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The Bond Strength on Over Lapping Bars Using Pullout Test

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***Abstract*— The behavior of reinforced concrete structures depends on sufficient bond strength between concrete and reinforcing steel. The perfect bond between the reinforcement surface and the concrete makes the transfer force work well. In this experiment, several forms of bars overlapped in the concrete and then tested pullout directly. This experiment is to get the tendency of the bond stress patterns that occur in overlapping bars. Another result of the study is the failure pattern of each specimen. The specimen size is 150×150×150 mm. In the center of the concrete cube is rib two overlapped bars. The reinforcement used plain and two ribs types of bars surface. The compression of concrete used is a minimum of 25 MPa. Furthermore, the specimen was subjected to a pullout test loaded in stages with 22 kN/minute speed. Loading stopped after the sample has collapsed. The pullout test uses the ASTM C234-91a standard. The failure pattern of plain reinforcement specimens with diameters of 12 mm, 16 mm, and 19 mm is a pullout or a slipped. The specimen with deform bar diameter 13 mm, 16 mm, and 19 mm occurs in splitting failure. The pullout test result, all samples in connection not yielded yet. The results show that the higher the bar diameter's development length, the higher the bond strength. The bond stress of the plain bar is smaller than the deform bar.**

***Keywords*— Bond stress; slip; tension test; failure pattern; lap splice.**

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I. INTRODUCTION

The adequate bond strength between concrete and steel affects the performance of reinforced concrete structures. The force transfer can work well if there is a perfect bond between the reinforcing and concrete walls [1]. The formation of this good bond if the reinforcement's surface is coarse so that for structural reinforced concrete used deform bar. The reinforcement surface roughness is expressed in the bond index's relative area value [2]–[6].

Several previous research on the strength of reinforcing reinforcement at lap splice had been done [3], [7]–[15]. One of the results obtained with higher concrete quality and better aggregate quality and installed transverse reinforcement resulted in a better bonding reinforcement than without ties. Likewise, the deform and bar diameter's relative width has increased strength using transverse reinforcement [3]. Another study about lap spliced by Canbay and Frosh is two different collapse patterns: horizontal direction (side-splitting failure) and face-splitting failure. In splitting failure, the attached stress pattern's vertical direction tends to increase linearly [9], [16].

Study on the contribution of transversal reinforcement to the elongated joint with a headed [7] and bending of the hook reinforcement [13], the results obtained show that transverse reinforcement is effective in increasing the strength of anchoring on head reinforcement [5]. This result supports Darwin's research [8], with the transverse reinforcement installation, there is an additional strength of 25% [8]. To predict the strength of anchoring in the joint connection with the header bar, a very crucial component is the ability of the attachment and bearing strength, including the effect of transverse reinforcement, cover, and the distance of bar [7]. The bond strength of lap spliced based on parameters: bar diameter, development length, the compressive strength of concrete, and transversal reinforcement installed at the connection location have also been carried out [11], [14],. Research shows that transverse reinforcement contributes to the bond strength, especially in a large bar [11]; this result corresponds to ACI 318 [17].

In this study, the bond strength of lap spliced using the direct pullout with several deform reinforcing shapes. Previous studies have not explicitly revealed the contribution of bar deform shape to bar bond strength with concrete in lap spliced and the failure pattern, so this research needs action.

Determining the development length of reinforcement can use pullout testing directly with one bar, but a direct pullout test with double bars is necessary.

A. The Bond Mechanism

The bond stress is an interaction between reinforcement and surrounding concrete. Factors that influence this bond stress are complex. Three factors are determining the bond stress: adhesion, friction, and interlocking force. Reliable transfer of force between reinforcement and concrete is needed for the optimal structural design. The mechanism of the force transfer from reinforcement to the surrounding concrete consists of (a) the adhesion between reinforcement with concrete, (b) friction force due to rough reinforcing surfaces, the shear force on the surface, and slip that occurs between steel bar with surrounding concrete, and (c) interlocking mechanism or bearing force on reinforcing form against concrete [9], [17]–[19]. The bond stress between reinforcement and concrete can be measured through a pullout test. The test results are analyzed and plotted in the bond stress and slip relationships graph, as presented in Figure 1 [20], [21].

