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THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
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ABSTRACT

The bond strength of two sets of No. 7 reinforcing bars was evaluated in accordance with ASTM A944. One set satisfied the criterion for maximum deformation spacing specified in ASTM A615, while the other had deformations that exceeded the maximum spacing. All bars exceeded 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 A615, is also reviewed. The test results match earlier research and demonstrate that (1) the bond strength of the bars with deformation spacings that exceed those specified in ASTM A615 is similar to the bond strength of the bars that meet the specification, and (2) the differences in bond strength observed in the tests are not statistically significant. The bars tested in this study with deformation spacings that exceed those specified in ASTM A615 will provide satisfactory bond performance and can be used in all concrete construction.

Keywords: bond (concrete to reinforcement); deformed reinforcement; relative rib area; structural engineering.

ACKNOWLEDGEMENTS

Funding and material support for this research was provided by Nucor Corporation.

INTRODUCTION

The Jackson Mill of Nucor Corporation rolled reinforcing bars with deformation spacings that exceed the maximum allowable value permitted by the governing specification, ASTM A615. The principal question is whether the wide deformation spacings compromise the bond strength of the bars.

This report describes research, including the research used to establish the requirements for deformations in ASTM A615 and bond tests performed in accordance with ASTM A944, that demonstrates that the reinforcing bars in question will provide satisfactory performance in bond and can be used in all reinforced concrete construction.

BACKGROUND*

The requirements for deformation height and spacing in ASTM A615 and other ASTM reinforcing bar standards are based on research performed by Arthur P. Clark (1946, 1949) at the National Bureau of Standards (now the National Institute of Standards and Technology). Clark's research demonstrated 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 (bars perimeter times distance between ribs) increases. The ratio is referred to as the "relative rib area." The relative rib area R_r can be expressed as

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

In the case of conventional reinforcing bars that have longitudinal ribs, R_r may be calculated as (ACI Committee 408 2009)

*The Background section is extracted and reproduced from Darwin et al. (2008).

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

where

h_r	=	average height of deformations, in. or mm
s_r	=	average spacing of deformations, in. or mm
$\sum gaps$	=	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.

Clark and other researchers (Soretz and Holzenbein 1979, Kimura and Jirsa 1992, Darwin and Graham 1993, Darwin et al. 1996a, 1996b, Zuo and Darwin 2000) 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 ½ in. or smaller, 4.5% for bars with a nominal diameter of $^5/_8$ in., and 5% for larger bars (ASTM A305-49). These provisions constitute the major deformation requirements in use today (ASTM A615, A706). With these provisions, combined with the ASTM limitation 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 (Choi et al. 1990).

Table 1 – Properties of bars meeting the requirements of ASTM A615

		Deformation Requirements, in.			
Bar Designation No.	**Nominal Diameter in.**	**Maximum Average Spacing**	**Minimum Average Height**	**Maximum Sum of Gaps**	**Minimum Relative Rib Area**
3	0.375	0.262	0.015	0.286	0.043
4	0.500	0.350	0.020	0.382	0.043
5	0.625	0.437	0.028	0.478	0.048
6	0.750	0.525	0.038	0.572	0.054
7	0.875	0.612	0.044	0.668	0.054
8	1.000	0.700	0.050	0.776	0.054
9	1.128	0.790	0.056	0.862	0.053
10	1.270	0.889	0.064	0.974	0.054
11	1.410	0.987	0.071	1.080	0.054
14	1.693	1.185	0.085	1.296	0.054
18	2.257	1.580	0.102	1.728	0.048

Using specially machined 1-in. diameter bars with relative rib areas ranging from 0.05 to 0.20 (within and above the typical range of R_r), Darwin and Graham (1993) demonstrated that the relative rib area plays no role in the bond strength for bars not confined by transverse reinforcement but does play a role for bars confined by transverse reinforcement. The results obtained by Darwin and Graham (1993) are summarized in Figure 1. It 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 (Figure 1) is that the bars with deformation height h = 0.10 had a deformation spacing of 1 in., equal to one bar diameter and, thus, greater than the value of 70% of the bar diameter allowed by ASTM A615, 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 (Darwin et al. 1996a, 1996b, Zuo and Darwin 2000). The role of the relative rib area is now well understood and widely accepted (ACI Committee 408 2003, 2009).

