Structural and Corrosion Performance of Continuous Galvanized Rebar (CGR)

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EXECUTIVE SUMMARY

Coated steel reinforcing bars are commonly used for corrosion protection and prevention of corrosion related damage in steel reinforced structural concrete. Epoxy-coated bars (ECB) and hot-dip galvanized (HDG) bars are two types of corrosion-resistant bars used in the construction industry. While the use of ECB is quite common, there is also a general consensus that the ECB has many deficiencies. HDG bars are very effective in providing corrosion resistance and are arguably economical in terms of cost-effectiveness.

Traditional HDG bars are provided with zinc coating with a minimum thickness of 150 μm (5.9 mils). The zinc-iron layers formed due to the metallurgical reactions of zinc with steel under the pure zinc outer layer make the interface undesirable from a bending and flaking standpoint.

A recent and developing technology called continuous galvanizing is a simple and cost-effective process. This modernized process is being used to produce continuous galvanized rebar (CGR). This report presents several potential and proven advantages of using CGR for corrosion protection of structural concrete reinforced with steel reinforcing bars. Research and test results presented in this report — and in many other reports developed by researchers elsewhere — demonstrate that CGR outperforms ECB and HDG in terms of structural and corrosion performance. This process also uses smaller quantities of zinc compared to HDG bars due to the smaller 50 μm (2 mils) coating thickness needed to provide the required corrosion performance. This smaller coating thickness over steel reinforcing bars is proven to be better corrosion resistant than the larger 150 μm (5.9 mils) thickness of HDG and the epoxy coatings of ECB. CGR is cost-effective compared to ECB and other corrosion-resistant bars, both in terms of the life-cycle costs and initial costs. CGR is projected to be longer lasting than ECB and other corrosion-resistant reinforcing bars for structural concrete applications.

The CGR manufacturing process contributes to a more sustainable future with numerous technical improvements, and is more environmentally friendly compared to other processes. The factory controlled atmosphere is free of Volatile Organic Compound (VOC) pollutants and hazardous air emissions. The automated process reduces the facility carbon footprint with operational efficiencies, and embodied energy impacts are minimized compared to antiquated production systems. The real ecological benefit of transportation and logistical advantages account for reducing harmful greenhouse gases (GHGs) and the relevant 100-year global warming potential (GWP100).

There is a galvanizing facility in Oklahoma using the continuous galvanizing process to produce GalvaBar™. Standard bar sizes are available in straight lengths of 20’, 40’ or 60’ in ASTM Grades of A615, A706 or A996. These bars can be bent like black bars without any additional restrictions on bend diameters or a need for special equipment. Several CGR implementation projects are currently in the pipeline.

INTRODUCTION

General

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 MMFX bars are common methods considered to address corrosion of steel reinforced structural concrete. Of these several corrosion-resistant alternatives, the use of coated bars (ECB or HDG) is generally accepted as being one of the most economical and convenient methods.

Coated Steel Reinforcing Bars

The discussion in this report will mostly focus on the relative merits and performance of continuously galvanized rebar (CGR) compared to that 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 examples of non-metallic coated bars are epoxy-coated bars. 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:

- Increased time to the initiation of corrosion
- Reduced corrosion of the steel bar due to the physical barrier provided by the coating
- Marginal increase in the initial cost to achieve superior corrosion resistance and increased service life

Some of the disadvantages of coated bars are:

- Additional cost due to coatings
- Reduced bond and pull-out strength
- Increased crack widths in structural concrete slabs and beams
- Damage to coatings during handling and construction, which would normally involve additional costs due to the need for touch-up

Epoxy-Coated Bars

The documented use of epoxy-coated reinforcing steel in bridge applications dates back to 1973. By 1987, at least 41 state departments of transportation 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 claimed to be reduced due to the lower maintenance costs for structures using ECB than those using black bars. As reported by EIG (Epoxy Interest Group) 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 based on the increased initial cost over a 75-year life was about 29 times the increased initial cost.[1] While ECB, is a commonly accepted coated bar, there are several deficiencies and disadvantages of using ECB which will be presented in a later section of this report.

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.[2] The first use of zinc-coated steel in concrete dates to about 1908, and the first regular use in the USA as a reinforcing material was in the 1930s.[3] 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 pre-fabricated 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 pre-fabricated reinforcement cages are then 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 as seen in Figure 1.[2] These zinc-iron alloy layers grow from the steel-zinc interface while the outermost layer remains as a pure zinc layer (Eta).

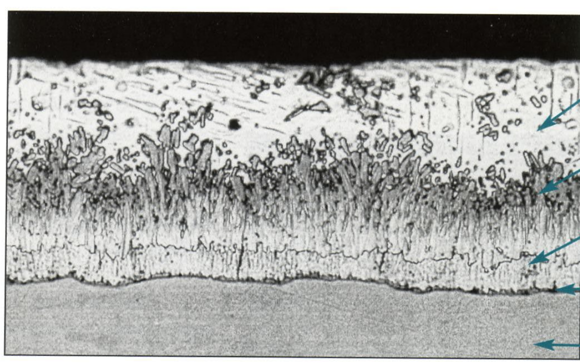

Figure 1 Typical Coating Structure of HDG Steel (Source: Yeomans, 2018[2])

The thickness of the HDG coatings will depend on the diameter of the reinforcing bar or the thickness of the unit being coated as well as the class designation (1 or 2). In case of steel reinforcing bars or inserts for structural concrete, the thickness of HDG coatings will depend on the diameter of the reinforcing bar or the thickness of the elements of the unit. ASTM A767-16 standard specification for

1 http://www.epoxyinterestgroup.org/about/economics/

2 Yeomans, S.R., "Galvanized Steel Reinforcement: Recent Developments and New Opportunities", Proceedings of 5th International Federation for Structural Concrete, Melbourne, Australia, Oct. 2018, Paper #38.

3 Concrete Reinforcing Steel Institute - CRSI (2016), "Frequently Asked Questions (FAQ) About Hot-Dip Galvanized Reinforcing Bars", CRSI Technical Note ETN-M-10-16, Schaumburg, IL, 6 pp.

zinc-coated (galvanized) steel bars for concrete reinforcement[4] recommends a minimum zinc coating thickness and equivalent weight in Table 1 of the standard which is reproduced below in Table 1. For Class 1, the minimum coating for #4 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 the fabricators to provide a coating of 150 to 180 μm (5.9 to 7.0 mils).

Table 1 ASTM A767 Requirements for Zinc Coating Thickness and Equivalent Weight (Mass)[4]

NOTE 1—The key value in this table is micrometres (μm) and is based on a zinc density of 7140 kg/m^3. The other values are based on conventions using the following formulae: mils = μm × 0.03937; oz/ft^2 = μm × 0.0232; g/m^2 = μm × 7.14; and mg/cm^2 = μm × 0.714.

Classification	Zinc Thickness		Weight [Mass]/Unit Area	
	mils	μm	oz/ft^2	mg/cm^2
Class 1				
Bar Designation No. 3 [10]	5.1	129	3.0	92
Bar Designation No. 4 [13] and Larger	5.9	150	3.5	107
Class 2				
Bar Designation No. 3 [10] and Larger	3.4	86	2.0	62

Galvanized coating is metallurgically bonded to the 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 as an effective corrosion-resistant rebar to protect 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 HDG bars. Several national and international standards are available on HDG bars and their use in the industry (e.g., ASTM A767-16, ASTM A780). 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.

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 (see Figure 1) 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 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, which is the standard specification for continuous hot-dip galvanized steel bars for concrete reinforcement,[5] recommends minimum average coating thickness grade and equivalent weight (mass) in the standard's Table 1 (reproduced as Table 2 in this report). ASTM A1094 requires a minimum coating thickness of 50 μm (2 mils) for continuous hot-dip galvanized steel bars. In practice, an average coating thickness of over 60 microns is not uncommon. However, a thinner

[4] ASTM A767/A767M - 16 Standard Specification for "Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement", 5 pages.
[5] ASTM A1094-18, "Standard Specification for Continuous Hot-Dip Galvanized Steel Bars for Concrete Reinforcement", 5 pages.

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 Requirements for Minimum Average Coating Thickness Grade and Equivalent Weight (Mass)[5]

Coating Grade	μm	mils	oz/ft²	g/m²	mg/cm²
50	50	2.0	1.2	360	36

[A] The value in micrometres (μm) is based on the Coating Grade. The other values are based on conventions using the following formulae: mils = μm × 0.03937; oz/ft² = μm × 0.0232; g/m² = μm × 7.14; and mg/cm² = μm × 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 a 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 2. GalvaBar has commissioned this process and has recently started producing reinforcing bars at its facility in Port of Catoosa in Oklahoma within the United States. The bars produced by GalvaBar with continuous galvanizing process are trademarked as GalvaBar. Further details regarding GalvaBar are provided on CMC website.[6]

The continuous galvanizing process is a simple and continuous coating process for straight and coil products with advantages in terms of speed and economy resulting from reduced use of zinc as well as a reduced need for energy for heating.

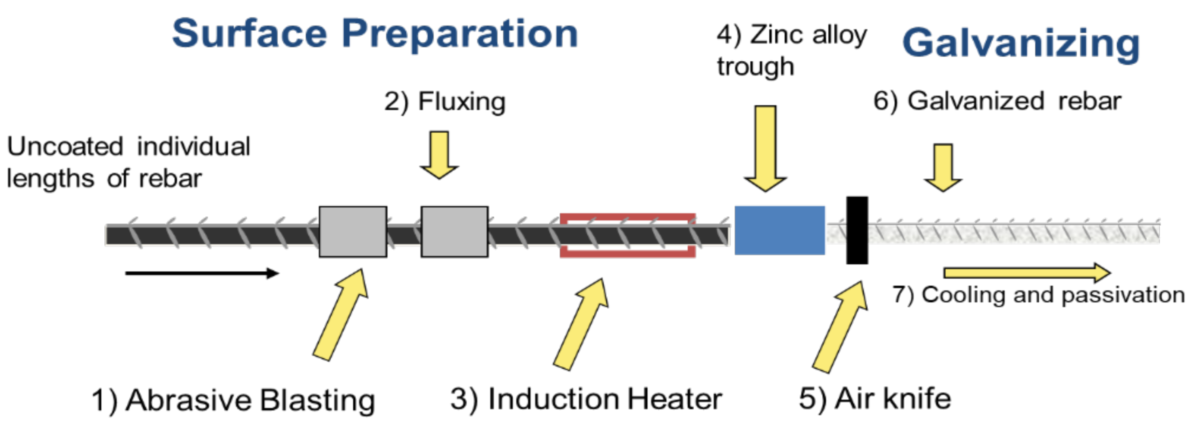

Figure 2 Continuous Galvanizing Process for Rebar (Source: Coating Controls)[7,8]

[6] GalvaBar, www.cmc.com/galvabar
[7] International Zinc Association, "Continuous Galvanized Rebar", www.zinc.org/cgr visited 02/08/2018
[8] Dallin, G., Gagné, M., Goodwin, F., and Pole, S., "Continuously Galvanized Reinforcing Steel", International Zinc Association, Durham, NC, 5 pages.

Advantages of Continuous Galvanized Rebar

Several researchers (including Gary Dallin and Frank Goodwin) have worked through the International Zinc Association (IZA) 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 ($Fe_2Al_{5-x}Zn_x$) 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 in Figure 1). A pure zinc coating of about 50 μm (2 mils) forms on the outside of this thin film and protects the rebar 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 steel, including high strength steels, will have the same coating, which is composed of nearly pure zinc conforming to ASTM B6-13 or B852-16.

While a HDG bar typically is coated with layers of thick zinc-iron alloys, the short dwell time in CGR and the use of 0.2% aluminum are able to 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.[2] CGR *can be bent, stretched, twisted or otherwise fabricated after the galvanizing process is complete without cracking or flaking of the coating*[7]. 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*[2].

CGR has been developed with excellent corrosion resistance and exceptional formability compared to other coated bars.[3] The corrosion resistance of CGR has been studied by several groups[9,10] in cooperation with the International Zinc Association. The report by Weyers[5] includes a cost analysis that compares the relative costs of bridge decks reinforced with different types of reinforcing bars in Virginia. 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 traditional HDG rebar. However, CGR can provide a similar or better service life for concrete structures at a lower cost.

Yeomans[2] 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.

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[9] Goodwin, F., "MD_71 Rebar Market Development", Visit Report: University of Waterloo, July 20, 2016, privately provided by AZZ Galvanizing-Canton.

