BEAM-END BOND TESTS AND BEND TESTS OF ZINC-CLAD NO. 6 REINFORCING BARS

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JARDEN ZINC PRODUCTS

Structural Engineering and Engineering Materials
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THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
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ABSTRACT

The bond strength of No. 6 zinc-clad bars was compared to that of uncoated conventional bars using beam-end tests performed in accordance with ASTM A944. The zinc-clad bars were also subjected to bend tests using bend diameters of 3.75, 4.5, and 6.0 in. (5, 6, and 8 bar diameters), as required for conventional and epoxy-coated No. 6 deformed bars, respectively, in accordance with ASTM A615 and ASTM A775.

The zinc-clad bars provided bond strength equal to 94.9 percent of that exhibited by conventional bars from the same heat of steel. The difference in bond strength is not statistically significant. The two types of reinforcement exhibited similar force-bond slip behavior. The cladding exhibited significant local deformation and, in some cases, tearing following bond failure. Full-scale splice and bending strength tests on reinforced concrete members to compare the performance of clad and conventional reinforcement are recommended to develop design criteria for use in the ACI Building Code (ACI 318). The bend test specimens with the 3.75-in. bend diameter exhibited small transverse tension cracks in the cladding on the outside of the bend. Cracks ranged in length from 0.1 in. to one-half the circumference of the bar. One of six bend test specimens with the 4.5 in. diameter bend exhibited transverse cracking in the cracking at the outside of the bend. The crack was located on the cladding seam and had a length less than 0.1 in. No other damage was observed for the specimens with the 4.5 in. diameter bend. The bend test specimens with the 6.0-in bend diameter exhibited no visible damage to the cladding. To limit access of moisture and chlorides between the cladding and the underlying reinforcing bar, tightly fitting corrosion-resistant caps for the ends of the bars should be developed and marketed along with the clad reinforcement.

Keywords: bent reinforcement; bond; clad reinforcement; deformed reinforcement; zinc cladding

INTRODUCTION

This report describes beam-end bond tests performed in accordance with ASTM A944 and bend tests performed in accordance with ASTM A615 and ASTM A775 on a prototype zinc-clad reinforcing bar. The beam-end tests were performed on conventional and zinc-clad bars manufactured from the same heat of ASTM A615 reinforcement. The tests are the first structural or mechanical tests performed on the new reinforcement. Recommendations are made for future tests to qualify the bars for structural applications.

EXPERIMENTAL WORK

MATERIALS

Bar properties

Size: No. 6
Grade 60

Conventional bar
Mean Deformation Height: 0.0437 in.
Mean Deformation Spacing: 0.476 in.
Mean Long. Rib Width: 0.144 in.
Relative Rib Area: 0.0808

Zinc-clad bar
Mean Deformation Height: 0.0386 in.
Mean Deformation Spacing: 0.477 in.
Mean Long. Rib Width: 0.178 in.
Relative Rib Area: 0.0688

Condition of bar surface and cladding: Free of visible defects

Average cladding thickness: 20.8 mils

The deformations of both the conventional and zinc-clad bars meet the requirements of ASTM A615, and the relative rib areas of both bars are within the usual range for conventional bars (Choi et al. 1990).

ASTM A944 BEAM-END TESTS

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 1.

Table 1 – 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

Specimen Preparation and Testing

The specimens were prepared and tested in accordance with ASTM A944. A summary of specimen properties is presented in Table 2.

Table 2 – Specimen Properties

Concrete Cover	1-1/2 in.
Embedment Length	10-1/2 in.
Lead Length	1/2 in.
Moisture Condition of Concrete during Test	Air dry
Age at Test	6 days
Compressive strength	5050 psi

The specimens had dimensions (width × length × depth) of 9 × 24 × 19.5 inches. The specimens were fabricated in accordance with ASTM A944. Specimens containing zinc-clad bars and specimens containing conventional steel bars 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.

Twelve beam-end specimens were cast and tested: six zinc-clad bars and six conventional steel bars. 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 3.

Table 3 – Loading rates

Specimen	Load Rate (kips/min)
Conv-1	6.94
Zinc-1	3.87
Conv-2	3.86
Zinc-2	6.51
Conv-3	4.40
Zinc-3	4.42
Conv-4	3.25
Zinc-4	3.81
Conv-5	6.46
Zinc-5	4.05
Conv-6	3.72
Zinc-6	6.21

