Update on Galvanized Reinforcing Bar for Concrete: Process, Life Prediction and Application Developments

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Abstract
During the last 3 years, great progress has been made in our understanding of the performance of galvanized rebar in concrete. The electrochemical reference points used to determine when uncoated rebar is corroding in concrete have been proven to be inaccurate for galvanized rebar; a new set of reference points is now used to assess performance. The growth of continuous galvanized rebar (CGR) has also been notable; an overview of CGR processing will be presented together with new performance information of CGR in concrete, including new pull-out test results. Recent projects using both general galvanized rebar and CGR will be presented that highlight the advantages of galvanizing rebar usage.

Introduction
Concrete reinforced by steel rebar is the most widely-used composite material in the world. To realize the full advantage of the steel reinforcement, a good bond strength must be developed between the surface of the rebar and the surrounding concrete. The rebar should be durable over the expected life of the structure, without corroding that not only weakens this bond strength but also induces stresses in the concrete that can cause cracking. The major cause of deterioration of reinforced concrete is the ingress of chloride, either from marine environments or from exposure to de-icing salt used on roadways. Carbonation of concrete can also contribute to destabilization of the gamma ferric oxide layer that is formed on the surface of black rebar after the pouring and curing of concrete. The volume of iron corrosion products can be 2-5 times that of the initially-placed steel rebar, inducing tensile stresses in the concrete that can nucleate and grow cracks. By contrast, the compound calcium hydrozincate (CHZ) which forms when galvanized rebar is placed in fresh concrete, has only a slightly higher volume than the zinc itself and facilitates a good bond between the surface of the galvanized rebar and the surrounding concrete as it sets.[1] Work in recent years has improved our knowledge of the behavior of galvanized rebar in concrete during simulated service conditions. Progress has also been made in development of the continuous reinforcing

bar galvanizing process. Several recent projects using galvanized rebar will also be described.

Corrosion Performance of Galvanized Rebar

The harsh Canadian winter climate requires the use of more concentrated de-icing salt to keep roadways clear in comparison with other locations. Typical Ontario brine consists of 16% $CaCl_2$ + 12% NaCl + 4% $MgCl_2$, giving a Cl content of 21%. In many other localities, Cl concentrations around 3% are used. To determine the performance of general galvanized, continuous galvanized and black rebar under simulated Canadian conditions, a set of concrete slabs containing these types of rebars were cast, cured for 40 days and exposed to this chloride brine for 64 weeks.[2] These were then assessed using the galvano-static pulse technique with a current pulse of 10 mA for 200s, checking the corrosion current and corrosion potential twice a week. Both sound and pre-cracked samples were used. Two varieties of pre-cracked samples were studied, those with cracks parallel to the rebar (longitudinal cracks) and those where the cracks were positioned across the width of the sample (transverse cracks), with the pre-crack always extending to the surface of the embedded rebar. After breaking the samples apart, no active corrosion was seen in either of the galvanized or black rebar in the initially sound blocks. On the other hand, in all of the pre-cracked concrete blocks, corrosion always started at the base of the crack and extended along or around the bars. Rebar samples tested included two early-stage continuous galvanized rebar samples, a conventional hot dip galvanized rebar sample and a hot dip rebar with an experimental Zn-Al coating. The two CGR coatings had specified coating thicknesses of 50 µm but in fact were received with thinner coatings averaging 41 µm for sample C1 and 33 µm for sample C2, whereas the Al-containing coating HDG-Al was specified as 30 µm thick but exhibited an average thickness of 26 µm. The CGR1 and CGR2 samples were produced during early stage trials in China and shipped to Canada. They were not passivated at the time of manufacture, but the time between the June 2014 production of the samples in China and February 2015 casting of research samples, including ocean freight from China to Canada, was sufficient to permit forming of the customary basic zinc carbonate passive layer. By contrast, the HDG-Al samples were produced by stripping the coating from several CGR sample received from China and re-galvanizing them in Zn-7%Al bath during January 2015, after which they were used with the C1 and C2 rebar for preparing samples. The 150 µm average thickness general galvanized coating termed HDG was in conformance with ASTM A767 and was passivated with a chromate treatment at the time of manufacture. A conventional mild steel was used for the black rebar comparison. The corrosion current measured for each of these samples with time for the uncracked samples is shown in Figure 1. It can be seen that the HDG and the two CGR samples had corrosion currents lower than .0003 A/m^2. These were relatively stable until about 550 days, after which active corrosion appeared to begin. At this point the HDG sample corrosion current increased the most rapidly of the coated samples, which is usually indicative of the start of corrosion of the Fe-Zn intermetallic. By contrast, the two CGR samples increased less and then corroded at lower rates than the HDG. By contrast, the HDG-Al sample and the black bar behaved in a similar manner, with an initial corrosion current of around 0.002 A/m^2. These also proceeded to about 550 days, after which the black rebar began corroding more rapidly before again decreasing, but still showing a higher corrosion current than the HDG and CGR samples, and about the same as the HDG-Al bar. Related work, conducted under comparable conditions, showed that after 450 days exposure, the microcomposite low-Cr steel, MMFX-2, was exhibiting active corrosion.[3] The equivalent corrosion rate for the HDG and CGR samples in Figure 1 is 0.1 µm/y (corresponding to 0.0001 A/m^2) whereas the MMFX-2 was corroding at an order of magnitude higher rate, 0.001 amperes per square meter, or 1 µm/y. This is about the same magnitude as observed in Figure 1 for the black bar and the HDG-Al bar. From a durability point of view, the maximum acceptable corrosion current for rebar embedded in concrete is 0.001 A/m^2.

