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ISSN 0543-5846
METABK 55(3) 337-340 (2016)
UDC – UDK 620.193:669.14:673.4:621.793:620.17=111

BOND STRENGTH OF HOT – DIP GALVANIZED REINFORCEMENT (B500B) WITH CONCRETE

Received – Primljeno: 2015-10-01
Accepted – Prihvaćeno: 2016-02-10
Original Scientific Paper – Izvorni znanstveni rad

This paper evaluates the effect of initial corrosion damage to the surface of the hot - dip galvanized steel coating in fresh concrete on its final bond strength. The tests were performed on uncoated and hot-dip galvanized ribbed reinforcements. The measurement of bond stress (τ_m) according to the standard procedure (ASTM C234; ČSN 73 1328) revealed decreased bond strength of the coated reinforcement. Both types of reinforcement exhibit similar values of maximum shear stress (τ). To make some general conclusion, the bond strength also needs to be verified on smooth profiles.

Key words: corrosion, steel, hot-dip galvanized coating, pull – out test, ASTM C234

INTRODUCTION

Corrosion of common concrete reinforcement still poses one of the fundamental corrosion problem. Commonly used carbon steel reinforcement corrodes in fresh and toughening concrete in passive state, however, it can be activated and corrode at high corrosion rates due to carbonation and seeping chloride anions.

Dense steel corrosion products cause cracking and fall - off of the concrete cover layer, further worsening the problem [1].

Extensive corrosion damage of uncovered reinforcement always require duly and costly sanation [1, 2].

Coating is a possible protection precaution for carbon steel reinforcement. From the economical point of view, organic coatings (i.e. epoxides, rarely PVC), eventually hot - dip galvanizing does not significantly increase the structure costs [2].

It has been unanimously proven that ribbed reinforcement with epoxide coating has decreased bond - strength with concrete [2]. The reason for this can be reduced possibility to form weak interactions between the coating and the cement and/or low strength of the epoxy coating which is thus not able to transfer the forces from steel to concrete. The stability of hot – dip galvanized reinforcement is still a matter of debate.

It is still not apparent how much the bond strength is affected by the initial corrosion reaction between coating and fresh concrete [3, 4]. In alkaline environment of fresh concrete, the zinc coating dissolves (anodic reaction (1)), forming Zn^{2+} [3, 4].

$$Zn - 2\,e^- \rightarrow Zn^{2+} \qquad (1)$$

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In high - pH environment, the Zn^{2+} transforms to zinc hydroxide – $Zn(OH)_2$ (2) [3].

$$Zn^{2+} + 2OH^- \rightarrow Zn(OH)_2 \qquad (2)$$

In the excess of calcium cation Ca^{2+}, the hydroxide forms $Ca[Zn(OH)_3]_2 \cdot 2\,H_2O$ (3) – compound known as calcium bi(trihydroxide zincate) – dihydrate [2, 3].

$$2Zn(OH)_2 + Ca(OH)_2 + 2H_2O \rightarrow Ca[Zn(OH)_3]_2 \cdot 2H_2O \qquad (3)$$

Product of the cathodic reaction in alkaline environment is hydrogen (4) [2,3].

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \qquad (4)$$

Older literature sources suggest that the complex zincate is able to passivate the reinforcement surface in case of pH up to 13,3 [2]. Recent studies negate that statement, showing that it is the complex zincate that causes destabilization of corrosion products on the zinc-coated steel (ZnO, $\varepsilon - Zn(OH)_2$) in alkaline environment without Ca^{2+} which are clearly able to form passive protective layer [5].

Growing calcium bis(trihydroxide zincate) – dihydrate can disrupt the cement and contribute to formation of non - binding layer. These phenomena can significantly reduce bond strength between concrete and the reinforcement. Developing bond can be further affected by hydrogen from the corrosion reaction which increases porosity of hardening cement on the phase interface [3, 4].

