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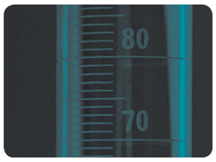

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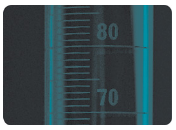

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Reference

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ABSTRACT

The bond strength of four sets of reinforcing bars is evaluated, two each with No. 5 and No. 10 (No. 16 and No. 32) bars, which have, respectively, nominal diameters of 0.625 and 1.27 in. (15.9 and 32.3 mm). One bar of each size satisfies the criterion for maximum deformation spacing in ASTM reinforcing bar specifications, while the other has deformations that exceed the maximum spacing. All bars exceed the requirements for minimum deformation height. Research related to the effect of deformation properties on bond strength, including the research used to establish the requirements for deformations in ASTM reinforcing bar specifications, is also reviewed. The test results match earlier research and demonstrate that (1) bond strength is not governed by the specific value of deformation height or spacing, but by the combination of the two as represented by the *relative rib area* of the bars and (2) the bond strength of the bars with deformation spacings that exceed those in ASTM reinforcing bar specifications is similar to the bond strength of the bars that meet the specification. Based on this and prior research, it is recommended that ASTM reinforcing bar specifications be modified to allow for deformation spacing up to 90 % (currently a maximum of 70 %) of the bar diameter provided the ratio of deformation height to deformation spacing is greater than or equal to the minimum ratio for bar deformations meeting the current requirements in ASTM reinforcing bar specifications.

AQ1
AQ2

Keywords

bond (concrete to reinforcement), deformed reinforcement, relative deformation area, relative rib area, structural engineering

Introduction

The deformations on reinforcing bars affect the bond strength between the bars and concrete. ASTM A615, A706, A955, A996, and A1035 [1–5] specify minimum deformation heights and maximum deformation spacings; however, research has demonstrated that it is the relative rib area, a function of the *ratio* of deformation height to deformation spacing, not the deformation height or the deformation spacing alone, that controls bond strength.

The work presented in this paper, supported by studies going back to the 1940s, provides a case for modifying the deformation spacing requirements in ASTM reinforcing bar specifications [1–5]. The research demonstrates that reinforcing bars with deformation spacings exceeding the specified maximums provide similar bond strengths to bars with similar relative rib areas, regardless of the spacing. It is recommended that the specifications be modified to allow for greater deformation spacings, provided that the relative rib area of a bar is at least as great as it is for reinforcement meeting the minimum requirements in the current specifications. This will allow for the use of a wider range of deformation patterns without the need for costly secondary testing and will bring the ASTM specifications [1–5] in line with current research regarding the bond strength of reinforcing bars.

Background

The requirements for deformation height and spacing in ASTM reinforcing bar specifications are based on research by Clark [6,7] who observed that the bond capacity of a reinforcing bar increases as the ratio of the rib bearing area (projected rib area normal to the bar axis) to the shearing area (bar perimeter times distance between ribs) increases (**Fig. 1**). Today, the ratio is most often referred to as the "relative rib area," R_r, [8] which is expressed as

$$R_r = \frac{\text{projected deformation area normal to bar axis}}{\text{nominal bar perimeter} \times \text{center-to-center deformation spacing}} \quad (1)$$

The term "relative deformation area," R_d, has been adopted in ASTM A955 [3].

In the case of conventional reinforcing bars that have longitudinal ribs, R_r may be calculated as [3,8,9]

$$R_r = \frac{h_r}{s_r}\left(1 - \frac{\sum gaps}{p}\right) \quad (2)$$

where

h_r = average height of deformations, in. or mm,

s_r = average spacing of deformations, in. or mm,

$\Sigma gaps$ = sum of the gaps between ends of deformations, plus the width of any continuous longitudinal lines used to represent the grade of the bar, multiplied by the ratio of the height of the line to h_r, in. or mm,

p = nominal perimeter of the bar, in. or mm.