[10] Weyers, R.E., "Virginia Bridge Deck Service Life Performance and Associated Costs: Influence of Reinforcing Steel Type", Sponsored by: International Zinc Association, Construction Materials Consultants, LLC, Blacksburg, VA, March 1, 2017, 37 pages.

PERFORMANCE EVALUATION OF CGR

Objective

The overall goal of this report is to summarize the findings from previous studies, which revealed that structural concrete reinforced with CGR outperforms concrete with epoxy-coated bars and other coated corrosion-resistant bars both in terms of structural performance and corrosion resistance. An additional objective is to document the suitability of CGR for bridge deck applications for wider dissemination among potential funding agencies and owners of bridges and other infrastructure.

Evaluation of Coated Reinforcing Bars

The test results from a recently concluded research project conducted at The University of Akron are further analyzed and summarized in this report. A series of structural and corrosion tests were conducted in the project on concrete with several types of reinforcing bars. The performance of structural concrete reinforced with CGR is compared with the performance of concrete reinforced with other common bar types. From those results, the performance of CGR was compared with that of a higher grade MMFX bars, the black bar and epoxy-coated bars.

This report summarizes the details related to:

- Pull-out and bond strength
- Crack widths
- Flexural and shear strength of slabs
- Corrosion performance
- Relative merits and demerits of different CGR
- Life-cycle cost analysis
- Environmental effects

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.

Tests Relevant to CGR

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 an embedment length of 2.5 inches. The dimensions of the prisms are 6”×6”×6” as shown in Figure 3. 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.

Accelerated Corrosion of Pullout Specimens

Of the 48 specimens mentioned in Table 3, a total of 24 specimens were subjected to accelerated corrosion for a period of 10 days. Five percent corrosion level was used as a 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. A typical test setup for the corrosion process is shown in Figure 4. Both corroded and non-corroded specimens were tested for pullout strength using a Baldwin universal testing machine with a capacity of 300 kips.

Figure 3 Pullout Specimen Details (Left) and Bar Types (Right)

Table 3 Test Matrix of Pullout Specimens

Types of Reinforcing bar	**Non-corroded specimens**		**Corroded specimens**	
	Without fiber	**With fiber**	**Without fiber**	**With fiber**
Black bar	2	2	2	2
Epoxy coated bar	2	2	2	2
MMFX bar	2	2	2	2
Stainless-steel bar	2	2	2	2
Hot-dipped galvanizing bar	2	2	2	2
CGR	2	2	2	2
Total	12	12	12	12

Figure 4 Test Setup of Pullout Specimens Subjected to Accelerated Corrosion

Pull-out Test Results

Load versus slip plots obtained from pull-out tests are compared with those for CGR in Figure 5 for common corrosion-resistant bars (CGR, MMFX, SS, and ECB) and in Figure 6 for common bars (black bars, ECB). In summary,

1. CGR out-performed all other types of bars tested in this study for both corroded and uncorroded conditions, with and without fiber.
2. CGR out-performed all the corrosion-resistant steel bars, and its performance was:
   - Better than ECB by a large margin
   - Clearly better than stainless steel bars
   - Relatively better than MMFX.
3. Addition of fiber to the concrete improved the performance of CGR (as with other bars) by at least 10 to 15%, both in corroded and uncorroded conditions.
4. From these test results, it is evident that CGR will provide better structural and corrosion performance in reinforced concrete than the other bars tested in the study.

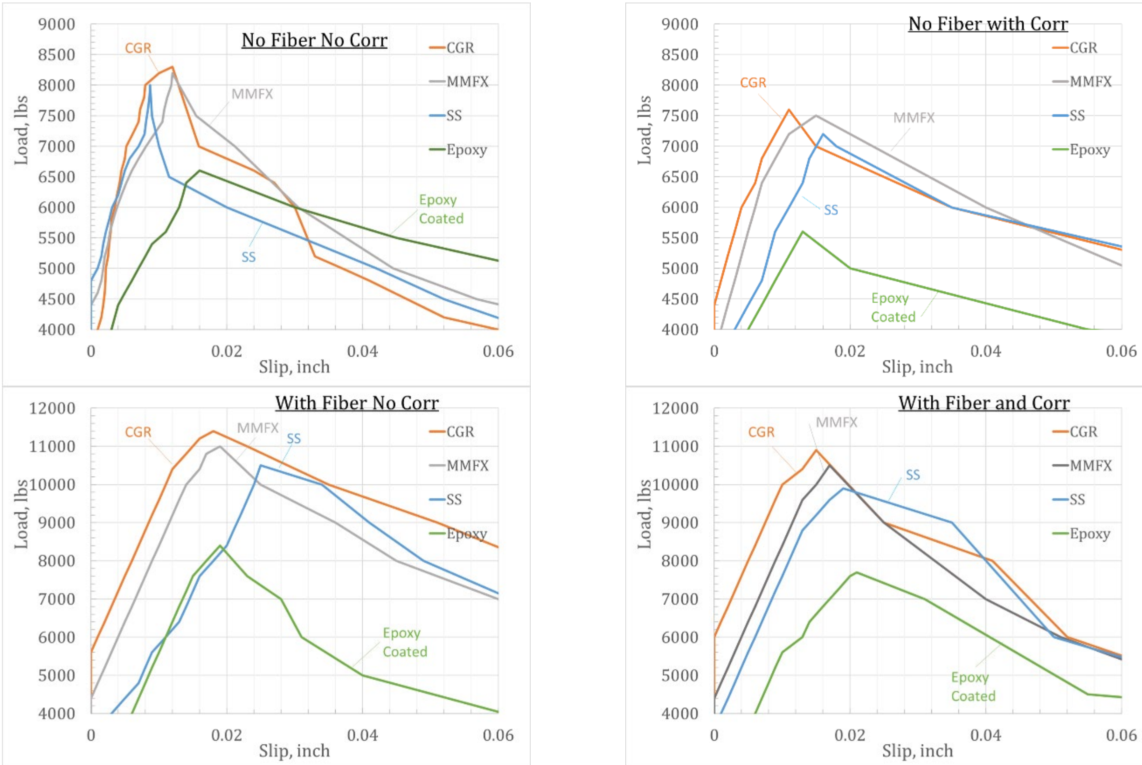


Figure 5 Comparison of Load-slip Curves of CGR with Those for Other Corrosion-Resistant Bars

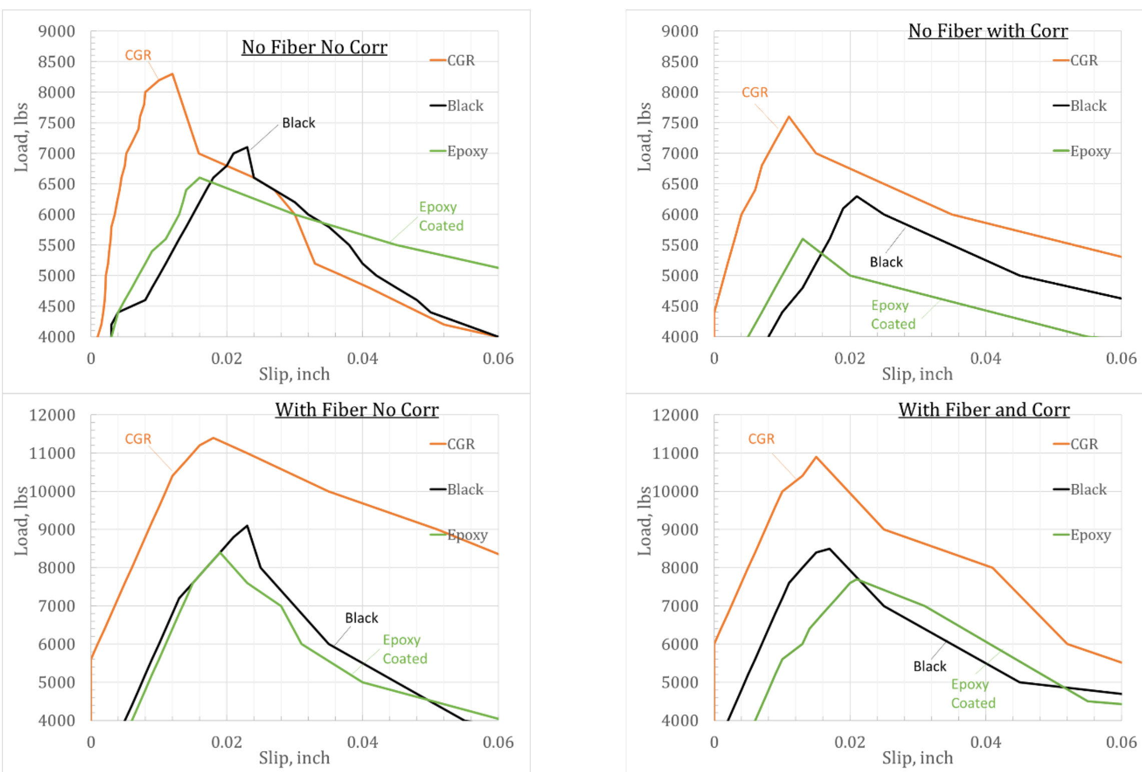


Figure 6 Comparison of Load-slip Curves of CGR with Those for Common Reinforcing Bars

SLAB CORROSION TESTS

Introduction

A serious problem with structural slab bridge decks is transverse cracking over the negative moment region. These cracks can greatly exceed the allowable limits recommended by ACI 224 for different exposure conditions. Black conventional steel has been replaced by epoxy-coated bars in bridge reinforcements in recent decades to protect structural concrete against corrosion. In the 1980s, most transportation agencies in the United States adopted epoxy-coated bars as the main corrosion protection of structural concrete where the reinforcing steel is prone to corrosion. However, it has been well documented that bridges with epoxy-coated steel have wider cracks than convention steel bridges. In addition, improper handling of epoxy-coated steel at construction sites can result in the development of defects over the bar length. With wider cracks in the deck and defects present on the bars, bridges constructed using epoxy-coated steel have exhibited accelerated corrosion damage in bridges at localized locations. To replicate this condition in laboratory tests, the corrosion process on the bridge decks was simulated by using an accelerated corrosion process while the test specimens are subjected to sustained loading.

Experimental Program to Study Corrosion Performance of Reinforced Concrete Slabs

Eighty slab specimens were made with dimensions shown in Figure 7 using conventional black bar as well as several types of corrosion-resistant reinforcing bars (epoxy-coated bars, hot-dipped galvanized bars, stainless steel bars, and MMFX bars). These slabs were cast using typical 4,500 psi concrete with and without polypropylene fiber dosage of 10 lb/yd^3.

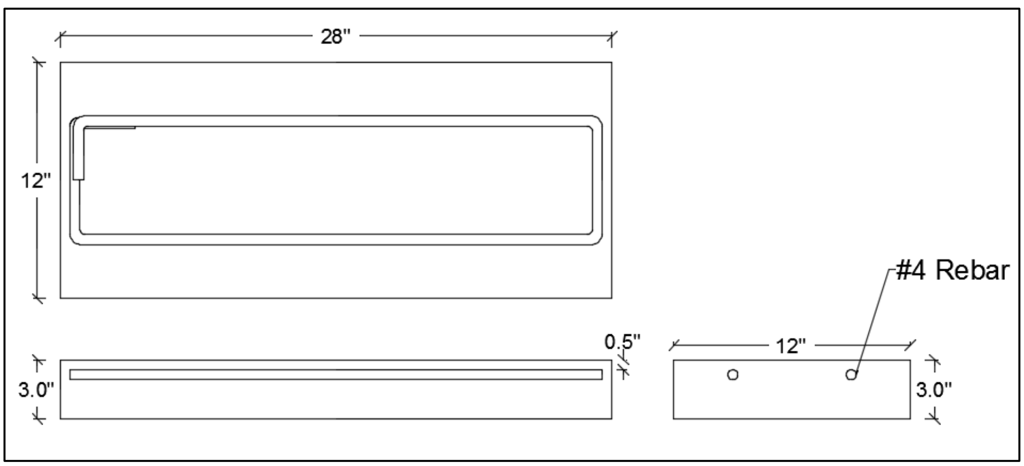


Figure 7 Schematic of the Slab Specimen Designed for Corrosion Testing

For specimens made using epoxy-coated steel bars, a 5% defect on the surface area of the coating was induced on the bars in order to initiate corrosion and replicate corrosion damage that can occur on site during the handling process. Figure 8 shows an epoxy-coated steel bar with manually applied defects. A 5% defect was introduced so as to induce corrosion damage rapidly. It was found that the final corrosion damage was similar in nature regardless of the defect size (2.5% or 5%). However, a 5% defect induces corrosion damage within a shorter duration of exposure.

