BOND STRENGTH OF PREFABRICATED EPOXY-COATED REINFORCEMENT

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16. Abstract

Prefabricated epoxy-coated reinforcement is used increasingly in reinforced concrete construction in which high corrosion resistance is required. It is well established that epoxy coating reduces bond strength between reinforcement and concrete, and some tests have found that bond strength decreases as coating thickness increases. For prefabricated epoxy-coated reinforcement, it can be difficult to maintain coating thicknesses within required tolerances 175 to 300 μm. Beam-end tests were carried out on uncoated bars, bars with green epoxy coating (203 μm coating thickness), and prefabricated (gray) epoxy coating (203 to 508 μm coating thickness). Tests showed that epoxy coating reduces bond strength, with similar reductions for green and gray coatings. In some cases, bond strength decreased with increasing coating thickness, but for the range of thicknesses investigated the reduction factor of current building codes was found to be conservative.

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BOND STRENGTH OF PREFABRICATED EPOXY-COATED REINFORCEMENT

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ABSTRACT

Prefabricated epoxy-coated reinforcement is used increasingly in reinforced concrete construction in which high corrosion resistance is required. It is well established that epoxy coating reduces bond strength between reinforcement and concrete, and some tests have found that bond strength decreases as coating thickness increases. For prefabricated epoxy-coated reinforcement, it can be difficult to maintain coating thicknesses within required tolerances 175 to 300 μm. Beam-end tests were carried out on uncoated bars, bars with green epoxy coating (203 μm coating thickness), and prefabricated (gray) epoxy coating (203 to 508 μm coating thickness). Tests showed that epoxy coating reduces bond strength, with similar reductions for green and gray coatings. In some cases, bond strength decreased with increasing coating thickness, but for the range of thicknesses investigated the reduction factor of current building codes was found to be conservative.

INTRODUCTION

Epoxy coatings are used to increase the corrosion resistance of steel reinforcement used in reinforced concrete construction. The coating can be applied either before or after the reinforcement is fabricated. In the former method, the epoxy coating is applied to straight reinforcing bars, which subsequently are bent (fabricated) into required shapes. Bars prepared using this procedure commonly are known as “green epoxy-coated bars” because of the green

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color of the epoxy that is used. Sometimes the fabrication process can cause damage to the green epoxy coating, leading to reduced corrosion resistance. Prefabricated epoxy-coated reinforcement (typically either purple epoxy-coated or gray epoxy-coated) has been developed to reduce potential damage to the protective coating. The reinforcement is first fabricated into required shapes, and then it is hung from a conveyor system and moved through the coating process. The epoxy coating for prefabricated epoxy-coated reinforcement can be more rigid, as specifications do not permit bending the reinforcement after coating. Although excellent quality control in epoxy coating thickness is possible with either method, it is more difficult to control coating thickness for prefabricated reinforcement than it is for green epoxy-coated reinforcement.

Epoxy coating on reinforcement reduces bond capacity in comparison with uncoated (black) bars [DeVries, 1989; Treece, 1989; Choi, 1991; Cleary, 1991; Hamad, 1993; Hester, 1993; Hadje-Ghaffari, 1994; Darwin, 1996; Idun, 1999; Miller, 2003]. Some studies [Choi, 1991] have found that bond strength decreases with increasing coating thickness for small bar sizes, while others have found that bond strength is insensitive to coating thickness within some coating thickness ranges [Treece, 1989; Miller, 2003]. Pullout tests from large concrete prisms [Mathey, 1976] found that pullout strength was insensitive to coating thickness in the range 25 to 279 μm (1 to 11 mils), but strength was lower for a bar with 635-μm (25-mil) coating thickness. All the tests cited were conducted on bars with green epoxy coating.

Prefabricated epoxy-coated reinforcement is being used in a range of applications, but especially where corrosion potential is high. Current specifications [ASTM A934-04] require epoxy coating thickness to be in the range from 175 to 300 μm (7 to 12 mils). Given the wide range of prefabricated shapes, it can be difficult to maintain the coating thickness within the specified range. It is important to understand the effect of larger coating thickness on bond strength. An experimental program was conducted to investigate that effect. The program and its results are reported here.

RESEARCH SIGNIFICANCE

The study reported here examines the effect of epoxy coating thickness on bond strength of prefabricated epoxy-coated reinforcement, and provides evidence that larger coatings can be permitted without penalty on development or splice length.

EXPERIMENTAL PROGRAM

One hundred and twenty eight beam end tests [ASTM A944-99] were conducted. The main test variables were bar size, epoxy coating type and thickness, and concrete cover and transverse reinforcement around the developed bars. Tests were run on No. 13[*], No. 19, No. 25, and No. 35 bars. Bars were either uncoated, green-coated (203 μm (8 mils) coating thickness), or gray-coated (203, 305, 406, and 508 μm (8, 12, 16, and 20 mils)). Reinforcement was Grade 60 (nominal yield stress 414 MPa (60 ksi)) and concrete was normal-weight with target compressive strength of 34 MPa (5000 psi).

Concrete cover and transverse reinforcement were selected to approximate some typical conditions for bridge construction in California. For No. 13 through No. 25 bars, a primary interest was for concrete cover around $3d_b$, where d_b is nominal diameter of the developed bar, as this condition is common for prefabricated bars. Larger-diameter bars are used as longitudinal

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[*]Bar size corresponds to nominal diameter in mm. No. 13, 19, 25, and 35 bars identified here correspond to US customary bar sizes No. 4, 6, 8, and 11.

reinforcement, typically anchored in large footings or beam-column joints with heavy transverse reinforcement. For those bars, a primary interest is bond behavior of bars in large concrete sections with relatively heavy transverse reinforcement.

Figure 1 shows test specimen configurations. Figure 1 (a) and (b) show side view and cross section for a No. 19 test bar; tests on No. 13 and 25 test bars used the same configuration but the test bar size was changed and the bar was shifted either up or down to maintain a clear cover of $3d_b$. For the No. 13, 19 and 25 bar tests, there was no confining transverse reinforcement. No. 35 test bars (Figure 1 (c) and (d)) had clear cover of $5.3d_b$ with relatively heavy spiral confining reinforcement. Spiral reinforcement ratio was ρ_s = 0.0102, based on the relation:

$$\rho_s = \frac{4A_{sp}D_s}{D_c^2 s} \qquad (1)$$

in which A_{sp} = nominal cross-sectional area of spiral reinforcement, D_s = outside diameter of spiral, D_c = width of concrete block, and s = pitch of spiral reinforcement.