The corrosion potentials of the rebars examined in Reference 2 are shown in Figure 2. These cannot be interpreted to understand their corrosion status with the customary ASTM C876 recommended potential values. For black bars, these are that when the measured potential is more positive than -125mV SCE there is a 90% probability of passive corrosion; when it is more negative than -275mV SCE there is a 90% probability of active corrosion. The situation with corroding Zn is very different because the initial active corrosion potential of Zn is -1100mV SCE; however, this becomes much more positive (anodic) as the CHZ layer is formed, bringing it up to about -300mV SCE. As explained in Reference 2, when Cl levels next to the rebar reach the point so that zinc corrosion begins, this exposes the Fe-Zn intermetallic layer and then the underlying steel and therefore the potential then decreases again into between -400mV and -680mV. Therefore, Reference 2 concluded that new corrosion thresholds should be used to judge the performance of galvanized rebar in concrete. These are shown by the dotted lines in Figure 2; i.e., for a potential more positive than -335mV SCE there is low probability of corrosion and for a potential more negative than -385mV SCE a high probability of corrosion with an uncertain region existing between these potentials, following the methodology of ASTM C876. This follows the same general direction as guidelines developed by the National Research Council of Canada,[4] which also suggests that more negative millivoltages be used to judge the behavior of Zn-coated rebar in concrete versus black rebar.

To study of the effect of corrosion performance on bond strength, pull-out tests were conducted at University of Akron using 15x15x15 cm prisms of concrete cast around a rebar length passing through one central axis.[5] Samples of continuous galvanized rebar MMFX, grade 2304 stainless steel, epoxy-coated and black bar were used. For these experiments, and the flexing experiments below, the CGR samples were produced by a USA manufacturer in conformance with ASTM A1094 and the CGR coating was given a trivalent chromate passivation coating during manufacture. The prisms were then immersed in a 5% NaCl solution and an impressed current of 0.2 A applied for a period of 10 days. A 2-day wetting and 1-day drying cycle was used to increase the effect of corrosion. A duplicate set of samples using polypropylene fiber added to the concrete at a rate of 3.4 kg/m^3, produced another set of samples with the same rebar. The results of the pull-out tests are shown in Figure 3, before and after corrosion testing. These results show that CGR out-performed all other types of bars tested in this study for both corroded and uncorroded conditions with and without fiber. This performance is better than epoxy-coated rebar by a large margin, clearly better than the stainless steel bars and relatively better than MMFX. The addition of fiber to the concrete improved the performance of CGR, and all other bars, by at least 10-15% in both the corroded and uncorroded conditions.

One of the most common means of degradation of reinforced concrete road deck is the development of cracks that result from continued flexing of the bridge over time as it carries live loads. Past work by the author of Reference 5 indicated that the same cracking behavior as seen in full-scale specimens can be found when using the same tension reinforcement ratio and the same effective cover of concrete over the rebar. To determine if it was advantageous to use CGR to minimize the development of cracks during bridge deck flexing, concrete test beams 20.3 x 20.3 x 243 cm were prepared.[5] On the beam side to be tensioned during flexing, 17 mm rebars were placed, and beams made with each of the rebar varieties, described in the previous paragraph. On the beam side to be placed in compression during flexing, a 13 mm black bar was always used. The stirrups surrounding the arranged longitudinally place bars were always a 10 mm black bar. After curing, flexing loads were applied to these beams. Crack widths were measured on an average of two beams for each type of bar. Results are shown in Figure 4. For slabs with and without fiber, the epoxy-coated bar showed wider crack widths than black rebar, which in turn showed wider widths than the CGR. The MMFX bar performed comparably with CGR, and both superior to the stainless bar. The epoxy bar results were far below these.

