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Review Article

Structural and Corrosion Performance of Continuous Galvanized Rebar (CGR)

Anil Patnaik[1]*, Srikanth Marchetty[2], Sourav Khatua[3], Nibras Khalid[4], and Michael Stroia[5]

[1]*The University of Akron, Akron, OH 44325-3905, USA*

[2]*TRC Worldwide Engineering, Allentown, PA 18195, USA*

[3]*KSK Construction Group, Brooklyn, NY 11249, USA*

[4]*Mustansiriya University, Baghdad, Iraq*

[5]*Commercial Metals Company, Pooler, GA 31322, USA*

***Corresponding author:** Anil Patnaik, Professor and Interim Department Chair, Civil Engineering, The University of Akron, Akron, OH 44325-3905, USA

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Abstract

Epoxy-coated bars (ECB) and hot-dip galvanized (HDG) bars are commonly used for corrosion protection of steel reinforced concrete but both these types of bars have some known deficiencies. For example, the zinc-iron layer formed at the interface between approximately 150 μm (5.9 mils) of coating and the steel bars is undesirable and causes flaking in HDG bars under bending. An emerging technology called continuous galvanizing is a simple and cost-effective process that is used to produce continuous galvanized rebar (CGR). Recent research and test results demonstrate that CGR outperforms ECB and HDG in terms of structural and corrosion performance. A smaller coating thickness of 50 μm (2 mils) of CGR has proven to be better corrosion-resistant than the larger 150 μm (5.9 mils) thickness of HDG and the epoxy coating of ECB. CGR is a cost-effective solution both in terms of the initial costs and life-cycle costs. Furthermore, the CGR manufacturing process is environmentally friendly compared to other coating processes.

Keywords: Steel reinforced concrete; galvanized steel bars; continuously galvanized rebars; corrosion-resistant bars; coated steel reinforcing bars; pull-out strength; epoxy-coated reinforcing bars

Abbreviations: CGR: Continuous galvanized rebar; ECB: Epoxy-coated bars; HDG: Hot dip galvanized; MMFX: Micro-composite Multi-structural Formable Steel; FRP: Fiber-reinforced polymer; ODOT: Ohio Department of Transportation

Introduction

Steel reinforced concrete is a versatile and economical building material that is commonly used in the construction industry. Under most circumstances, reinforced concrete is adequately strong and durable to provide maintenance-free service for decades. However, corrosion of steel reinforcement embedded in concrete is a problem-particularly in coastal and saline or corrosive environments.

Corrosion can be the primary cause for premature and accelerated degradation of the structure and can lead to reduced service life. In the last 30 years, several preventive methods have been introduced to delay and manage corrosion damage to structural steel reinforced concrete. Use of coated bars such as epoxy-coated bars (ECB), hot-dip galvanized (HDG) bars and the use of corrosion-resistant reinforcement such as fiber reinforced polymer (FRP) bars, stainless steel bars or Chrome Alloy MMFX bars are common methods considered to address the corrosion issues of steel reinforced structural concrete. Of these several corrosion-resistant reinforcing bar alternatives, the use of coated bars (ECB or HDG) is generally accepted as being one of the most economical and convenient methods. A relatively new technology called continuous galvanizing is a simple and cost- effective process that is used to produce continuous galvanized rebar (CGR).

Coated Steel Reinforcing Bars

The discussion in this paper is focused on the relative merits and performance of CGR compared to that of other types of coated bars and uncoated bars. The coatings used on coated bars can be metallic or non-metallic. Some examples of metallic coating are HDG and stainless-steel cladding, and an example of non-metallic coatings for bars is epoxy-coating. Duplex bars are provided with a combination of metallic and non-metallic coatings. The outermost coating of the coated bars commonly acts as a physical barrier for the protection of carbon steel reinforcing bars. However, some coatings such as zinc coating can also function as a sacrificial anode. The use of a steel reinforcing bar with coating applied to its surface provides many advantages over those without coating (black bars). The following are some of these advantages:

a. Increased time to the initiation of corrosion

b. Reduced corrosion of the steel bar due to the physical barrier provided by the coating

c. Minimal increase in the initial cost to achieve superior corrosion resistance and increased service life

Some of the disadvantages of coated bars are:

a) Additional cost due to coatings

b) Reduced bond and pull-out strength

c) Increased crack widths in structural concrete slabs and beams

d) Damage to coatings during handling and construction, which would normally involve additional costs due to the need for touch-up, and if not repaired can cause accelerated corrosion