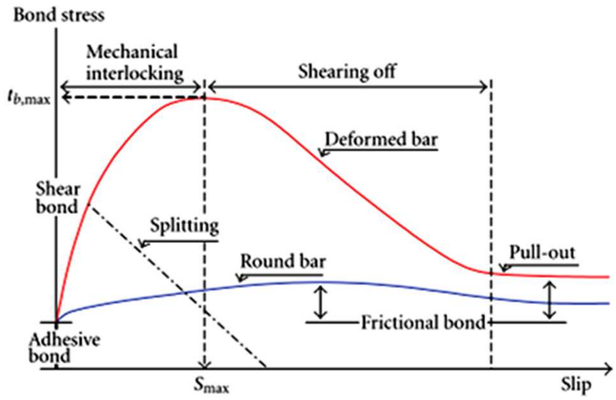

Fig. 1 The bond stress – slip relation [20], [21]

Fig. 1 illustrates the pattern of the relationship between the bond stress surrounding concrete and the slip that occurs. The adhesion value is the bond stress when the slip still zero. Friction is the maximum stress difference between the adhesion value [20]–[22]. Adhesion occurs when the load is still small on the deform bar, then friction and interlocking forces. If the concrete breaks, the graph has not reached the peak stress directly down, the failure pattern is brittle [22]. When the bond stress has reached the maximum, the pullout failure decreases and, at a certain point, tends to be constant then collapses [20], [21]. Several parameters that influence the mechanism of reinforcing bond stress with concrete are the bar rib's roughness and shape. The rib geometry contributes to bond strength.

The form and size of the reinforcing rib in some previous studies are realized in one parameter: the bond index or relative rib area (f_R). Bond index is the ratio of high rib area to distance between ribs [3], [21]–[23]. The bond index between 0.04 - 0.10 increases bond strength up to 40%. The interaction of bar rib with concrete reduces the risk of a split in the concrete [7], [23], [24]. The bond index formula (f_R) is presented in the eq. 1.

$$f_R = \frac{d_e^2 - d_i^2}{4 \cdot d \cdot s} \tag{1}$$

with f_R = bond *index* or relative rib area, d_e = outer diameter of rib reinforcement, d_i = inner diameter of rib reinforcement, d = nominal diameter of reinforcement, s = distance between rib as to as.

B. Bond Stress on a Lap Splice

The bond stress distribution in the lap splice is reading the strain during testing. The bond stress formula of the lap spliced (τ) is presented in the Eq. 2 [25], [26].

$$\tau_i = \frac{d_b \cdot E_s}{4}\left[\frac{(\varepsilon_i - \varepsilon_{i-1})}{(x_i - x_{i-1})}\right] \tag{2}$$

with d_b = bar diameter, E_s = elasticity modulus of steel, ε_i = axial strain, x_i = *strain gauge* position (mm).

The value of bond strength in the lap spliced can know with the assumption that the strain that occurs in the free end is zero. The stress that occurs in the short and long lap spliced is a different; the stress value along short lap spliced tends to be the same. The bond stress of each bar at the lap spliced, the most significant number occurs on the side of the reinforcement pulled, then the smaller the middle and equal to zero at the free end [6], [25], [27].

II. The Material and Method

The specimens were cube concrete with a dimension of 150 mm × 150 mm × 150 mm, in the middle installed two overlapping bars (Fig. 2). Concrete compressive strength (fc ') is 29 MPa. The deform bars consists of fishbone rib (ST) brand TGS (Toyogiri Iron Steel) and slop rib (SC) Brand KS (Krakatau Steel) with diameters D13 mm, D16 mm, and D19 mm (Fig. 3). The results of the two types of rib were compared with the bond strength of the plain bar.