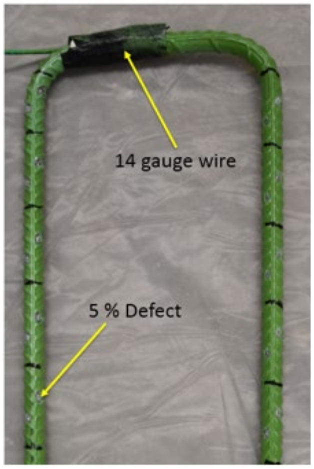


Figure 8 Wire and Defects Applied to the Epoxy-Coated Bars

Test Setup for Corrosion Testing

The test setup for the corrosion testing was designed to replicate the actual conditions observed on bridge decks. Each slab was supported in a specially fabricated test frame, and a constant sustained load was applied to the slab using a hydraulic jack. A salt solution tank was attached to the tension face of the slab. A stainless steel plate was used to act as a cathode. Figure 9 shows the test setup for the accelerated corrosion of a typical test slab.

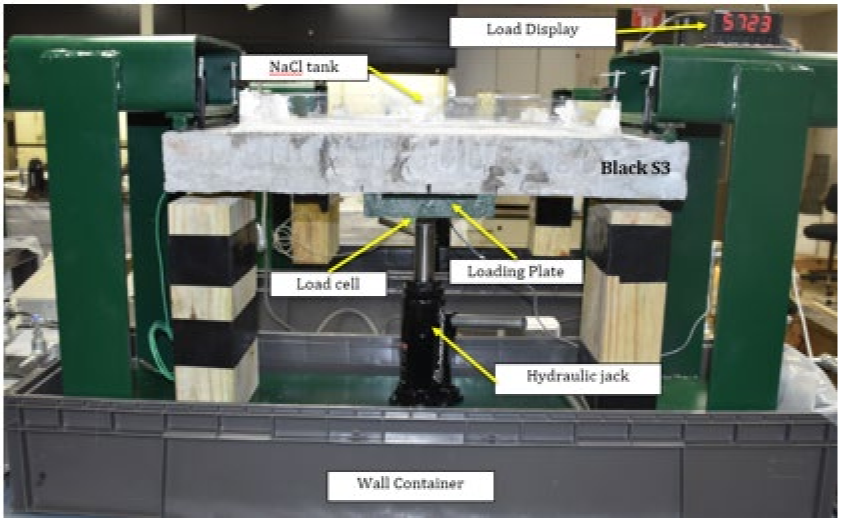


Figure 9 Typical Setup of Corrosion Tests for Slabs

A 10-kip load cell having a digital display was used with each hydraulic jack to continuously monitor the load applied on the test slab. A sustained load of 4.2 kips (i.e. 40% of the failure load of the slab) was maintained throughout the corrosion process. The applied load level was selected to replicate the dead load stresses that constantly act on bridge decks.

Accelerated Corrosion Process

During the 21-day testing period, a cycle of two days of wetting followed by one day of drying was used, and the current was calculated for a two-week period (equivalent to 1.2 million seconds) using Faraday's equation:

$$\Delta m = MIt/zF$$

where Δm is the mass of steel consumed (grams); M is the atomic weight of the metal (56 grams or 0.1232 lb for Fe); I is the current (amperes); t is time (seconds); z is the ionic charge (which is equal to 2); and F is Faraday's constant (96,500 amperes/second). A theoretical corrosion level of 15% was achieved over 21 days. The corrosion setup used in this study is shown in Figure 10 and Figure 11.

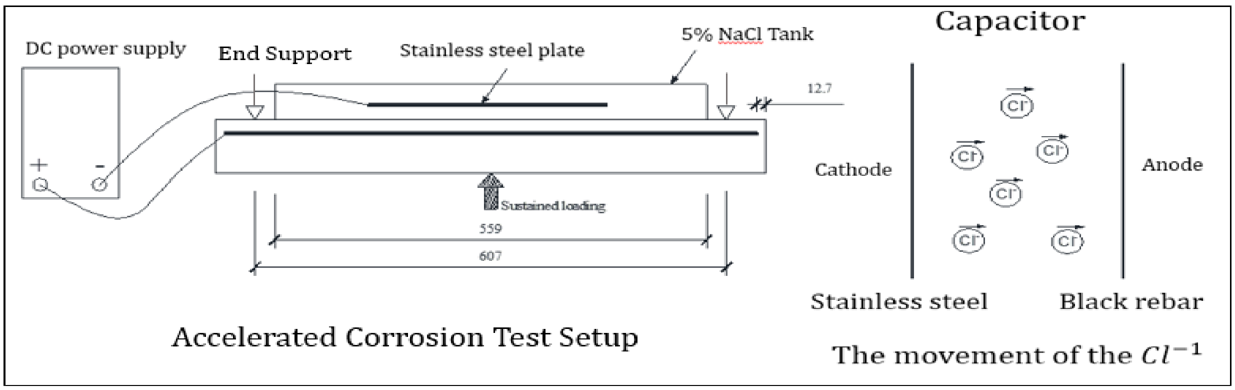


Figure 10 Schematic of the Corrosion Test Setup

Flexural Loading for Pre-Cracking

Test slabs that are subjected to the corrosion process were cracked prior to the corrosion tests by applying a three-point load in a UTM of 300-kip capacity. The span of the test slabs was 24 inches, and a load between 40% and 50% of the capacity of the slab was applied to create cracks. Once the slab was loaded to the desired level, the slab surface was monitored to make sure a crack became visible. Three specimens for each bar type were pre-cracked and tested.

Flexural Testing

Pristine slabs and corroded slab specimens were tested for flexural capacity loss after the corrosion process was completed. Three specimens for each set were tested to obtain the average flexural capacity for pristine and corroded specimens. This process was repeated for all the test slabs.

Results of Flexural Testing

Flexural testing was conducted on corroded and corresponding pristine slab specimens to determine the loss in moment carrying capacity of the slabs due to corrosion. A three-point bending test was performed with a span of 24 inches on a UTM of 300-kip capacity universal testing machine. A load rate of 30 lbs /sec was applied during testing. The capacities of corroded and un-corroded slabs for slabs made with different reinforcing bar types were then compared. Results for the slabs made without fiber are presented in Table 4.

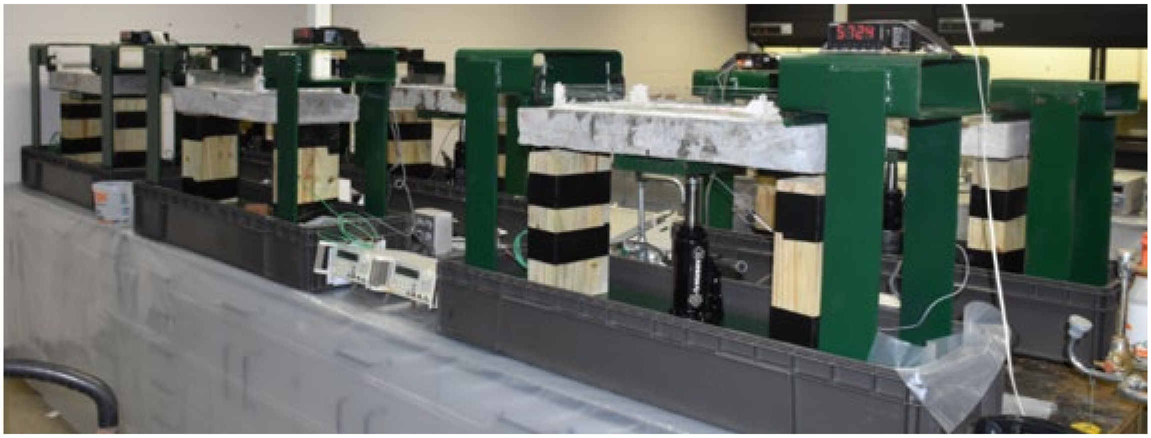


Figure 11 Typical Setup of Accelerated Corrosion Tests

Table 4 Flexural Capacity of Slabs without Fiber

Specimen Type	Average Capacity Uncorroded (lbs)	Average Capacity Corroded (lbs)	Reduction in Capacity (%)
Black bar	9,400	7,133	24
ECB	9,033	6,150	32
MMFX	11,373	9,689	15
Stainless Steel	10,767	8,793	18

Slabs cast with corrosion resistant reinforcing bars along with 10 lb/yd^3 of polypropylene fiber were also subjected to a three-point bending test to determine their corrosion performance under conditions similar to those of the specimens with no fiber. Results for un-corroded and corroded specimens with fiber and the flexural capacity loss are presented in Table 5.

Table 5 Flexural Capacity of Slabs with Fiber

Specimen Type	Average Capacity Uncorroded (lbs)	Average Capacity Corroded (lbs)	Reduction in Capacity (%)
Black bar with Fiber	10,460	8,543	18
ECB with Fiber	10,617	7,937	25
HDG with Fiber	10,250	8,517	17
MMFX with Fiber	11,637	10,257	12
SS with fiber	11,103	9,567	14

Figures 12 and 13 present charts showing the flexural capacity test results of slabs with no fiber and with fiber, respectively. As can be seen in Figure 12, epoxy-coated bars with 5% damage induced on the coating showed the largest extent of corrosion compared to the other bar types, in terms of maximum flexural capacity loss due to loss in bond and reduced area of steel. MMFX bars showed the best corrosion resistance and the lowest loss of pull-out strength. In hot-dip galvanized bars, the zinc coating protected the bar from corrosion for a few days; once the sacrificial layer was compromised, the base metal showed a similar effect as the black bars. Hence, the capacity loss for the slab with hot-dip galvanized bars is much closer to that of slabs with black bars. Slabs with stainless steel bars also showed good performance after corrosion as well as a smaller loss of flexural capacity due to corrosion.

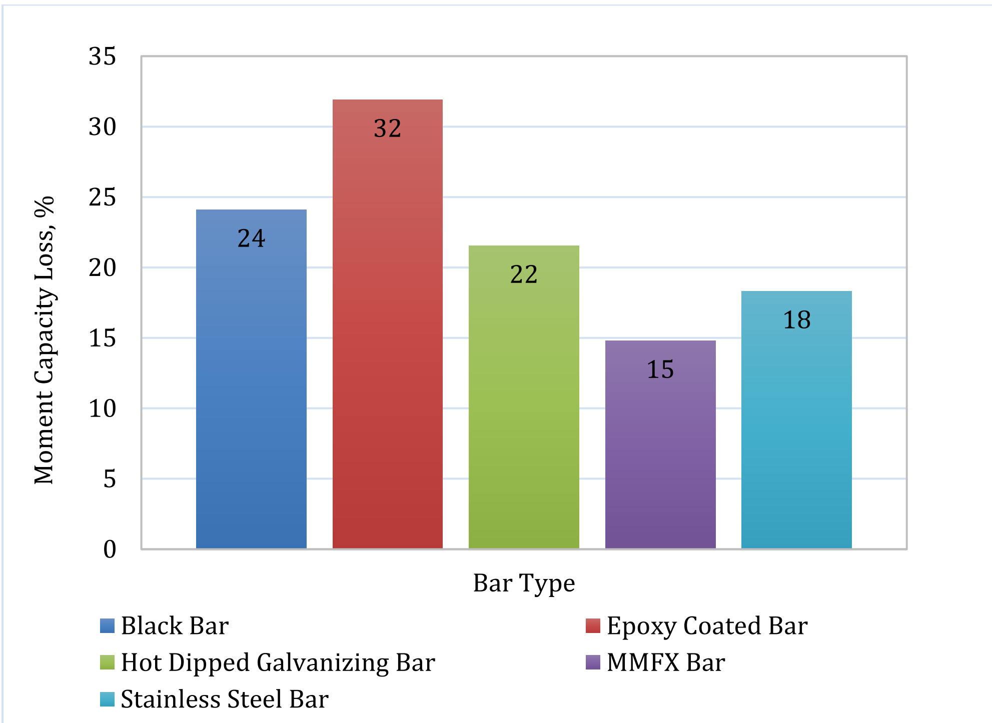


Figure 12 Flexural Capacity Loss Due to Corrosion of Specimens with no Fiber

Figure 14 shows the comparison of slabs with and without fiber in terms of percentage reduction in capacity loss. The performance of slabs with fiber was much better than the performance of slabs with no fiber. The trend in the percentage of capacity loss was similar to the trend of the capacity loss for slabs without fiber. Slabs made with epoxy-coated bars with a 5% induced defect showed the most moment capacity loss, and the slabs made with MMFX showed the least moment capacity loss. It can be observed that the addition of fiber results in a smaller loss of capacity, even though the slabs have undergone an accelerated corrosion process.