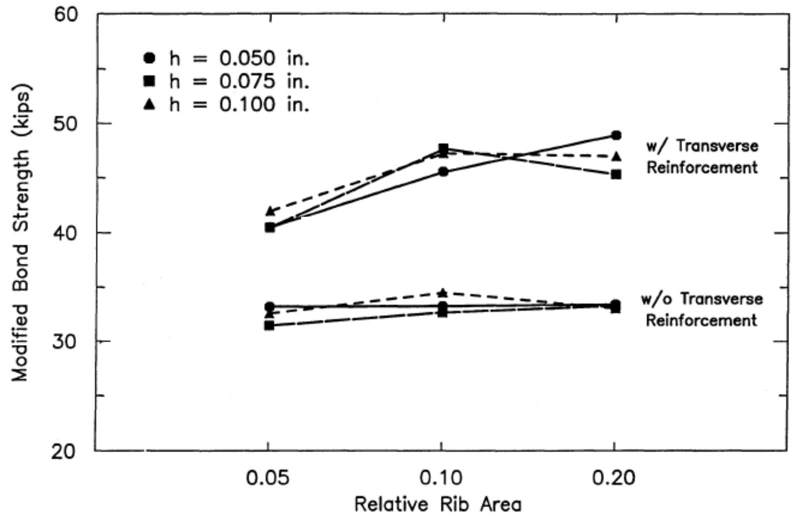

Figure 1 – Relationship between bond strength and relative rib area for machined bars with heights of deformation equal to 0.05, 0.075, and 0.100 in. (Darwin and Graham 1993)

The bond test used by Darwin and Graham (1993) has been standardized as ASTM A944 "Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens." One application of the test procedure is to qualify epoxy-coated reinforcement specified in ASTM A775 and A934.

In the current study, No. 7 bars are tested for bond strength in accordance with ASTM A944. The bond strength of bars with deformations that exceed the maximum spacing requirements is compared with the bond strength of bars that meet the spacing requirements.

EXPERIMENTAL WORK

Bar Properties

Two sets of No. 7 reinforcing bars were tested in this study. For each set, deformation height and spacing were measured at three locations along the bar and the average relative rib area calculated using Eq. (2). Average height measurements were obtained in two ways:

1- In accordance with ASTM A615, a single deformation height measurement was obtained by taking the average of three measurements at the midpoint and quarter points between the two longitudinal ribs.

2- For relative rib area calculations, the height for a single deformation was obtained by the mean of measurements at the midpoint, the average of ends, and the two points midway between the midpoint and the end points.

Three deformations were measured on each side of the bar. Both sets of bars exceeded the ASTM A615 requirements for minimum deformation height.

Deformation spacing was determined by measuring the distance between a minimum of 10 deformations and dividing by the number of deformations spanned. Three such measurements were taken on each side of the bar of the two sets of bars received, one set satisfied the criterion for maximum deformation spacing, while the other had deformations that exceeded the maximum spacing. The individual bar readings are presented in Tables A.1 and A.2 in Appendix A, and the bar properties are summarized in Table 2. All bars had values of relative rib area R_r that exceeded the minimums listed in Table 1, with values of 0.078 for bars that did not meet the spacing requirements and 0.110 for those that met the spacing requirements.

Table 2 – Bar Properties

			Deformation Properties, in.					
Meets Specification for Spacing	**Bar Designation No.**	**Nominal Diameter in.**	**Average Spacing***			**Average Height**	**Sum of Gaps**	**Relative Rib Area**
			Side 1	**Side 2**	**Total**			
No	7	0.875	0.631	0.648	0.639	0.0556	0.279	0.078
Yes	7	0.875	0.492	0.492	0.492	0.0593	0.245	0.110

* Maximum spacing in accordance with ASTM A615 = 0.612 in. for No. 7 bars

Concrete

The concrete used to fabricate the test specimens was supplied by a local ready mix plant. The concrete contained Type I/II Portland cement; ¾-in. nominal maximum size crushed limestone, and Kansas River sand, and had a water-cement ratio of 0.42. Adva 140, a Type F superplasticizer produced by W. R. Grace, was used to improve the workability of the mix. The mix proportions of the concrete are provided in Table 3.