Tests were conducted using the beam-end test method (ASTM A944-99), in which the test bars are pulled from a beam-end specimen in which the bars are embedded (Figure 1). The test bar enters the beam-end specimen at the loaded end, extends into the specimen along a short unbonded length, extends further along a bonded length, and has an additional unbonded length before terminating within the test specimen. The test specimen is positioned in a test rig so that the test bar can be pulled slowly from the test specimen (Figure 2). During a test, when the test bar is pulled, the beam-end specimen is restrained from translation through a compression reaction and restrained from rotation through a tie-down. These boundary conditions approximate those of the end region of a simply-supported beam.

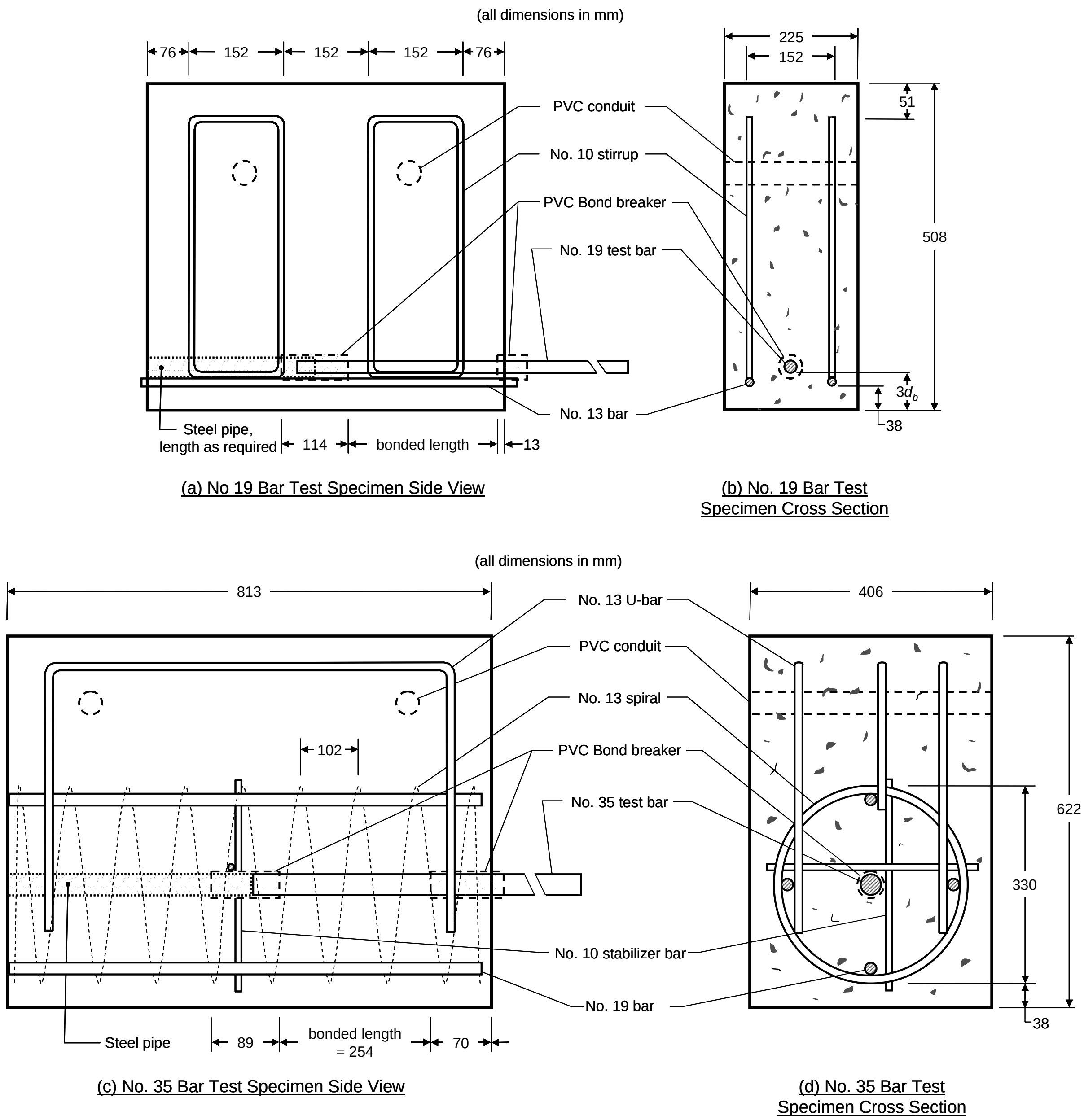


Figure 1 – Beam end test specimens

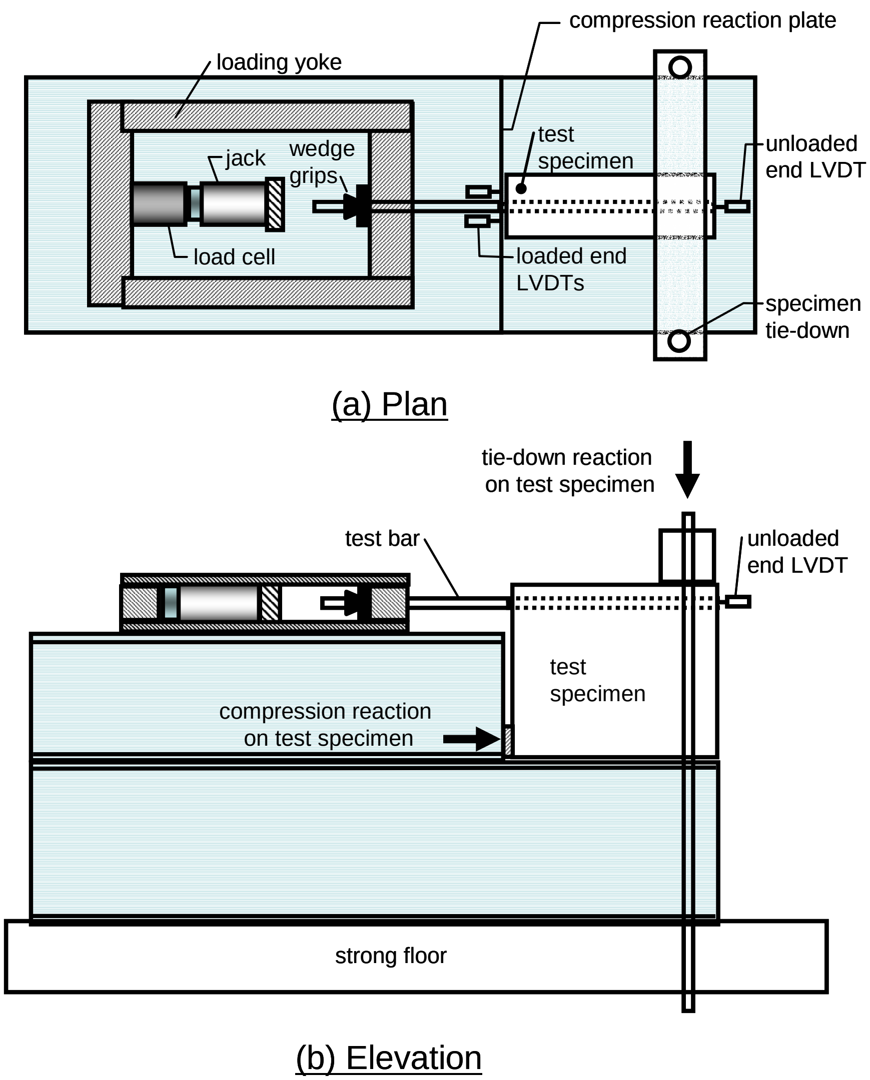


Figure 2 – Test setup

Bonded lengths were derived partly from ASTM A944-99, which specifies a bonded length of 254 mm (10 in.) for No. 19 bars in beam-end tests [ASTM A944-99]. This length corresponds to length-to-diameter ratio of 13.3. This same length-to-diameter ratio was applied approximately to the No. 13 and No. 25 bar tests, leading to target lengths of 171, 254, and 330 mm (6.75, 10, and 13 in.) for the No. 13, 19, and 25 bar tests, respectively. For some of the No.

13 bar tests, the length was reduced to 102 mm (4 in.) because the longer length resulted in bar yield prior to bond failure. Bond lengths for the No. 35 bar tests were set at 254 mm (10 in.); the relatively shorter length was deemed appropriate because these bars were confined by transverse reinforcement, which was expected to improve bond strength.

Additional details of the test specimens include:

- Unbonded lengths at the loaded end were 13 mm (0.5 in.) for No. 13, 19, and 25 test bars, and 70 mm (2.75 in.) for No. 35 test bars, respectively.
- Additional longitudinal reinforcement was provided on either side of the test bar to provide tension capacity past the bonded length of the test bar.