Results

The specimens were tested over a four-hour period. The average concrete compressive strength was 5050 psi (individual cylinder strengths of 4900, 5060 and 5180 psi). The maximum bond forces (bond strengths) of the specimens are shown in Table 4. The mean bond strength of the specimens containing the zinc-clad bars is 94.9 percent of the mean bond strength of the specimens containing conventional steel bars. The specimens with zinc-clad bars had bond strengths that ranged from 19282 to 24224 lb with a mean bond strength of 21869 lb, a standard deviation of 1688 lb, and a coefficient of variation of 0.077. The specimens containing conventional steel bars had bond strengths that ranged from 20831 to 26076 lb, with a mean bond strength of 23056 lb, a standard deviation of 2216 lb, and a coefficient of variation of 0.096. The mean bond strength for the specimens with zinc-clad bars differs by 1187 lb, less than one standard deviation, from the mean bond strength of the specimens with conventional steel bars, 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 = 1.04 with 11 degrees of freedom and α = 0.321,[1] also indicating that the difference in strength is not statistically significant.

Bar slip at the loaded end of the specimens is presented in Figures 1 and 2, and slip at peak load is summarized in Table 5. For the zinc-clad specimens, slip at peak load ranged from 0.069 in. to 0.114 in., with a mean of 0.0865 in., a standard deviation of 0.0166 in., and a coefficient of variation of 0.192. For the conventional steel specimens, slip at peak load ranged from 0.086 in. to 0.102 in., with a mean of 0.0875 in., a standard

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

deviation of 0.0129 in., and a coefficient of variation of 0.147. From the data collected, no significant difference in slip was observed between the conventional steel specimens and the zinc-clad specimens.

Table 4 – Bond Strengths

Specimen	Force, lb.	
	Steel	Zinc
1	25238	22935
2	20858	21423
3	20831	22226
4	23201	21126
5	26076	19282
6	22129	24224
Avg.	23056	21869
Std. Dev.	2216	1688
COV	0.096	0.077
	Ratio	94.9%