Epoxy-Coated Bars

The documented use of epoxy-coated reinforcing steel in bridge applications dates to 1973. By 1987, at least 41 state departments of transportation within the United States were using ECB as the only corrosion protection system in their concrete decks. Currently, ECB use is widespread in bridges, buildings, wharves, and other structures. The initial cost of structures using ECB can increase moderately compared to those using black bars, but the life cycle cost of the structure is reduced due to the lower maintenance costs for structures using ECB than those using black bars. As reported by EIG (Epoxy Interest Group [1]) for bridges, the initial cost increases by about 4% per yd^2 of the deck area due to the use of ECB, but the rate of return calculated relative to the increased initial cost over a 75-year life was about 29 times the increased initial cost. While ECB is a commonly accepted coated bar, there are several known and well-recognized deficiencies and disadvantages of using ECB.

Hot-Dip Galvanized Coated Bars

Hot dip galvanized (HDG) structural steel and concrete reinforcing bars have been used for corrosion protection in the construction industry for a long time. The first use of zinc-coated steel in concrete dates to around 1908, and the first regular use of HDG bars in the United States as a reinforcing material was in the 1930s. The first applications of galvanized reinforcement for bridge decks were implemented in the 1950s. HDG has been used in bridge decks, pavements, crash barriers, parking structures, and chemical and petrochemical industries for all these years.

In traditional HDG, the surfaces of prefabricated steel with straight lengths, bends and/or welds are cleaned using any cleaning process that allows the zinc to bond with steel. The clean reinforcing bars or prefabricated reinforcement cages are immersed into a molten bath of zinc at about 840° F (450° C) until the zinc reacts with the steel surface to form zinc-iron intermetallic alloys. The immersed steel reaches the temperature of the molten zinc within the zinc bath and metallurgical reaction takes place resulting in a series of zinc-iron alloy layers. These zinc-iron alloy layers grow from the steel-zinc interface while the outermost layer remains as a pure zinc layer (Eta).

The thickness of the HDG coatings will depend on the diameter of the steel reinforcing bar for structural concrete or the thickness of the unit being coated as well as the class designation [2,3]. ASTM A767-16 [2] standard specification for zinc-coated (galvanized) steel bars for concrete reinforcement recommends a minimum zinc coating thickness and equivalent weight in Table 1 of the standard which is reproduced in this paper as Table 1. For Class 1, the minimum coating for #4 (13mm diameter) or larger size bars is 150 μm (5.9 mils); for Class 2 bars, the minimum specified coating is 86 μm (3.4 mils). To meet this requirement, it is not uncommon for fabricators to provide a coating of 150 to 180 μm (5.9 to 7.0 mils).

Galvanized coating is metallurgically bonded to steel which will result in a tough, scratch-resistant, and well-adhered coating that is less susceptible to damage during shipping and handling. Galvanized reinforcing bars have been accepted in the concrete industry [4-6] as an effective corrosion-resistant rebar to protect steel reinforced concrete structures from deicing salts and other corrosive agents. A substantial body of knowledge developed over several decades through research and validation of field applications currently exists to support the beneficial use of HDG bars. Several national and international standards are available on HDG bars and their use in the industry (e.g., ASTM A767-16 [2], ASTM A780-20

[7]). Currently, the preferred method of applying zinc to the surface of steel reinforcing bars is by hot dipping reinforcing bars into a molten bath of zinc. The corrosion resistance and the service life of concrete reinforced with HDG bars depends on the thickness of the zinc coating and the exposure condition.

Table 1: ASTM A767 [2] Requirements for Zinc Coating Thickness and Equivalent Weight (Mass).

Classification	Zinc Thickness		Weight (Mass)/Unit Area	
	mils	µm	oz/ft²	mg/cm²
Class 1				
Bar Designation No. 3 (10mm)	5.1	129	3	92
Bar Designation No. 4 (13mm) and Larger	5.9	150	3.5	107
Class 2				
Bar Designation No. 3 (10mm) and Larger	3.4	86	2	62
Note 1: The key value in this table is micrometer (µm) and is based on a zinc density of 7140 kg/m³. The other values are based on the following conversion formulas: mils = µm × 0.03937; oz/ft² = µm × 0.0232; g/m² = µm × 7.14; and mg/cm² = µm × 0.714.				

Continuous Galvanized Rebar (CGR)

There is a good potential to improve the hot-dip galvanizing process because this batching process results in a thickness of zinc and zinc-iron coating in excess of the minimum ASTM A767 limit of 150 µm (5.9 mils) for Class 1 coatings. Such large thicknesses give rise to some practical limitations in structural concrete applications. A recent and developing technology called continuous galvanizing is proving to be a simple and efficient method to produce continuous galvanized rebar (CGR). This new process offers a cost-effective alternative to hot-dip galvanizing of steel. The CGR is showing promise to be a better corrosion resistant bar than the other forms of corrosion-resistant bars with coatings such as epoxy coating or duplex coatings.