Table 3 – Concrete Mixture Proportions

Material	**Quantity (SSD)**
Type I/II Cement	564 lb/yd^3
Water	238 lb/yd^3
Kansas River Sand	1516 lb/yd^3
Crushed Limestone	1709 lb/yd^3
Estimated Air Content	1.50%
Superplasticizer Adva 140	28 fl oz

Table 4 – Specimen Properties

Bar Size	**No. 7**
Nominal Concrete Cover	1.8 in.
Embedment Length	12.5 in.
Lead Length	1/2 in.
Moisture Condition of Concrete during Test	Air dry
Age at Test	12 days
Average Compressive strength	5010 psi

Specimen Preparation and Testing

The specimens were prepared and tested in accordance with ASTM A944. A summary of specimen properties is presented in Table 4.

The specimens had dimensions (width × length × depth) of 9 × 24 × 20 in. The specimens were fabricated in accordance with ASTM A944. Specimens containing bars that met and did not meet specifications were alternated in the order of casting to minimize the effects of differences in concrete properties from different portions of the batch, as recommended in ASTM A944. Test cylinders were cast in accordance with ASTM C192 and cured under the same ambient conditions as the test specimens. When the compressive strength of the concrete exceeded 3000 psi, wet curing was discontinued, the forms were removed, and the specimens and concrete cylinders were allowed to dry. Specimens were tested 12 days after casting. The average concrete compressive strength at the time of testing was 5010 psi (individual cylinder strengths of 4780, 5020, and 5220 psi).

Thirteen beam-end specimens were cast and tested. Seven specimens contained bars that did not meet the deformation spacing requirements of ASTM A615 and six specimens contained bars that met all of requirements of ASTM A615. Specimen No.1 was used to verify the functionality of the testing equipment and does not appear in this report.

During the tests, displacements at the loaded and unloaded ends of the bars were measured using linear variable differential transformers (LVDTs), while loads were measured using a calibrated load cell. The test method requires that loads be applied so that the peak lead is attained in 3 to 10 minutes. As shown in Table 5, the loading rates for the specimens satisfied the requirements in ASTM A944, except for specimen 6, which had a time to peak load that was slightly lower than 3-minute minimum specified.

Table 5 – Loading Rates

No. 7 bar specimens		
Specimen	**Time to Peak Load (min.)**	**Load Rate (kips/min)**
2	3:00	8.93
3	3:17	7.14
4	3:01	9.01
5	3:40	7.11
6	2:50	7.72
7	3:26	7.14
8	3:38	6.70
9	3:09	7.13
10	4:31	5.61
11	3:45	7.03
12	3:56	7.40
13	3:58	6.63

RESULTS

The specimens were tested over a six-hour period. Figure 2 shows the relationship between the load and bar displacement at the loaded end of the test bar for specimens containing bars with deformations that met the requirements of ASTM A615. The loaded end displacements varied from 0.03 to 0.067 in. with average of 0.052 in. at the peak loads. Figure 3 shows the relationship between the load and bar displacement at the unloaded end for specimens with bars with deformations that met the requirements of ASTM A615. The unloaded end displacements were approximately zero until the peak load was reached, after which the bar began to slip.