- Stirrups were provided for shear resistance, but were oriented parallel to the “pull” direction to avoid confining the test bar along its bonded length. Stirrups were in the form of closed stirrups for the No. 13, 19, and 25 bar test specimens and U-bars for the No. 35 bar test specimens.

Table 1 summarizes test specimen information.

Table 1a – Strengths for No. 13 Bars with 171-mm (6.75-in.) Bonded Length

Coating Thickness		Coating Type	f'_c, MPa	Failure Load, kN
μm	mils			
0	0	NA	31.6	58.0
0	0	NA	30.8	58.8
0	0	NA	31.6	58.6
203	8	green	39.2	57.9
203	8	green	39.2	57.5
203	8	green	39.2	56.6
203	8	green	39.2	51.2
203	8	green	39.3	61.8
203	8	green	39.3	56.7
203	8	gray	39.2	56.9
203	8	gray	39.2	52.0
203	8	gray	39.2	51.5
203	8	gray	39.3	51.5
203	8	gray	39.3	53.8
203	8	gray	39.3	56.7
305	12	gray	31.6	53.4
305	12	gray	30.8	59.7
305	12	gray	30.8	57.2
406	16	gray	31.6	58.0
406	16	gray	30.8	50.9
406	16	gray	30.8	54.2
508	20	gray	30.8	57.3
508	20	gray	31.6	53.0
508	20	gray	31.6	56.5
			Mean = 35.2	

Table 1b – Strengths for No. 13 Bars with 102-mm (4-in.) Bonded Length

Coating Thickness		Coatin g Type	f'_c, MPa	Failure Load, kN
μm	mils			
0	0	NA	29.1	38.8
0	0	NA	29.1	47.2
203	8	gray	29.1	40.0
203	8	gray	29.1	47.5
305	12	gray	29.1	39.9
305	12	gray	29.1	40.2
406	16	gray	29.1	42.2
406	16	gray	29.1	35.6
406	16	gray	31.6	37.0
508	20	gray	29.1	35.6
508	20	gray	31.6	39.5
508	20	gray	29.1	35.6
			Mean = 29.5	

Table 1c – Strengths for No. 19 Bars with 254-mm (10-in.) Bonded Length

Coating Thickness		Coating Type	f_c', MPa	Failure Load, kN
μm	mils			
0	0	NA	37.0	109.2
0	0	NA	37.0	111.9
0	0	NA	36.0	116.9
0	0	NA	34.9	100.3
0	0	NA	34.9	104.4
203	8	green	38.0	102.7
203	8	green	38.0	105.2
203	8	green	37.8	103.6
203	8	green	37.8	106.7
203	8	green	37.8	98.7
203	8	green	37.8	101.9
203	8	gray	37.8	109.0
203	8	gray	37.8	95.6
203	8	gray	37.8	102.3
203	8	gray	37.8	107.2
203	8	gray	38.5	98.3
203	8	gray	38.5	104.5
203	8	gray	34.9	103.5
203	8	gray	32.6	100.1
305	12	gray	36.0	99.9
305	12	gray	36.0	111.3
305	12	gray	36.0	99.2
305	12	gray	34.9	98.9
305	12	gray	32.6	103.7
406	16	gray	36.0	105.8
406	16	gray	36.0	105.5
406	16	gray	36.0	107.2
406	16	gray	34.9	102.9
406	16	gray	32.6	92.7
406	16	gray	32.6	96.7
508	20	gray	37.0	106.4
508	20	gray	36.0	102.2
508	20	gray	36.0	146.3
508	20	gray	32.6	108.9
508	20	gray	32.6	111.1
508	20	gray	32.6	104.7
			Mean = 35.9	