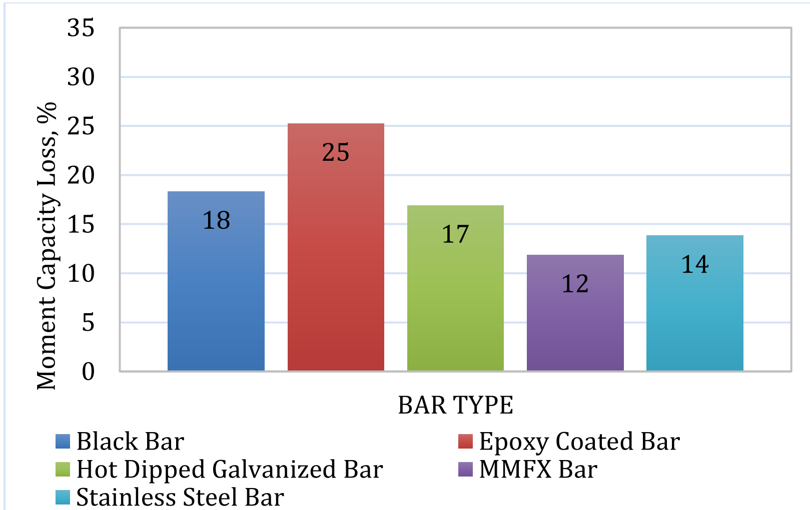


Figure 13 Flexural Capacity Loss Due to Corrosion of Specimens with Fiber

CGR bars were not available to be tested at the time of this series of testing. However, from the test results obtained from the other tests described in this report, CGR is expected to perform as well as MMFX bars for cases with and without the addition of fiber.

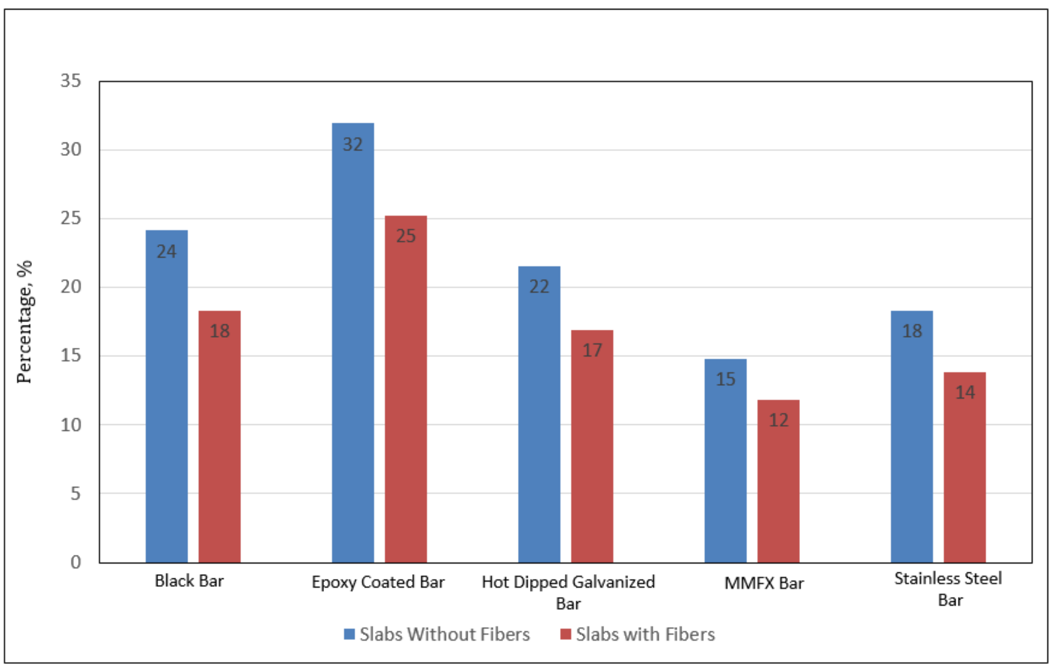


Figure 14 Percentage Reduction in Capacity Loss of Slabs with and without Fiber

After the intended corrosion testing was completed, all types of bars exhibited severe deterioration at the surface of the bars, regardless of the coatings used on the bars. Addition of fiber did not seem to reduce the surface deterioration even though the structural flexural strength of slabs is better maintained due to the addition of fiber compared to that of the slabs with no fiber.

Summary and Conclusions from Corrosion Testing

Continuous span structural slab bridges are constantly subjected to the dead loads of the bridge that keep the cracks open over the deck surface in the tension region near the pier supports. These crack openings provide a pathway for chlorides to reach the embedded reinforcement. Service loads on the bridges allows these cracks to open further, leading to an increase in the amount of chlorides passing through the deck to the reinforcement. To replicate this condition in laboratory tests, the corrosion process on the bridge decks was simulated by using an accelerated corrosion process while the test specimens are subjected to sustained loading to simulate the permanently acting 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 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 is much closer to that of slabs with black bars. Tests with CGR reinforced slabs were not included in this series. However, from other tests conducted in this project, it is expected that CGR will perform at par or better than MMFX bars for cases with and without the addition of fiber.

CRACK WIDTH TESTS

Introduction

This section presents the results of direct tension tests on prism specimens. The reinforcement bars validated in the experimental program were 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.

The mechanical properties of the six bar types included in this study (Figure 15 and Figure 16) were determined using ASTM E8 standards. A summary of the mechanical properties are listed in Table 6.

Figure 15 Various Reinforcement Bars Machined at the Center for Tensile Strength Testing

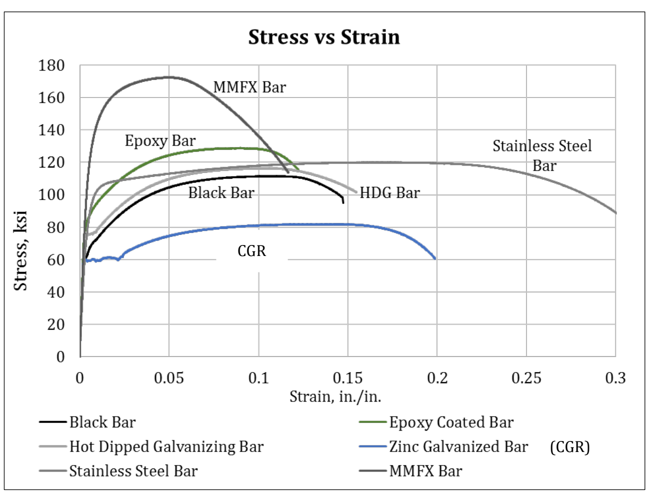


Figure 16 Stress vs. Strain Curves for #5 Bars of Various Types

Table 6 Yield and Ultimate Strength of #5 Reinforcing Bars

Serial No.	Type of Rebar	Average Yield Strength (ksi)	Average Tensile Strength (ksi)
1	Black Bar	65	111
2	Epoxy-Coated Bar	76	129
3	Hot-Dipped Galvanized Bar	71	117
4	CGR	62	83
5	Stainless-Steel Bar	96	121
6	MMFX Bar	128	171

Crack Width Determination using Direct Tension Tests

Direct tension tests were performed to study crack development in prism specimens with different type of reinforcing bars. These tests were performed to determine how well the reinforcing bar is bonded to the surrounding concrete and to compare the crack widths and the distribution of cracks along the length of the prism for different bar types. The data collected in this test are applied load, stress in the bar, crack widths, and crack spacing.

Prisms specimens with a length of 90 inches were designed to maintain the same reinforcement ratio and the same ratio of the dimensions of the sides as in the tension zone surrounding the reinforcing bars in a typical bridge section. The section details of the resulting prism specimen are shown in Figure 17.

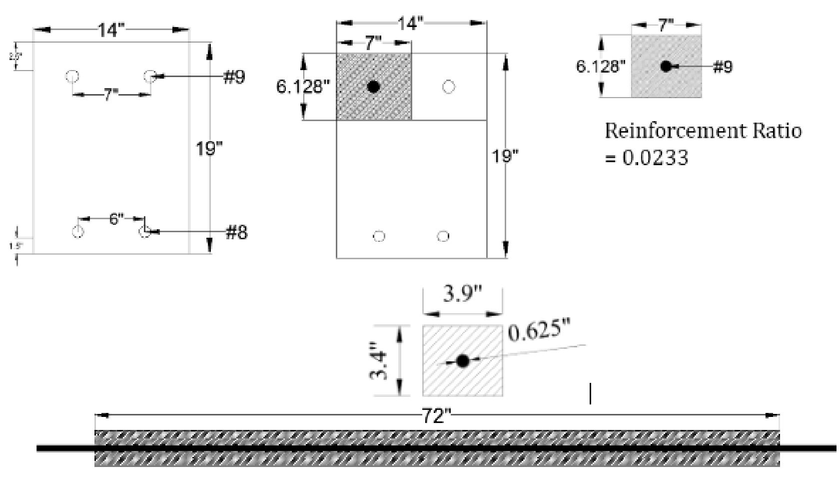


Figure 17 Sectional Details of Long Prism Specimens

The test setup was designed to apply tensile force axially as shown in Figure 18.

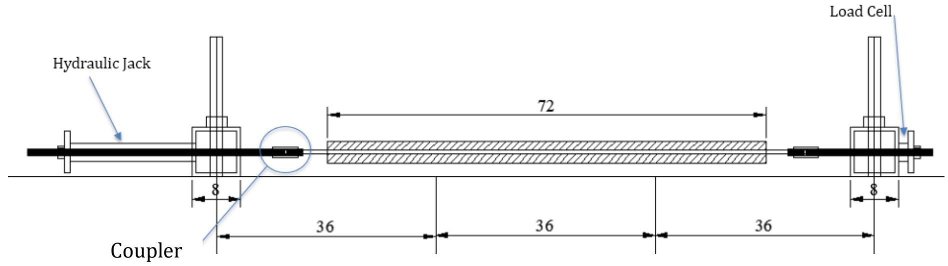


Figure 18 Test Setup for Long Prisms

A total of 24 long prisms (two specimens each of six reinforcing bar types, with and without fiber) were cast with cross-sectional dimensions of 3.4”×3.9” and the reinforcement ratio of 0.0233. Specimens with and without 10 lb/yd^3 of polypropylene fiber were made in duplicates with (i) black bar, (ii) epoxy-coated bar, (iii) dual-coated Z-Bar, (iv) stainless steel bar, (v) hot-dipped galvanized bar, and (vi) CGR. Specimens were tested for axial direct tension cracking after 28 days. The average concrete strength was 4,800 psi on the day of testing. The typical test setup for the long specimen testing is shown in Figure 19. Crack widths were measured and recorded manually using crack gage at every 0.5 kips of load.

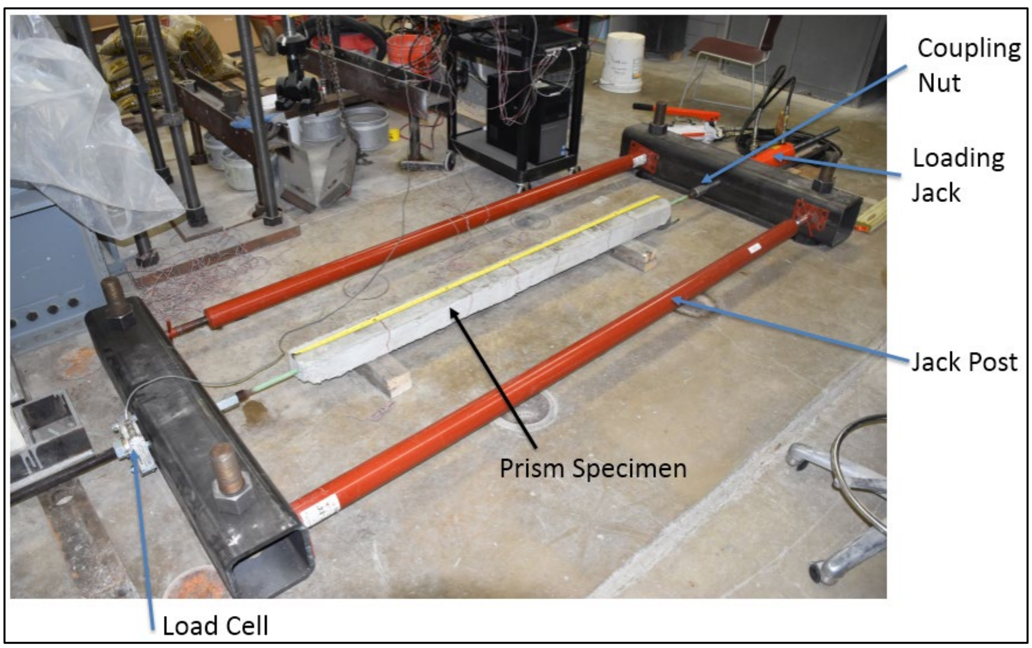


Figure 19 Test setup for Testing of Long Prisms

Test Results for Direct Tension Tests

Test results for different reinforcing bars, both with no fiber and with fiber are shown in Figure 20 and Figure 21.