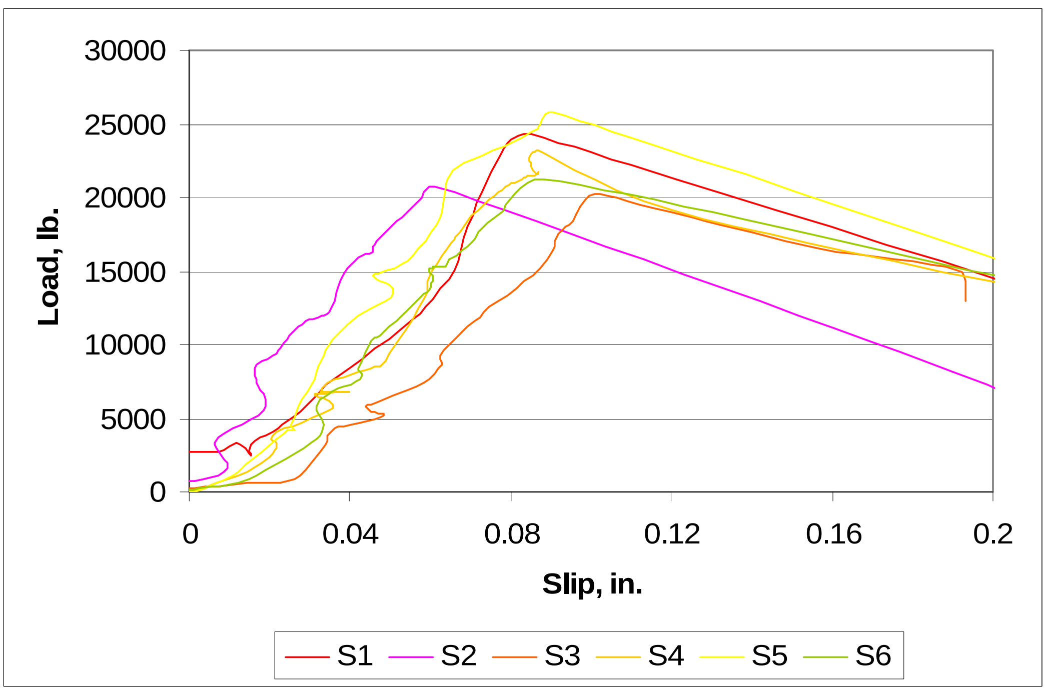


Figure 1 – Load versus loaded end slip for conventional steel specimens

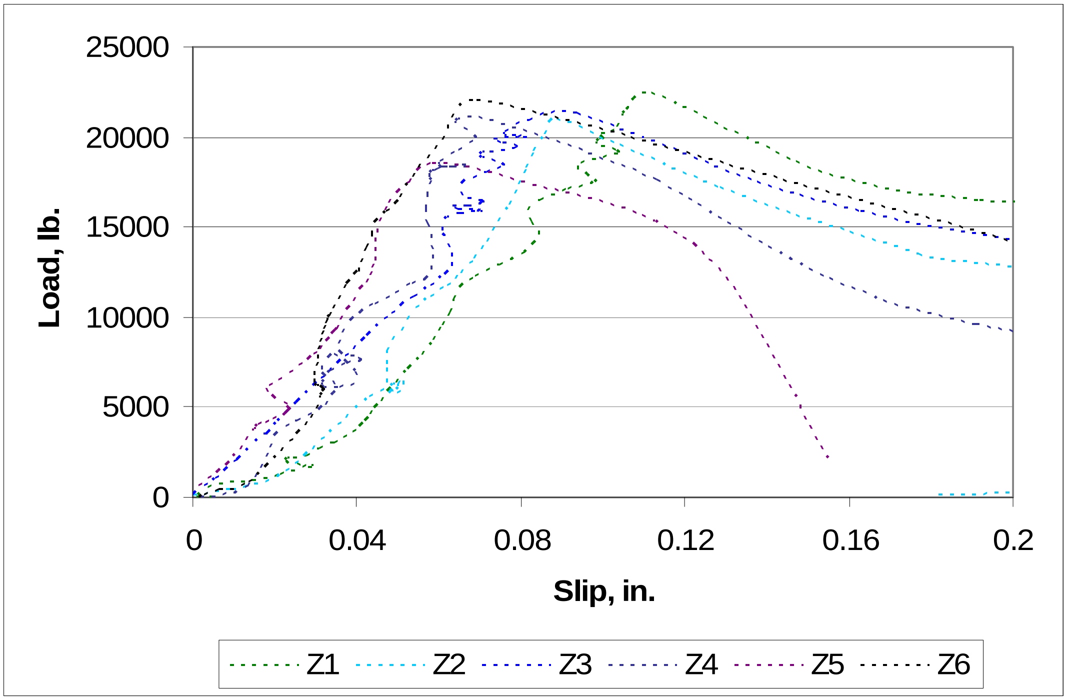


Figure 2 – Load versus loaded end slip for zinc-clad specimens

Table 5 – Loaded End Slip at Peak Load

Specimen	Slip at Peak Load (in.)	
	Steel	**Zinc**
1	0.087	0.114
2	0.064	0.094
3	0.102	0.089
4	0.086	0.071
5	0.092	0.069
6	0.094	0.082
Avg.	0.0875	0.0865
Std. Dev.	0.0129	0.0166
COV	0.147	0.192

Autopsy Results

After testing, three zinc-clad specimens (Specimens Zn-1, 2 and 5) were randomly selected for autopsy. All three specimens showed significant damage to the cladding in the region of maximum bond stress, as shown in Figure 3. On Specimen Zn-1, the damage was significant enough to expose the underlying steel (Figure 4).

Figure 3 –Damage to zinc cladding after bond test. Specimen Zn-2

Figure 4 – Damage to zinc cladding with underlying steel exposed (center). Specimen Zn-1

BEND TESTS

Bend tests were performed in accordance with ASTM A615 and A775 using five-bar and eight-bar bend diameters, respectively. In addition, tests were performed using a six-bar bend diameter.

Six zinc-clad bars were subjected to a bend test as specified in ASTM A615. The bend diameter was 3.75 in., as required for conventional Grade 60 No. 6 deformed bars. All specimens exhibited bridging of the cladding between the deformations on the outside of the bend. Four of the six specimens developed several small cracks in the cladding, approximately 0.1 in. in length, as shown in Figure 5. Of these four specimens, the number of cracks ranged from two to five with an average of three cracks per specimen. One specimen developed three longer cracks approximately 0.25 in. in length (Figure 6), and the remaining specimen developed one large crack running the length of the rib (one-half the circumference of the bar) in addition to one small crack (Figure 7). No damage to the cladding was observed on the inside of the bend.

Figure 5 – Bend test. No. 6 zinc-clad bar with 3.75-in. bend diameter showing multiple small cracks in the cladding

