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Bond Strength and Development Length of Galvanized Reinforcing Steel

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Abstract: **In reinforced concrete systems, ensuring that a good bond between the concrete and the embedded reinforcing steel is critical to long-term structural performance. Without good bond between the two, the system simply cannot behave as intended. The bond strength of reinforcing bars is a complex interaction between localized deformations, chemical adhesion, and other factors. For many years, the standard practice has been to coat reinforcing steel with an epoxy coating which provides a barrier between the steel and the corrosive elements of water, air, and chloride ions. Recently, there has been an industry led effort to use galvanizing to provide the protective barrier commonly provided by traditional epoxy coatings. However, as with any new structural product, questions exist regarding both the structural performance and corrosion resistance of the system. The work presented in this paper sought to understand the structural performance of galvanized reinforcing steel as compared to epoxy coated steel. This work consisted of a series of controlled laboratory tests. The results of this work indicate that there is no appreciable difference between the bond strength of epoxy coated reinforcing steel and galvanized reinforcing steel. Although some differences were observed, no notable difference in either peak load, slip, or failure mode could be identified.**

Keywords: **bond, bridges, concrete, epoxy, galvanized.**

I. INTRODUCTION

Galvanized steel has been used throughout the civil engineering and construction industry in many forms including steel reinforcement, bolts, ties, anchors, dowel bars, piping, and other structural elements. Although the application of zinc coated steel in concrete structures dates back to 1908, its popular use in the US came during the 1930s and its interest continued to increase after the World War II and throughout the 1960s and 70s. It was prominently used in bridge and highway construction across the Snow Belt states that experienced heavy snowfall in winter. The application of galvanized reinforcing steel diminished, however, in the late 1970s when the FHWA temporarily classified galvanizing as an experimental system. This ruling was rescinded in 1983 and, since that time, there has been a steady world-wide use (especially in countries like Australia, New Zealand, South Africa, etc.) of galvanized reinforcement in multiple weathering conditions [1].

Some studies [1, 2, 3 and 4] report that concrete bonds better to galvanized reinforcement than it does to uncoated steel. Chemical reactions that occur with galvanized steel result in a stronger adhesion between the reinforcement and concrete as well as increased frictional resistance to slipping. When galvanized reinforcement comes in contact with wet cement, a layer of calcium hydroxyl-zincate is formed at the surface [5]. Once formed, this layer firmly adheres to zinc coating as well as its surrounding concrete, resulting in an increase in bond strength compared to uncoated steel. Tests have shown that as the zinc coating is corroded, its surrounding areas are densified, which would lead to further bonding in that area. These chemical reactions do not occur to uncoated or epoxy coated steel.

Coating of reinforcing bars has been broadly adopted as one of the measures for providing corrosion protection in concrete as the need to design for durability has become an important practice in civil engineering. Among several general coating systems, two coating materials have been prominently used in structural practice (although typically in different applications), hot-dip galvanizing and epoxy coating. Galvanizing provides a metallurgical alloy coating and zinc iron alloys adherent to the steel, which protects the steel from corrosion by providing both an exterior barrier (i.e., zinc coating) as well as sacrificial protection (i.e., anodic function of a zinc) to the underlying steel. Epoxy coating provides a physical barrier that protects the steel from corrosion by isolating the steel base from the elements needed for corrosion to occur (e.g., oxygen, moisture, and chloride ions). The coating also acts as an electrical insulator and minimizes the flow of corrosion current as long as it is not damaged. While galvanized reinforcing steel has been frequently used by some countries (e.g., Australia, etc.) and some studies dispute the effectiveness of epoxy coating, numerous states in the United States require the use of epoxy coating as a means of extending reinforced concrete service lives.

In reinforced concrete systems, a good bond between reinforcing steel and concrete is critical for developing a desired/required load carrying capacity of the system. As the bond between concrete and reinforcing steel is fundamental to the strength-based performance of structural concrete, it is essential to investigate the performance of the structural elements in which these methods are employed. Although there exists some studies [6, 7, 8, 9, 10 and 11] on performance comparison between galvanized steel and epoxy coated bars, most studies focused on evaluating either corrosion performance or structural behavior. Quite interestingly, there is very little consistency between the results regardless of the performance metric being assessed. Therefore, there exists a need for conducting an experimental investigation to verify the bond characteristics of these two types of reinforcing steel.