Clark [6,7] and other researchers [10–15] have demonstrated that R_r, not the minimum rib height or maximum deformation spacing, controls the bond strength between reinforcing steel and concrete.

Rather than including a criterion for R_r in ASTM standards, however, Clark's study was used to establish a maximum average spacing of deformations equal to 70 % of the nominal diameter of the bar and a minimum height of deformations equal to 4 % for bars with a nominal diameter of 1/2 in. (13 mm) or smaller, 4.5 % for bars with a nominal diameter of 5/8 in. (16 mm), 5 % for bars up to a diameter of 1.693 in. (43 mm), and 4.5 % for bars with a diameter of 2.257 in (57.3 mm) [16]. These provisions remain in use today [1–5], and when combined with the specified limit on the maximum width of longitudinal ribs (equal to 25 % of the nominal perimeter of the bar), reinforcing bars meeting the ASTM deformation criteria will provide minimum values of R_r on the order of 0.05, as shown in **Table 1**. In practice, U.S. reinforcing steel typically has values of R_r between 0.057 and 0.084 [17].

Using specially machined 1 in. diameter bars with values of R_r ranging from 0.05 to 0.20 (within and above the typical range), Darwin and Graham [12] demonstrated that relative rib areas in this range play no role in bond strength for bars not confined by transverse reinforcement but do play a role for bars confined by transverse reinforcement such as stirrups or ties. The results obtained by Darwin and Graham [12] are summarized in **Fig. 2**. The figure shows that the bond strength of bars confined by transverse reinforcement is principally controlled by the relative rib area, which is governed by the combination of deformation height and spacing, not by the minimum height or the maximum spacing alone. One item worth noting (**Fig. 2**) is that the bars with deformation height $h = 0.10$ in. (2.5 mm)

FIG. 1 Schematic of reinforcing bar showing deformations (after Ref [8]).

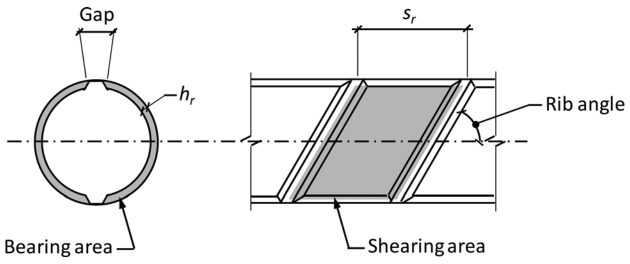


TABLE 1 ASTM reinforcing bar deformation requirements [1–4].

		Deformation Requirements, in. (mm)			
Bar Designation No.	Nominal Diameter in. (mm)	Maximum Average Spacing	Minimum Average Height	Maximum Sum of Gaps	Minimum Relative Rib Area[a]
3 (10)	0.375 (9.5)	0.262 (6.7)	0.015 (0.38)	0.286 (7.2)	0.043
4 (13)	0.500 (12.7)	0.350 (8.9)	0.020 (0.51)	0.382 (9.8)	0.043
5 (16)	0.625 (15.9)	0.437 (11.1)	0.028 (0.71)	0.478 (12.2)	0.048
6 (19)	0.750 (19.1)	0.525 (13.3)	0.038 (0.97)	0.572 (14.6)	0.054
7 (22)	0.875 (22.2)	0.612 (15.5)	0.044 (1.12)	0.668 (17.0)	0.054
8 (25)	1.000 (25.4)	0.700 (17.8)	0.050 (1.27)	0.776 (19.4)	0.054
9 (29)	1.128 (28.7)	0.790 (20.1)	0.056 (1.42)	0.862 (21.8)	0.053
10 (32)	1.270 (32.3)	0.889 (22.6)	0.064 (1.63)	0.974 (24.8)	0.054
11 (36)	1.410 (35.8)	0.987 (25.1)	0.071 (1.80)	1.080 (27.4)	0.054
14 (43)	1.693 (43.0)	1.185 (30.1)	0.085 (2.16)	1.296 (31.0)	0.054
18 (57)	2.257 (57.3)	1.58 (40.1)	0.102 (2.59)	1.728 (43.8)	0.048