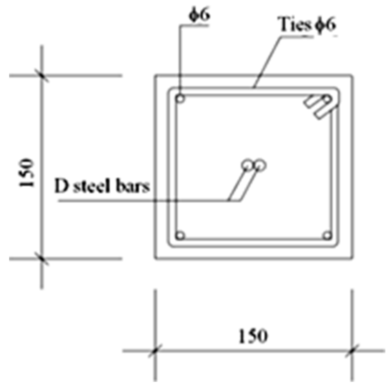

Fig. 2 Specimen dimensions

Pullout testing uses a Universal Testing Machine (UTM). The specimens located in the middle with both ends of the bars clamped (Fig. 4). The sample tested after the specimen is more than 28 days old. After 28 days passed, the sample tested direct pullout. A strain gauge installed on one of the bars to determine the bond stress on the other overlapping reinforcement, as shown in Fig. 5 [25]. A strain gauge installed on one of the bars determines the bond stress on the additional overlapping bar, as shown in Figure 4 [22]. The strain gauge outputs analyzed using Eq. (2) to get bond stress and the pattern of failure that occurs from each specimen.

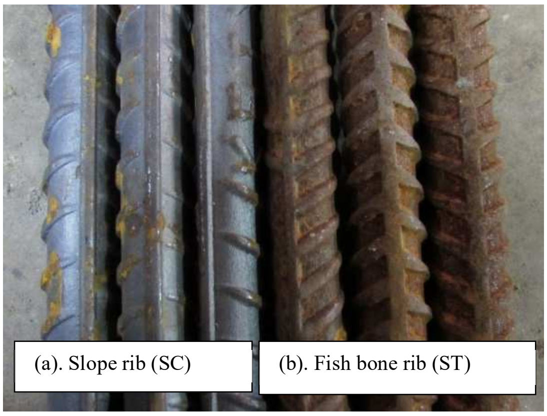

Fig. 3 Deform bars (a). slope rib (SC), (b). fishbone rib (ST)

Fig. 4 The setting of pullout testing using UTM

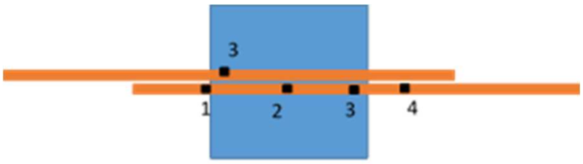

Fig. 5 Strain gauge placement layout

III. RESULTS AND DISCUSSION

TABLE I
THE VALUE OF RELATIVE RIB AREA (BOND INDEX)

Form of rib bars	D	n	Rib area A_R (mm2)	Rib spacing Ld (mm)	Rib angle (°)	bond index f_R	Average f_R
Slope rib (SC)	D13	1	60.575	8	65	0.1094	
		2	62.468	8	65	0.1145	**0.11**
		3	56.789	8	65	0.0965	
	D16	1	97.014	10	65	0.1089	
		2	106.479	10	65	0.1312	**0.13**
		3	108.845	10	65	0.1368	
	D19	1	144.812	12	65	0.1119	
		2	136.293	12	65	0.0977	**0.11**
		3	141.972	12	65	0.1067	
Fish bone rib (ST)	D13	1	37.2	6	60	0.1753	
		2	30.0	6	60	0.1271	**0.16**
		3	37.2	6	60	0.1753	
	D16	1	68.8	8	60	0.1481	
		2	68.8	8	60	0.1481	**0.14**
		3	64.0	8	60	0.1276	
	D19	1	122.0	10	60	0.1599	
		2	120.0	10	60	0.1544	**0.15**
		3	118.0	10	60	0.1489	

The rib bar measurement to get bond index or relative rib area is shown in Table 1. The slope rib bar threads' bond index values ranged from 0.11 to 0.13, while the fishbone rib bars were obtained from 0.14 to 0.16. The bond index on the slope rib bars is lower than the reinforcement of the fishbone rib.

A. The Failure Pattern of Specimen

The collapse in the specimen of the mutual connection of plain reinforcement in diameter 12 mm, 16 mm, and 19 mm is a pullout or a reinforced bar; in Figure 5, there is no visually showing splitting. The plain bars specimen of the diameter: 12 mm, 16 mm, and 19 mm undergo pullout failure, Fig. 6 there is no showing splitting.