Table 1d – Strengths for No. 25 Bars with 330-mm (13-in.) Bonded Length

Coating Thickness		Coating Type	f_c', MPa	Failure Load, kN
μm	mils			
0	0	NA	36.7	166.8
0	0	NA	36.7	185.0
0	0	NA	36.7	166.8
0	0	NA	32.6	175.9
0	0	NA	31.6	182.4
203	8	green	37.0	167.5
203	8	green	37.5	180.1
203	8	green	37.5	184.6
203	8	green	37.5	184.1
203	8	green	37.5	160.0
203	8	green	37.5	202.3
203	8	gray	37.5	165.2
203	8	gray	37.5	158.7
203	8	gray	37.5	177.2
203	8	gray	37.9	160.6
203	8	gray	37.9	184.6
203	8	gray	32.6	157.7
203	8	gray	31.6	207.9
305	12	gray	36.4	163.9
305	12	gray	36.4	167.8
305	12	gray	36.4	178.5
305	12	gray	32.6	190.3
305	12	gray	31.6	145.3
406	16	gray	36.4	183.1
406	16	gray	36.4	155.7
406	16	gray	36.4	151.8
406	16	gray	31.6	158.3
406	16	gray	31.6	162.2
406	16	gray	31.6	150.5
508	20	gray	36.4	149.2
508	20	gray	36.7	154.3
508	20	gray	36.7	157.4
508	20	gray	31.6	151.2
508	20	gray	31.6	157.0
508	20	gray	31.6	153.8
			Mean = 35.2	

Table 1e – Strengths for No. 35 Bars with 254-mm (10-in.) Bonded Length

Coating Thickness		Coating Type	f'_c, MPa	Failure Load, kN
μm	mils			
0	0	NA	38.0	501.3
0	0	NA	36.6	483.9
0	0	NA	36.6	496.8
203	8	green	38.0	452.8
203	8	green	36.6	474.6
203	8	green	32.5	442.6
203	8	gray	38.1	499.5
203	8	gray	36.6	447.9
203	8	gray	31.6	422.6
305	12	gray	38.0	391.4
305	12	gray	38.0	477.3
305	12	gray	32.5	453.7
406	16	gray	38.0	456.8
406	16	gray	37.9	451.0
406	16	gray	36.6	467.9
508	20	gray	37.9	504.4
508	20	gray	36.6	431.5
508	20	gray	31.6	371.9
			Mean = 36.2	

TEST SPECIMEN CONSTRUCTION

Beam-end specimens were constructed from manufacturer-supplied test bars and prefabricated stirrups and spirals. Tolerance for bonded lengths, test bar cover, and overall specimen dimsnsions was ±1 mm (±1/16 in.), while tolerance for other dimensions was ±6 mm (±1/4 in.). Reinforcement was held in place using steel chairs or external wood templates (concrete dobies were used instead of steel ties for the second casting of No. 25 test bars; no effect of this substitution was identified). Unbonded lengths at the loaded and unloaded ends were formed by passing the test bar through short lengths of polyvinyl chloride (PVC) pipes whose ends were sealed with modeling clay or a bead of hot glue (Figure 1). Test bars were wiped clean with alcohol prior to casting to ensure absence of dirt and oil.

Specimens were cast in three different casting groups. The first two casting groups each contained twelve No. 13, 19, and 25 bar specimens plus ten No. 35 bar specimens (46 total specimens per casting group). The third casting group contained twelve No. 13, 19, and 25 bar specimens (36 total specimens). Test specimens were cast in ganged wood forms. No. 13, 19, and 25 bar specimens were cast with the test bars oriented horizontally near the bottom of the form, while No. 35 bar specimens were cast with the test bar oriented vertically with the loaded end at the top. Concrete was placed in two lifts. For a given casting, the first lift was placed in all specimens before any specimen received the second lift. Each specimen was vibrated at four points or more using a high-frequency internal vibrator. Forty 152 mm by 305 mm (6 in. by 12 in.) cylinders were cast according to [ASTM C192-02] and cured in the same environment as the test specimens. All test specimens (including cylinders) were covered with wet burlap and plastic during curing. Forms were stripped after concrete strength reached at least 22 MPa (3200 psi).

TEST PROCEDURE

Beam-end specimens were tested according to ASTM A944-99. Figure 2 shows the test apparatus. For testing, a beam-end specimen was situated at one end of the test apparatus with the horizontally oriented test bar at the top of the specimen (specimens were rotated from their casting position to this testing position). A mechanical wedge grip fixed in a cross-beam engaged the loaded end of the test bar. The cross-beam was pulled longitudinally using a 900-kN (200-kip) capacity hydraulic jack and a yoke that transferred force from the jack to the cross-beam, thereby pulling the test bar. Teflon sheets were placed along sliding surfaces of the test apparatus to reduce friction losses. As the beam-end specimen was pulled, the concrete at the bottom of the test specimen reacted in compression against the loading apparatus. A hold-down at the back end of the beam-end specimen restrained the specimen against overturning.

Prior to testing, a beam-end specimen was shimmed and aligned so the test bar was parallel to the loading frame. A thin layer of hydrostone was cast between the compression zone at the bottom of the beam-end specimen and the loading apparatus to ensure an even bearing surface. The hold-down mechanism at the back end of the beam-end specimen was hand-tightened. A load cell was placed in line with the hydraulic actuator to read applied loads. To measure slip of the loaded end of the test bar relative the front face of the concrete, a coupler was clamped to the test bar at the loaded end (Figure 2). Two linear potentiometers were mounted, one on each side of the coupler, and targeted the front face of the concrete. The average of the readings is reported here as the test bar slip. Other potentiometers measured unloaded end slip, but data from those are not reported here. During a test, load was applied using a hand pump to monotonically increase applied load. The loading rate, monitored using a load cell, was approximately 10, 20, and 30 kN (2, 5, and 7 kips) per minute for No. 13, 19, and 25 test bars, and 50 to 90 kN (10 to 20 kips) per minute for No. 35 test bars.

MATERIAL PROPERTIES

Concrete was normal weight aggregate provided by a ready-mix truck. The mix included ASTM C-150 Type II Portland Cement, ASTM C-618 Class F - Fly Ash, 20-mm (¾-in.) pea gravel from Pleasanton, CA, and ASTM C-33 Sand. Slump ranged from 130 to 150 mm (5 to 6 in.). Forty standard cylinders were cast for each batch. Compression strength tests were done throughout the beam-end test period, ranging between age 8 and 23 days, depending on the casting group. Split cylinder tests and modulus of elasticity tests were performed at the beginning and at the end of the testing period. Modulus of elasticity was defined as the slope of the stress-strain relation between approximately 10% and 40% of the compressive strength. Concrete compressive strengths ranged from 29.1 to 39.3 MPa (4200 to 5700 psi). Modulus of elasticity averaged 25,600 MPa (3700 ksi) and split cylinder tensile strengths ranged from 2.65 to 3.55 MPa (385 to 515 psi).