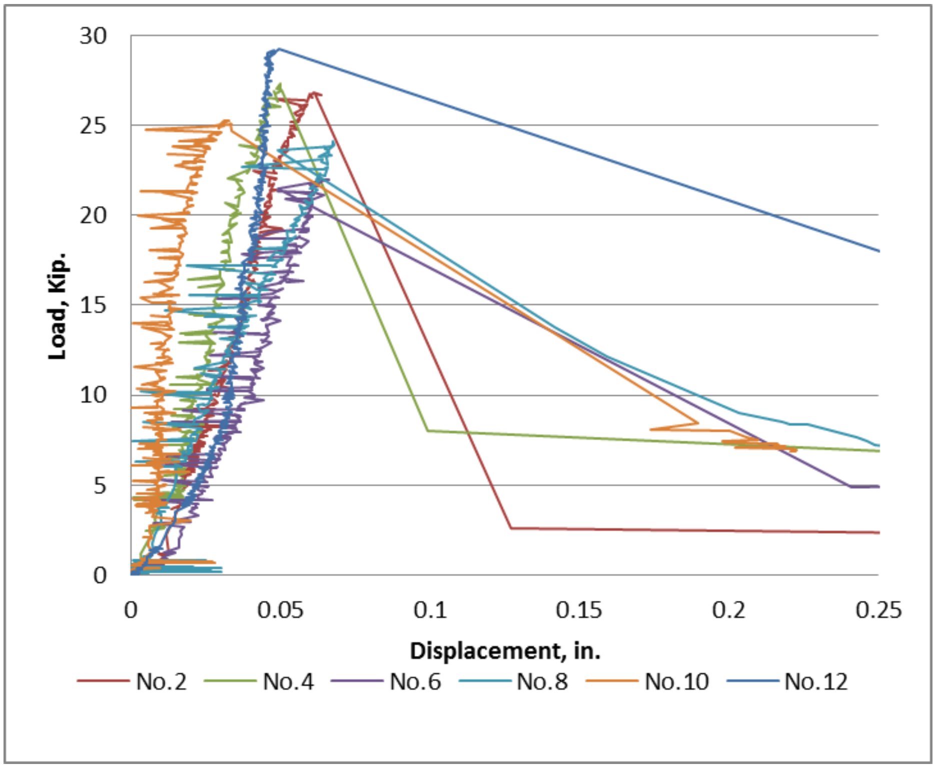

Figure 2 – Loaded-end slip versus load for specimens with reinforcement meeting the deformation spacing requirements in ASTM A615.

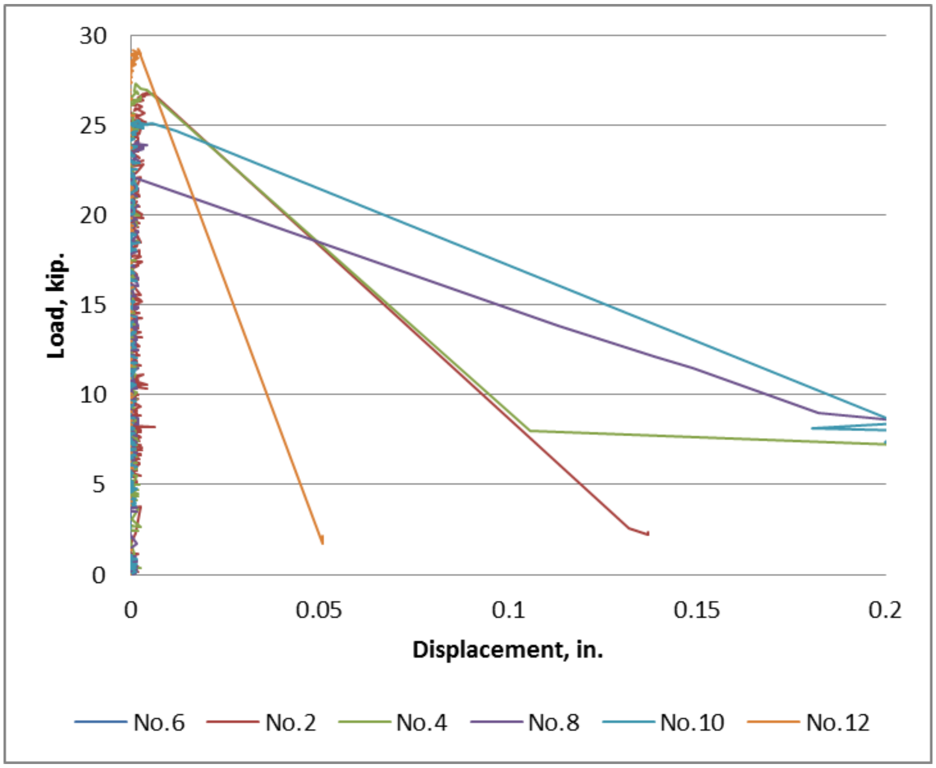

Figure 3 – Unloaded-end slip versus load for specimens with reinforcement meeting the deformation spacing requirements in ASTM A615.

Figure 4 shows the relationship between the load and bar displacement at loaded end for specimens with bars with deformations that did not meet the requirements of ASTM A615. The loaded end displacements varied from 0.02 to 0.10 in. with an average of 0.049 in. at the peak loads. Although the variation of the loaded end displacement for specimens containing bars which did not meet the ASTM requirements was more than that of the specimens reinforced with bars which met the ASTM requirements, the average slip was approximately the same. Figure 5 shows the relationship between the load and bar displacement at unloaded end for specimens with bars with deformations that did not meet the requirements of ASTM A615. Problems with the LVDT connection prevented data from being recorded for specimen 11. As with the bars that met the specifications, the unloaded end displacements were approximately zero until the peak load was reached, after which the bar began to slip.