The primary objectives of this study were to investigate the difference in bond strength and development length between galvanized reinforcing steel and epoxy coated bars by means of beam end test. A total of 18 specimens with various bar sizes were tested and the results from load-slip measurements were used as an indicative of the variation in bond strength. The specimens were fabricated and tested in accordance with ASTM A944-10. It is noted that this study was not intended to define a new design method or an independent relationship for each specimen tested. It was rather intended to compare, in a relative manner, the bond strength of concrete-to-galvanized reinforcing steel to concrete-to-epoxy coated bars.

II. EXPERIMENTAL PROGRAM

A. Test Specimen:

The specimens were divided into two sets based upon the coating material used on the reinforcing bars in the specimens: a set of 9 specimens with galvanized test bars and a set of 9 specimens with conventional epoxy coated test bars. To investigate the common types of bars used in bridge construction three different bar sizes were evaluated. Each specimen had a single test bar of either #6, #8 or #10 bar (3 of each size per coating combination) cast into a concrete block that was reinforced with 4 double-legged closed shear stirrups oriented parallel to the sides of the concrete block which were positioned to avoid confining the test bar along its bonded length, and 2#8 flexural reinforcing bars running parallel to the test bar. Shear stirrups used were #3 bars for the specimens with #6 and #8 test bars, and #4 bars for the specimens with #10 test bars. In all cases both the longitudinal reinforcement and shear stirrups were uncoated reinforcing steel.

The test bar was extended from the front surface of the specimen a distance that was compatible with the test apparatus. Two PVC pipes were used as bond breakers to control the bonded length of the test bar and to avoid a localized conical failure of the concrete at the loaded end of the specimen (and as specified in ASTM A944-10). As shown in Figure 1, each test bar is unbonded a short distance through the bond breaker at the loaded end, extends along a bonded length, and has an additional unbonded length through the bond breaker placed near the unloaded end. All concrete blocks had the same length and depth of 24 in. and 20 in., respectively. The width of the specimens with the #6 and #8 test bars were 9 in. while the specimens with #10 test bars had a width of 10 in. The compressive strength of the concrete used in the specimens was between 6,500 psi and 7,000 psi with an average value of 6,827 psi.

Each specimen was labeled in the following format: "size of longitudinal rebar", followed by a letter "E" for epoxy coated or "G" for galvanized, followed by the specimen number. For example: "8G-2" corresponds to the 2nd of the three test specimens containing a #8 galvanized test bar. Sample photographs of specimens used in the beam end test are presented in Figure 2.