Recent work has also helped to clarify the relationship between the extent of rebar corrosion in the concrete and cracks that form in the concrete, for both black and galvanized rebar.[6] Here, general galvanized rebar, made to ASTM A767, and black bar were cast in concrete and tested with 3 different levels of concrete cover. Impressed current was used to accelerate corrosion on some samples, while other samples were tested without impressed current. The magnitudes of corrosion loss required to initiate cracking in concrete were found to be similar for bars tested with and without impressed current. Table 2 shows the average corrosion loss causing crack initiation for conventional and general galvanized reinforcement for the samples that were subjected to impressed current, based upon the percentage of bar surface area showing active corrosion, measured in the micron readings shown in the table. The reading for general galvanized rebar for the 12.5 mm of cover is quite high. For the other two depths of cover, which are more typical of actual construction, it was found that the crack initiation in the galvanized rebar sample only begins after more than twice the amount of corrosion seen with the black rebar. The samples that were tested using impressed current showed much higher average corrosion losses at crack initiation than those that had not used impressed current. In the latter case, the galvanized rebar cracked with an average corrosion loss of 12.4 µm, which is over twice the average corrosion loss required to crack concrete with black rebar, 5.41 µm. The corresponding ratio is 2.3, which is similar for that seen in the two accelerated tests for which higher depths of cover were used in Table 2. Moreover, the losses required to produce a given crack width, after the initiation of cracks, was considerably higher for galvanized reinforcement than conventional reinforcement.

Not only the amount of corrosion products produced, but also the amount of time required to produce the amount of corrosion required for cracking, is favorable with general galvanized samples. Table 3 shows the average time, measured in weeks, required to initiate cracking for the six samples of general galvanized and black rebar. The galvanized samples required almost four times as long to crack as the conventional rebar samples, without accelerating them by use of impressed current.

CGR Process Development Status

The continuous galvanized rebar process was introduced at APGGC 2016.[7] Since this time, continuous rebar production has been established in China with Xiamen Newsteel and also in the USA with AZZ Coatings. Continuous galvanized rebar, made to ASTM A1094, features a 50 µm coating that is nearly all metallic Zn overlay. As with continuously galvanized sheet, only a sub-micron-thick layer of Fe-Al interface layer is present,[8] rather than the thick Fe-Zn layer found in general galvanized coatings, permitting the ductility or bending properties of CGR to only be limited by the mechanical properties of the steel itself. For the customer, this enables CGR to be bent at the site of application, whereas for more severe bends, general galvanized rebar must first be bent and then general galvanized, requiring additional time and cost. As indicated in some of the corrosion tests above, the absence of the Fe-Zn layer also contributes to several aspects of improved corrosion performance. The new information described in this paper, with regard to both pull-out strength and reduction of crack widths in comparison with competitive materials, should also prove advantageous for potential customers. We expect that several other CGR lines will be installed globally in the near future.

In the typical CGR process sequence, the incoming black bar is shot blasted to remove scale, then fluxed in an Al-tolerant, highly acidified flux. After drying, it passes through the hot-dip coating section where it resides for no more than 20 seconds, compared with the several minutes of dipping time required for general galvanizing. The shorter heat exposure is expected to result in less mechanical property changes for higher strength rebar that contains significant fractions of martensite or bainite that are sensitive to tempering when exposed to zinc bath temperatures for prolonged periods of time.[9]

Recent New Galvanized Rebar Projects

The first bridge constructed with CGR spans Buffalo Creek in Independence, Iowa. It is a 2-lane, 18.6 m long composite bridge. General galvanized steel was used for the pilings, structural beams, guard rails and miscellaneous items, while the concrete abutments, parapets and bridge deck used 75 tons of CGR to reinforce the concrete. A picture of the bridge is shown in Figure 5. This bridge is in a rural area; closure of the bridge for replacement resulted in significant detours for local residents. The ability to bring CGR to the site and bend it on site to exactly the required shapes saved construction time and in addition it was competitively priced.

The Mario Cuomo Bridge, formerly known as the New NY Bridge, spanning the Tappan Zee section of the Hudson River, was open last year in New York State. This is owned by the New York State Thruway Authority. For a typical section of roadway near Albany, the New York State capital, 30 tonnes per lane-km of de-icing salt are applied each winter.[10] This authority started using epoxy-coated rebar in the 1980's and switched to general galvanized rebar in the 1990's when doubts began to arise about the effectiveness of epoxy-coated rebar in the long term. For this bridge, nearly 6,000 precast panels, each 3.6 m long and between 6.7 and 13.7 m wide on the approaches, and 973 panels in the main span, as well as 68 300-ton pile caps and 134 12-foot girder assemblies are reinforced with hot-dip galvanized rebar. Furthermore, 43 pairs of concrete piers were built using galvanized reinforcing steel cages, such as the one shown in Figure 6. 59,000 tons of hot-dip galvanized rebar was used. Beyond the reinforcement, hot-dip galvanized steel was also used in the 1126 km of metal strand stay cables which provide essential support for the bridge. The cables are supported by four 125m concrete pylons/towers reinforced with galvanized steel cages, each sitting at a five-degree angle to maintain the tension in the cables to allow for a more open structure. The towers are reinforced by two 650-ton galvanized steel crossbeams that also support the road deck.