All reinforcement was ASTM A615 Grade 60 deformed reinforcement. All test bars were specified to be from a single heat, and all had the same deformation pattern (samples are shown in Figure 3). Measured yield stresses (based on nominal cross-sectional areas) were 431, 423, 428, and 415 MPa (62.5, 61.4, 62.1, and 60.2 MPa) for No. 13, 19, 25, and 35 test bars. Epoxy thicknesses were inspected using the non-magnetic on ferrous material method designated by [ASTM G12-83]. Five coated bars of each bar size were randomly selected and each was tested at 40 locations. All coating thicknesses were found to be within 1 mil of the reported value.

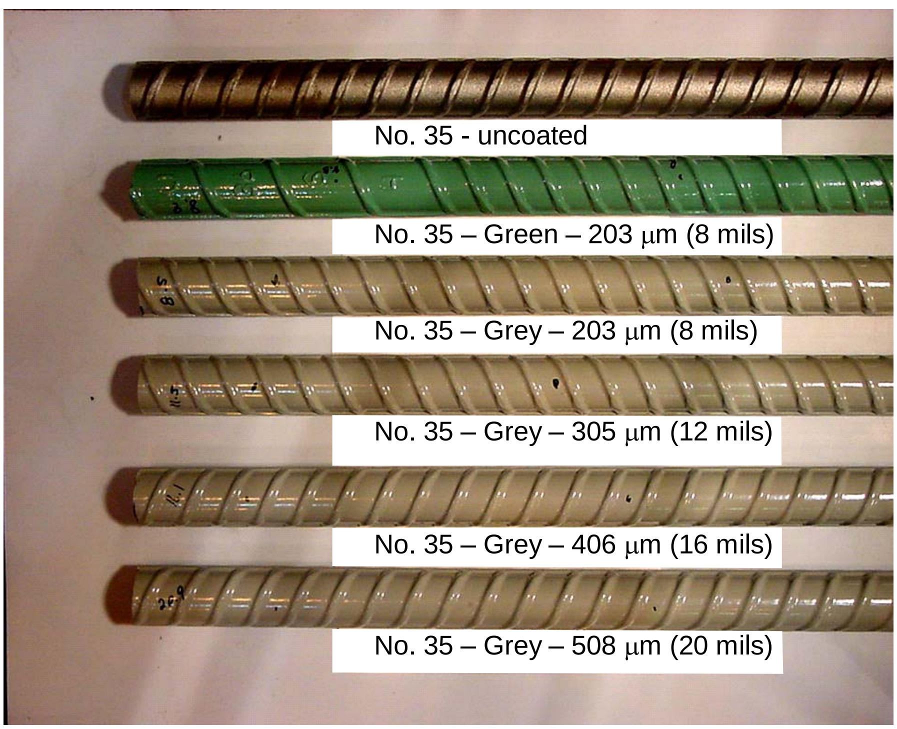


Figure 3 – No. 35 test bar photographs

OBSERVED BEHAVIOR

Figure 4 plots typical measured relations between load and slip at the loaded end of the test bar. The load-slip relation gradually softens as the load increases to the peak load, followed by reduction in tension force associated with bond failure. Failure tended to be abrupt and accompanied by a loud noise for the No. 13, 19, and 25 bar tests without transverse reinforcement. The force reduction was more gradual for the No. 35 bar tests, apparently because of confinement by the spiral reinforcement. Prior to failure, in most tests the bars with epoxy coating had softer load-slip response than bars without coating, though this was not always the case. Furthermore, there was no consistent correlation between stiffness and coating type or thickness.