Concrete - reinforcement bond strength is key element for the loading capacity of the whole concrete structure. Some experts proved that formation of zincates and hydrogen has no effect on evolution of bond strength [2, 3]. Others reported decreased bond strength from their experiments [6, 7].

The difference in their conclusions can arise from various reasons. Geometry of the reinforcement, cement composition (effect of chromate and chloride anions), alkalinity of the cement during hydration, cement treatment during curing and also the chosen testing procedure can all have significant effect [7].

This paper verifies the bond strength of hot-dip galvanized ribbed reinforcement (B500B [8]) with the so - called "Normal Strength Concrete".

EXPERIMENTAL

Comparison tests of bond - strength were realized on hot - dip galvanized ribbed reinforcements and reinforcements without coating with the same surface geometry of normal diameter of 14 mm (B500B). The pull - out test [9, 10] (Figure 1) after 28 - day curing in moist atmosphere (95 % R.H.) was used. Total bonding length of reinforcement in concrete was set, according to the standard (ČSN 73 1328), to 84 mm. The reinforcement bar was held in axis-aligned position by plastic holders. The testing was performed on the MTS 500 kN machine equipped with displacement gauge LVDT B20. Samples were cubic, prepared from concrete of typical mechanical properties – mixed Portland slag cement (CEM II/B – S 32,5 R) with coarse aggregate.

Coating was prepared by the standard hot -dip technology at 450 ± 10 °C.

Five samples of each type were tested. Concrete is classified as C40/50, with the watter to cement ration of w/c = 0,5. Content of individual oxides in concrete was analyzed by the XRF method (Axio – PANalytical), concentration of chloride and CrO_4^{2-} was analyzed by the ICP – OS (Integra XL) - Table 1.

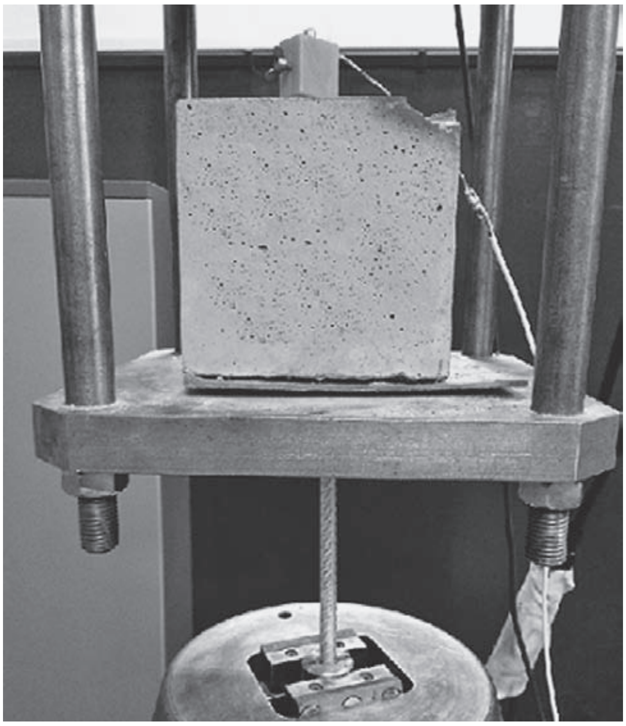

Figure 1 Experimental setup for the pull-out test

Steel reinforcement were coated by a commercial galvanizer. The samples were degreased (alkaline degreasing bath) and pickled in hydrochloric acid.

Table 1 **Chemical analysis of the concrete (XRF/ICP - OS) / wt. %**

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3
54,5	26,9	5,1	3,3	2,6
MgO	Na_2O	K_2O	Cl^-	CrO_4^{2-}
3,9	0,2	0,6	0,053	$1\cdot10^{-3}$

Table 2 **Content of impurities in the substrate steel /wt. %**

Element	XRF	GDS-OS
C	-	0,47
Al	0,03	0,04
Si	0,22	0,20
P	0,01	0,01
S	0,02	0,01
Cr	0,08	0,07
Mn	0,58	0,69
Cu	0,09	0,11
Zn	0,03	0,03

