BOND STRENGTH OF REINFORCING BARS WITH DEFORMATION SPACINGS THAT EXCEED MAXIMUM SPECIFIED IN ASTM A615

By

David Darwin
JoAnn Browning
Matthew O'Reilly
Lihua Xing

A Report on Research Sponsored by

NUCOR Corporation

Structural Engineering and Materials Laboratory
SL Report 08-1
March 2008

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

BOND STRENGTH OF REINFORCING BARS WITH DEFORMATION SPACINGS THAT EXCEED MAXIMUM SPECIFIED IN ASTM A615

By

David Darwin

JoAnn Browning

Matthew O'Reilly

Lihua Xing

A Report on Research Sponsored by the

NUCOR Corporation

Structural Engineering and Engineering Materials

SL Report 08-1

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.

LAWRENCE, KANSAS

March 2008

ABSTRACT

No. 5 and No. 10 bars are tested for bond strength in accordance with ASTM A944. For each bar size, the bond strength of bars with deformations that exceed the maximum spacing requirements in ASTM A615 is compared with the bond strength of bars that meet the spacing requirements. 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 A615, 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, (2) 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 (3) 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 have relative rib areas that exceed the minimum values that result from the provisions of ASTM A615. They 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 Birmingham Mill of Nucor Corporation rolled reinforcing bars in various sizes with deformation spacings that exceed the maximum allowable value permitted by the govern 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 2001)

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

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 0.840 (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 2001, 2003).

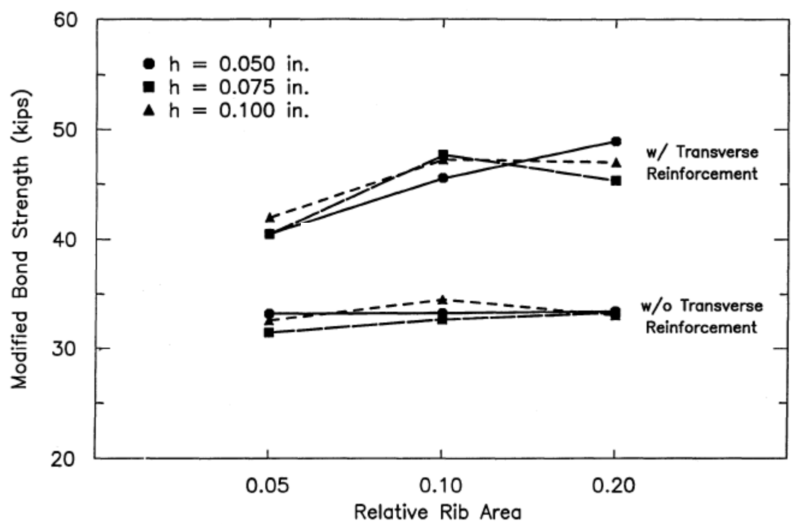

Figure 1 Relationship between bond strength and relative rib area for machined bars with heights of deformation equal to 0.05, 0.075, and 0.100 in. (Darwin and Graham 1993)

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. 5 and No. 10 bars are tested for bond strength in accordance with ASTM A944. For each bar size, 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. The results match those of earlier tests and demonstrate that the bars will provide satisfactory bond performance and can be used in all reinforced concrete construction.

EXPERIMENTAL WORK

Bar Properties

Two heats of No. 5 bars and two heats of No. 10 bars were tested in this study. For each, deformation height and spacing were measured at five locations on both sides of one bar, and the average relative rib areas were calculated using Eq. (2). All bars exceeded the requirements for minimum deformation height. One bar of each size satisfied the criterion for maximum deformation spacing, while the other had deformations that exceeded the maximum spacing. The individual bar readings are presented in Table A.1 through A.4 in Appendix A, and the bar properties are summarized in Table 2. All bars had relative rib areas R_r that exceeded the minimums listed in Table 1, with values ranging from 0.070 to 0.084.