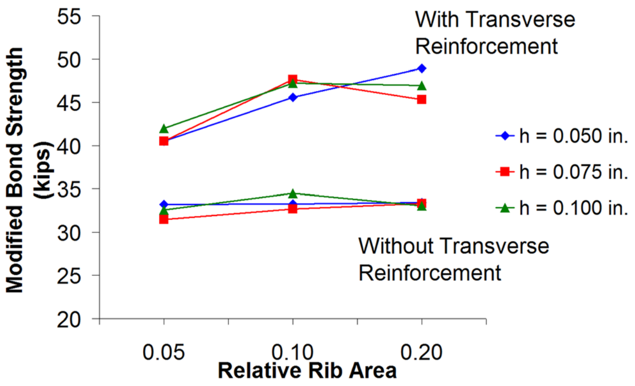
[a] Based on maximum average spacing and minimum average height. Included for reference.

had a deformation spacing of 1 in. (25 mm), equal to one bar diameter and, thus, greater than the value of 70 % of the bar diameter allowed by ASTM, but performed as well as bars with closer deformation spacings. These observations have been shown to be true for conventional reinforcement with a wide range of relative rib areas [13–15]. The role of the relative rib area is now well understood and widely accepted [3,8,9].

The bond test used by Darwin and Graham [12] has been standardized as ASTM A944 "Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens" [18]. One application of the test procedure is to qualify coatings of epoxy-coated reinforcement specified in ASTM A775 and A934 [19,20].

In the current study, hot-rolled No. 5 and No. 10 (No. 16 and No. 32) bars were tested for bond strength in accordance with ASTM A944 [17]. For each bar size, the bond strength of bars with a deformation spacing that exceeded the maximum permitted by ASTM specifications [1–5] was compared with the bond strength of bars that met the spacing requirements. The results match those of earlier tests and demonstrate that the bars with deformation spacings in excess of those currently permitted by ASTM will provide satisfactory bond performance. Full details of the study are reported in Ref. [21].

FIG. 2 Relationship between bond strength and relative rib area for machined bars with heights of deformations equal to 0.05, 0.075, and 0.100 in. (1.27, 11.91, and 2.54 mm) (after Ref. [11]).



Experimental Work

BAR PROPERTIES

Four sets of reinforcing bars were tested in this study, two each with No. 5 and No. 10 (No. 16 and No. 32) bars. For each set, deformation height and spacing were measured on three bars and the average relative rib area calculated using Eq 2. All bars exceeded the requirements for minimum deformation height. One set of each size satisfied the criterion for maximum deformation spacing, while the other had deformations that exceeded the maximum spacing. The bar properties are summarized in **Table 2**. All bars had values of relative rib area R_r that exceeded the minimum values listed in **Table 1**, with values ranging from 0.070 to 0.084.

CONCRETE

Non-air-entrained concrete supplied by a local ready mix plant was used to fabricate the test specimens. The mixture proportions are summarized in **Table 3**.

SPECIMEN PREPARATION AND TESTING

The bars were tested, as delivered, with mill scale on the surface. Prior to specimen fabrication, the bar surface was cleaned with acetone to remove any grease or oils. The specimens were prepared and tested in accordance with ASTM A944 [18], as shown in **Fig. 3**. A summary of specimen properties is presented in

TABLE 2 Properties of bars used in the tests.