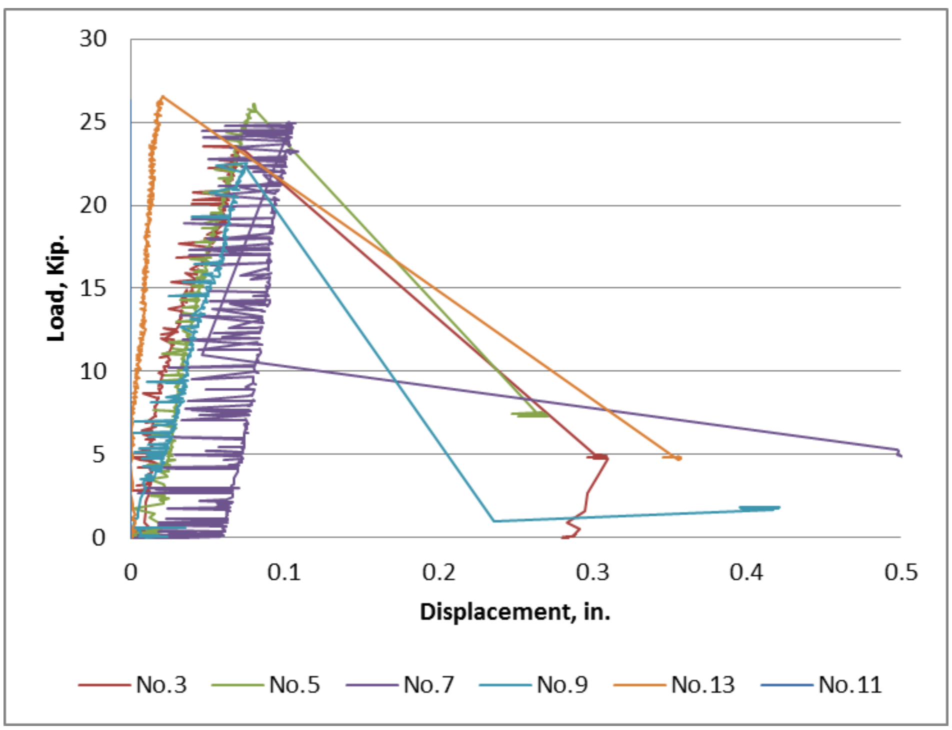

Figure 4 – Loaded-end slip versus load for specimens with reinforcement that exceeded the maximum deformation spacing requirements in ASTM A615.