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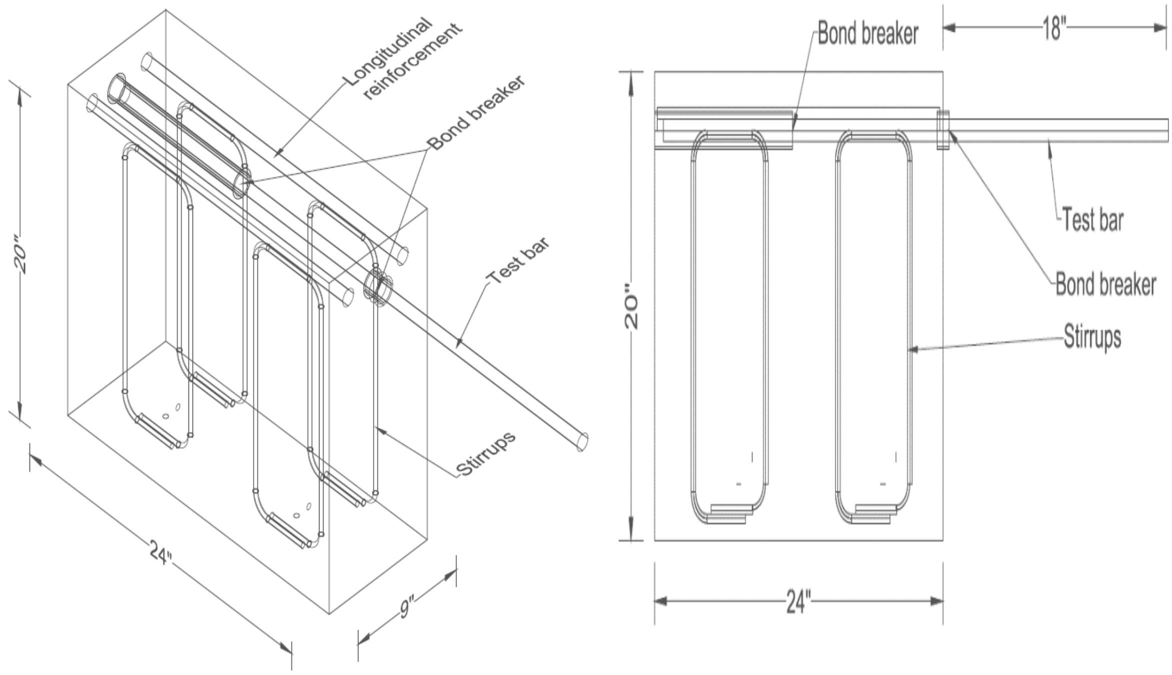

(a) Isometric view **(b) Side view**

Fig. 1: Detailed drawings of a typical test specimen.

(a) Isometric view showing the loaded-end **(b) Isometric view showing the unloaded-end**

Fig. 2: Sample photographs of specimens.

B. Test Setup and Procedure:

The test setup (Figure 3) was assembled following the guidelines given in ASTM A944-10 with a minor modification made in assembling the apparatus; the double hydraulic ram and yoke system was replaced with a single actuator pulling on the threaded bar coupled with a test bar. This was done to prevent uneven loading from the two-jack system. The free end of the test bar was butted against a hollow steel conduit by means of a mechanical coupler to provide access to the free end of the test bar for measuring slip. The test system was assembled such that it had sufficient capacity to prevent yielding of the various components during testing.

Two linear variable differential transformers (LVDTs) were attached to the loaded end by means of a clamp with the sensor core touching the front face of each specimen. A third LVDT was attached to the rear of the specimen for measuring slip of the unloaded end by means of an "L" bracket with the sensor core touching the unloaded end of the test bar through the PVC bond breaker. The entire apparatus was placed on the floor and secured to the Iowa State University

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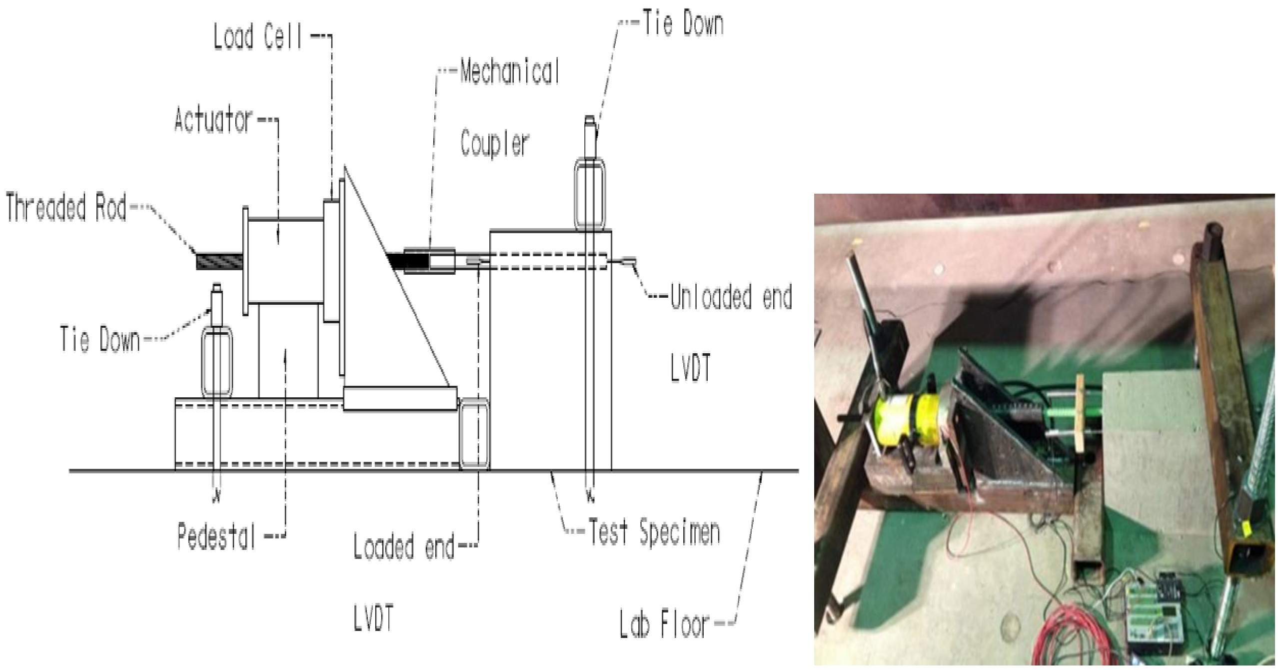
Structural Engineering Laboratory floor with a hydraulically secured tie down.