			Deformation Properties, in. (mm)			
Meets Specified Spacing	Bar Designation No.	Nominal Diameter in. (mm)	Average Spacing[a]	Average Height	Sum of Gaps	Relative Rib Area
No	5 (16)	0.500 (12.7)	0.440 (11.2)	0.0412 (1.04)	0.312 (7.9)	0.079
Yes	5 (16)	0.500 (12.7)	0.391 (9.9)	0.0377 (0.96)	0.260 (6.6)	0.084
No	10 (32)	1.270 (32.3)	0.901 (22.9)	0.0735 (1.86)	0.564 (14.3)	0.070
Yes	10 (32)	1.270 (32.3)	0.768 (19.5)	0.0656 (1.67)	0.559 (14.2)	0.073

[a] Maximum spacing in accordance with ASTM A615 = 0.437 in. (11.1 mm) for No. 5 (No. 16) bars and 0.889 in. (22.6 mm) for No. 10 (No. 32) bars.

Table 4. An unbonded lead length (length of bar isolated from concrete using PVC pipe) of 1/2 in. (12.7 mm) was used in accordance with ASTM A944 [18] to limit the probability of a cone-type pullout failure. The embedment lengths (l_e) given in **Table 4** equal the sum of the lead length and the bonded length (length of bar in contact with the concrete) of the bar.

Fourteen beam-end specimens were cast and 13 were tested for each bar size—seven specimens contained bars that did not meet the ASTM deformation spacing requirements [1–5] and six specimens contained bars that did. Specimen 1 for the No. 5 (No. 16) tests and Specimen 13 for the No. 10 bar (No. 32) tests were used to verify the functionality of the testing equipment and are not used in the comparisons that follow.

Results

MAXIMUM BOND FORCES

The maximum bond forces developed by the No. 5 (No. 16) bar specimens in the beam-end tests are shown in **Table 5**. The mean maximum bond force of the specimens containing the No. 5 (No. 16) bars with the deformation spacing that exceeded that allowed in ASTM reinforcing bar specifications [1–5] is 104.1 % of the mean maximum bond force of the specimens containing bars that met the specification. The maximum bond forces developed by the specimens with the No. 5 (No. 16) bars that did not meet the specifications ranged from 13,106 to 17,384 lb (58.3 to 77.3 kN) with a mean value of 16,289 lb, standard deviation of 1487 lb (6.6 kN), and coefficient of variation of 0.091. The maximum bond forces developed by the specimens containing the bars that met the specifications ranged from 14,647 to 16,911 lb (65.1 to 75.2 kN), with a mean value of 15,647 lb (69.6 kN), standard deviation of 849 lb (3.8 kN), and coefficient of variation of 0.054. The mean maximum bond force for the specimens with bars that did not meet specification differs by 642 lb (2.9 kN), less than one standard deviation, from the mean maximum bond force of the specimens with the bars that met the specification, indicating little statistical difference between the two.

TABLE 3 Concrete mixture proportions.

Material	Quantity (SSD)
Type I/II cement	564 lb/yd^3 (335 kg/m^3)
Water	238 lb/yd^3 (141 kg/m^3)
Kansas river sand	1516 lb/yd^3 (899 kg/m^3)
Crushed limestone	1709 lb/yd^3 (1013 kg/m$^{3)}$
Estimated air content	1.50 %
Superplasticizer adva 100	28 fl oz (1.08 L)

The data were analyzed using the Student's t-test (used to analyze small data sets). Student's t-test compares the means and variances of two data sets to determine the probability α that any differences in the mean values could have arisen by chance; that is, that differences in the mean values μ_1 and μ_2 are due to natural variability, not differences in the systems. For example, $\alpha = 0.05$ indicates a 5 % chance that the test will incorrectly identify (or a 95 % chance of correctly identifying) a statistically significant difference in sample means when, in fact, there is no difference. For this analysis, a two-tailed test is performed, meaning that there is a probability of $\alpha/2$ that μ_1 is greater than μ_2 and $\alpha/2$ that μ_1 is less than μ_2 when, in fact, μ_1 and μ_2 are equal. $\alpha \leq 0.20$ is often used to indicate statistical significance. Using Student's t-test for this data set gives $\alpha = 0.371$, further demonstrating that the difference in bond force is not statistically significant.