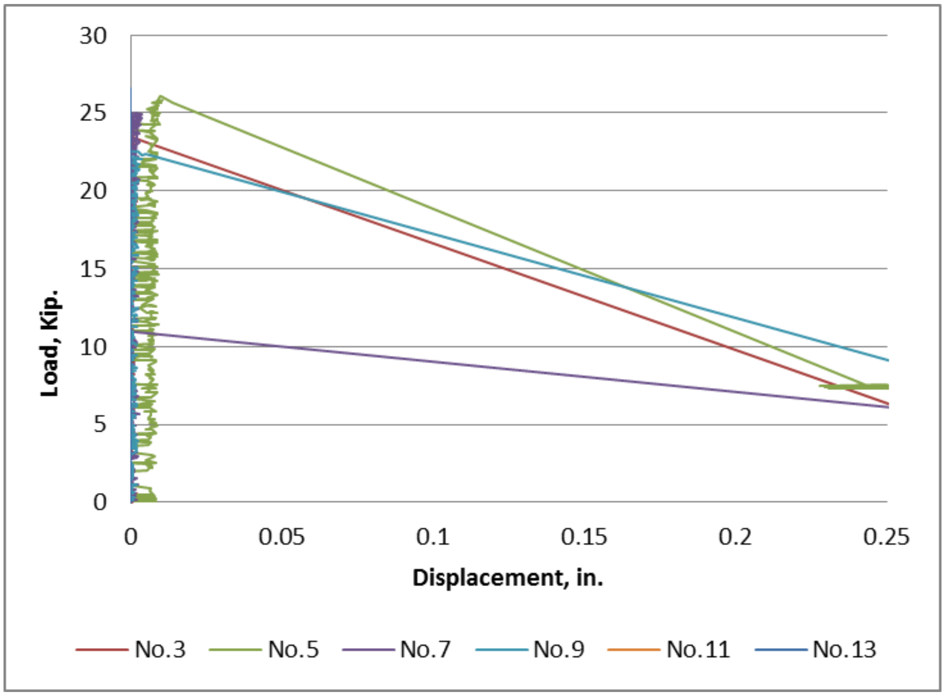

Figure 5 – Unloaded-end slip versus load for specimens with reinforcement that exceeded the maximum deformation spacing requirements in ASTM A615.

Figure 6 shows a typical failure pattern for a beam- end specimen. In general, the mode of failure for all of the specimens was splitting along the top surface of the specimen. This type of failure is expected in specimens that have a top cover smaller than the side cover, as is the case for ASTM A944 specimens.

Figure 6 – Specimen No. 2 after failure.

Bond Strength

The maximum bond forces (bond strengths) of the specimens are shown in Table 6.

Equation 3 (ACI Committee 408 2003) was used to normalize the results to account for the effect of the actual cover, which varied slightly from the target cover of 1.8 in.

$$\frac{T_c}{f_c'^{1/4}} = [63 l_d (c_{min} + 0.5 d_b) + 2130 A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right) \quad (3)$$

Where

T_c = the bond force that would be developed without transverse reinforcement, lb.

c_{min} = minimum cover, in.

c_{max} = maximum cover, in.

l_d = development length, in.

d_b = diameter of bar, in.

A_b = Area of bar, in.^{2}

Table 6 – Bond Strengths – No. 7 Bars

Specimen	Actual Force, lb		Actual Cover, in.	Adjusted Force*, lb	
	Meets Specification	Does Not Meet Specification		Meets Specification	Does Not Meet Specification
2	26,804		1.92	25,996	
3		23,575	1.95		22,693
4	2,7315		1.81	27,216	
5		26,100	1.88		25,551
6	21,996		1.83	21,826	
7		24,989	1.87		24,556
8	24,105		1.88	23,616	
9		22,529	1.79		22,588
10	25,251		1.91	24,564	
11		26,351	1.89		25,783
12	29,224		1.71	29,953	
13		26,536	1.88		25,997
Average	25,783	25,013		25,529	24,528
Std. Dev	2556	1645		2862	1544
COV	0.099	0.066		0.112	0.063
	Ratio	97%		Ratio %	96.1%

***** Adjusted Force scales the load to account for variations in cover.

The correction factor is the ratio of the calculated bond strength for the bar with target cover to the calculated bond strength for the bar with the actual cover. The mean bond strength of the specimens with the deformation spacing that exceeded that allowed in ASTM A615 is 96% of the mean bond strength of the specimens containing bars that meet the specification. The specimens with the bars that did not meet the specifications had adjusted bond strengths that ranged from 22,588 to 25,997 lb with an adjusted mean bond strength of 24,528 lb, standard deviation of 1543 lb, and coefficient of variation of 0.063. The specimens containing the bars that met the specification had adjusted bond strengths that ranged from 21,826 to 29,953, with an adjusted mean bond strength of 25,528 lb, standard deviation of 2861 lb, and coefficient of variation of 0.112. The adjusted mean bond strength for the specimens with bars that did not meet the specification differs by 1000 lb, equals 35% of one standard deviation, from the adjusted mean bond strength of the specimens with the bars that met the specification, indicating little statistical difference between the two. To compare the mean bond strengths of bars that exceed ASTM A615 limits with the ones which meet the specification, Student's t-test was performed. Student's t-test is a method of statistical analysis that compares two data sets to determine the probability α that any differences between the two data sets could have arisen by chance. Differences are considered statistically significant if the probability is 5% or less (α is less than 0.05) that the difference between the two data sets has resulted by chance. For these tests, $\alpha = 0.47$, and thus, the difference in bond strength between the two sets of bars is not considered to be statistically significant.