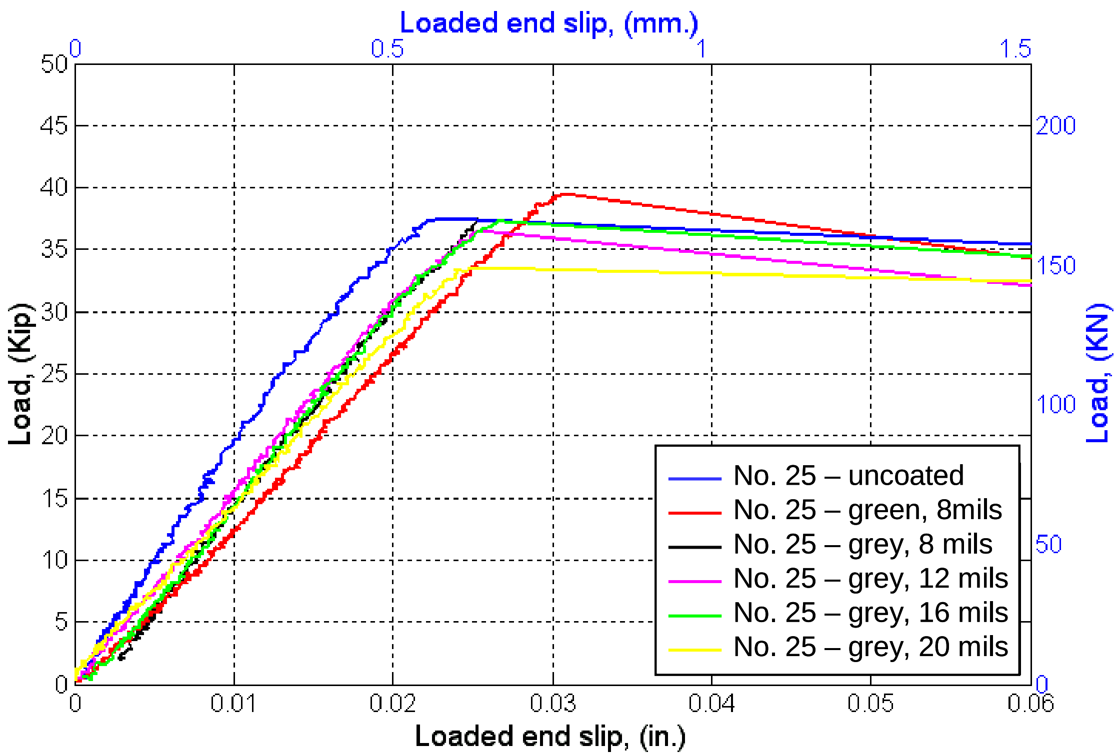


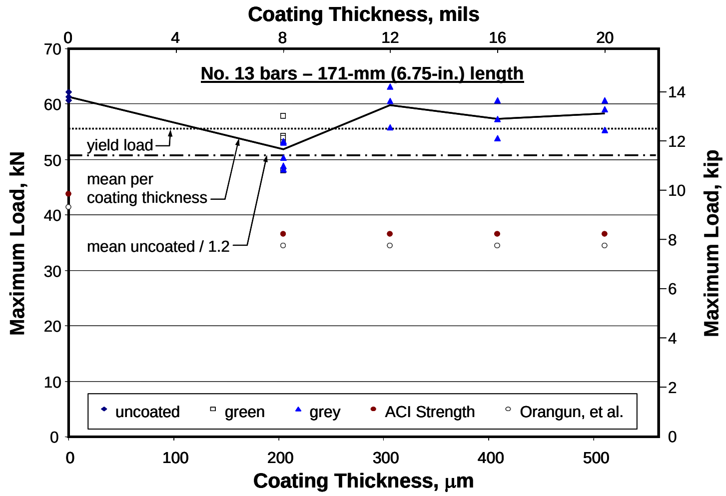
Figure 4 – Measured relations between applied tension force and slip at the loaded end of No. 25 test bars

For the No. 13, 19, and 25 bar tests, initial cracking usually originated just above the test bar on the front face of the specimen. This crack typically propagated to the top surface, then extended along the top surface above the test bar; other cracks typically developed as the longitudinal crack extended. Splitting failure occurred for all specimens, typically when the longitudinal crack had propagated to about 80 to 100 percent of the bonded length. For the No. 35 bar tests, at around three quarters of the load capacity, typically three radial cracks appeared on the front (loaded-end) face, which extended as longitudinal cracks on the two side and top faces. Inclined cracks also occurred beyond the end of the bonded length. Failure was by pullout mode, with the radial cracks widening as the test bar was pulled from the section.

Test results are presented in Table 1. For the No. 13 bar tests with 102-mm (4-in.) bonded length, and for No. 19 and 25 bar tests, bond failure occurred prior to yielding of the test bar. For the No. 13 bar tests with 171-mm (6.75-in) bonded length and for the No. 35 bar tests, bond failure occurred after yielding of the test bar.

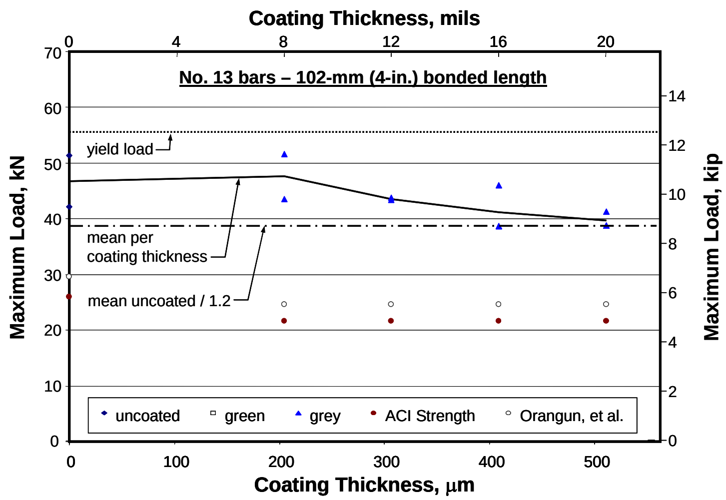
EVALUATION OF TEST RESULTS

Test results for different test bar diameters are compared in Figure 5. Concrete compressive strengths varied during testing. To approximately account for the effect of this variation on bond strengths, all pullout strength results were normalized to the target concrete compressive strength of 34.5 MPa (5000 psi) by multiplying the measured result by the factor $\sqrt{f_c^{'}/34.5}$, in which f'_c = concrete compressive strength in MPa measured on the day of testing. This factor did not change results significantly because compressive strengths did not vary widely (range from 29.1 to 39.3 MPa (4200 to 5700 psi). Trends reported here for normalized data appear similar to those for non-normalized data.



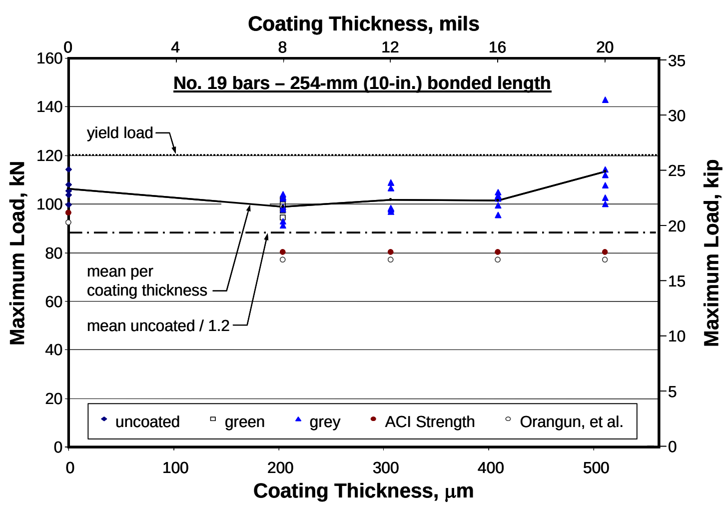
(a) No. 13 bars – 171-mm (6.75-in.) bonded length

Figure 6 – Normalized failure loads



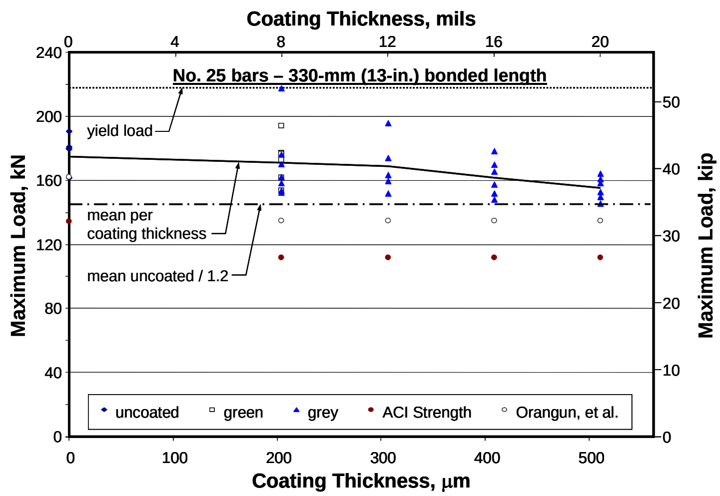
(b) No. 13 bars – 102-mm (4-in.) bonded length