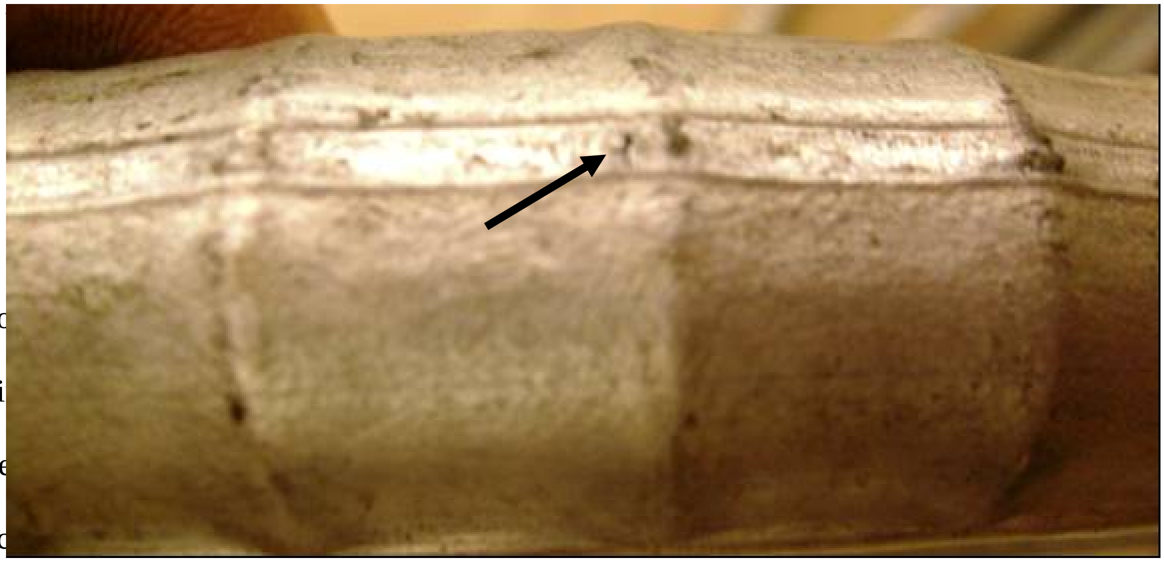
Figure 6 – Bend test. No. 6 zinc-clad bar with 3.75-in. bend diameter showing multiple longer cracks in the cladding

Figure 7 – Bend test. No. 6 zinc-clad bar with 3.75-in. bend diameter showing a full-width crack in the cladding

Six additional zinc-clad bars were subjected to a bend test as specified for epoxy-coated bars in ASTM A775. The bend diameter was 6.0 in. All specimens exhibited bridging of the cladding between the deformations on the outside of the bend; however, at this larger bend diameter no cracking or other visible damage to the cladding was observed, as shown in Figure 8.

Figure 8 – Bend test. No. 6 zinc-clad bar with 6-in. bend diameter showing no damage to the cladding

To evaluate cladding performance at an intermediate bend diameter, six additional zinc-clad bars were subjected to a bend test with a 4.5 inch bend diameter. All specimens exhibited bridging of the cladding between the deformations on the outside of the bend. One specimen exhibited a small transverse tear in the cladding, as shown in Figure 9. The crack was located in the seam formed by the overlapping zinc cladding and had a length less than 0.1 inches. The remaining five specimens exhibited no damage to the cladding.



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The following conclusions are based on the test results presented in this report.

1. The zinc-clad bars provide a bond strength equal to 94.9 percent of that exhibited by conventional bars from the same heat of steel. The difference in bond strength is not statistically significant. The two types of steel exhibit similar force-bond slip behavior.

2. The cladding exhibits significant local deformation and, in some cases, tearing following bond failure.

3. At a five-bar diameter bend (3.75 in.), the bend test specimens exhibit small transverse tension cracks in the cladding on the outside of the bend. Cracks ranged in length from 0.1 in. to one-half the circumference of the bar.

4. At a six-bar diameter bend (4.5 in.), one out of six bend test specimens exhibit a transverse tension crack in the cladding seam on the outside of the bend. The crack was less than 0.1 inch in length. The other specimens exhibit no damage to the cladding.

5. At an eight-bar diameter bend (6 in.), bend test performance was acceptable, with no visible damage to the cladding.

RECOMMENDATIONS

1. To develop design criteria for use in the ACI Building Code (ACI 318), full-scale splice and bending strength tests should be performed on reinforced concrete members to compare the performance of clad and conventional reinforcement. The bond tests are recommended because (1) ASTM A944 generally gives higher relative bond strengths for coated bars than is observed in splice tests, the test type used to develop design criteria; (2) although the zinc-clad bars provided a relative bond strength of 94.9 percent of the bond strength of conventional bars, this is less than the value of 95.9 percent measured for ASTM A1055 dual coated bars (ZBARS) (Darwin 2006); and the nature of the damage to the cladding in the beam-end tests will raise significant questions by the structural community. The full-scale bond tests will be used to establish the degree to which the zinc-clad bars can provide the same or similar strengths and crack distributions as conventional A615 bars in reinforced concrete members.
2. No. 6 zinc-clad bars should be bent with a minimum bend diameter of eight bar diameters as specified for epoxy-coated bars in accordance with ASTM A775. Other sizes of zinc-clad bars should be subjected to bend tests to determine if the ASTM A775 criteria apply to those sizes as well.

3. To limit access of moisture and chlorides between the cladding and the underlying reinforcing bar, tightly fitting corrosion-resistant caps for the ends of the bars should be developed and marketed along with the clad reinforcement.

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