DISCUSSION

The similarity in bond strengths between the bars with deformation spacings that exceeded those specified in ASTM A615 to those that met the specification is as expected based on the original work by Clark (1946, 1949) and subsequent studies (Soretz and Holzenbein 1979, Kimura and Jirsa 1992, Darwin and Graham 1993, Darwin et al. 1996a, 1996b, Zuo and Darwin 2000). 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 it was not in the current tests. The bars that did not meet the specifications of ASTM A615 showed similar bond strengths to bars that did meet the specifications, despite having a lower relative rib area (0.0765 vs. 0.107), this indicates that these bars will provide satisfactory bond performance and can be used in all concrete construction.

CONCLUSIONS

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

1. The bond strengths of the bars with deformation spacings that exceed those specified in ASTM A615 are similar to those that meet the specification. The differences in bond strength are not statistically significant.

2. The bars tested in this study with deformation spacings that exceed those specified in ASTM A615 will provide satisfactory bond performance and can be used in all concrete construction.

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Appendix A

Table A.1 – Deformation readings for No. 7 bars, deformation spacing exceeds requirements of ASTM A615

Rib height (mm)

Side A							ASTM
Location	Adjacent to rib	Half way	Midpoint	Half way	Adjacent to rib	Avg.	Avg.
1	1.24	1.38	1.27	1.67	1.35	1.40	1.44
2	1.23	1.30	1.27	1.67	1.20	1.36	1.41
3	1.14	1.46	1.39	1.35	1.30	1.36	1.40
Side B							
Location	**Adjacent to rib**	**Half way**	**Midpoint**	**Half way**	**Adjacent to rib**	**Avg.**	**Avg.**
1	1.12	1.46	1.36	1.71	1.49	1.46	1.51
2	1.28	1.45	1.25	1.57	1.67	1.44	1.42
3	1.32	1.38	1.30	1.66	1.65	1.46	1.45

Average Rib height: 1.41 mm

Rib Spacing

Side	Location	Meas. (in.)	(mm)	# of spaces	Avg. Spacing (mm)
A	1	5.687	144.44	9	16.05
	2	5.664	143.86	9	15.99
	3	5.691	144.55	9	16.06
B	1	5.826	147.98	9	16.44
	2	5.843	148.41	9	16.49
	3	5.822	147.87	9	16.43
Average:					16.24

Gap width

Side	Location	Meas. (in.)	(mm)
A	1	0.139	3.53
	2	0.143	3.63
	3	0.143	3.63
Avg.:		0.14	3.60
B	1	0.137	3.47
	2	0.136	3.45
	3	0.141	3.58
Avg.:		0.14	3.51
Sum:		0.28	7.10

Relative Rib area: 0.0780

Table A.2 – Deformation readings for No. 7 bars, deformation spacing satisfies requirements of ASTM A615

Rib height (mm)

Side A							**ASTM**
Location	**Adjacent to rib**	**Half way**	**Midpoint**	**Half way**	**Adjacent to rib**	**Avg.**	**Avg.**
1	1.40	1.53	1.40	1.59	1.35	1.47	1.51
2	1.41	1.41	1.39	1.53	1.48	1.44	1.44
3	1.20	1.31	1.37	1.62	1.44	1.41	1.43
Side B							
Location	**Adjacent to rib**	**Half way**	**Midpoint**	**Half way**	**Adjacent to rib**	**Avg.**	**Avg.**
1	1.64	1.63	1.58	1.59	1.43	1.58	1.60
2	1.52	1.64	1.63	1.54	1.26	1.55	1.60
3	1.68	1.59	1.52	1.67	1.44	1.59	1.59

Average Rib height: 1.51 mm

Rib Spacing

Side	**Location**	**Meas. (in.)**	**(mm)**	**# of spaces**	**Avg. Spacing (mm)**
A	1	4.4115	112.05	9	12.45
	2	4.445	112.90	9	12.54
	3	4.43	112.52	9	12.50
B	1	4.443	112.85	9	12.54
	2	4.432	112.57	9	12.51
	3	4.415	112.14	9	12.46
Average:					12.50

Gap Width

Side	**Location**	**Meas. (in.)**	**(mm)**
A	1	0.118	2.99
	2	0.129	3.27
	3	0.118	2.99
Avg.:		0.12	3.09
B	1	0.115	2.92
	2	0.126	3.20
	3	0.131	3.32
Avg.:		0.124	3.14
Sum:		0.24	6.23

Relative Rib area: 0.109