The Turcot Interchange is a three-level stack freeway interchange, and the largest in the province of Québec. Originally completed in time for the 1967 Montreal Expo, it has seen even heavier doses of deicing salt that that used on the New York Thruway, and has required constant repair over the years. A complete reconstruction began in 2012, with the expected project completion date of July 1, 2019. To speed construction and reduce cost, many of the roadway decks for overpasses using galvanized rebar are precast in a nearby factory, which also allows for temperature regulation, thus improving quality. The use of precast slabs allows for faster construction, resulting in cost savings. The retaining walls, certified also for use as for overpass abutments, are also usually made from precast forms. This project is using 15,000 tons of galvanized rebar; views of this project are shown in Figure 7.

Beyond bridges, galvanized rebar is also used in building construction. One of the newest buildings being made using galvanized rebar is 11 Hoyt St., Brooklyn, NY. The remarkable outer appearance of this 57-story building containing 481 apartments is achieved with curved precast panels. The building is expected to open for occupancy in mid-2020. Architect images of the building are shown in Figure 8. Here, the main concerns are both cosmetic and functional. Red rust staining from corroding black rebar must be prevented; the façade should be free of maintenance concerns relating to both cosmetic and structural consequences of rebar corrosion for many years longer because of the use of galvanized rebar.

Conclusions

The recent research summarized in this paper confirms and extends our knowledge about the performance of both general galvanized and continuous galvanized reinforcing bar for concrete. Its superior performance, compared with other types of reinforcing bar in chloride-containing environments, is manifest through its delayed time until corrosion initiation, lower corrosion rates and the consequences of this improved corrosion performance for reduced formation of cracks in the corroded concrete material. The bond strength of CGR has been shown to be superior to that of other products, and this has been shown to be related to the formation of a dense CHZ layer on the surface of the zinc as the concrete sets and cures.[10] This improved bond strength is likely related to reduced density of surface cracks in concrete after repeated flexing that simulates conditions seen with a typical road deck.

References

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Table 1. Rebar Specimens Tested in U. Waterloo Research (Reference 2)

Designation	Description	Average Measured Thickness, µm (std dev)
C1	CGR, 0.5% coating Al	41 (±14)
C2	CGR 0.9% coating Al	33 (±12)
HDG-Al	CGR 8.9% coating Al	26 (±13)
HDG	In specification with ASTM A767	150 (±41)
Black	Uncoated Mild steel (400W)	uncoated

Table 2. Average corrosion losses at crack initiation for black and galvanized reinforcement for specimens tested with impressed current, µm, based on percentage of bar surface area showing active corrosion (Reference 6)

Depth of Cover (mm)	Black Rebar µm - Avg (std)	Galvanized Rebar µm - Avg (std)	Ratio Galv/Black
12.5	10.5 (2.8)	65.5 (24.3)	6.2
25.4	22.4 (5.5)	55.1 (10.7)	2.5
51.0	29.7 (4.6)	68.8 (20.3)	2.3

Table 3. Average time to crack initiation for black and galvanized reinforcement for specimens tested without impressed current, weeks (Reference 6)

Black Rebar Weeks – Avg (std)	Galvanized Rebar Weeks – Avg (std)	Ratio Galv/Black
21.2 (3.7)	80.7 (3.4)	3.8