Table 2 – Properties of bars used in the tests

			Deformation Properties, in.			
Meets Specification for Spacing	**Bar Designation No.**	**Nominal Diameter in.**	**Average Spacing***	**Average Height**	**Sum of Gaps**	**Relative Rib Area**
No	5	0.500	0.440	0.0412	0.312	0.079
Yes	5	0.500	0.391	0.0377	0.260	0.084
No	10	1.270	0.901	0.0735	0.564	0.070
Yes	10	1.270	0.768	0.0656	0.559	0.073

* Maximum spacing in accordance with ASTM A615 = 0.437 in. for No. 5 bars and 0.889 in. for No. 10 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 0.425. Adva 100, a Type F superplasticizer, 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 100	28 fl oz

Table 4 – Specimen Properties

	No 5.	No. 10
Concrete Cover	1-1/4 in.	2-5/8 in.
Embedment Length	8-7/8 in.	14-3/8 in.
Lead Length	1/2 in.	1/2 in.
Moisture Condition of Concrete during Test	Air dry	Air dry
Age at Test	12 days	9 days
Compressive strength	5120 psi	5030 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 No. 5 bar specimens had dimensions (width × length × depth) of 9 × 24 × 19 in., while the No. 10 bar specimens had dimensions of 9 × 24 × 19.5 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 2000 psi, wet curing was discontinued, the forms were removed, and the specimens and concrete cylinders were allowed to dry.

Fourteen beam-end specimens were cast and 13 were tested for each bar size; 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. For the No. 5 and 10 bar tests, respectively, Specimens 1 and 13, containing bars that met the specification, were used to verify the functionality of the testing equipment and do 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 calibrated load cells that served as loading rods for the test. The loading rates for the specimens satisfied the requirements in ASTM A944 and are given in Table 4.

RESULTS

No. 5 bar specimens – The specimens containing the No. 5 bars were tested over a five-hour period. The average concrete compressive strength was 5120 psi (individual cylinder strengths of 5070, 5140 and 5160 psi). Electronic interference impaired the accuracy of the LVDTs used to measure bar slip. Therefore, the loaded and unloaded end displacements for specimens with No. 5 reinforcement have been omitted from this report.

Table 4 – Loading rates

No. 5 bar specimens		No. 10 bar specimens	
Specimen	Load Rate (kips/min)	Specimen	Load Rate (kips/min)
2	3.41	1	6.30
3	4.60	2	6.06
4	2.40	3	6.24
5	3.24	4	8.60
6	2.21	5	6.93
7	3.07	6	11.04
8	4.45	7	9.62
9	4.02	8	11.00
10	1.95	9	10.50
11	3.96	10	9.68
12	5.52	11	10.05
13	2.98	12	10.14
14	3.58	14	12.44

No. 10 bar specimens – The specimens containing the No. 10 bars were tested over a four-hour period. The average concrete strength was 5030 psi (individual cylinder strengths of 5070, 4760 and 5260 psi). Figures 2 and 3 show the bar displacements for specimens with bars with deformations that met the requirements of ASTM A615. Figures 4 and 5 show the bar displacements for specimens with bars with deformations that exceeded the maximum spacing specified in ASTM A615.

Bond Strength

The maximum bond forces (bond strengths) of the No. 5 bar specimens are shown in Table 5. The mean bond strength of the specimens containing the No. 5 bars with the deformation spacing that exceeded that allowed in ASTM A615 is 104.1% of the mean bond strength of the specimens containing bars that met the specification. The specimens with the bars that did not meet the specifications had bond strengths that ranged from 13106 to 17384 lb with a mean bond strength of 16289 lb, a standard deviation of 1487 lb, and a coefficient of variation of 0.091. The specimens containing the bars that met the specification had bond strengths that ranged from 14647 to 16911, with a mean bond strength of 15647 lb, a standard deviation of 849 lb, and a coefficient of variation of 0.054. The mean bond strength for the specimens with bars that did not meet specification differs by 642 lb, less than one standard deviation, from the mean bond strength of the specimens with the bars that met the specification, indicating little statistical difference between the two. The data was analyzed using the Student's t-test (used to analyze small data sets), giving T = 0.932 with 11 degrees of freedom and α = 0.371,[*] also indicating that the difference in strength is not statistically significant.