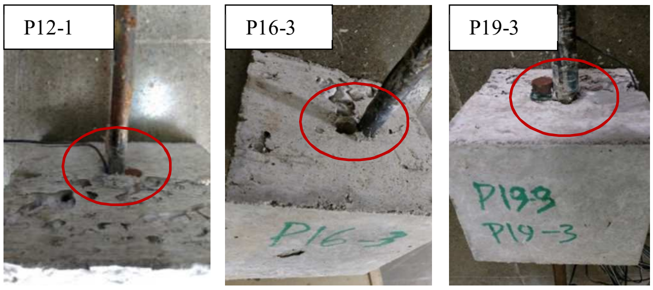

Fig. 6 The pullout failure pattern of plain bars specimen

In contrast to plain bars, damage of the slope rib bars the diameter of 13 mm, 16 mm, and 19 mm is splitting failure (Fig. 7).

Fig. 7 The splitting failure pattern of slope rib bars specimen (SC)

All the specimen of the fishbone rib failure is splitting (Fig. 8).

Fig. 8 The splitting failure pattern of fishbone rib bars specimen (ST)

The damage pattern of the two rib types shows the splitting failure. In Fig. 7 and 8, cracks starting from around the bars radiate to the concrete's outer side. The small diameter (D13) of the two rib types specimen is crack, but bigger than D13 the concrete is a break, even though the sample was put in the stirrup. This pattern of failure is similar to the research from Gaurav (2017), Canbay (2005), Lagier (2016), and Gangolu (2016). The influence of rib causes an interlocking mechanism, where the force of concrete distributed through the rib of the bar. As a result of distribution the longitudinal and radial directional forces so that the concrete presses occur, if the stress arises beyond the concrete compressive capacity, it will cause a radial crack, and it continues to develop, it causes splitting failure[9], [26], [28]–[30]. In the plain bars, Fig. 6 shows the bar has slipped in the plain bars, there is no crack on the concrete surface. This failure pattern is identical with M. N. Hassan's (2012) research that the lap spliced of plain reinforcement has failed due to the bond between reinforcement and concrete to slip [31].

B. The Bar Stress and the Bond Stress on Lap Splice

Experimental results of the lap splice showed none of the bars undergo yield. In Table 2 and Fig. 9, there are not fs/fy ratio greater than or equal to 1. The most effective rate is 0.97 (SC13_3). The higher the diameter of the reinforcement, the lower the stress. The plain bar stress is smaller than a deform bar.

TABLE II
THE EXPERIMENT RESULT AND THE FAILURE OF SPECIMEN

No	Specimen	Dia. bar (mm)	l_d/d	P_{max} (N)	f_s (MPa)	f_y (MPa)	$f_{b\ average}$ (MPa)	f_s/f_y	Failure Pattern
1	P13_1	11.84	12.67	11040	100	338	1.98	0.30	Pullout
2	P13_2	11.84	12.67	15265	139	338	2.74	0.41	Pullout
3	P13_3	11.84	12.67	8916	81	338	1.60	0.24	Pullout
4	SC13_1	12.87	11.66	39208	302	347	6.47	0.87	Splitting
5	SC13_2	12.87	11.66	36084	278	347	5.95	0.80	Splitting
6	SC13_3	12.87	11.66	43954	338	347	7.25	0.97	Splitting
7	ST13_1	13.03	11.52	47521	357	442	7.74	0.81	Splitting
8	ST13_2	13.03	11.52	45661	343	442	7.44	0.78	Splitting
9	ST13_3	13.03	11.52	45886	344	442	7.48	0.78	Splitting
10	P16_1	15.96	9.40	10757	54	318	1.43	0.17	Pullout
11	P16_2	15.96	9.40	17092	85	318	2.27	0.27	Pullout
12	P16_3	15.96	9.40	13474	67	318	1.79	0.21	Pullout
13	SC16_1	15.96	9.40	42382	212	341	5.64	0.62	Splitting
14	SC16_2	15.96	9.40	47968	240	341	6.38	0.70	Splitting
15	SC16_3	15.96	9.40	28912	145	341	3.85	0.42	Splitting
16	ST16_1	15.87	9.45	47973	243	450	6.42	0.54	Splitting
17	ST16_2	15.87	9.45	44475	225	450	5.95	0.50	Splitting
18	ST16_3	15.87	9.45	39015	197	450	5.22	0.44	Splitting
19	P19_1	19.04	7.88	17677	62	283	1.97	0.22	Pullout
20	P19_2	19.04	7.88	3340	12	283	0.37	0.04	Pullout
21	P19_3	19.04	7.88	20040	70	283	2.24	0.25	Pullout
22	SC19_1	18.89	7.94	31366	112	380	3.53	0.30	Splitting
24	SC19_3	18.89	7.94	37600	134	380	4.23	0.35	Splitting
25	ST19_1	19.03	7.88	44265	156	420	4.94	0.37	Splitting
26	ST19_3	19.03	7.88	47214	166	420	5.27	0.40	Splitting