ASTM A1094-18 [3], which is the standard specification for continuous hot-dip galvanized steel bars for concrete reinforcement, recommends minimum average coating thickness grade and equivalent weight (mass) in the standard's Table 1 (reproduced in Table 2 in this paper). ASTM A1094 requires a minimum coating thickness of 50 µm (2 mils) for continuous hot-dip galvanized steel bars, which is just ⅓rd of what is needed for Class 1 HDG coatings. In practice, an average coating thickness of about 60 microns is not uncommon. However, a thinner coating of about 50 µm (2 mils) for continuously galvanized rebar (CGR) provides equivalent or superior corrosion resistance than the thicker 150 µm (5.9 mils) hot-dip galvanized zinc-iron coating specified in ASTM A767.

Table 2: ASTM A1094 [3] Requirements for Minimum Average Coating Thickness Grade and Equivalent Weight (Mass).

Coating Grade	mm	mils	oz/ft²	g/m²	mg/cm²
50	50	2	1.2	360	36
The value in micrometers (mm) is based on the Coating Grade. The other values are based on the following conversion formulas: mils = mm × 0.03937; oz/ft² = mm × 0.0232; g/m² = mm × 7.14; and mg/cm² = mm × 0.714					

In a continuous galvanizing process, blast-cleaned and preheated reinforcing bars are coated by passing individual bars through a molten zinc or zinc-alloy flooded trough or a tube located above a zinc or zinc-alloy bath. Reinforcing bars can travel at increased speeds with a reduced dwell time in the zinc bath. The bars are then passed immediately through an air wiping device to remove excess coating from the bars. A conceptual process diagram for CGR is shown in Figure 1. The typical details of a commercially produced CGR known as GalvaBar are provided in Reference [8].

Advantages of Continuous Galvanized Rebar (CGR)

Several researchers, e.g., [9-11], have worked through the International Zinc Association (IZA) [12] and widely reported that the formation of the zinc-iron alloy layers that occur during the batch HDG process is avoided in CGR. This is achieved by adding a small percentage (0.2%) of aluminum to the zinc bath and by having much shorter immersion times compared to that for HDG (several minutes). The zinc-iron reaction is inhibited at the interface by the formation of a very thin iron-aluminum-zincate alloy (Fe2Al5-xZnx) film at the zinc-steel interface, leading to the prevention of thick zinc-iron alloy layers that form in the HDG process (Zeta, Delta, Gamma layers). A pure zinc coating of about 50 µm (2 mils) forms on the outside of this thin film and protects the re-bar from corrosion. The zinc coating thickness in CGR is substantially smaller compared to that of HDG bars thereby reducing the zinc consumption by more than half. The CGR zinc coating is also lighter due to the smaller coating thickness. The zinc coating on HDG is estimated to increase the original weight of the bar by approximately six to eight percent. However, this weight increase for CGR will be about 2 to 3% depending on the bar size. All grades of CGR steel, including high strength steels, will have the same coating, which is composed of nearly pure zinc conforming to ASTM B6-18 [13] or B852-22 [14].

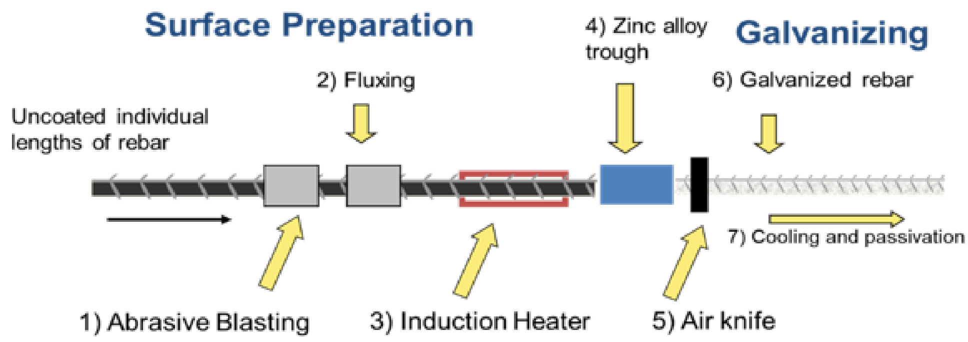

Figure 1: Continuous Galvanizing Process for Rebar [8] Courtesy of Commercial Metals Company, Pooler, GA.