The testing was performed by manually pumping the actuator at a constant rate and applying a tensile load until cracks formed on the top and front face of the specimen. Each specimen was positioned in the apparatus so that the test bar was pulled slowly from the specimen. As the specimen was pulled, the bottom of the test specimen reacted in compression against the loading apparatus. This system created a self-contained loading apparatus. A tie-down at the back end of the specimen restrained the specimen against overturning. A load cell was placed in line with the actuator to read the applied loads. As per ASTM A944-10, the tensile load was applied parallel to the axis of the test bar and the target loading rate was such that failure does not occur within the first three minutes (180 seconds) of testing. The process was repeated for all specimens. An average measurement between the two LVDTs was reported as the test bar slip at the loaded end. Both the magnitude of the applied load and the specimens' corresponding slip were recorded. The time taken for the failure of the test specimen after the application of the load was also recorded.



(a) Elevation view **(b) Photograph of the test setup**

Fig. 3: Test apparatus details.

C. Results:

During the testing, it was considered a 'failure' of a specimen when the applied load caused cracks to develop along the specimen and/or the test bar was observed to have slipped. Tables 1 and 2 summarize the results of the beam end tests for the galvanized reinforcing steel and epoxy coated bars, respectively. In these tables, the load at which a failure occurred and its corresponding slips at the loaded and unloaded ends are given for each specimen.

The average bond strength of #6 epoxy coated bar was 28.6 kips with an average slip at the loaded and unloaded ends of 0.037 inches and 0.004 inches, respectively. For the #6 galvanized bars, the average bond strength was 28.5 kips with an average slip at the loaded and unloaded ends of 0.031 inches and 0.004 inches, respectively.

The average bond strength for the #8 epoxy coated rebar was 28.8 kips with an average slip at the loaded and unloaded ends of 0.019 inches and 0.004 inches, respectively. The average bond strength of the #8 galvanized rebar was 29.5 kips with an average slip at the loaded and unloaded ends of 0.016 inches and 0.002 inches, respectively. The relationship between the loads at failure vs. the average loaded end slip for the #8 galvanized bars and the #8 epoxy coated bars are shown in Figure 4.