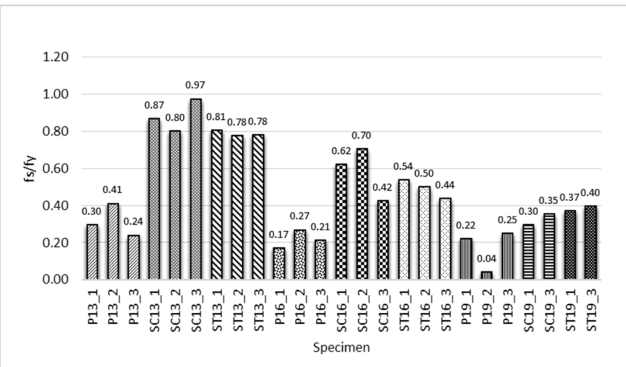

Fig. 9 The bar stress to yield stress ratio of each specimen

The results also show that the higher the ratio of the length of the lap splice (Ld) to the bar diameter (d) the more significant the stress that occurs in the bar (Fig. 10). The trend of this result is in equal with some previous experiments [3], [9], [27], [29].

Based on Fig. 10, the plain bar has a lower reinforcement stress value than the deform reinforcement, the smaller Ld / d ratio also shows a decrease in stress. With the same Ld/d ratio, the reinforcement stress of fishbone rib tends to be higher than the slope rib.

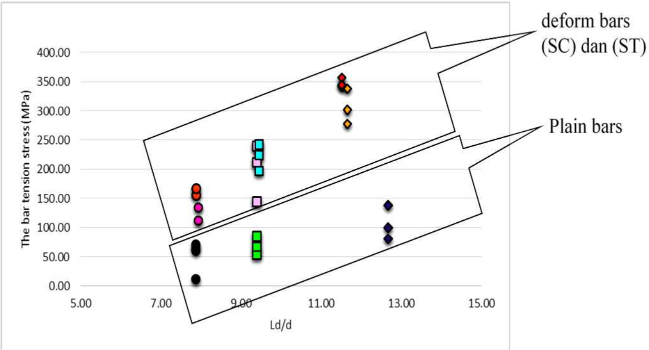

Fig. 10 The stress bar vs the lap spliced to bar diameter

Likewise, with the average bond stress on reinforcement (f_b), the plain bar is lower than a deform bar. From Figure 11, the average bond stress of the fishbone rib is higher than the slope rib.

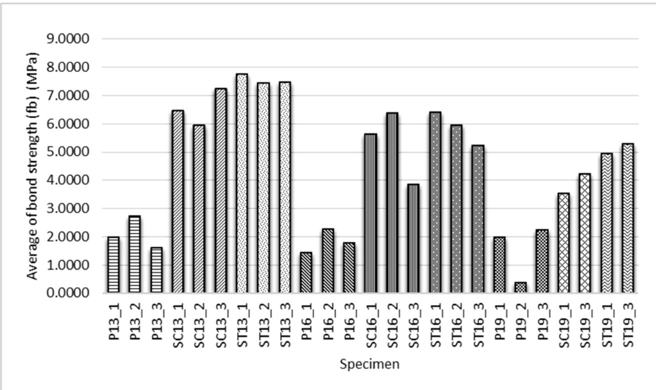

Fig. 11 The average bond stress of specimen

With the same lap splice length and the bar diameter increases, the decreasing stress value is obtained.

The slope rib and fishbone rib have different rib angles, the spacing of rib, and rib height, so the bond index is desperate. The fishbone rib has a higher bond index than the slope rib, so the bond strength is also higher. This result is by previous research from Bosco and Silva that the higher the bond index value, the higher the bond strength of the reinforcement [29], [32], [33]. In Silva's research and the bond index, the rib angle is very influential on bond strength. The smaller the rib angle results in, the higher the ultimate bond strength. In this case, the edge of the fishbone rib was lower than the slope rib; it turned out that the average bond stress of fish bones ribs to be more significant than the slope rib.