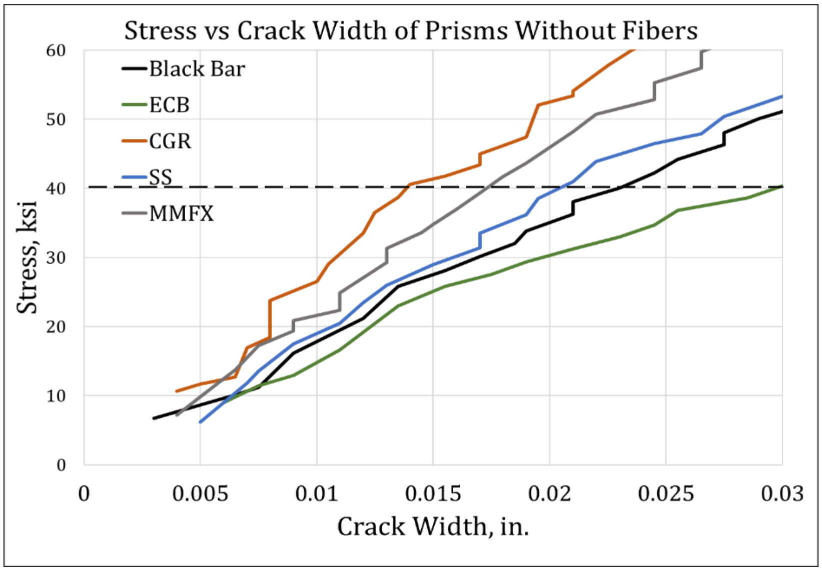


Figure 20 Comparison of Crack Widths for Prisms without Fiber

From the test results, it is observed that the 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. The crack widths on specimens containing fiber with epoxy-coated bars were wider compared to the specimens with other bar types, whereas specimens with MMFX and CGR bars showed smaller crack widths. The crack widths for specimens with fiber were smaller by about 25% as compared to the corresponding specimens without fiber. A comparison of crack widths for the bars tested in this study at a stress of 40 ksi is presented in Table 7. CGR bars showed consistently smaller crack widths at all loads compared to MMFX and all other bar types.

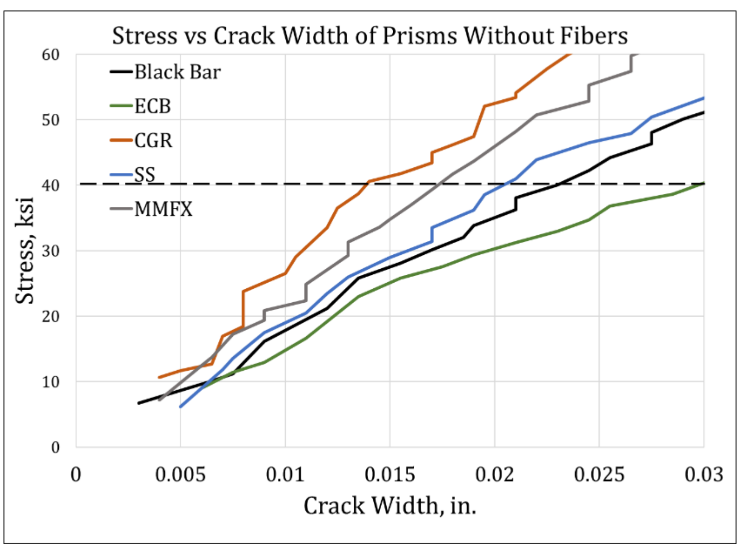


Figure 21 Comparison of Crack Widths for Prisms with Fiber

Table 7 Comparison of Crack Widths at a Stress of 40 ksi for Specimens with and without Fiber

Serial No.	Bar Type	Crack width of Non-Fiber Slab (in.)	Crack Width of Slab with Fiber (in.)
1	Black	0.023	0.0175
2	Epoxy-Coated	0.03	0.0235
3	Hot-Dip Galvanized	0.025	0.019
4	CGR	0.014	0.011
5	Stainless-Steel	0.021	0.0155
6	MMFX	0.017	0.013

SLAB TESTS TO STUDY FLEXURAL CRACKING

Typical three span continuous slab bridges are designed in such a way that the span length of exterior spans is 0.8 times of that of interior span. Figure 22 shows bending moment diagram and the inflection points for a three span continuous slab bridge subjected to uniform loading.

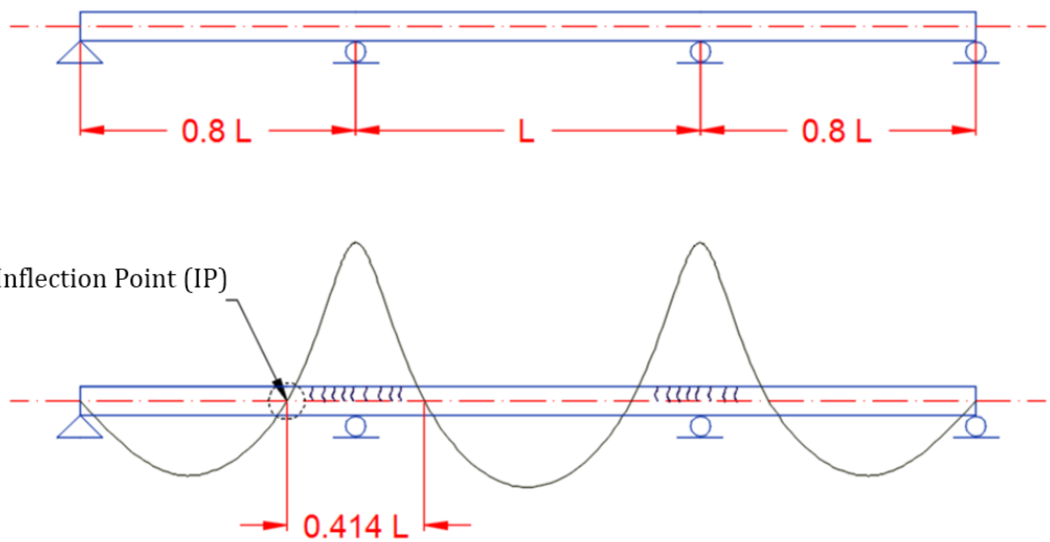


Figure 22 Bending Moment Diagram Showing Inflection Points

The span length between the inflection points at the ends of the negative moment region of a typical bridge span can be considered to be simply supported for the purpose of designing test specimens. Based on the results from several full-scale and reduced scale tests, reduced-scale slab specimens demonstrated similar cracking behavior as the full-scale specimens at any given stress level. It is evident that, when using the same tension reinforcement ratio and the same effective cover, the crack widths at a given stress level on the reduced-scale slab section are similar to the crack widths on a full-scale slab section. Based on this finding, a test specimen section of 13-in. × 8-in. with a span length of 7.5 ft. (total length of 8 ft.) was selected for flexural tests to determine the cracking behavior of slabs reinforced with corrosion-resistant reinforcing bars.

Slab Specimens with Different Types of Reinforcement

A typical section of test beams is shown in Figure 23. The test setup is shown in Figure 24. Six different reinforcing bar types were used on the tension side of the test slabs, with two slabs made for each bar type. A total of 24 slab specimens with and without fiber were cast to study flexural cracking. The tension steel was #5 bar of different types of reinforcement, whereas the compression steel was #4 black bar in all specimens. The applied load, stress in the bar, crack widths, and deflections were monitored and recorded continuously during the testing process. Two specimens of each bar type were tested to determine the average of two sets of results.

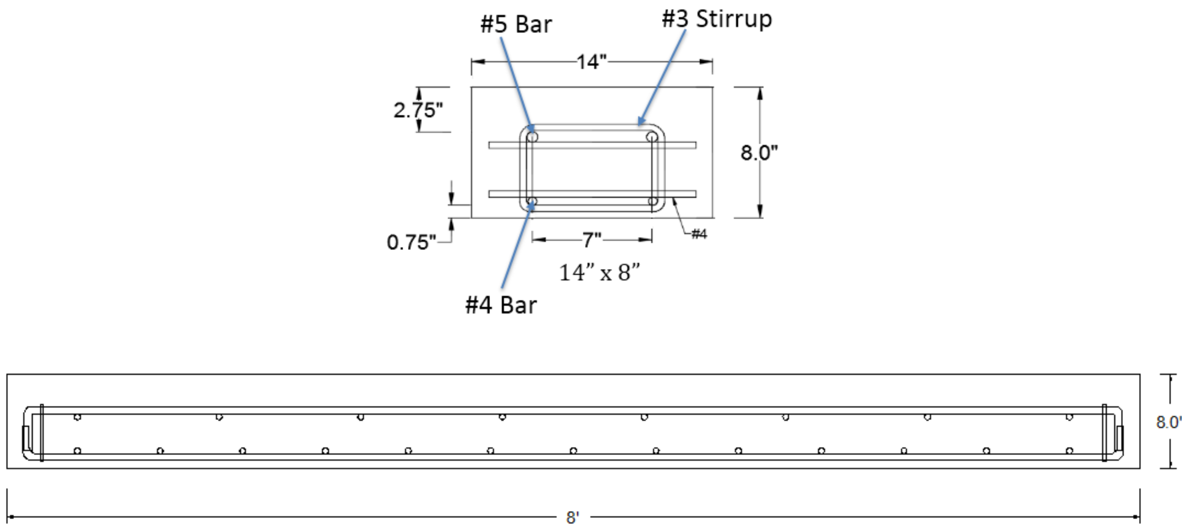
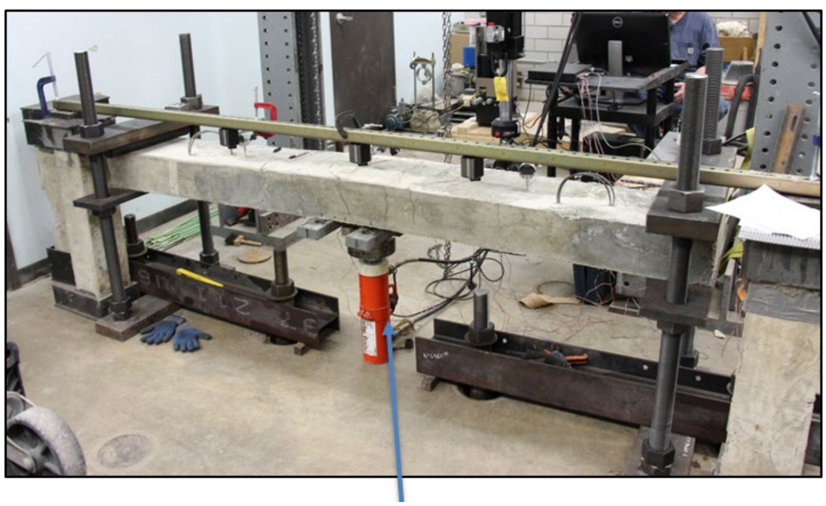


Figure 23 Test Slab Details



Loading from the bottom to cause cracking at the top

Figure 24 Test Set-up

Test Results of Slabs with and without Fiber and with Different Bar Types

Strains and applied loads during the test, deflections, crack spacing and crack widths were measured during the tests. The crack widths were averaged from the results of two specimens for each bar type. Figure 25 shows a comparison of stress versus crack widths for slab specimens with CGR with and without fiber and common reinforcing bars (black bars and ECB). Figure 26 and Figure 27 show similar comparisons for slab specimens with corrosion-resistant bars, both with and without fiber.