While a HDG bar typically is coated with layers of thick zinc-iron alloys, the short dwell time for CGR and the use of 0.2% aluminum can retard or eliminate the possibility of the formation of zinc-iron alloy layers. This pure zinc layer, along with a very thin ternary alloy layer, enhances adhesion and formability in CGR. The continuous galvanizing process results in a more flexible and adherent galvanized coating than that of HDG, without any zinc loss due to flaking during shipping and handling. CGR can be bent, stretched, twisted, or otherwise fabricated after the galvanizing process is complete without cracking or flaking of the coating. Lack of zinc-iron alloy layers below the pure zinc layer also improves corrosion resistance of the CGR relative to HDG, using less zinc without compromising corrosion protection.

The galvanizing process for CGR allows coated bars to be developed with excellent corrosion resistance and exceptional formability compared to other coated bars. The corrosion resistance of CGR has been studied by several groups, in cooperation with the International Zinc Association [12]. The report by Weyers [15] includes a cost analysis that compares the relative costs of bridge decks reinforced with different types of reinforcing bars in the state of Virginia in the United States. It was reported that the use of CGR is more cost-effective than the use of epoxy-coated bars or stainless-steel bars. The service life of bridge decks with galvanized bars was shown to be 100 years, while that of decks with epoxy-coated bars was reported to be 55 years. Weyers' report refers to the traditional HDG rebar. However, CGR will provide a similar or better service life for concrete structures at a lower cost. Yeomans [16,17] reported that Xiamen New Steel (Fujian Province in Southeast China), has been producing CGR since 2011 with documented applications in railway, highway, and subway construction in China. A CGR pilot plant was also commissioned in Dubai by Super Galvanizing.

Performance Evaluation of CGR

Objective

The overall goal of this study was to evaluate the relative performance of coated bars for structural concrete both in terms of structural performance and corrosion resistance.

Evaluation of coated reinforcing bars

The test results from a recently concluded research project performed at The University of Akron are briefly summarized in this paper. A series of structural and corrosion tests were conducted in a research project on the effectiveness of several types of structural concrete reinforcing bars. The performance of structural concrete reinforced with different types of corrosion-resistant bars commonly used in the construction industry was studied. From those results, the performance of CGR was compared with that of a higher grade MMFX bars, the black bar, and epoxy-coated bars.

The primary performance measures included in the study were:

a. Pull-out and bond strength

b. Development of crack widths

c. Flexural and shear strength of slabs

d. Corrosion performance

This paper includes details on pull-out and bond strength of CGR and other commercially available corrosion-resistant bars. General findings on other aspects of performance measures are summarized but details are presented elsewhere [18,19].

Pull-Out Strength Tests

Pull-out tests provide a good indication of the performance of the corresponding corroded or uncorroded reinforced structural concrete in: (i) bond strength development, (ii) moment strength of beams and slabs, (iii) cracking potential of beams and slabs, (iv) fatigue loading of beams and slabs, and (v) impact loading on concrete structures. Such tests are cost-effective and particularly useful for making comparisons between different reinforcing bars and different concrete types.

Test Description

Pull-out tests were conducted using prism specimens under identical conditions for different types of corrosion resistant bars with/without corrosion; and with/without 10 lb/yd^3 polypropylene fiber. The test specimens were cast with #5 bars with a nominal diameter of 0.625 inch or 16mm, with an embedment length of 2.5 inches (63mm). The dimensions of the prisms are 6″×6″×6″ (152mm×152mm×152mm) as shown in Figure 2. The specimens were cast with Ohio Department of Transportation (ODOT) typical QC2 concrete mix design with a minimum 28-day compressive strength of 4,500 psi (31 MPa).

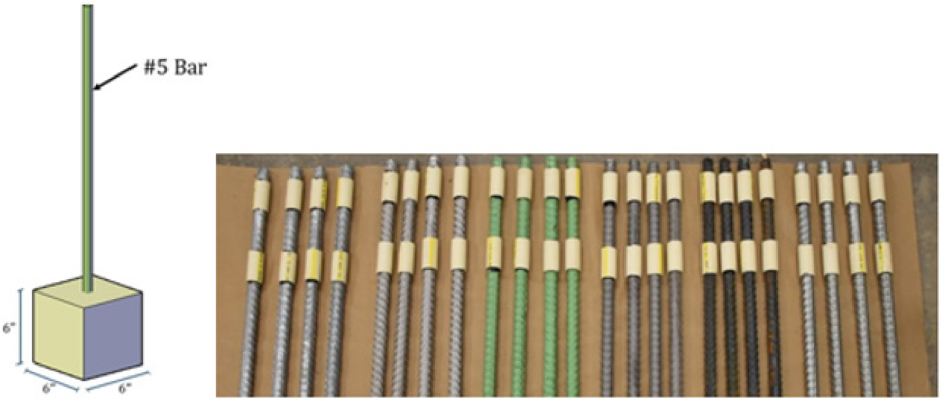

Figure 2: Pull-out test details (left: specimen details, and right: bar types).