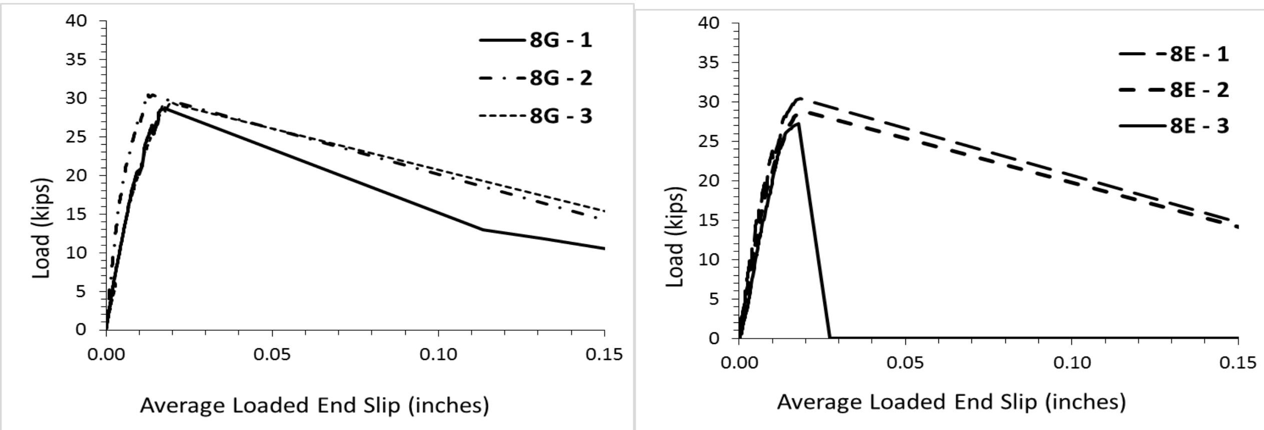
The average bond strength of #10 epoxy coated rebar was 32.2 kips with an average slip at the loaded and unloaded ends of 0.014 inches and 0.004inches, respectively. The average bond strength of the #10 galvanized rebar was 36.3kips with an average slip at the loaded and unloaded ends of 0.017 inches and 0.008 inches, respectively.

TABLE 1: SUMMARY OF BEAM END TESTS (EPOXY COATED TEST BARS)

Specimen	Load at failure (kips)	Slip at failure	
		Loaded end (in.)	Unloaded end (in.)
6E-2	25.710	0.0319	0.0044
6E-4	30.148	0.0353	0.0051
6E-5	29.855	0.0446	0.0031
6E-avg	**28.571**	**0.0372**	**0.0042**
(Std. Dev.)	(2.5)	(0.0066)	(0.0010)
8E-1	30.468	0.0185	0.0033
8E-2	28.745	0.0200	0.0039
8E-3	27.268	0.0179	0.0040
8E-avg	**28.827**	**0.0188**	**0.0038**
(Std. Dev.)	(1.6)	(0.0011)	(0.0004)
10E-1	32.911	0.0147	0.0040
10E-2	30.663	0.0119	0.0039
10E-3	33.136	0.0148	0.0029
10E-avg	**32.237**	**0.0138**	**0.0036**
(Std. Dev.)	(1.4)	(0.0016)	(0.0006)

TABLE 2: SUMMARY OF BEAM END TESTS (GALVANIZED TEST BARS)

Specimen	Load at failure (kips)	Slip at failure	
		Loaded end (in.)	Unloaded end (in.)
6G-1	31.584	0.0335	0.0041
6G-3	27.059	0.0332	0.0046
6G-4	26.757	0.0273	0.0046
6G-avg	**28.467**	**0.0313**	**0.0044**
(Std. Dev.)	(2.7)	(0.0035)	(0.0003)
8G-1	28.565	0.0170	0.0017
8G-2	30.595	0.0124	0.0015
8G-3	29.394	0.0201	0.0030
8G-avg	**29.518**	**0.0165**	**0.0020**
(Std. Dev.)	(1.0)	(0.0039)	(0.0008)
10G-3	35.559	0.0140	0.0025
10G-4	33.365	0.0153	0.0029
10G-5	40.064	0.0211	0.0194
10G-avg	**36.329**	**0.0168**	**0.0083**
(Std. Dev.)	(3.4)	(0.0038)	(0.0096)



(a) #8 galvanized test bars **(b) #8 epoxy coated test bars**

Fig. 4: Load vs. loaded end slip.

D. Discussion:

From the results presented in Tables 1 and 2 and sample plots in Figure 4, the bond strength of galvanized reinforcing bars can be compared with that of epoxy coated bars. In general the galvanized reinforcing bars performed comparably to the epoxy coated bars.