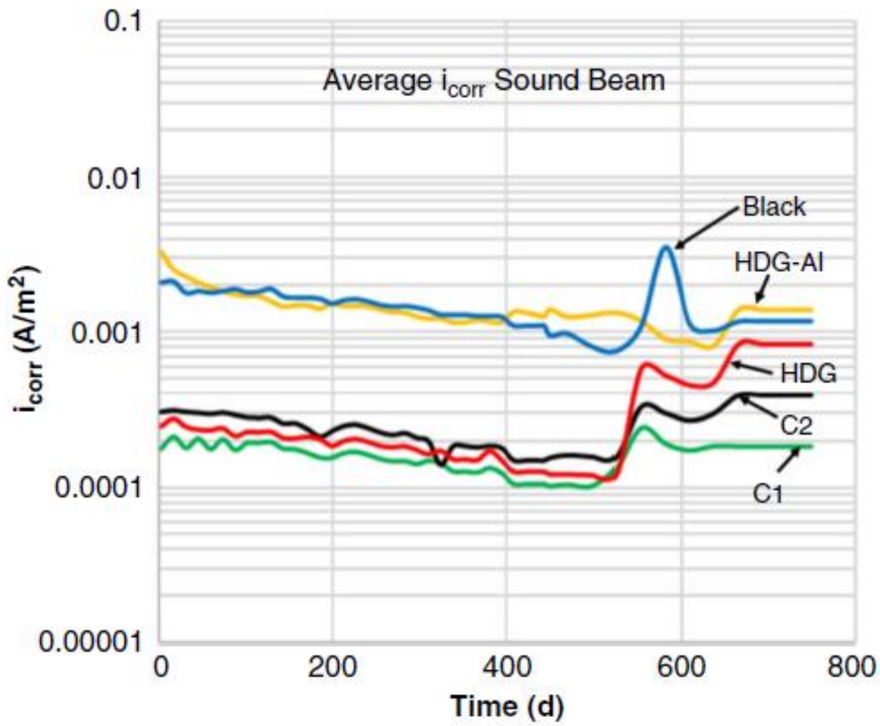

Figure 1. Average values of the corrosion current densities of five replicate specimens of CGR (C1,C2), general galvanized (HDG to ASTM A767 and HDG-7%Al) and black rebar exposed in sound (non-cracked) concrete over a 2.1 year exposure time to Ontario multichloride deicing solution (Reference 2).

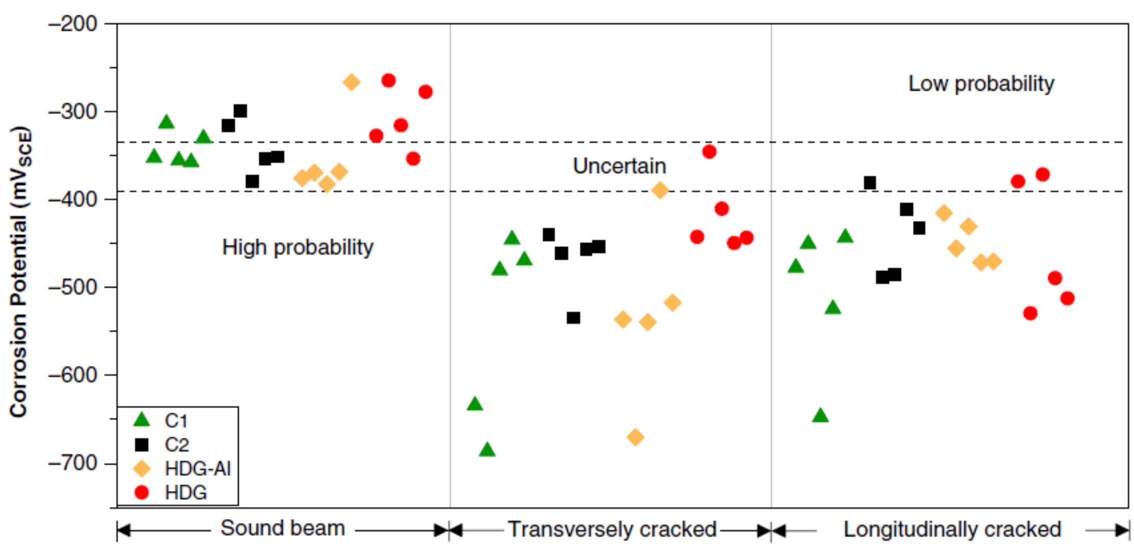

Figure 2. Potential guideline for assessing the probability of corrosion of galvanized steels in concrete. Each point represents a potential value at the end of 64 week exposure to Ontario multichloride deicing solution (Reference 2).