C. The Bond Stress Distribution in Lap Splice

Bond stress distribution between the concrete reinforcement at the lap splice presented with locations strain gauge in Fig. 12.

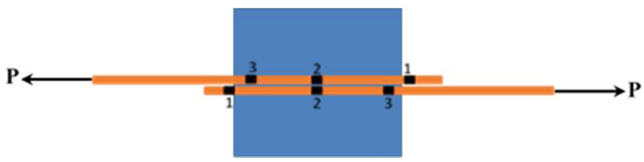

Fig. 12 The measurement point of bond stress

Determination bond stress distribution between steel bar with concrete on the lap splice based on the strain gauge output is attached to the reinforcement (Fig. 12) point no. 2 and 3. For point no. 1 at the free end, is the furthest side of the reinforcement position, assuming the value is zero [34] (Tang, 2017). This stress distribution uses eq. 2. The graph of stress distribution is plotted based on the percentage of the maximum tensile axial forces that can resist during testing pullout, starting at 15%, 25%, 50%, 75%, and 100% of Pmax. The bond stress distribution of lap splice D13 presented in Fig. 13, 14, and 15.

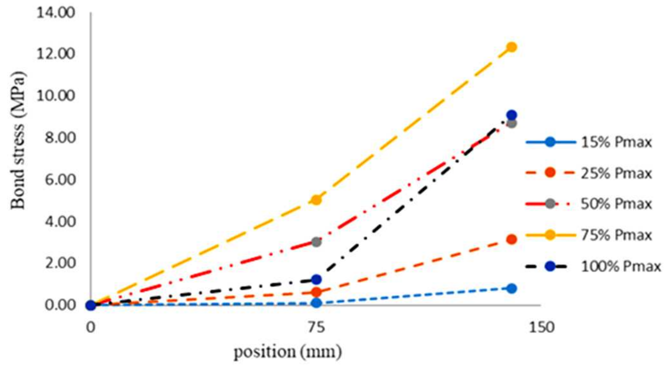

Fig. 13 Bond stress distribution based on position with specific axial force on P13 specimen

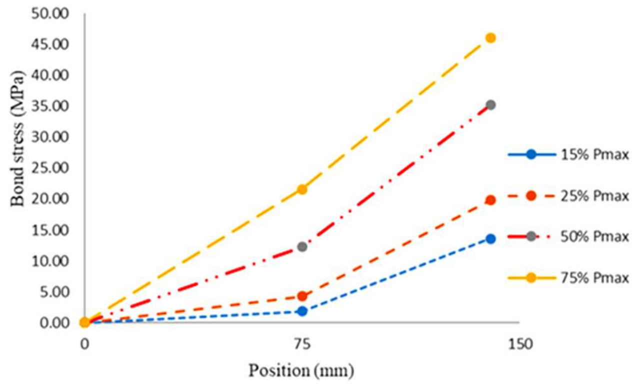

Fig. 14 Bond stress distribution based on position with specific axial force on SC13 specimen

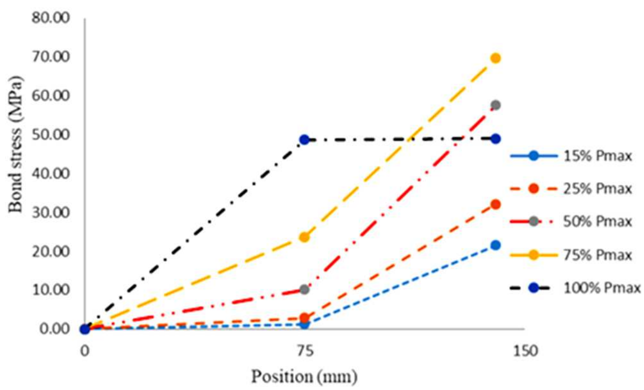

Fig. 15 Bond stress distribution based on position with specific axial force on ST13 specimens

The pattern of bond stress distribution on specimens P13, SC13, and ST13 shows the same forms. However, ST13 samples with stress at 100% of maximum loading at points 2 & 3 obtained relatively equal value, whereas the other stress distributions point 2 tend to be smaller than point 3. The bond stress distribution of the lap splice of steel bar with D16 shown in Fig. 16, 17, and 18.