The bond strength of the #8 and #10 galvanized bars were larger than those of the same size epoxy coated bars while the specimens with the #6 epoxy coated bar showed a slightly larger bond strength than that of the #6 galvanize bar. In terms of percentage, #6, #8 and #10 galvanized bars had a failure load that was 0.37% less, 2.4% greater and 12.7% greater than their epoxy coated counter-parts, respectively. It is noted that the specimen 10G-5 seemed to have outperformed the other specimens with the same size of galvanized test bars. If this specimen is considered an outlier and is excluded from the data, the average failure load for the specimens with the #10 galvanized bars decreases to 34.462 kips, only 6.9% greater than their counterparts.

The average slip of the epoxy coated bars decreased as the bar size increased as one could expect. For the specimens with galvanized steel, however, the minimum average slip was obtained from the specimens with #8 test bars while the specimens with #10 test bars had the greatest slip. This may be due to the specimen 10G-5, which had the slips at the loaded and the unloaded ends of 0.0168 inches and 0.0083 inches, respectively, that are significantly larger than the other two specimens with the same test bar size.

The load-slip relation generally softens as the load reaches the maximum load, followed by reduction in tensile force associated with bond failure. It is noted that the force reductions of specimens '8E-3' and '10E-2' were more abrupt than those of others. It is speculated that this phenomenon was due to poor consolidation of the concrete along the top and front faces of these specimens.

After testing was completed, the failed specimens were visually inspected. Figure 5 shows typical crack patterns of the specimens observed during the testing. In general, longitudinal cracks initiated around the loaded end and propagated to the top surface, and then toward the unloaded end of the specimen along the test bar. This indicates a typical splitting mode of failure which was observed, to various extents, in all specimens. In general, the width of the longitudinal crack increased as the applied load increased. In most cases, the failure was by pullout mode with relatively smaller radial cracks developing around the loaded end as the test bar was pulled from the specimen.

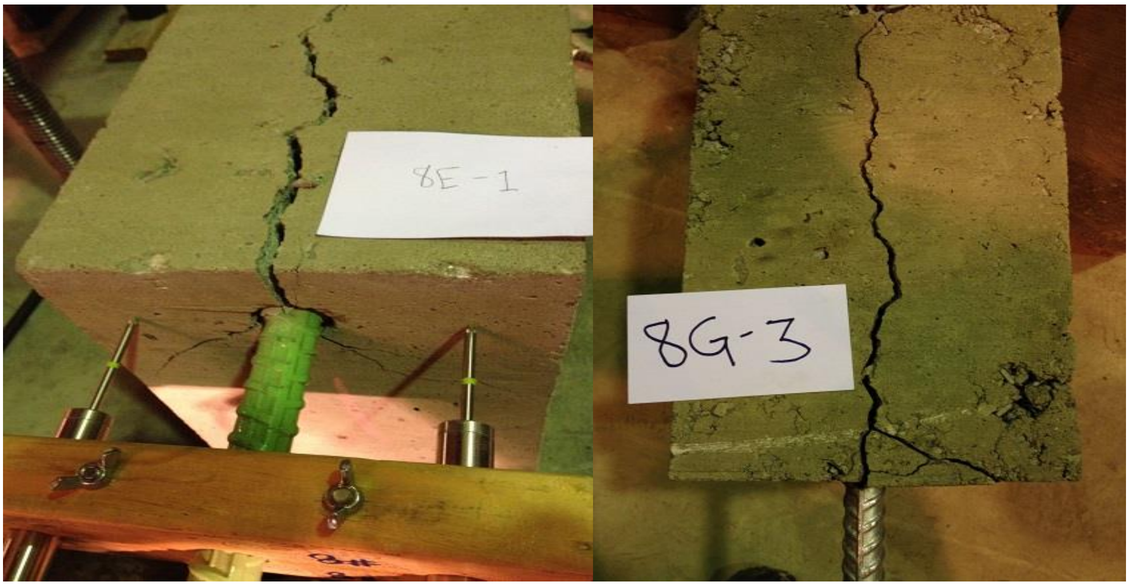
Finally, it is noted that the time elapsed before failure for a few specimens (i.e., 8E-2, 8E-3, 8G-3, and 10G-4) were less than what was recommended by the ASTM A944. Therefore, the results from those specimens may need to be disregarded. However, it is not anticipated that the slightly shorter test times had a notable influence on the overall test results.