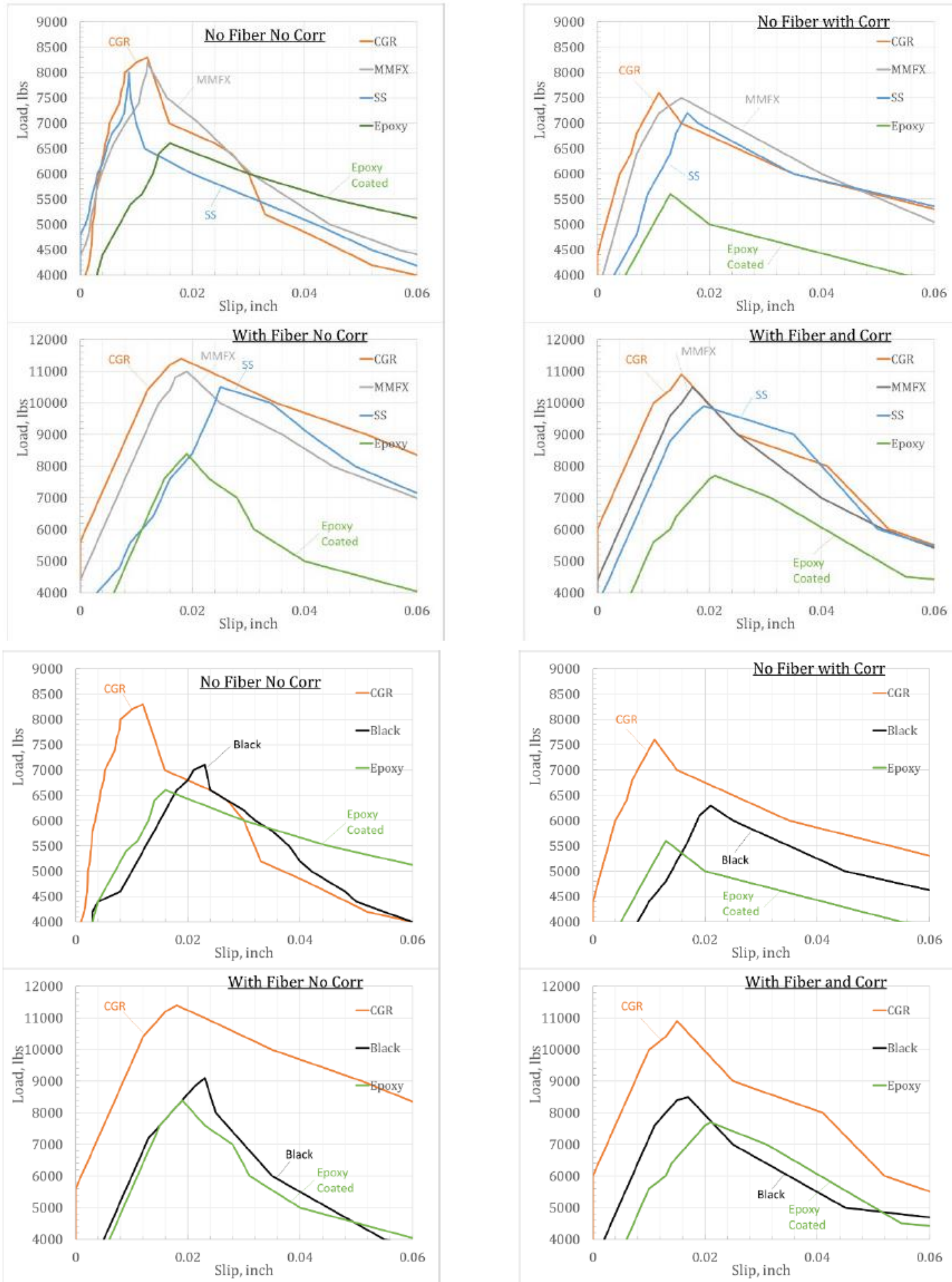

Figure 3. Comparison of Load-Slip Results of Pull-out Tests, Before and After Corrosion Exposure, of CGR, Black, Epoxy-Coated, MMFX and Grade 2304 Stainless Steel Rebars (Reference 5).