Figure 6 (continued) – Normalized failure loads

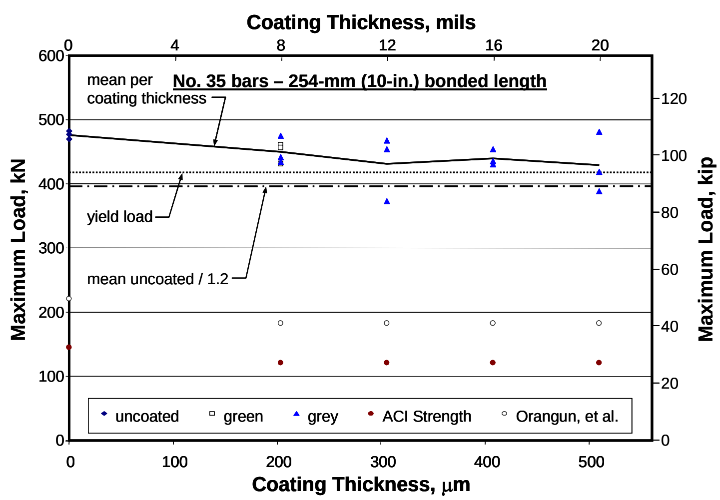


(c) No. 19 bars – 254-mm (10-in) bonded length

Figure 6 (continued) – Normalized failure loads



(d) No. 25 bars – 330-mm (13-in.) bonded length
Figure 6 (continued) – Normalized failure loads



(e) No. 35 bars – 254-mm (10-in.) bonded length
Figure 6 (continued) – Normalized failure loads

Figure 6a compares results for No. 13 test bars with 171-mm (6.75-in.) bonded length for different coating types and thicknesses. Individual test data are shown by individual symbols. Additionally, results for each different coating thickness were averaged and the average values were connected by lines to show the mean trend of bond strength with increasing coating thickness (for 203-μm (8-mil) coating thickness, green and gray test results were combined). As shown, several bars had bond failure for load higher than the reinforcement yield load. While this might obscure relative bond strengths, it is noteworthy that bond strengths did not decrease with increasing coating thickness. Figure 6b compares results for No. 13 test bars with 102-mm (4-in.) bonded lengths. Bond failure occurred for load less than the yield load for all tests. The bond strength of the prefabricated epoxy-coated bars (gray) apparently decreased with increasing coating thickness; average C/U ratios were 1.02, 0.93, 0.88, and 0.85 for coating thicknesses of 203, 305, 406, and 508 μm (8, 12, 16, and 20 mils).

Figure 6c compares results for No. 19 test bars. Bond strength appears to not be affected by coating thickness. Results in Figures 6d and 6e (for No. 25 and 35 test bars) show minor decrease in bond strength with increasing coating thickness.

The ACI Building Code [ACI 318-2002] specifies longer development lengths for epoxy-coated reinforcement than for non-coated bars. For cover not less than $3d_b$, the length is increased by factor 1.2. The implicit bond-strength reduction factor is 1/1.2 = 0.83. Figure 6 shows a dot-dash line, which corresponds to the ratio of the average bond strength for uncoated bars of that test series and the modification factor 1.2. Almost all data points fall above the dot-dash line, regardless of coating type or thickness.

ACI 318-2002 specifies tension development lengths for deformed reinforcement as:

$$l_d = \frac{9}{10}\frac{f_y}{\sqrt{f_c^{'}}}\frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b}\right)}, MPa \qquad (2)$$

$$l_d = \frac{3}{40}\frac{f_y}{\sqrt{f_c^{'}}}\frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b}\right)}, psi \qquad (2a)$$

in which f_y = reinforcement nominal yield stress, f'_c = concrete compressive strength, α = reinforcement location factor (= 1.0 for bottom-cast bars), β = coating factor (= 1.2 for cover =

$3d_b$), γ = reinforcement size factor (= 0.8 for No. 19 and smaller bars, = 1.0 otherwise), λ = lightweight aggregate concrete factor (= 1.0 for normalweight concrete), c = concrete cover over test bar measured to center of bar (mm (in.)), K_{tr} = transverse reinforcement index, and d_b = bar diameter of developed bar (mm (in.)). $K_{tr} = A_{tr}f_y/10s$ (MPa), ($K_{tr} = A_{tr}f_y/1500s$ (psi)), in which A_{tr} = total cross-sectional area (mm^2(in.^{2})) of all transverse reinforcement that is within the spacing s (mm (in.)) and that crosses the potential plane of splitting, This development length expression does not contain a strength reduction factor ϕ; instead, the expression was developed to implicitly account for reinforcement overstress factor of 1.25, that is, the development length is intended to provide strength for bar stress = $1.25f_y$.

In light of the preceding paragraph, the expected force capacity per ACI 318-2002 was calculated as follows. First, development length was calculated using Equation (2) for f_y = 414 MPa (60,000 psi), the nominal yield strength of Grade 60 reinforcement. Assuming this length is for tension force of $1.25f_yA_s$, the expected tension force capacity of the test specimens was calculated as $(l_{provided}/l_d)(1.25A_sf_y)$, where $l_{provided}$ = bonded length for test specimen, l_d = development length per Equation (2), A_s = nominal cross-sectional area of test bar, and f_y = 414 MPa (60,000 psi). For all bars with epoxy coating, β = 1.2 was assumed, regardless of coating thickness. Results are shown by the solid circles in Figure 6. In all cases, ACI 318-2002 is conservative.

Orangun, Jirsa, and Breen [Orangun, 1977] evaluated development length and lap-splice data from tests and derived Equation (3) for bond strength:

$$u = \frac{1}{12}\left(1.2 + 3\frac{C}{d_b} + 50\frac{d_b}{l_{provided}} + \frac{3}{10}\frac{A_{tr} f_y}{sd_b}\right)\sqrt{f_c^{'}}, MPa \tag{3}$$

$$u = \left(1.2 + 3\frac{C}{d_b} + 50\frac{d_b}{l_{provided}} + \frac{A_{tr} f_y}{500 s d_b}\right)\sqrt{f_c^{'}}, psi \qquad (3a)$$

in which u = bond strength (MPa (psi)) and C = clear cover or half clear spacing (mm (in.)). C/d_b is limited to 2.5, and $3A_{tr}f_y/10sd_b$ in Eq. (3) (as well as $A_{tr}f_y/500sd_b$ in Eq. (3a)) is limited to 3. For the No. 13, 19, and 25 bar tests, $A_{tr} = 0$. For the No. 35 bar tests, the cover parameter C exceeds $2.5d_b$, indicating expected pullout failure rather than splitting failure; therefore, $A_{tr}f_y/sd_b$ is taken equal to 0.0. Expected force capacity of a bar is calculated as $T = u\pi d_b l_{provided}$, which is based on the product of the uniform bond stress capacity u and the bonded area along the length $l_{provided}$. Equation (3) does not address the effect of epoxy coating. In this study, however, it is assumed that the bond strength will reduce by the factor 1/1.2 as specified in ACI 318-2002. The open circles in Figure 6 present the results. In all cases, the measured strengths are greater than those obtained from Equation (3) modified by the factor 1/1.2.