III. CONCLUSION

The laboratory testing program was carried out to evaluate and compare the bond strength of galvanized reinforcing steel to that of epoxy coated bars. The evaluation process was based on the ASTM A944 test protocols. To perform the beam end tests, a total of 18 specimens – 9 specimens with galvanized test bars and 9 specimens with epoxy coated test bars – were constructed. The load at failure and the slip at the loaded and unloaded ends were noted and analyzed with the help of LVDTs.

The following conclusions were made based upon the laboratory test results:

- The bond behavior of the galvanized reinforcing steel was similar to that of the conventional epoxy coated bars. The difference in bond strength between them was not significant.
- In general, #8 and #10 galvanized reinforcing bars had an average bond strength that was higher than that of the same size epoxy coated bars. Although this may indicate that galvanized steel could potentially be an adequate replacement for epoxy coated bar, one may dispute it based on the test results on the slip at failure.
- The force reduction after reaching the peak load was abrupt for the specimens with poor concrete consolidation whereas it was gradual for other specimens.
- The during- and post-test observation revealed that the failure was by typical splitting and pullout mode for most specimens.



(a) Specimen with #8 epoxy coated test bar **(b) Specimen with #8 galvanized test bar**

Fig. 5: Photographs showing crack patterns of the specimens.

REFERENCES

[1] Yeomans, S.R., "Galvanized steel reinforcement in concrete," 1st edition, Elsevier Science, 2004.

[2] AGA, "Hot-dip galvanizing for corrosion prevention: a guide to specifying and inspecting hot-dip galvanized reinforcing steel," American Galvanizers Association, Centennial, CO, 2004.

[3] Kayyali, O.A., and Yeomans, S.R., "Bond and slip of coated reinforcement in concrete," Construction and Building Materials, Vol.9, No.4, 1995, pp.219-226.

[4] Yeomans, S.R., "Comparative studies of galvanized and epoxy-coated steel reinforcement in concrete," Durability of concrete-2nd international conference, SP126, American Concrete Institute, Farmington Hills, MI, 1991, pp.335-370.

[5] Ishikawa, T., Cornet, I., and Bresler, B., "Electrochemical study of the corrosion behavior of galvanized steel in concrete," Proceedings of the 4th international congress on metallic corrosion, NACE, 1972, pp.556-559.

[6] ACI Committee 408, "Bond and Development of Straight Reinforcing Bars in Tension (ACI 408R-03)," American Concrete Institute, Farmington Hills, MI, 2003.

[7] Hester, C.J., Salamizavaregh, S., Darwin, D., and McCabe, S.L., "Bond of epoxy-coated reinforcement: splices," ACI Structural Journal, V.90, No.1, Jan.-Feb. 1993, pp.89-102.

[8] Azizinamini, A., Stark, M., Roller, J., and Ghosh, S., "Bond performance of reinforcing bars embedded in high-strength concrete," ACI Structural Journal, V.90, No.5, Sept.-Oct. 1993, pp.554-561.

[9] Darwin, D., Tholen, M.L., Idun, E.K., and Zuo, J., "Splice length of high relative rib area reinforcing bars," ACI Structural Journal, V.93, No.1, Jan.-Feb. 1996, pp.95-107.

[10] Zuo, J., and Darwin, D., "Bond strength of high relative rib area reinforcing bars," SM Report No.46, University of Kansas, Center for Research, Lawrence, Kansas, 1998.

[11] Azizinamini, A., Chisala, M., and Ghosh, S., "Tension development length of reinforcing bars embedded in high strength concrete," Engineering Structures, V.17, No.7, 1995, pp.512-522.