[*] $\alpha > 0.20$ is generally considered to indicate that the difference between two means is not statistically significant.

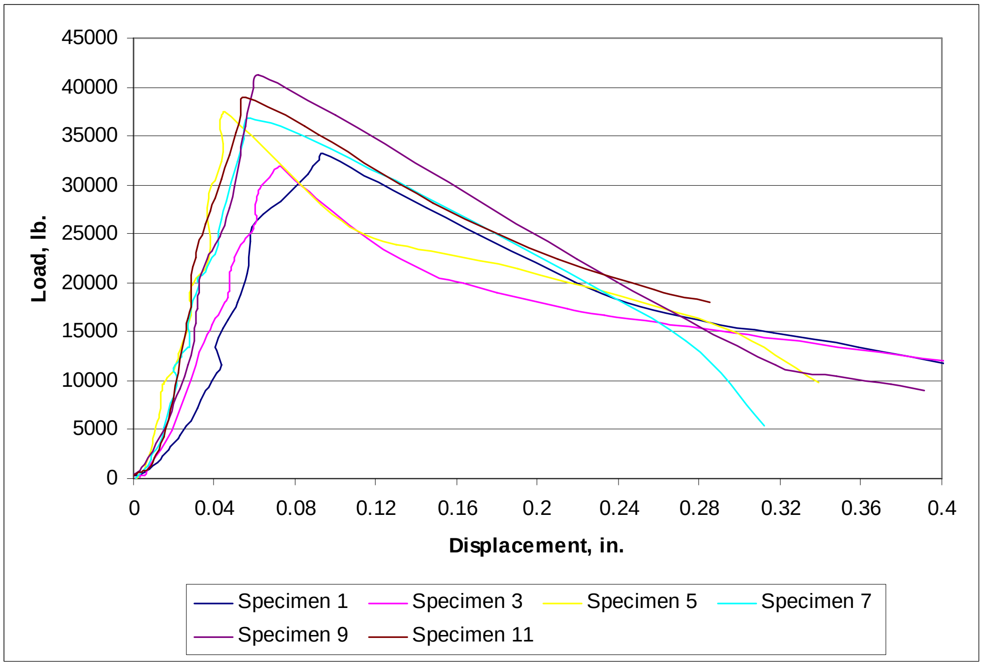

Figure 2 – Loaded-end slip versus load for specimens with reinforcement meeting the deformation spacing requirements in ASTM A615.