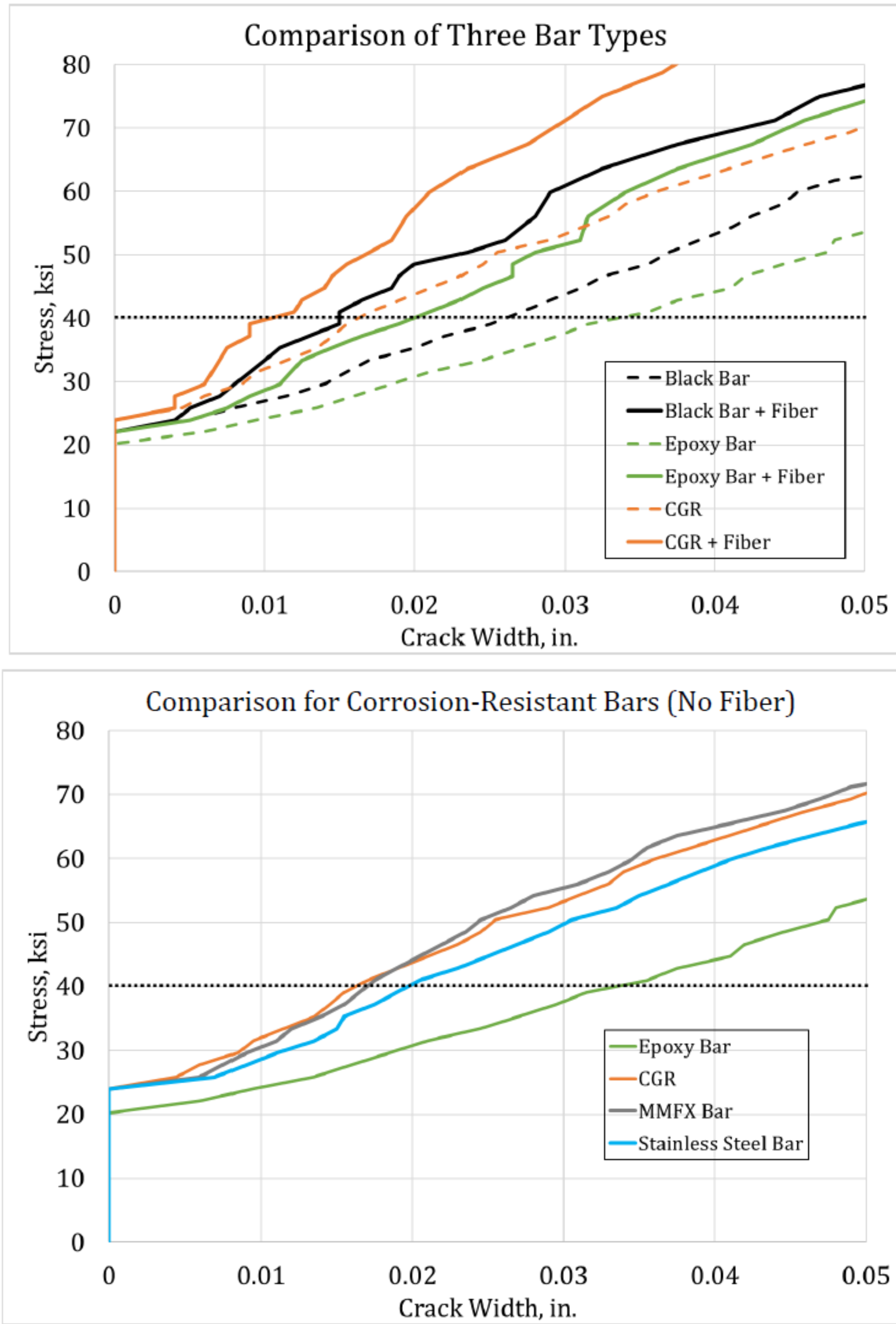

Figure 4. (top) Comparison of Crack Widths for Slabs with and without Fiber and with Black Bars, ECB and CGR (bottom) Stress vs. Crack Widths for Slabs with Different Bar Types (No Fiber) (Reference 5).

Figure 5. First bridge constructed with CGR, using 75 tons: Buffalo Creek Bridge in Independence, Iowa, USA (Source: AZZ Metal Coatings)