The maximum bond forces developed by the No. 10 (No. 32) test specimens are shown in **Table 6**. The mean maximum

FIG. 3 Schematic of test apparatus [17].

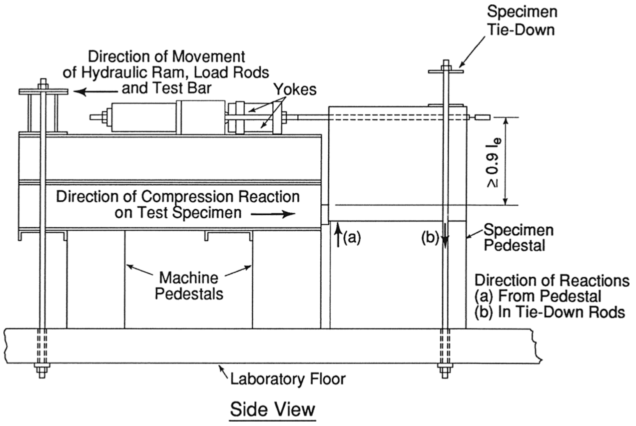


TABLE 4 Specimen properties.

Bar Designation No.	5 (16)	10 (32)
Concrete cover	1–1/4 in. (31.8 mm)	2–5/8 in. (66.7 mm)
Embedment length (l_e)	8–7/8 in. (225 mm)	14–3/8 in. (365 mm)
Lead length	1/2 in. (12.7 mm)	1/2 in. (12.7 mm)
Moisture condition of concrete during test	Air dry	Air dry
Age at test	12 days	9 days
Compressive strength	5120 psi (35.3 MPa)	5030 psi (34.7 MPa)

bond force of the specimens with the No. 10 (No. 32) bars with the deformation spacing that exceeded that allowed in ASTM specifications [1–5] is 96.4 % of the mean maximum bond force of the specimens with bars meeting the specification. The maximum bond forces of the specimens with the bars that did not meet the specifications ranged from 32,885 to 41,655 lb (146.3 to 185.3 kN), with a mean of 36,283 lb (161.4 kN), standard deviation of 3070 lb (13.7 kN), and coefficient of variation of 0.085. The maximum bond forces of the specimens containing the bars that met the specifications ranged from 32,022 to 42,929 (142.4 to 202.0 kN), with a mean of 37,653 lb (167.5 kN), standard deviation of 4133 lb (18.3 kN), and coefficient of variation of 0.110. Like the No. 5 (No. 16) bars, the mean maximum bond force for the specimens with bars that did not meet specifications differs by a relatively small amount, 1370 lb (6.1 kN) (again less than one standard deviation), from the mean maximum bond force of the specimens with the bars that met the specifications, indicating little statistical difference between the two values. Analysis using the Student's t-test, $\alpha = 0.507$, also indicates that the difference in strength is not statistically significant.

TABLE 5 Maximum bond forces, lb (kN)–No. 5 (No. 16) bars.

Specimen	Meets Specifications	Does Not Meet Specifications
2		16,939 (75.3)
3	15,766 (70.1)	
4		16,837 (74.9)
5	14,748 (65.6)	
6		17,173 (76.4)
7	16,067 (71.5)	
8		16,756 (74.5)
9	15,744 (70.0)	
10		13,106 (58.3)
11	16,911 (75.2)	
12		17,384 (77.3)
13	14,647 (65.1)	
14		15,831 (70.4)
Average	15,647 (69.6)	16,289 (72.5)
Std. Dev	849 (3.8)	1487 (6.6)
COV	0.054	0.091
	Ratio	104.1 %

Discussion

The similarity in bond strengths between the bars with deformation spacings that exceeded those specified in ASTM A615, A706, A955, and A996 [1–5] and those that met the specifications is as expected based on the original work by Clark [6,7] and subsequent studies [10–15]. Those studies have shown that the relative rib area R_r, not the specific value of deformation height or spacing, controls bond strength and that the effect of R_r is apparent only when confining transverse reinforcement is present, which was not the case in the current tests. The fact that the bars in question have values of R_r, 0.077, and 0.070 for the No. 5 and No. 10 bars (No. 16 and No. 32), respectively, that exceed the minimum values that result from the ASTM provisions [1–5] (**Table 1**) indicates that these bars will provide satisfactory bond performance.