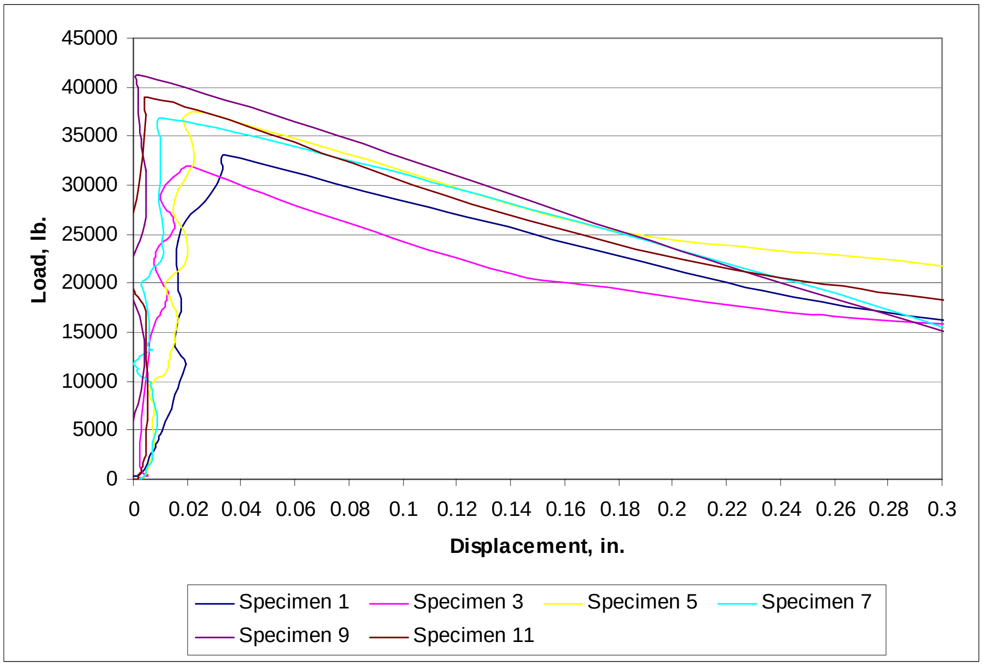

Figure 3 – Unloaded-end slip versus load for specimens with reinforcement meeting the deformation spacing requirements in ASTM A615.

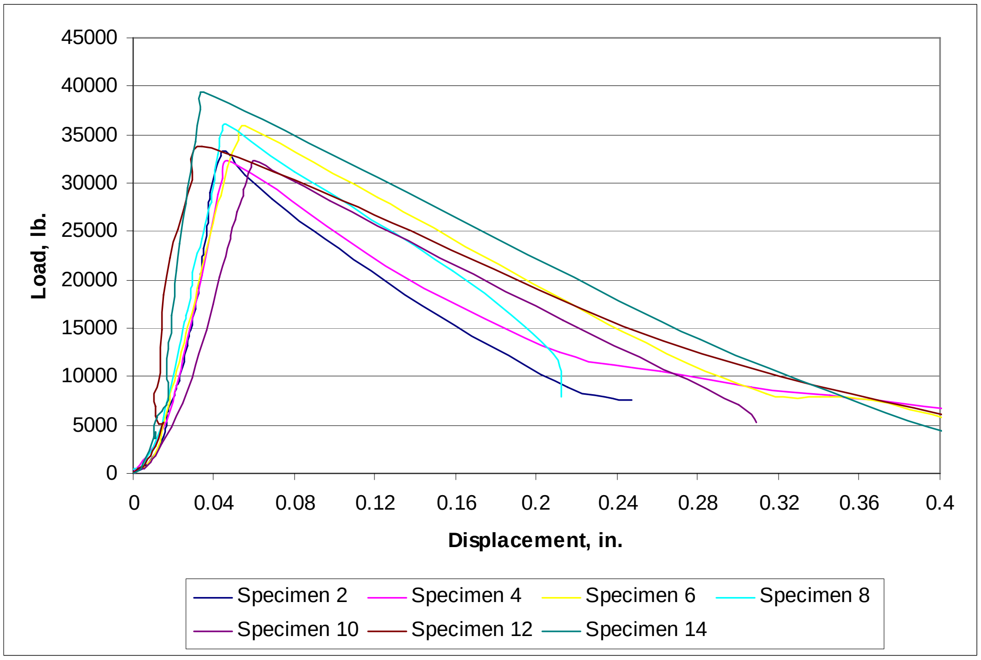

Figure 4 – Loaded-end slip versus load for specimens with reinforcement that exceeded the maximum deformation spacing requirements in ASTM A615.