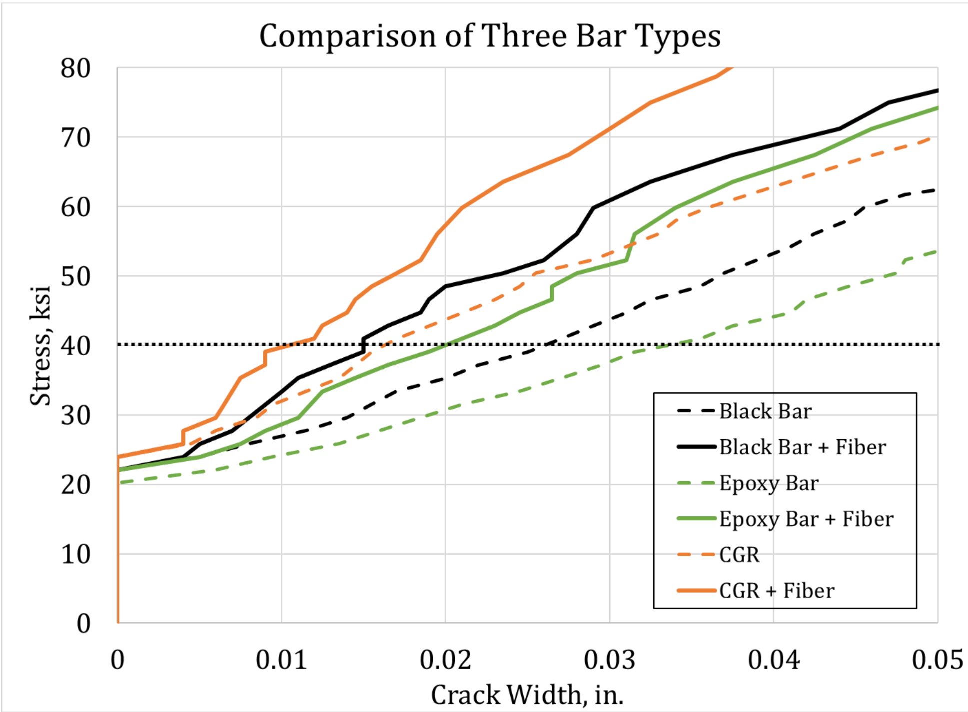


Figure 25 Comparison of Crack Widths for Slabs with and without Fiber and with Black Bars, ECB and CGR

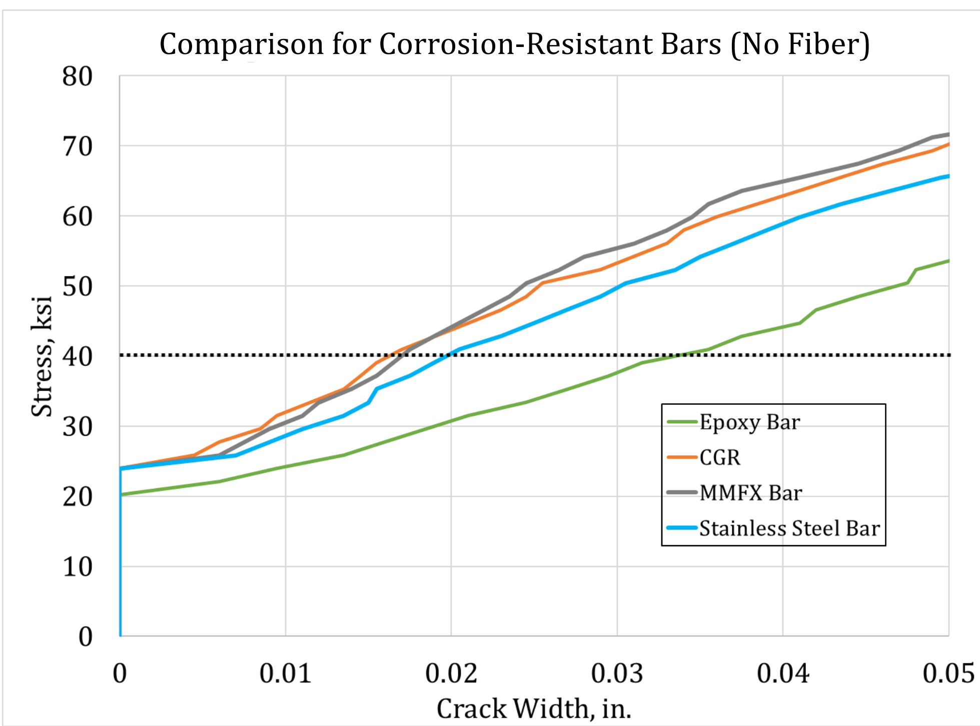


Figure 26 Stress vs. Crack Widths for Slabs with Different Bar Types (No Fiber)

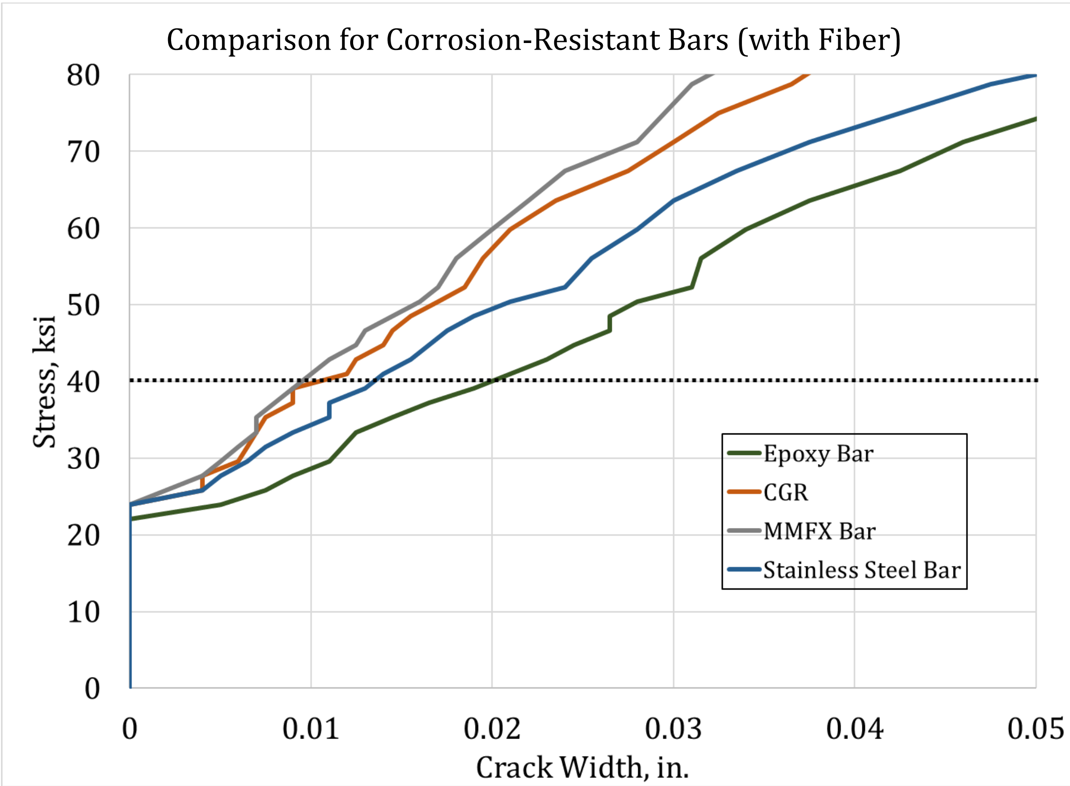


Figure 27 Stress vs. Crack Widths for Slabs with Different Bar Types (with Fiber)

In the case of slabs without fiber, the test specimens with epoxy-coated bars showed wider cracks compared to those with other bar types, whereas slabs with MMFX and CGR showed smaller crack widths. In case of slabs with fiber, a similar trend was observed, with much closer values for most bar types. The crack widths observed for slabs with and without fiber are compared at 40 ksi stress and are presented in Table 8. From the crack width data, it is clear that slabs reinforced with CGR had the smallest crack widths. The crack widths of slabs with ECB and those with black bars are significantly larger. Slabs with MMFX showed similar crack widths as those reinforced with CGR. Addition of fiber substantially reduces crack widths.

Table 8 Percentage Reduction in Crack Widths on Slabs with Fiber at 40 ksi

Serial No.	**Bar Type**	**Crack Width Slabs without Fiber (in.)**	**Crack Width of Slab with Fiber (in.)**
1	Black	0.027	0.015
2	Epoxy-Coated	0.035	0.020
3	CGR	0.0155	0.010
5	Stainless Steel	0.0205	0.013
6	MMFX	0.017	0.009

The load versus deflection plots were compared for all slabs with and without fiber to determine the difference in deflections. There was very little difference between the deflections of slabs with different bar types.

Summary

The tests described in this section have demonstrated that CGR reinforcement reduces 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, it was clear that CGR reinforced slabs developed cracks having about the same width as the slabs with MMFX, but with substantially smaller widths than slabs reinforced with stainless steel bars or ECB.

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 318-14 and AASHTO recognize this reduced bond strength and adjust the design equations accordingly. The results presented in this report 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 hydroxyzincate*.[3]

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 28). Because of metallurgical bonding of zinc with steel, CGR has a tough and scratch-resistant coating and a zinc-steel interface that is well bonded.

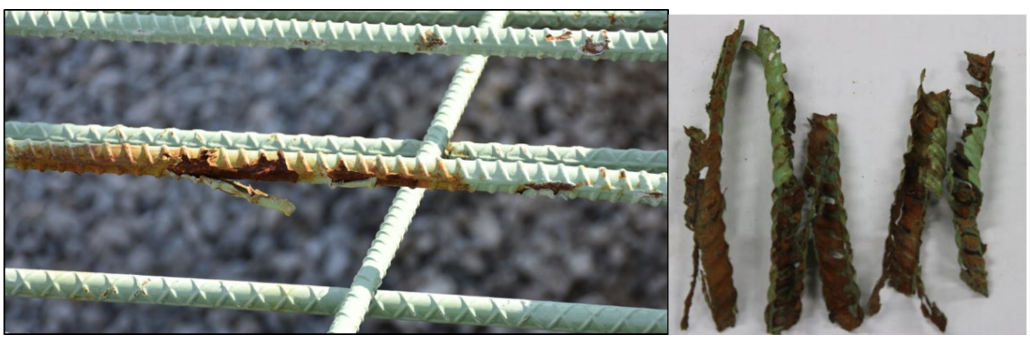


Figure 28 Condition of Epoxy Coating in a Demolished Bridge Deck after About 25 Years of Service

Corrosion Performance

It is generally accepted 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 perfect 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 not uncommon to see damage to the epoxy coating larger than 2%, and the coating damage many times is not touched up. This surface damage to ECB makes it susceptible to accelerated corrosion at the location of the coating damage.

Bond Development with Concrete

Lack of proper bonding between ECB and the surrounding concrete is a major deficiency of ECB reinforced structural concrete. Figure 29 shows the breaking of bond under static loading and Figure

30 shows the crumbling of the concrete surrounding an epoxy-coated bar under impact loading. This type of deficiency is more serious for larger thicknesses of epoxy coating. Dual-coated reinforcing bars are also similarly disadvantaged.

Figure 29 Lack of Bond Between Epoxy-Coated Bars and Concrete Under Static Loading

Figure 30 Lack of Bond Between Epoxy-Coated Bars and Concrete Under Impact Loading[11]

[11] Patnaik, A., "Rockfall Concrete Barrier Evaluation and Design Criteria" Ohio Department of Transportation, Project # SJN 134640, May 2015.

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 total present cost.[2] 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 over 100 years. CGR will perform better than HDG, and the life-cycle costs for bridges constructed using CGR are expected to be even lower than decks constructed with HDG reinforcement.

COMMENTS ON THE ENVIRONMENTAL EFFECTS AND CARBON FOOTPRINT OF CGR

GalvaBar is a sustainable material created through an environmentally friendly process that is free of volatile organic compounds (VOCs) and other hazardous air pollutants.[7] Its extraordinary flexibility and durability contribute to the construction of stronger, safer infrastructure.

The positive environmental impact of CGR is particularly noteworthy, considering the following:

- 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.

- 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.

- 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 will have a positive impact on sustainability.

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

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

CONCLUSIONS

In summary, CGR reinforced structural concrete has shown better structural and corrosion performance than ECB, black bars and stainless steel bars. The CGR performance is better than MMFX. The following conclusions are drawn from the work described in this report:

1. 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.

2. Slabs with epoxy-coated bars with 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. Tests with CGR reinforced slabs were not included in this series. However, from the other tests conducted in this project, the indications are that 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.

3. 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.

4. 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. 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 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.

ACKNOWLEDGMENTS

Many of the tests described in this report were conducted as part of the author's previously completed ODOT projects at The University of Akron. Several graduate students of the University of Akron — Dr. Srikanth Marchetty, Dr. Mohamed Habouh, Mohamed Essili, Abdullah Alzlfawi, Umang Pawar, and Sourav Khatua — performed the tests described in this report.