Accelerated Corrosion of Pullout Specimens

Of 48 specimens, a total of 24 specimens were subjected to accelerated corrosion for a period of 10 days. Five percent corrosion level corresponding to the mass loss was used as the basis and the current intensity was calculated using Faraday's equation. An impressed current of 0.02 A was applied to the bars; a specially made casing using stainless steel plates was used as the cathode. A 5% NaCl solution was used as electrolyte in a plastic tank, in which the specimens were immersed until the solution just reached the top surface. A two-day wetting and one day drying cycle was used to increase the effect of corrosion. Both corroded and non-corroded specimens were tested for pullout strength using a Baldwin universal testing machine with a capacity of 300 kips (1,335 kN).

Pullout Test Results

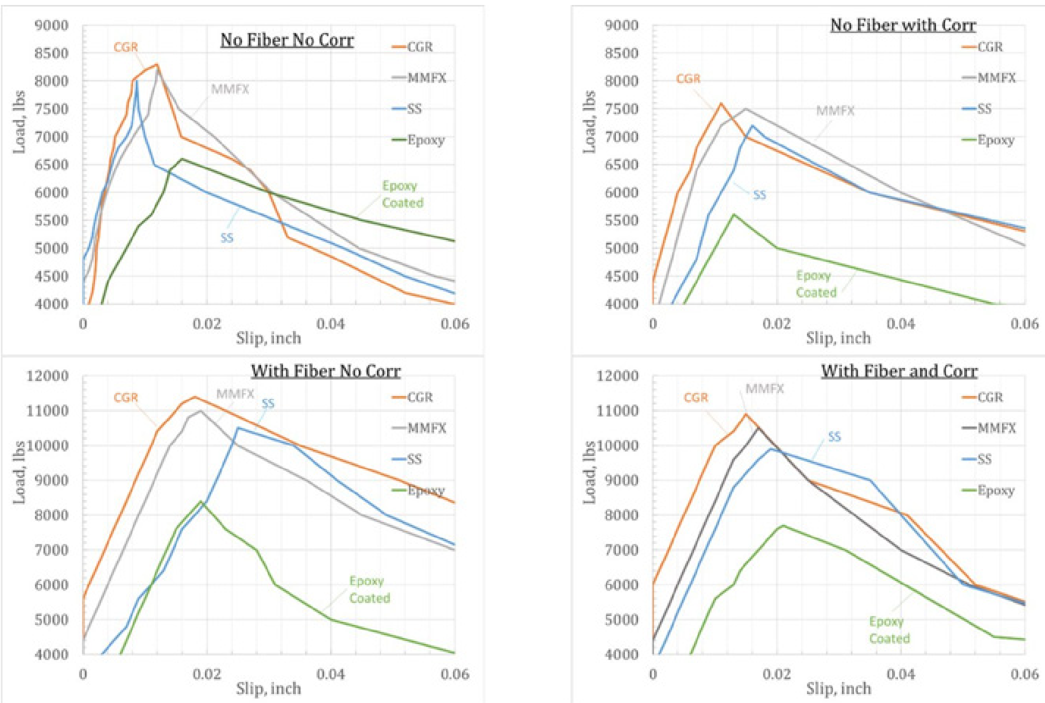

Figure 3: Comparison of load-slip curves of CGR with those for other corrosion-resistant bars.

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Load versus slip plots obtained from pull-out tests are compared in Figure 3 for common corrosion- resistant bars (CGR, MMFX, SS, and ECB) and in Figure 4 for common bars (black bars, ECB).