The results obtained by Darwin and Graham [12] indicate that for a constant R_r, deformation spacing s_r may be increased up to the diameter of the bar d_b without affecting bond strength, although the following recommendation will be limited to a somewhat more conservative value of $0.9d_b$. Based on results reported here and in prior research [13–15], it is recommended that the ASTM reinforcing bar specifications be modified with the addition of the following (using ASTM A615 [1] as the example):

> "7.6 The maximum deformation spacing listed in **Table 1** (of ASTM A615) may be exceeded provided that:
>
> 7.6.1 The deformation spacing is less than or equal to 90 % of the nominal bar diameter, and,

TABLE 6 Maximum bond forces, lb (kN)–No. 10 (No. 32) bars.

Specimen	Meets Specifications	Does Not Meet Specifications
1	33,702 (149.9)	
2		33,888 (150.7)
3	32,022 (142.4)	
4		33,727 (150.0)
5	37,726 (167.8)	
6		37,304 (165.9)
7	38,968 (173.3)	
8		36,588 (162.7)
9	42,929 (202.0)	
10		32,885 (146.3)
11	40,571 (190.9)	
12		37,934 (168.7)
14		41,655 (185.3)
Average	37,653 (167.5)	36,283 (161.4)
Std. Dev	4,133 (18.3)	3,070 (13.7)
COV	0.110	0.085
	Ratio	96.4 %

TABLE 7 (New **Table 2** in ASTM A615)—Requirements for bars with high deformation spacing.

Bar Designation No.	Maximum Deformation Spacing, in. (mm)	Minimum Ratio[a]
3 (10)	0.337 (8.5)	0.057
4 (13)	0.450 (11.4)	0.057
5 (16)	0.562 (14.3)	0.064
6 (19)	0.675 (17.2)	0.071
7 (22)	0.787 (20.0)	0.071
8 (25)	0.900 (22.8)	0.071
9 (29)	1.015 (25.8)	0.071
10 (32)	1.143 (29.1)	0.071
11 (36)	1.269 (32.2)	0.071
14 (43)	1.523 (38.7)	0.071
18 (57)	2.031 (51.6)	0.064

[a] Ratio of average deformation height to average deformation spacing.

7.6.2 The ratio of deformation height to deformation spacing is greater than or equal to the minimum ratio presented in a new Table in ASTM A615."

The proposed new table for ASTM A615 is presented as **Table 7** in this paper.

The minimum ratios presented in the proposed table equal the ratios of the minimum allowable deformation height and the maximum deformation spacing prescribed in the ASTM reinforcing bar specifications [1–5] and will result in minimum relative rib areas equal to those obtained under the current specifications (shown in **Table 1**). For simplicity, the ratio of deformation height to deformation spacing is recommended in lieu of the relative rib area.

Conclusions and Recommendations

The following conclusions and recommendations are based on the results of the tests and analysis presented in this report:

(1) The test results match earlier research findings and demonstrate that bond strength is not governed by the specific value of deformation height or spacing, but by the combination of the two, as represented by the *relative rib area* of the bars.

(2) The bond strengths of the bars with deformation spacings that exceed those specified in the ASTM reinforcing bar specifications are similar to those that meet the specifications. The observed differences in bond strength are not statistically significant.

(3) The ASTM reinforcing bar specifications should be modified to allow for bar deformations to be spaced up to 90 % of the nominal bar diameter, provided that the minimum ratios of deformation height to deformation spacing based on the current requirements are satisfied.

ACKNOWLEDGMENTS

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