The major source of the test results presented in this report is:

Patnaik, A. and Marchetty, S., "Reduction of Bridge Deck Cracking through Alternative Material Usage", Final Report, Ohio DOT/FHWA SJN 135260, January 11, 2018, 344 pages.

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AUTHOR RESUME

Dr. Anil Patnaik is currently a professor of structural engineering and the associate chair of the Department of Civil Engineering at The University of Akron in Ohio, USA. He earned his Ph.D. from the University of Calgary, and Master's degree in Structural Engineering from the Indian Institute of Technology in Kanpur, and a Bachelor's degree in Civil Engineering from National Institute of Technology, Rourkela in India. He has held academic positions at South Dakota School of Mines and Technology (SDSM&T) in Rapid City, Curtin University in Perth (Australia) and currently, at the University of Akron in Ohio for over twenty years.

His current and recently funded research projects are on corrosion of reinforced concrete and steel structures, reinforced concrete members subjected in impact loads; synthetic and basalt fiber reinforced concrete (FRC); fiber reinforced polymer (FRP) materials for structural concrete applications; repair and strengthening of existing structures; construction and long term performance monitoring of bridge decks; structural slab bridges; prestressed concrete adjacent box-beam bridges, and carbon footprint assessment and life cycle analysis (LCA).

He is the author or co-author of over 120 technical papers, and 100 research and design reports. He also co-edited two conference proceedings on high volume fly ash concrete and high performance high strength concrete, and authored a design guide book on basalt FRP reinforced structural concrete. He also worked as a practicing engineer for several years in design and construction of large industrial, commercial and offshore structures, and tall buildings. He taught and continues to teach several courses on structural engineering including reinforced and prestressed concrete design, FRP reinforced concrete design, senior design, tall building design, steel design and structural analysis at the undergraduate and graduate levels.

APPENDIX

GalvaBar™ Specifications and Guidelines

GALVABAR™

In the United States, a plant in Oklahoma produces GalvaBar™ using a continuous galvanizing process. This plant (Figure 31) uses a highly automated, proprietary process to produce CGR at significant cost efficiencies, including lower material and labor costs. The GalvaBar production process at this plant can be applied to many grades of steel, providing a consistent coating with no risk of embrittlement. GalvaBar complies with the requirements of ASTM A1094/1094M-16 for continuous hot-dip galvanized steel bars and concrete reinforcement. Further details of GalvaBar are available on the CMC website.[6]

Figure 31 GalvaBar Production Facility in Oklahoma, USA[7]

GalvaBar is a galvanized rebar with specialized thin zinc alloy coating that provides the well-known corrosion protection of zinc and the added benefit of exceptional formability. GalvaBar can be bent, twisted, or stretched after galvanizing without cracking, peeling or flaking. Two examples of CGR bends are shown in Figure 32. The material specifications, frequently asked questions and the guidelines for construction practices for GalvaBar (as posted on the CMC website[7]) are included in the appendix at the end of this report.

Figure 32 Bendability of GalvaBar

GalvaBar Implementation

GalvaBar has been used in a project in Iowa for the Buffalo Creek Bridge in Independence, Iowa, with a 200’ deck (Figure 33). The abutments and parapets utilized continuous galvanized GalvaBar. GalvaBar was also supplied for the Coffee Creek Wastewater Treatment Plant in Edmund, Oklahoma. GalvaBar is being used for many balconies, seawalls and foundation projects in Florida. GalvaBar has been shipped as far as Bahamas and can also be purchased from Menards home improvement centers.

Figure 33 Buffalo Creek Bridge in Independence, Iowa

GalvaBar was used in the Abutments and Parapets of this Bridge

GALVABAR®

ASTM A1094 SPECIFICATION

1. Product Name

GalvaBar®

2. Manufacturer

5101 Bird Creek Ave.
Catoosa, OK 74015
Phone: 918.379.0090

GalvaBar is owned and manufactured by Commercial Metals Company.

Email: **galvabar@cmc.com**
Web: **www.cmc.com/galvabar**

3. Product Description

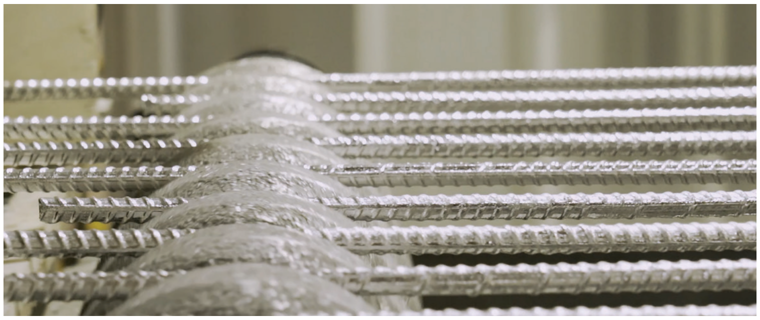
GalvaBar is a Continuous Galvanized Rebar (CGR) with a pure zinc coating for construction projects featuring exceptional formability that complies with ASTM A1094/A1094M. Stock length bundles can be staged prior to being released by fabrication, creating a consistent flow of product, since GalvaBar is processed prior to fabrication. ASTM A1094 improves lead time project delivery methods with a seamless supply of corrosion resistant rebar with increased quality control and customer satisfaction. GalvaBar is procured both as a process to the client, and rebar as a product.

Combined with the metallurgically bonded coating and distinctive cathodic protection principal, Continuous Galvanized Rebar (CGR) reduces corrosion rates and extends corrosion performance. ASTM A1094 bars provide superior corrosion performance compared to conventional reinforcement. GalvaBar has exceptional abrasion resistance that can be fabricated and shipped without special equipment.

Composition and Materials

GalvaBar consists of a minimum 50 micron pure zinc coating (2 mil); metallurgically bonded to steel rebar.

See our video, "**CMC GalvaBar - Process Overview**", on YouTube.



GalvaBar can be used but not limited to conditions for corrosion resistant reinforced concrete construction applications in the following forms:

- Architectural Building
- Features
- Balconies
- Bridge Decks
- Cast-In-Place Concrete
- Critical Infrastructure
- Coastal Structures
- Corrosive Environments
- Dowels and Tie Bars
- Elevated Podium Slabs
- Energy Structures
- Foundations
- Masonry Construction
- Mission Critical
- Parking Garages
- Precast Concrete
- Piers and Docks
- Resilient Construction
- Shotcrete Structures
- Transportation Sectors
- Waste/ Water
- Treatment

Features and Benefits

Design

- Designate the ASTM A1094/A1094M Standard Specification for Continuous Hot-Dip Galvanized Steel Bars for Concrete Reinforcement
- Specify GalvaBar as a replacement for ASTM A767 Standard Specification for Zinc-coated (Galvanized) Steel Bars for Concrete Reinforcement
- Engineered like uncoated "black" rebar for bend diameters and splice/lap lengths (A615, A706, A996, A1035)

Performance

- Formability — can be fabricated after galvanizing without peeling or flaking
- Fabrication — by any rebar fabricator without specialized equipment
- Durability — bond strength and slip resistance in concrete is superior to uncoated "black" bar
- Efficiency — splice/lap same as uncoated rebar
- Longevity — Proven protection of zinc dating hundreds of years

Processing

- Automated factory-controlled procedures to optimize quality control of standard mill lengths up to 60+ feet
- Consistent flow of inventoried product allowing for field changes to be addressed
- Transport seamlessly through current supply chains without double handling or additional logistics
- Logistical improvements handling and staging in stock lengths prior to being released by fabrication
- Storage outside in weather without degradation

Cost

- Significantly less expensive than other corrosion resistant reinforcement technologies including non-ferrous, high strength, stainless steel and GFRP/ CFRP rebar.
- Competitive with epoxy coated rebar (ECR)
- Lowest total of ownership over the life of a structure

Types, Dimensions and Sizes

Sizes

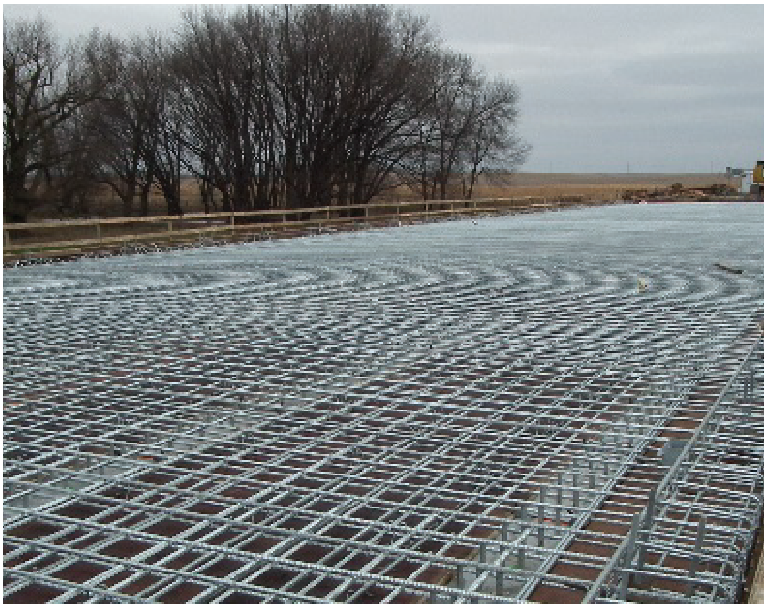
- #3 to #11 available

Finish

- Passivation-quench treatment available per ASTM A1094

Product Limitations

The GalvaBar process currently includes rebar sizes #3 through #11.



Other Applicable *CSI MasterFormat* Categories

- **03 21 13** Galvanized Reinforcement Steel Bars
- **03 33 13** Heavyweight Architectural Concrete
- **03 33 16** Lightweight Architectural Concrete
- **03 41 16** Precast Concrete Slabs
- **03 41 23** Precast Concrete Stairs
- **03 45 13** Faced Architectural Precast Concrete
- **04 05 19** Masonry Anchorage and Reinforcing
- **04 72 00** Cast Stone

4. Technical Data

Applicable Standards

American Association of State and Highway Transportation Officials (AASHTO):

- **M 111** Standard Specification for Zinc (Hot-Dipped Galvanized) and coatings on iron and steel products

ASTM International:

- **ASTM A123/123M** Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products
- **ASTM A90/A90M** Test Method for Weight [Mass] of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings
- **ASTM A153/153M** Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware
- **ASTM A615/A615M** Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
- **ASTM A641** Specification for Zinc-Coated (Galvanized) Carbon Steel Wire
- **ASTM A706/A706M** Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement
- **ASTM A767/A767M** Standard Specification for Zinc-coated (Galvanized) Steel Bars for Concrete Reinforcement
- **ASTM A780/A780M** Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings
- **ASTM A996/A996M** Specification for Rail-Steel and Axle-Steel Deformed Bars for Concrete Reinforcement
- **ASTM A1035/A1035M** Standard Specification for Deformed and Plain Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement
- **ASTM A1094/A1094M** Standard Specification for Continuous Hot-Dip Galvanized Steel Bars for Concrete Reinforcement
- **ASTM B6** Specification for Zinc
- **ASTM B487** Test Method for Measurement of Metal and Oxide Coating Thickness by Microscopical Examination of Cross Section
- **ASTM B852** Specification for Continuous Galvanizing Grade (CGG) Zinc Alloys for Hot-Dip Galvanizing of Sheet Steel
- **ASTM E376** Practice for Measuring Coating Thickness by Magnetic-Field or Eddy-Current (Electromagnetic) Testing Methods

Concrete Reinforcing Steel Institute (CRSI):

- Manual of Standard Practice
- Placing Reinforcing Bars

International Standards of Organization (ISO):

- **ISO 1461** Hot-dip galvanized coatings on fabricated iron and steel products
- **ISO 14657** Zinc-coated steel for the reinforcement of concrete
- **AS/NZS 4680** (Origin – Australia/New Zealand) Hot-dip galvanizing (zinc) coatings on fabricated ferrous articles

US Federal Specifications:

- **DOD-P-21035** Paint, High Zinc Dust Content, Galvanizing Repair
- **MIL-P-26915** Primer Coating, Zinc Dust Pigmented

Environmental Considerations

GalvaBar is a sustainable material created through an environmentally responsible process free of volatile organic compounds (VOCs) and hazardous air pollutants.

The 100 percent recyclability of galvanized steel is an exemplary measure of environmental stewardship.

Contact manufacturer for CRSI information.

5. Installation

Installations require no special handling equipment for protection from the elements at the job site.

Do not bend or straighten bars in a manner that may injure the material. Splicing to be performed per manufacturer's instructions and according to project drawings.

Follow manufacturer's instructions, project drawings and per ASTM Practice A780/A780M.