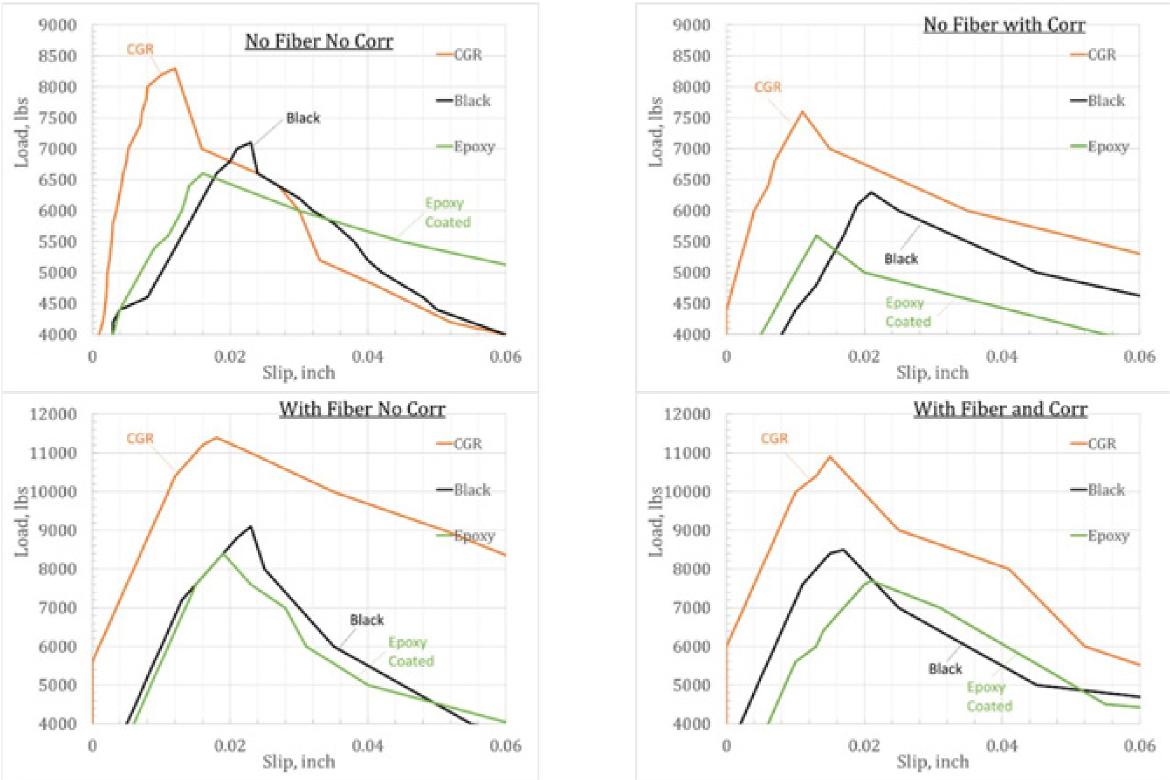

Figure 4: Comparison of load-slip curves of CGR with those for common reinforcing bars.

In Summary

A. CGR outperformed all other types of bars tested in this study for both corroded and uncorroded conditions, with and without fiber.

B. CGR out-performed all the corrosion-resistant steel bars, and its performance was:

i. Better than ECB by a large margin

ii. Clearly better than stainless steel bars

iii. Marginally better than MMFX.

C. The addition of fiber to the concrete improved the performance of the bars by at least 10 to 15%, both in corroded and uncorroded conditions.

D. From these test results, CGR was observed to provide better structural and corrosion performance in reinforced concrete than the other bars tested in the study, particularly the ECB.

Other Tests Performed

Several other tests were completed in this study and are only briefly described in this section. For complete details, please refer to the original reports [18,19].

Slab Corrosion Tests

To replicate in the laboratory, the condition of sustained loads due to their self-weight acting on bridge decks, tests were designed using an accelerated corrosion process while test specimens were subjected to sustained loading. This condition simulates permanently acting sustained dead loads. Eighty slab specimens were cast with conventional black steel as well as with several types of corrosion-resistant reinforcing bars (epoxy-coated bars, hot-dipped galvanized bars, stainless steel bars, and MMFX bars). Slabs with epoxy-coated bars with up to 5% damage induced on the coating showed the largest extent of corrosion damage compared to the other bar types, in terms of maximum flexural capacity loss due to corrosion. MMFX bars showed good corrosion resistance. The capacity loss for the slabs with hot-dip galvanized bars was much closer to that of slabs with black bars. Tests with CGR reinforced slabs were not included in this series.

Crack width tests

Direct tension tests were conducted on prism specimens with black steel bars (control), epoxy-coated bars, grade 2304 stainless steel bars, MMFX corrosion-resistant alloy steel bars, hot-dipped galvanized bars, and zinc galvanized bars (CGR). As very little research has been performed on the use of corrosion-resistant reinforcing steel as a means for reducing cracks on bridge decks, tests were designed to gain insight into the effects of each reinforcement type on cracking in direct tension. Specimens with epoxy-coated bars showed wider cracks at a given load or stress level compared to specimens with other bar types, whereas prism specimens with MMFX and CGR showed smaller crack widths. Specimens with black bars and hot-dipped galvanized bars showed similar cracking behavior. A comparison of crack widths for the bars tested in this study at a stress of 40 ksi (275 MPa) revealed that CGR bars develop consistently smaller crack widths at all loads compared to MMFX and all other bar types.