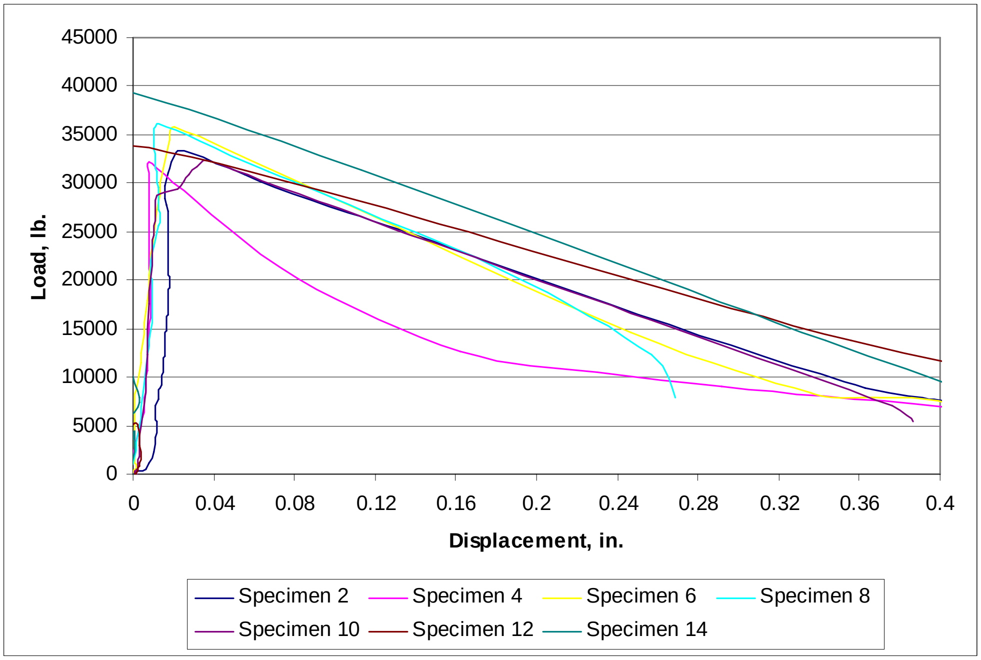

Figure 5 – Unloaded-end slip versus load for specimens with reinforcement that exceeded the maximum deformation spacing requirements in ASTM A615.

Table 5 – Bond Strengths – No. 5 Bars

	Force, lb	
Specimen	**Meet Specification**	**Do Not Meet Specification**
2		16939
3	15766	
4		16837
5	14748	
6		17173
7	16067	
8		16756
9	15744	
10		13106
11	16911	
12		17384
13	14647	
14		15831
Average	15647	16289
Std. Dev	849	1487
COV	0.054	0.091
	Ratio	104.1%

The maximum bond forces of the No. 10 test specimens are shown in Table 6. The mean bond strength of the specimens with the bars with the deformation spacing that exceeded that allowed in ASTM A615 is equal to 96.4% of the mean bond strength of the specimens with bars meeting the specification. The specimens with the bars that did not meet the specifications had bond strengths that ranged from 32885 to 41655 lb, with a mean bond strength of 36283 lb, a standard deviation of 3070 lb, and a coefficient of variation of 0.085. The specimens containing the bars that met the specification had bond strengths that ranged from 32022 to 42929, with a mean bond strength of 37653 lb, a standard deviation of 4133 lb, and a coefficient of variation of 0.110. Like the No. 5 bars, the mean bond strength for the specimens with bars that did not meet specification differs by a relatively small amount, 1370 lb (again less than one standard deviation), from the mean bond strength of the specimens with the bars that met the specification, indicating little statistical difference between the two values. Analysis using the Student's t-test, T = 0.6855, 11 degrees of freedom, and α = 0.507, also indicates that the difference in strength is not statistically significant.

Table 6 – Bond Strengths – No. 10 Bars

	Force, lb	
Specimen	**Meet Specification**	**Do Not Meet Specification**
1	33702	
2		33888
3	32022	
4		33727
5	37726	
6		37304
7	38968	
8		36588
9	42929	
10		32885
11	40571	
12		37934
14		41655
Average	37653	36283
Std. Dev	4133	3070
COV	0.110	0.085
	Ratio	96.4%

DISCUSSION

The similarity in bond strengths between the bars with deformation spacings that exceeded those specified in ASTM A615 and 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 fact, however, that the bars in question have values of R_r, 0.079 and 0.070 for the No. 5 and No. 10 bars, respectively, that exceed the minimum values that result from the provisions of ASTM A615 (Table 1) 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 tests match earlier research 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 ASTM A615 are similar to those that meet the specification. The differences in bond strength are not statistically significant.

3. The bars tested in this study with deformation spacings that exceed those specified in ASTM A615 have relative rib areas that exceed the minimum values that result from the provisions of ASTM A615. They will provide satisfactory bond performance and can be used in all concrete construction.