COMPARISON WITH TRENDS OBSERVED IN OTHER TESTS

Previous studies have found that epoxy coating on reinforcement reduces bond strength in comparison with uncoated (black) bars [DeVries, 1989; Treece, 1989; Choi, 1991; Cleary, 1991; Hamad, 1993; Hester, 1993; Hadje-Ghaffari, 1994; Darwin, 1996; Idun, 1999; Miller, 2003]. Some studies [Choi, 1991] have found that bond strength decreases with increasing coating thickness for small bar sizes, while others have found that bond strength is insensitive to coating thickness within the range 127 to 356 μm (5 to 14 mils) [Treece, 1989] or up to 406 μm (16 mils) for No. 19 or larger bars [Miller, 2003]. Pullout tests from large concrete prisms [Mathey, 1976] found that pullout strength was insensitive to coating thickness in the range 25 to 279 μm

(1 to 11 mils); for a single test with 635- μm (25-mil) coating thickness the bond strength was reduced.

Figure 7 presents results from Miller, et al. [Miller, 2003] in which No. 19 test bars with three different deformation patterns (B, C, and S) and different coating thickness were tested in beam-end specimens similar to those reported here for No. 19 bars. Clear cover over test bars was $2d_b$, as opposed to $3d_b$ for the tests reported in this paper. The data display typical scatter

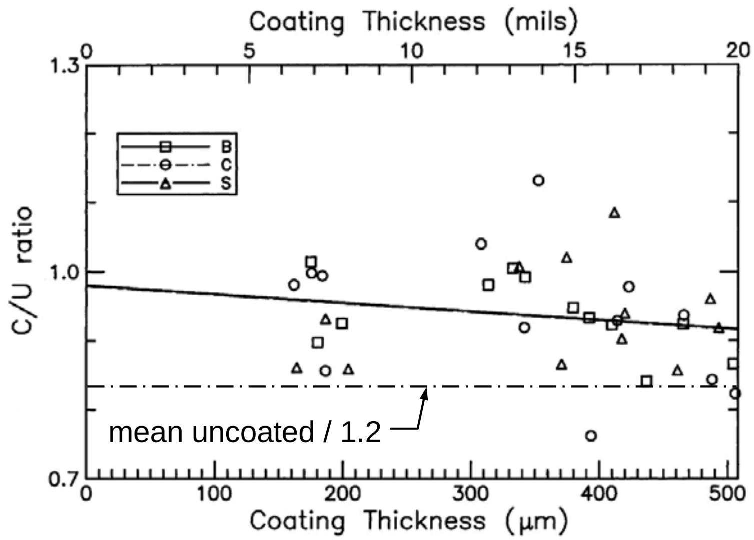


Figure 7 – Bond strengths for epoxy-coated reinforcement (after Miller [2003])

for beam-end tests, and show a trend of gradually decreasing bond strength with increasing coating thickness. Almost all tests show C/U ratio equal to or exceeding 1/1.2 (dot-dash line of Figure 7), which is the bond strength ratio in ACI 318-2002 for epoxy-coated bars with cover not less than $3d_b$. For the tests reported by Miller, et al., the nominal clear cover was $2.0d_b$, in which case ACI 318-2002 specifies a modification factor of 1/1.5. Miller et al. suggests excluding some of the data points that are at the extremities of the results, including the single point that falls significantly below the dot-dash line of Figure 7.

In the present study, bond strength decreased with increasing coating thickness for No. 13, 25, and 35 bars, but not for No. 19 bars. It is unclear whether the difference in behavior of No. 19 bars in the two test programs is because of concrete cover thickness ($2.0d_b$ in the Miller et al. study versus $3.0d_b$ in the present study), epoxy coating type (green in the Miller et al. study versus gray in the present study), or some other variable.

IMPLICATIONS FOR DESIGN

The present study examined bond strength of prefabricated (gray) epoxy-coated reinforcement with clear cover equal to or exceeding $3d_b$, with or without transverse reinforcement, for epoxy coating thickness up to 20 mils. ACI 318-2002 provisions for epoxy-coated reinforcement are conservative for this range of coating thicknesses and bond conditions.

SUMMARY AND CONCLUSIONS

One hundred and twenty eight beam end tests were done on No. 13, No. 19, No. 25, and No. 35 bars. Bars were either uncoated, green-coated (203 μm (8 mils) coating thickness), or gray-coated (203, 305, 406, and 508 μm (8, 12, 16, and 20 mils) coating thickness). Concrete cover over test bars was $3d_b$ or larger. No. 35 bar tests had relatively heavy transverse reinforcement, while all other tests had no confining transverse reinforcement. Reinforcement was Grade 60 and concrete was normal-weight with target compressive strength of 34 MPa (5000 psi). For these test conditions, the following conclusions are drawn:

1. For some bar sizes, prefabricated epoxy-coated reinforcement had bond strength less than that of equivalent uncoated bars. For coating thickness as large as 508 μm (20 mils), however, the bond strength reduction was less than 15 percent. Therefore, the ACI 318-2002 development length modification factor of 1.2 for epoxy-coated bars

with large cover and spacing is conservative up to the maximum coating thickness tested (508 μm (20 mils)).

2. Bond strength of green and gray (prefabricated) epoxy-coated bars with 203 μm (8 mils) coating thickness was similar for all bar sizes. Comparison data are not available for other coating thicknesses.
3. Bond strength of yielding bars was not adversely affected by epoxy coatings, regardless of coating thickness (up to 508 μm (20 mils)).
4. Failure of anchored bars without transverse reinforcement was sudden, whereas failure of anchored bars with transverse reinforcement was more gradual.
5. ACI 318-2002 equations for bond strength of uncoated and coated bars were conservative.

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