Slab tests to study flexural cracking

The span length between the inflection points at the ends of the negative moment region of a typical three-span bridge deck can be considered to be simply supported for the purpose of designing test specimens. Test specimens with a section of 13-in. × 8-in. (330mm × 203mm) with a span length of 7.5 ft. or 2,285mm (total length of 8 ft. or 2,440mm) were used for flexural tests to determine the cracking behavior of slabs reinforced with corrosion-resistant reinforcing bars. The test results demonstrated that CGR reinforcement reduced crack widths in flexural members such as bridge deck slabs and beams significantly compared to black bars and ECB. When compared to the cracking behavior of structural slabs reinforced with other corrosion-resistant bar types such as MMFX, stainless steel and ECB, CGR reinforced slabs developed cracks having about the same width as the slabs with MMFX, but with substantially smaller widths than slabs reinforced with ECB or stainless-steel bars.

Deficiencies of ECB

Some of the deficiencies of ECB that are well recognized in the industry are as follows:

Development Lengths and Pull-out Strength

It is generally accepted that ECB will need about 8 to 12% longer development length, splice length and anchorage length compared to that of black bars. ACI 318-19 [20] and AASHTO recognize this reduced bond strength and adjust the design equations accordingly. The results presented in this paper also proved that the pull-out strength of ECB embedded in concrete is smaller than that of black bars by a similar margin. CGR will need no such additional development length, lap splice length or anchorage length. The adhesion of concrete with galvanized reinforcement is better than that of uncoated steel due to the formation of a surface layer of calcium hydroxy zincate.

Epoxy Coating on Reinforcing Bars

The polymer-based coatings on ECB are generally soft and are susceptible to scratching and damage. Peeling of the epoxy coating from the bar surface is common after the bars are subjected to corrosion (Figure 5). Because of the metallurgical bonding of zinc with steel, CGR has a tough and scratch-resistant coating and a zinc-steel interface that is well bonded.

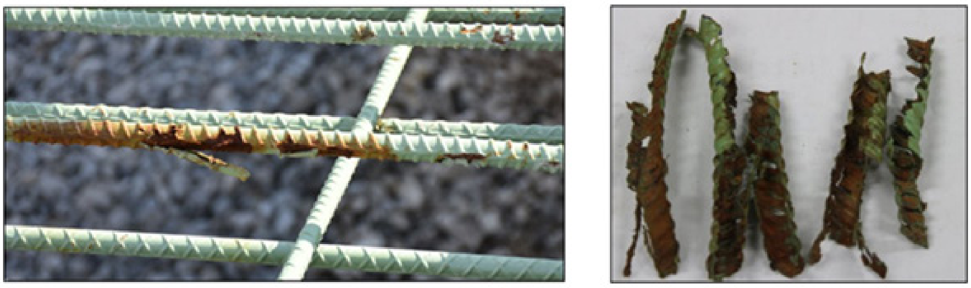

Figure 5: Condition of epoxy coating in a demolished bridge deck after about 25 years of service.

Corrosion Performance

It is generally expected that the epoxy coating on the reinforcing bars will provide the bar with adequate protection from corrosion. While this is theoretically true if the epoxy coating on the bars is intact and undamaged, in practice the coating is damaged during handling and concrete placement. The design codes and specifications recognize this possibility and allow coating damage of up to 2% of the surface area. However, at construction sites, it is not uncommon to see damage to the epoxy coating larger than 2%, and the touching up of the damaged coating is many times overlooked. This surface damage to ECB makes it susceptible to accelerated localized corrosion at the location of the coating damage with much more severity than that of uncoated bars.

Bond Development with Concrete

Lack of proper bonding between ECB and the surrounding concrete is a major deficiency of ECB reinforced structural concrete. Figure 6 shows the breaking of bond under static loading and Figure 7 shows the crumbling of the concrete surrounding an epoxy-coated bar under impact loading. This type of deficiency is more common and serious for larger thicknesses of epoxy coating. Dual-coated reinforcing bars are also similarly disadvantaged.

Figure 6: Lack of bond between epoxy-coated bars and concrete under static loading.

Figure 7: Lack of bond between epoxy-coated bars and concrete under impact loading.