RESULTS AND DICSUSION

The steel composition was, prior to the coating, verified by the XRF (Axios – PANalytical) and GDS – OS (Horiba Jobin Yvon GD Profiler II) methods (Table 2). The silicon content puts the steel in the Sebisty region (silicon killed steel, Si content of 0,15 – 0,25 wt. %). Such steel does not exhibit undesired increase in coating thickness which predominantly consists of brittle ζ phase ($FeZn_{13}$) – Sandelin effect. Concentration of phosphorus (P) is low enough to prevent further negative effect on produced coating composition [3, 11].

Produced coating was of typical composition: ($\Gamma + \Gamma_1$), ($\delta_k + \delta_k$), ζ and Fe + Zn solid solution η (0,03 wt. % Fe) [11]. Phase distribution is shown in Figure 2.

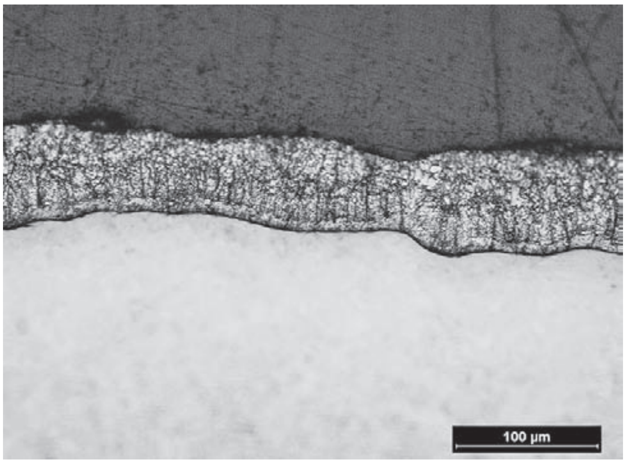

Figure 2 Cross-cut of hot - dip galvanized ribbed steel reinforcement

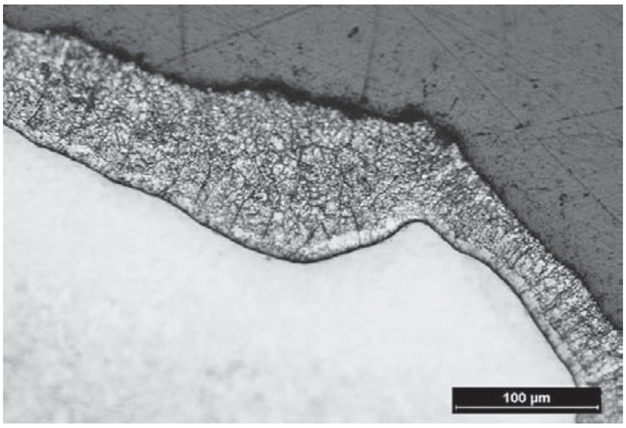

Figure 3 Detail of the coating showing the cross - cut section near the base of the rib

It is apparent from the metallurgical study that zinc coating can locally smoothen the surface of the reinforcement (Figure 3). This phenomenon was not further studied in this work.

Comparison of bond - strength tests is shown in the bar diagram in Figure 4 and 5. Figure 4 compares the bond strength τ_m, i.e. at upper displacement of bar equal to 0,001 mm for both types of reinforcement. Lower shear stress resulted in shift of hot - dip galvanized reinforcement. The ultimate shear stress, i.e. – stress necessary to completely pull - out the reinforcement from concrete is presented on Fugure 5. Contrarily, these results suggest similar bond strength of the two sample types.

