10.1680/macr.13.00198.
20. Bamonte P, Gambarova PG. High-bond bars in NSC and HPC: study on size effect and on the local bond stress-bar slip relationship. ASCE–J Struct Eng. 2007;133(2):225–34.

AUTHOR BIOGRAPHIES

Giovanni Metelli, Associate Professor, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Italy, Email: giovanni.metelli@unibs.it.

John Cairns, Honorary Professor, School of the Built Environment, Heriot Watt University, Edinburgh, UK, Email: J.J.Cairns@hw.ac.uk.

Antonio Conforti, Assistant Professor, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Italy, Email: antonio.conforti@unibs.it.

Giovanni A. Plizzari, Full Professor, Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), University of Brescia, Italy, Email: giovanni.plizzari@unibs.it.

How to cite this article: Metelli G, Cairns J, Conforti A, Plizzari GA. Local bond behavior of bundled bars: Experimental investigation. *Structural Concrete*. 2021;22:2322–2337. https://doi.org/10.1002/suco.202000576