Life-Cycle Costs of Structures Reinforced with Galvanized Bars

In a study by the American Galvanizers Association that compared bridge decks constructed using epoxy-coated, galvanized, and solid stainless-steel bars in chloride exposed conditions, galvanized steel was found to have the lowest life cycle cost and the least total present cost. The service life of bridge decks constructed using galvanized reinforcement was estimated to be 100 years in comparison to decks with epoxy-coated reinforcement with 55 years of service life. Decks constructed using solid stainless-steel bars were predicted to have a service life of over 100 years. CGR performs better than HDG, and the life-cycle costs for bridges constructed using CGR are even lower than decks constructed with HDG reinforcement.

Comments on Environmental Effects and Carbon Footprint of CGR

CGR is a sustainable concrete reinforcing material created through an environmentally friendly process that is free of volatile organic compounds (VOCs) and other hazardous air pollutants. Its superior flexibility and durability contribute to the construction of stronger, safer infrastructure.

The positive environmental impact of CGR is possible due to the following factors:

a. The embodied energy needed for continuous galvanizing process is much less than that for the HDG process. The CGR bath is much smaller than HDG zinc baths. Therefore, the amount of conductive energy needed to heat the zinc bath is reduced. CGR is a flexible on-demand process that can be started and stopped easily, contributing to energy savings.

b. The dwell time for HDG is dependent upon the thickness of the bar (i.e., the time to maintain high temperature of the reinforcing bars to complete the coating reaction with the core steel is variable). CGR can run at the same consistent speed regardless of the bar size (dwell time is minimized). This large reduction in dwell time for CGR reduces the conductive energy consumption significantly.

c. Factory controlled consistent zinc coating thickness for CGR substantially reduces the amounts of zinc consumption compared to the HDG process which is steel-chemistry dependent. The carbon footprint savings from smaller consumption of zinc translate to a positive impact on sustainability.

d. The improved logistical advantages contribute to better quality control and field performance accountability. Reduced transportation and handling contribute to a safer and more efficient delivery process that results in decreasing the embodied energy impacts.

e. Reduction in concrete cover is possible with CGR and therefore the reduction in the quantity of concrete due to the reduced concrete cover in structures such as slabs, pavements, precast systems, architectural elements, etc. will also reduce greenhouse gas emissions and improve positive environmental impacts.

Conclusions

CGR reinforced structural concrete has shown in this study to have a better structural and corrosion performance than ECB, black bars and stainless-steel bars. The CGR performance is marginally better than MMFX as well. The following conclusions are drawn from the research described in this paper:

a. The pull-out strength of CGR bars embedded in concrete is substantially greater than that of ECB and is marginally greater than that of stainless steel and MMFX bars. Pull-out strength provides an approximate indication of flexural strength, deflections and crack widths for slabs and beams.

b. Slabs with epoxy-coated bars with up to 5% surface damage induced on the coating show the largest extent of corrosion damage compared to the other bar types in terms of maximum flexural capacity loss due to corrosion. CGR will perform at par or marginally better than MMFX bars in cases of exposure to corrosive environment with and without the addition of fiber.

c. Structural concrete with epoxy-coated bars exhibits wider cracks at a given load or stress level compared to specimens with other bar types, whereas MMFX and CGR bars exhibit smaller crack widths. CGR bars consistently showed smaller crack widths at all load levels compared to MMFX and all other bar types.

d. Use of CGR reinforcement in structural concrete results in significant reduction of crack widths in flexural members such as bridge deck slabs and beams compared to black bars and ECB. When compared to the cracking behavior of structural slabs reinforced with bars using other corrosion-resistant coatings and bar types, CGR reinforced slabs develop cracks having about the same width as the slabs reinforced with MMFX, but with substantially smaller widths than slabs reinforced with stainless steel bars or ECB.

Contrary to the general perception in the structural concrete and construction industry, ECB is not as effective in providing corrosion resistance as expected. Localized damage to the epoxy coating on bars induces severe corrosion damage to structural concrete. The deficiencies of ECB reinforced concrete include wider crack widths in flexural members reinforced with ECB, inferior pull-out strength, and inadequate corrosion performance once the coating becomes damaged. General lack of adequate bond with the surrounding concrete under static and dynamic loading is a severe limitation, particularly for applications needing impact or blast resistance.

The structural and corrosion performance of CGR reinforced structural concrete has proven to be much better than that of concrete reinforced with coated bars such as ECB and about the same or better than that of concrete reinforced other corrosion resistant bars such as stainless steel or MMFX bars.

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Conflict of Interest

No conflict of interest.

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