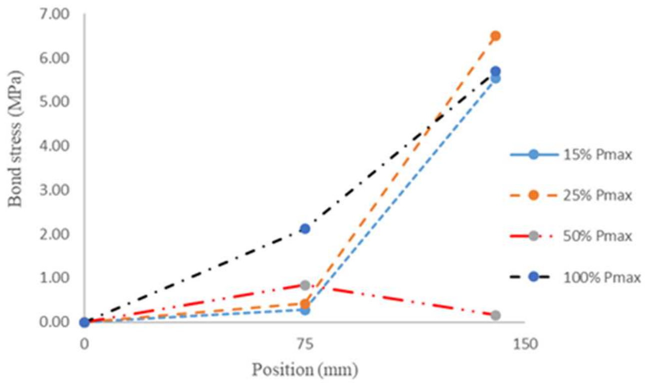

Fig. 16 Bond stress distribution based on position with specific axial force on P16 specimen

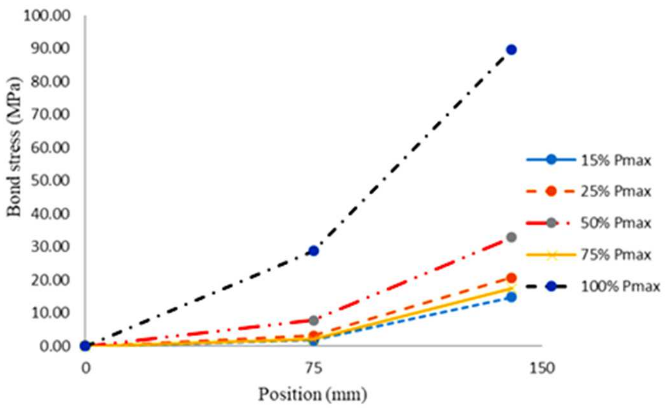

Fig. 17 Bond stress distribution based on position with specific axial force on SC16 specimen

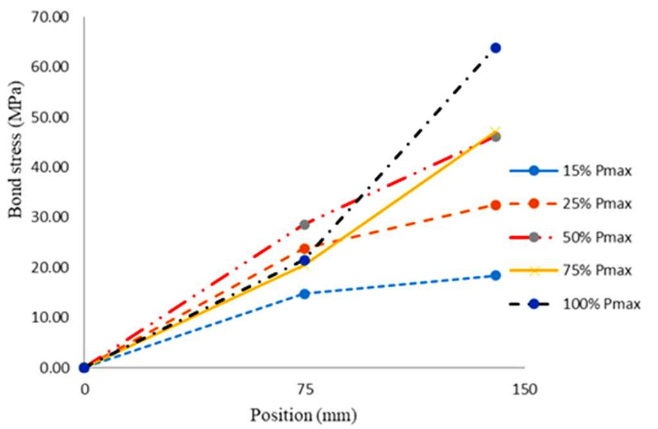

Fig. 18 Bond stress distribution based on position with specific axial force on ST16 specimen

The bond stress distribution in specimens P16, SC16, and ST16, have a relatively similar pattern, except for specimen P16, when the load is 50% of maximum loading, the stress value at point 2 is more significant than at point 3.

Furthermore, the bond stress distribution of lap splice of steel bar with D19 is shown in Fig. 19, 20, and 21.

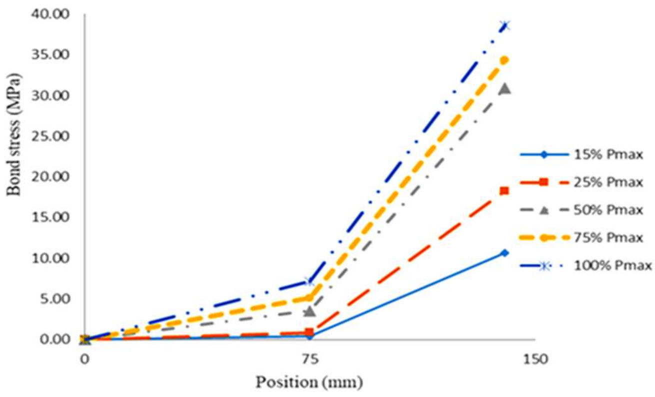

Fig. 19 Bond stress distribution based on position with specific axial force on P19 specimen