REFERENCES

ACI Committee 408. 2001. *Splice and Development Length of High Relative Rib Area Reinforcing Bars in Tension* (ACI 408.3-01), American Concrete Institute, Farmington Hills, MI.

ACI Committee 408. 2003. *Bond and Development of Straight Reinforcing Bars in Tension* (ACI 408R-03), American Concrete Institute, Farmington Hills, Michigan, 49 pp.

ASTM A305. 1949. "Specification for Minimum Requirements for the Deformations of Deformed Steel Bars for Concrete Reinforcement," (ASTM A305-49), American Society for Testing and Materials, Philadelphia, 1949.

ASTM A615. 2007. "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," (ASTM A615/615M-07), ASTM International, West Conshohocken PA.

ASTM A706. 2006. "Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement," (ASTM A706/A706M-06a), ASTM International, West Conshohocken PA.

ASTM A775. 2007. "Standard Specification for Epoxy-Coated Steel Reinforcing Bars," (ASTM A775/A775M-07b), ASTM International, West Conshohocken PA.

ASTM A934. 2007. “Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars,” (ASTM A934/A934M-07), ASTM International, West Conshohocken PA.

ASTM A944. 2005. “Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens,” (ASTM A944-05), ASTM International, West Conshohocken PA, 4 pp.

ASTM C192. 2007. “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory ,” (ASTM C192/C192M-07), ASTM International, West Conshohocken PA.

Choi, Oan Chul; Hadje-Ghaffari. Hossain; Darwin, David; and McCabe, Steven L., 1990. "Bond of Epoxy-Coated Reinforcement to Concrete: Bar Parameters," *SL Report* 90-1, University of Kansas Center for Research, Lawrence, Jan., 43 pp.

Choi, Oan Chul; Hadje-Ghaffari, Hossain; Darwin, David; and McCabe, Steven L., 1991. "Bond of Epoxy-Coated Reinforcement: Bar Parameters," *ACI Materials Journal*, Vol. 88, No. 2, Mar.-Apr., pp. 207-217.

Clark, A. P. 1946. "Comparative Bond Efficiency of Deformed Concrete Reinforcing Bars," ACI Journal, *Proceedings* Vol. 43, No. 4, Dec., pp. 381-400.

Clark, A. P. 1949. "Bond of Concrete Reinforcing Bars," ACI Journal, *Proceedings* Vol. 46, No. 3, Nov., pp. 161-184.

Darwin, D. and Graham, E. K. 1993. “Effect of Deformation Height and Spacing on Bond Strength of Reinforcing Bars,” *ACI Structural Journal*, Vol. 90, No. 6, Nov.-Dec., pp. 646-657.

Darwin, D., Tholen, M. L., Idun, E. K., and Zuo, J. 1996a. “Splice Strength of High Relative Rib Area Reinforcing Bars,” *ACI Structural Journal*, Vol. 93, No. 1, Jan.-Feb., pp. 95-107.

Darwin, D., Zuo, J., Tholen, M. L., and Idun, E. K. 1996b. “Development Length Criteria for Conventional and High Relative Rib Area Reinforcing Bars,” *ACI Structural Journal*, Vol. 93, No. 3, May-June, pp. 347-359.

Zuo, J. and Darwin, D. 2000. “Bond Slip of High Relative Rib Area Bars under Cyclic Loading,” *ACI Structural Journal*, Vol. 97, No. 2, Mar. - Apr, pp. 331-334.

Appendix A

Table A.1 – Deformation readings for No. 5 bars, deformation spacing exceeds requirements of ASTM A615

No.5 — Rib Height h_r, mm — Out of specification

10 sets	1	2	3	4	5	6	7	8	9	10
end	0.79	0.92	0.93	0.78	0.79	0.95	1.09	0.89	0.93	0.79
1/4	0.84	0.99	1.2	1.04	1.06	1.01	1.27	1.12	1.02	1.04
1/2	1.18	1.09	1.12	1.08	1.3	1.25	1.15	1.05	1	1.18
1/4	1	0.95	1.11	1.24	1.12	1.11	1.04	1.04	1.18	1.14
end	0.79	0.7	0.99	0.9	0.88	0.96	0.85	0.87	0.99	1.11
End average	0.79	0.81	0.96	0.84	0.835	0.955	0.97	0.88	0.96	0.95
Set average	0.95	0.96	1.10	1.05	1.08	1.08	1.11	1.02	1.04	1.08
Overall average (mm)										**1.05**
Overall average (inch)										0.0412