Product installation guidelines and additional resources available at: **www.cmc.com/galvabar**

6. Availability and Cost

Please contact manufacturer for availability and pricing.

7. Maintenance

This product requires no maintenance.

8. Technical Services

Contact Galvabar for technical support. GalvaBar facilities will coordinate with steel mills and fabrication detailers to be sure all questions are answered and code requirements are met. Services include design professional consultation, continued education courses, and project-site assistance.

9. Filing Systems

- SpecLink
- Additional product information is available upon request.

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GalvaBar® (ASTM A1094) Frequently Asked Questions

Below you will find answers to the questions we get most often about GalvaBar®. More product information is available at cmc.com/galvabar or you can contact your regional sales representative who will be happy to help answer your questions.

What is GalvaBar?
GalvaBar is a continuously galvanized rebar (CGR) process where properly cleaned rebar is in the molten zinc for only a few seconds and the coating is pure zinc except for a very thin alloy layer at the interface between the zinc and the steel. The coating not only is very adherent and impact resistant, but also is very formable and withstands all post coating forming operations without cracking or peeling. While the continuous hot dip galvanizing steel sheet process has been used for over 8 decades to produce galvanized steel sheet and wire products, it is a recent development for rebar.

Is there a specification for GalvaBar?
Yes. ASTM A1094 / A1094M Continuous Hot-Dip Galvanized Steel Bars for Concrete Reinforcement and A1055/A1055M Zinc and Epoxy Dual-Coated Steel Reinforcing Bars.

Where can I get GalvaBar?
GalvaBar is available in two ways: you can have your supplier ship direct to the nearest GalvaBar plant or purchase the already processed GalvaBar from our distribution partners. Please email galvabar@cmc.com for directions or questions.

How much more weight should I expect to be billed for galvanized zinc pick up?
GalvaBar is charged on the theoretical black weight of the rebar we process so you will not incur any additional charges for zinc pickup or environmental fees.

What lengths can you galvanize?
We typically process GalvaBar continuously in 20', 40' or 60' lengths depending on your requirements. We can also process any straight length a steel mill can produce from 20' to over 64'.

Why would I need material over 40'?
60' material or job specific mill lengths can provide you with better control of your yield loss for bars over 40' on your project. Job specific mill lengths under 40' can accomplish the same goal on larger projects.

What is your lead time?
We can process a truckload of GalvaBar in a few hours so lead time will typically depend on how fast you can get us the black bar to process. With our distribution partners we have many sizes of GalvaBar in warehouse points around the country for just in time shipping.

How much will it cost?
GalvaBar is very competitive with epoxy coated rebar and significantly less expensive than non-ferrous, high strength semi-stainless, fiberglass and stainless rebar. GalvaBar has the lowest cost of ownership over the life of a structure.

How long will GalvaBar last?
GalvaBar will last as long as a traditionally hot-dip galvanized rebar.

Will GalvaBar crack, peel or flake on a tight bend? Do I need protective rolls on my equipment?
No, GalvaBar does not crack even on the tightest bends. Consult ASTM A615, A706, or A996 for proper bend diameters. You will not need any special equipment for fabricating, just bend it like black bar!

Won't I have a lot more drop to factor into my pricing?
By using the different length options available to fabricate, there should only be a slight increase in your yield factor. Because GalvaBar can be designed like uncoated rebar, you will use less steel than epoxy coated rebar or stainless rebar.

Should I be concerned about embrittlement?
No. Even higher-strength reinforcement is not impacted by the GalvaBar process. There will be no effect on mechanical properties of the rebar. We can process any grade of steel produced to ASTM A615, A706, or A996.

We don't quote many galvanized projects. Is there a need?
One great advantage of GalvaBar is that it opens up new markets to rebar fabricators providing opportunities for higher margin business. The fabricator can control the flow of material through the shop without special equipment or wear and tear on machinery. Fewer logistics, shorter lead times, controlled labor and the ability to adjust on the fly — with GalvaBar you can expand your market by becoming more competitive quoting these projects.

How does it help me in my shop?
GalvaBar is very clean to work with since it does not crack or peel or have any mill scale. This will keep your machines operating efficiently and you'll have less time cleaning up than before.

Can Epoxy be applied to GalvaBar?
Yes, ASTM A1055/A1055M Zinc and Epoxy Dual-Coated Steel Reinforcing Bars. This product is perfect for extreme environments and still very competitive with all stainless steel grade rebar. Make sure to notate on your purchase order the intent to "Dual Coat" the material. This helps in coordination of the process.

Is galvanized reinforcement suitable for use in lightweight precast or tilt-up construction?
Absolutely. Where the cover is intentionally reduced and/or thin elements may crack, the corrosion protection afforded by the zinc coating ensures that the reinforcement does not prematurely corrode.

Do you offer accredited lunch and learn seminars?
Yes, we do! Contact galvabar@cmc.com.

GALVABAR®

Guidelines for Construction Practices

Requirements for continuous hot-dip galvanized steel construction practices are delineated in the following guidelines. These guidelines are intended to serve as a resource for installing GalvaBar in accordance with Practice A1094A/1094M.

Guidelines For Use Of Continuous Hot-Dip Galvanized Reinforcing Bars Installation

- The galvanized coating shall be passivated with a chromate treatment in accordance with the Zinc Coating Specification Standard Process in Section 6.5 Chromating, to preclude a reaction between the reinforcing bars and fresh cement paste.
- Coating damage incurred during shipment, storage, handling, and placing of continuous hot-dip galvanized reinforcing bars should be repaired with a zinc-rich formulation in accordance with Practice A780/A780M. Prior to repairing damaged coating, rust should be removed from the damaged areas by suitable means.
- When handling, care should be exercised to avoid damaging the coating.
- Continuous hot-dip galvanized reinforcing bars should be off-loaded as close as possible to their points of placement or under the crane so that the bars can be hoisted to the area of placement to minimize rehandling.
- Continuous hot-dip galvanized reinforcing bars should be stored off the ground on protective cribbing, and timbers should be placed between bundles when stacking of the bundles is necessary. Space the cribbing sufficiently close to prevent sags in the bundles.
- Continuous hot-dip galvanized reinforcing bars and uncoated reinforcing bars should be stored separately.
- If the extent of damaged coating exceeds 2% of the surface area of the continuous hot-dip galvanized reinforcing bar in any 1-ft [0.3-m] length, the coated bar should be rejected.
- If the extent of damaged coating does not exceed 2% of the surface area in any 1-ft [0.3-m] length, all damaged coating discernible to a person with normal or corrected vision should be repaired with a zinc-rich formulation in accordance with Practice A780/A780M. The 2% limit on maximum allowed damaged coating should include previously re-paired areas damaged before shipment as required by Specification Standard A1094/A1094M.
- Take note when uncoated steel reinforcement, or any other embedded metal dissimilar to zinc is permitted in the same structural concrete member with or in close proximity to continuous galvanized reinforcing bars (CGR).
    - *Zinc is naturally protective to steel, galvanized reinforcement can be safely mixed with uncoated in concrete. However, if galvanized steel and carbon steel are to be connected in concrete, say for example between dif-ferent mesh layers of an exposed panel or the upper section only of reinforcement in a pile foundation in the ground, the best option is to ensure that the point of connection between the two materials is well embedded and sufficiently deep such that there is no corrosion risk for either material, but especially so the steel. If corrosion of the uncoated steel were to initiate at the connection, the zinc on the adjacent bar will simply act to cathodically protect the carbon steel. Clearly, the protection afforded by the dissolution of the zinc will cause the zinc to slowly dissolve and this is, of course, not the preferred outcome. To an extent this could be seen as wasting the benefit obtained by using galvanized steel in the first instance. So, to be safe, minimize the connections between galvanized steel and carbon steel as far as possible but if this is necessary then keep the point of connection deeply embedded in sound concrete where the risk of corrosion of the steel is minimal.*
- Continuous hot-dip galvanized reinforcing bars should be supported on wire bar supports that are hot-dip galvanized, on wire bar supports coated with epoxy or another polymer, or on supports made of plastic. When precast concrete bar supports with embedded tie wires or dowels are used with coated bars, the wires or dowels should be coated with zinc or polymer. Reinforcing bars used as support bars should be hot-dip galvanized.
- Embedded steel items used with continuous hot-dip galvanized reinforcing bars should be zinc-coated (galvanized) or coated with non-metallic materials.
- Continuous hot-dip galvanized reinforcing bars should be fastened (tied) with tie wire coated with zinc or polymer.
- If continuous hot-dip galvanized reinforcing bars are cut in the field, the bar ends should be coated with a zinc-rich formulation in accordance with Practice A780/A780M.
- After installing mechanical splices on continuous hot-dip galvanized reinforcing bars, damaged coating and areas of removed coating should be repaired with a zinc-rich formulation in accordance with Practice A780/A780M. Exposed parts of mechanical splices should be coated with the same zinc-rich formulation that is used for the repair of damaged coating
- After completing welds on continuous hot-dip galvanized reinforcing bars, damaged coating should be repaired with

a zinc-rich formulation in accordance with Practice A780/A780M. Welds should be coated with the same zinc-rich formulation that is used for the repair of damaged coating

- After field bending or straightening continuous hot-dip galvanized reinforcing bars, damaged coating should be re-paired with a zinc-rich formulation in accordance with Practice A780/A780M.
- After placement of continuous hot-dip galvanized reinforcing bars; the coated bars should be inspected for damaged coating prior to placing concrete. Where damaged coating exists, it should be repaired with a zinc-rich formulation in accordance with Practice A780/A780M.

Guidelines For Use Of Continuous Hot-Dip Galvanized Reinforcing Bars Splicing

- Continuous hot-dip galvanized reinforcing bars shall be furnished in the lengths indicated on the drawings.
- Splicing of bars, except where shown on the drawings, shall not be permitted without the acceptance of the engineer.
- Continuous hot-dip galvanized reinforcing bars splices shall be staggered.
- In cases where permission is granted to splice bars, other than those shown on the drawings, the additional material required for the lap shall be furnished by contractor at contractor's own expense.
- The minimum distance between staggered splices for continuous hot-dip galvanized reinforcing bars shall be the length required for a lapped splice in the bar.
- All continuous hot-dip galvanized reinforcing bar splices shall be full contact splices.
- Splices shall not be permitted at points where the section is not sufficient to provide a minimum distance of two (2) inches between the splice and the nearest adjacent bar or the surface of the concrete.

Guidelines For Use Of Continuous Hot-Dip Galvanized Reinforcing Bars Welding

- Welding of continuous hot-dip galvanized reinforcing bars shall be done only if detailed on the drawings or if authorized by engineer in writing.
- Welding of continuous hot-dip galvanized reinforcing bars shall be done by a certified welder.
- The welding shall conform to AWS D1.4/D1.4M with the modifications and additions specified hereinafter.
- Where AWS D2.0 Specifications for Welded Highway and Railway Bridges is referenced, the reference shall be construed to be for AWS D1.1.
- Where the term AWS D1.1/D1.1M is used it shall mean the American Welding Society Structural Welding Code, D1.5/ D1.5M as modified and amended by the AASHTO Standard Specifications for Welding of Structural Steel Highway Bridges.
- After completion of welding, coating damage to continuous hot-dip galvanized reinforcing bars shall be re-paired in accordance with Practice A780/A780M.
- When required or permitted, a mechanical connection may be used to splice continuous hot-dip galvanized reinforcing bars or as substitution for dowel bars.
- The mechanical connection shall be capable of developing a minimum of one hundred twenty five percent (125%) of the yield strength of the reinforcing bar in both tension and compression.
- All parts of mechanical connections used on coated bars, including steel splice sleeves, bolts, and nuts shall be coated with the same material used for repair of coating damage.

Guidelines For Use Of Continuous Hot-Dip Galvanized Reinforcing Bars With Non Galvanized Steel Forms

- Continuous hot-dip galvanized steel reinforcing bars contain a zinc or zinc-alloy coated surface that is of a different electrochemical potential than uncoated steel or stainless steel.
- When forms for casting concrete are made of uncoated steel or stainless steel, the use of continuous hot-dip galvanized steel reinforcing bars necessitates an electrical isolation of the continuous hot-dip galvanized steel reinforcing bars from the forms.
- Should electrical contact between the two occur, the result will be a shadowing of a ghost appearance of the reinforcing bar on the finished concrete surface.
- Zinc ions will tend to migrate to the surface of the concrete and appear in a darker color, or shadow, on the concrete surface, in the shape of the reinforcing bar configuration.
- In more severe cases, the concrete can adhere to the metal forms.

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