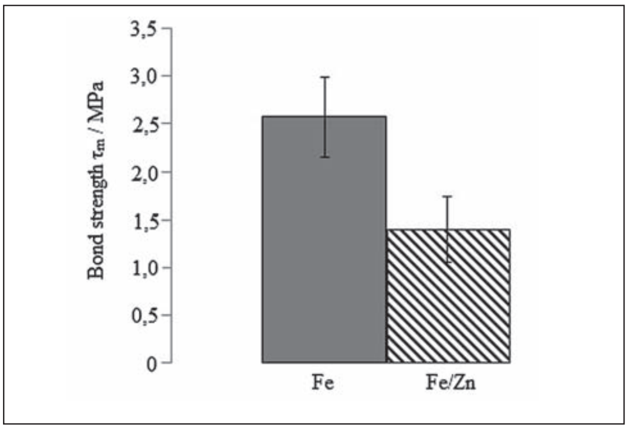

Figure 4 Comparison of recorded bond strengths (0,001 mm displacement), Fe – uncoated steel, Fe/Zn – hot - dip galvanized steel

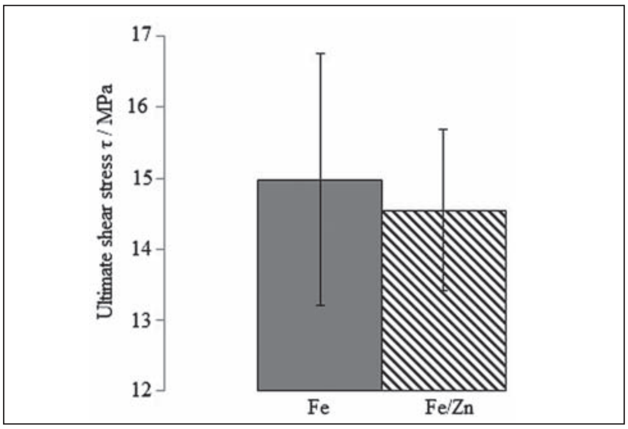

Figure 5 Comparison of ultimate shear stresses, Fe – uncoated steel, Fe/Zn – hot - dip galvanized steel

However, the bonding is in this case influenced by mechanical aspect of ribs interconnection with concrete – aspect determining the mechanical properties of reinforced concrete (tensile strength, but also the compressive strength). Bond strength τ_m results in Figure 4 suggest decrease in bond strength of zinc coated reinforcement. Nevertheless, for more general conclusion about effect of hot – dip galvanized reinforcement on bond strength with concrete (effect of expanding corrosion products of zinc and effect of forming hydrogen on porosity of cement), the tests should be performed on smooth specimens (without ribs).

Based on the evaluation from the standard (ČSN 73 1328 - 0,001 mm displacement – measurement of bond strength τ_m) it can be stated that the bond strength was indeed decreased. The reason for this was the corrosion of zinc coating in fresh concrete, however, smoothening of the surface of the ribbings by zinc coating could also have negative effect. Low concentration of Cl^- in cement could not affect corrosion of zinc coating (η phase). On the other hand, low amount of CrO_4^{2-} anions in concrete cannot prevent corrosion of zinc (η phase) in active state and simultaneous hydrogen production.

CONCLUSIONS

Normative evaluation of reinforcement -concrete bond strength shows that even ribbed reinforcement exhibits decreased bond strength with concrete. Although the pull - out of the reinforcement are achieved by similar shear stresses. Nevertheless, in this regime, the bond strength is already strongly affected by mechanical properties of concrete.

Decreased bond strength of hot - dip zinc coated is caused by initial corrosion attack of the η phase in fresh concrete. During this step, corrosion products based on $Ca[Zn(OH)_3]_2 \cdot 2\ H_2O$ grow on the surface of coated steel, disintegrating the cement at the phase interface. Forming hydrogen also has negative effect by increasing the porosity of cement. For general assumptions about corrosion of hot – dip galvanized steel and its effect on bond strength, the testing should be performed on smooth coated reinforcement profiles.

New concrete structures should follow the principles of concrete reinforcement, taking the danger of decreased bond strength of this reinforcement into account.

Acknowledgments

This research has been supported by Czech Science Foundation, project GA ČR No 14-20856S.

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Note: The responsible translator for the English language is K. Štětková, CTU – Klokner Institute, Prague, Czech Republic