Rib Spacing s_r, mm

10 sets	1	2	3	4	5	6	7	8	9	10
length	134	99.1	122.9	123.1	133.9	145.8	146.1	134.9	133.4	100.4
# of spacings	12	9	11	11	12	13	13	12	12	9
set average	11.17	11.01	11.17	11.19	11.16	11.22	11.24	11.24	11.12	11.16
Overall average (mm)										**11.17**
Overall average (inch)										0.440

Height of the continous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
Line height	0.4	0.36	0.41	0.36	0.4	0.39	0.39	0.38	0.37	0.36
Average line height										**0.38**

Width of Gaps and continuous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
rib gap	3.44	3.61	3.72	3.65	3.89	3.59	3.69	3.78	3.82	3.62
rib gap	3.47	3.54	3.62	3.74	3.61	3.52	3.65	3.7	3.89	3.68
continuous lines	1.65	1.72	1.75	1.63	1.65	1.62	1.64	1.61	1.64	1.61
Sum of gap	7.51	7.78	7.98	7.98	8.10	7.70	7.94	8.07	8.31	7.89
Average of sum (mm)										**7.93**
Average of sum (inch)										0.312

Relative rib area
0.079

Table A.2 – Deformation readings for No. 5 bars, deformation spacing satisfies requirements of ASTM A615

No.5 Rib Height h_r, mm — In specification

10 sets	1	2	3	4	5	6	7	8	9	10
end	0.95	1.03	0.88	0.74	0.64	0.81	0.62	1.03	0.76	0.89
1/4	1.02	1.01	1.02	1.01	0.91	0.97	1.06	1.16	0.98	1
1/2	0.44	1.01	1.01	0.94	1.01	0.91	1.15	1.13	1.06	1.09
1/4	0.84	0.88	1.11	0.86	1	1.02	1.1	1.01	1.04	1.06
end	0.81	0.89	0.6	0.67	0.94	1.04	0.95	1.04	0.96	0.77
End average	0.88	0.96	0.74	0.705	0.79	0.925	0.785	1.035	0.86	0.83
Set average	0.80	0.97	0.97	0.88	0.93	0.96	1.02	1.08	0.99	1.00
Overall average (mm)										**0.96**
Overall average (inch)										0.0377

Rib Spacing s_r, mm

10 sets	1	2	3	4	5	6	7	8	9	10
length	130	129.1	127.7	118.8	118.7	119.9	108.3	119.5	129.8	130.5
# of spacings	13	13	13	12	12	12	11	12	13	13
set average	10.00	9.93	9.82	9.90	9.89	9.99	9.85	9.96	9.98	10.04
Overall average (mm)										**9.94**
Overall average (inch)										0.391

Gaps, mm

10 sets	1	2	3	4	5	6	7	8	9	10
rib gap	3.31	3.29	3.36	3.34	3.11	3.38	3.35	3.28	3.35	3.25
rib gap	3.48	2.85	3.51	3.29	3.32	3.27	3.39	3.3	3.11	3.39
Sum of gap	6.79	6.14	6.87	6.63	6.43	6.65	6.74	6.58	6.46	6.64
Average of sum										**6.59**
Average of sum (inch)										0.260

Relative rib area

0.084

Table A.3 – Deformation readings for No. 10 bars, deformation spacing exceeds requirements of ASTM A615