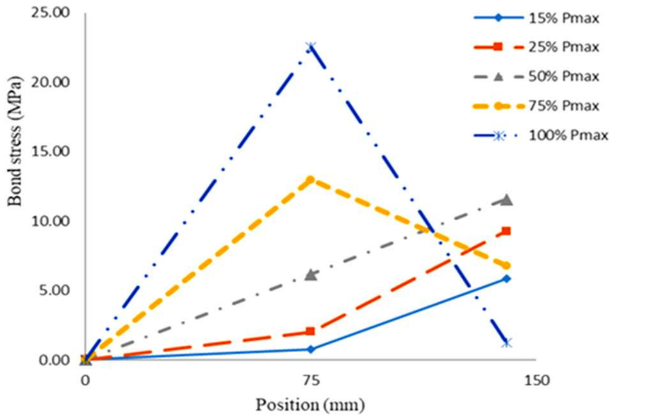

Fig. 20 Bond stress distribution based on position with specific axial force on SC19 specimen

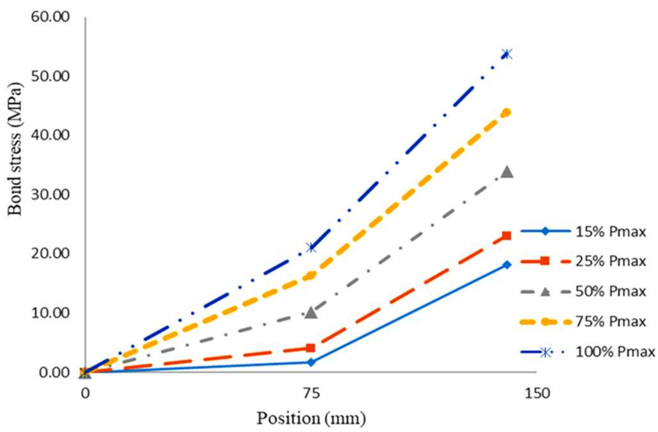

Fig. 21 Bond stress distribution based on position with specific axial force on ST19 specimen

The pattern of bond stress distribution at specimens of P19 and ST19 shows the same forms while SC19 samples with 75% and 100% of maximum loading at point 2, the values obtained are higher than point 3, whereas other stress distributions at point 2 tend to be smaller than point 3.

The bond stress distribution of lap splice of experimental results taken from 3 points, no. 1 is the point-free end with value 0 and position 0. Point no. 2 is located in the center of reinforced concrete in concrete, a distance of 75 mm from the outer side. Point no. 3 is at a distance of 140 mm from position 0. The stress distribution pattern of all specimens tends to be similar in plain bars, threads, and different reinforcing diameters. These results have the same shape as the results of previous studies by Bournas (2011) and Lagier (2016) [35], [36].

IV. Conclusion

Based on the experiment of all specimens can be concluded as follows. The Pattern damage specimen's plain reinforcement diameter of 12 mm, 16 mm, and 19 mm are pullout failures. The deform reinforced of both slope rib and fishbone rib, diameter 13 mm, 16 mm, and 19 mm undergo splitting collapse. The pullout lap splices all specimens have not the yield bar yet. There is only one specimen with a ratio of fs / fy reaching 0.97, a specimen of 13 mm diameter of slope rib. The results show that the higher the rate of lap splice length (Ld) to the bar diameter, the higher the average bond stress obtained. The bond stress of the plain bar is smaller than the deform bar. The experiment results show that the higher the length of the development length (Ld) to the reinforcement's diameter, the higher the average bond stress obtained. In bond stress of plain bar that occurs is smaller than the bar of a slope rib screw and fishbone rib.

Nomenclature

E_s	elasticity modulus of steel	MPa
d_e	outer diameter of rib reinforcement	mm
d_i	inner diameter of rib reinforcement	mm
d	nominal diameter of reinforcement	mm
f_R	bond index or relative rib area	
s	distance between rib as to as	mm
ε_i	axial strain	
τ	The bond stress of the lap spliced	MPa

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