No.10 Rib Height h_r, mm Out specification

10 sets	1	2	3	4	5	6	7	8	9	10
end	1.91	1.98	2.03	1.82	1.99	1.99	1.97	2.08	1.93	2.14
1/4	2.07	2.13	1.98	1.76	1.78	1.86	1.97	1.79	1.96	1.8
1/2	1.97	1.69	1.97	1.56	1.7	1.67	1.96	1.6	2.14	1.74
1/4	1.82	1.78	1.79	1.95	1.77	1.87	2.12	2.09	2.05	1.6
end	1.75	1.74	1.53	1.91	1.86	1.8	1.65	1.82	1.99	1.59
End average	1.83	1.86	1.78	1.865	1.925	1.895	1.81	1.95	1.96	1.865
Set average	1.92	1.87	1.88	1.78	1.79	1.82	1.97	1.86	2.03	1.75
Overall average (mm)										**1.87**
Overall average (inch)										0.0735

Rib Spacing s_r, mm

10 sets	1	2	3	4	5	6	7	8	9	10
length	136.8	138.5	137.5	138.4	137.6	137.5	113.1	114.1	137.6	113.8
# of spacings	6	6	6	6	6	6	5	5	6	5
set average	22.80	23.08	22.92	23.07	22.93	22.92	22.62	22.82	22.93	22.76
Overall average (mm)										**22.89**
Overall average (inch)										0.901

Height of the continous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
Line height	0.35	0.34	0.26	0.23	0.31	0.33	0.27	0.27	0.29	0.28
Average line height										0.293

Width of Gaps and continuous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
rib gap	6.8	7.2	7.2	6.8	7.0	6.9	7.3	7.2	7.0	6.9
rib gap	7.0	6.9	7.0	6.9	7.0	7.1	7.0	7.0	7.1	7.0
continuous lines	1.96	1.95	1.96	1.91	1.87	1.94	1.93	1.95	1.96	1.98
Sum of gap	14.11	14.41	14.51	14.00	14.29	14.30	14.60	14.51	14.41	14.21
Average of sum										**14.33**
Average of sum (inch)										0.564

Relative rib area

0.070

Table A.4 – Deformation readings for No. 10 bars, deformation spacing satisfies requirements of ASTM A615

No.10 — Rib Height h_r, mm — In specification

10 sets	1	2	3	4	5	6	7	8	9	10
end	1.79	1.71	1.63	1.49	1.61	1.66	1.21	1.56	1.62	1.3
1/4	1.73	1.73	1.61	1.52	1.6	1.8	1.63	1.54	1.74	1.64
1/2	1.93	1.54	1.75	2.04	1.7	1.68	1.99	1.51	1.74	1.62
1/4	1.65	1.51	1.82	1.61	1.69	1.69	1.6	2.11	1.61	1.67
end	1.55	1.48	1.51	1.57	1.61	1.65	1.74	1.6	1.59	1.52
End average	1.67	1.595	1.57	1.53	1.61	1.655	1.475	1.58	1.605	1.41
Set average	1.75	1.59	1.69	1.68	1.65	1.71	1.67	1.69	1.67	1.59
Overall average (mm)										**1.67**
Overall average (inch)										0.0656

Rib Spacing s_r, mm

10 sets	1	2	3	4	5	6	7	8	9	10
length	137.9	137.8	137.1	136.2	116.2	115.1	135.9	137.2	135.36	138.3
# of spacings	7	7	7	7	6	6	7	7	7	7
set average	19.70	19.69	19.59	19.46	19.37	19.18	19.41	19.60	19.34	19.76
Overall average (mm)										**19.51**
Overall average (inch)										0.768

Height of the continous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
Line height	0.21	0.28	0.29	0.26	0.25	0.27	0.24	0.25	0.3	0.3
Average line height										0.265

Width of Gaps and continuous line, mm

10 sets	1	2	3	4	5	6	7	8	9	10
rib gap	7.1	7.2	6.9	7.2	7.3	6.7	6.9	7.1	7.1	6.9
rib gap	7.2	7.0	7.0	7.1	7.2	6.8	7.1	6.8	7.0	6.8
continuous lines	2.04						2.02	2.04	2.05	2.05
Sum of gap	14.62	14.20	13.90	14.30	14.50	13.50	14.32	14.22	14.43	14.03
Average of sum										**14.20**
Average of sum (inch)										0.559

Relative rib area

0.073