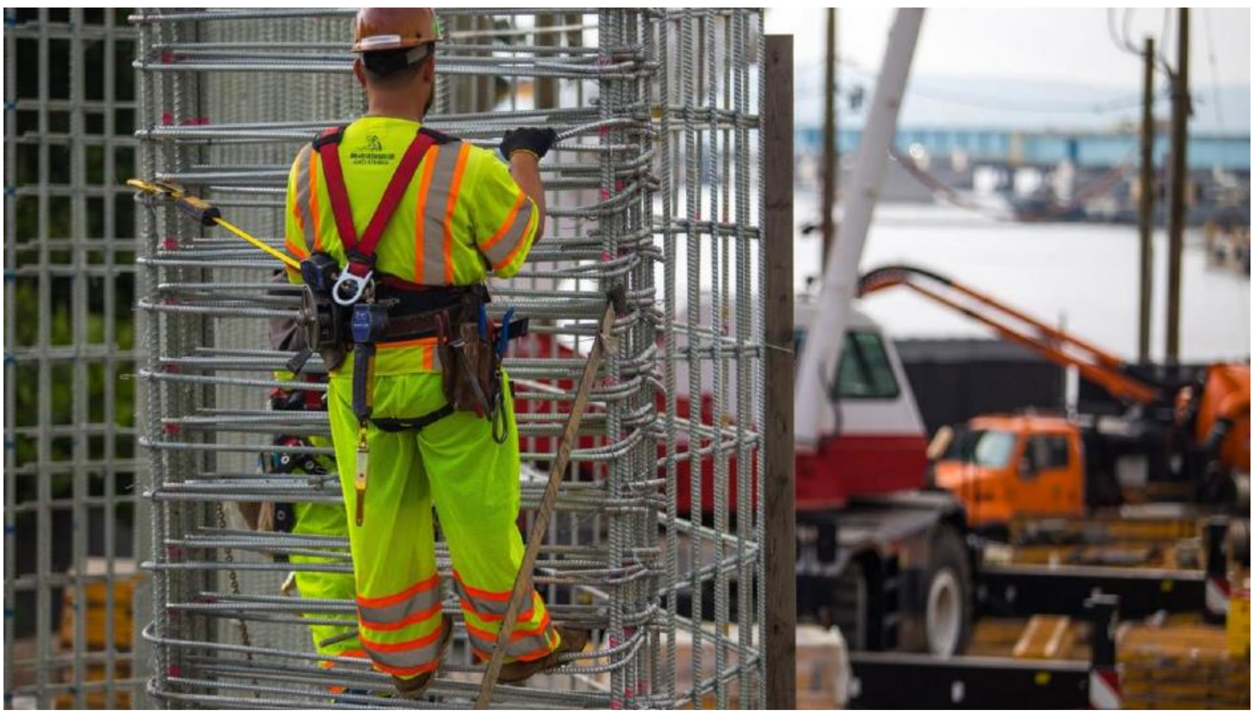

Figure 6. Galvanized rebar cage being fabricated during construction of one of the 43 pairs of piers required for the Mario M. Cuomo bridge across the Tappan Zee, New York.

Figure 7. The Turcot Interchange reconstruction project on the southwest side of Montreal. Decks and abutments are made from both precast and cast-in-place concrete reinforced with galvanized rebar.

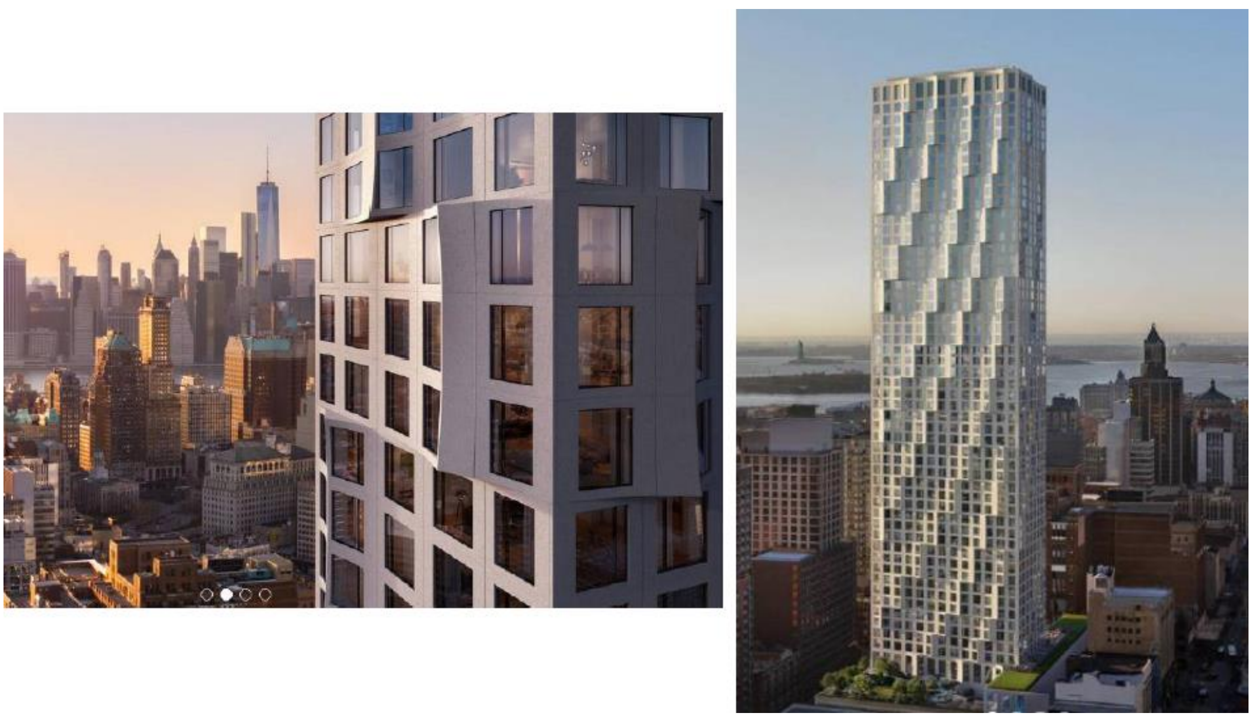

Figure 8. Architect’s renderings of 11 Hoyt St., Brooklyn, NY. The distinctive façade is made of precast panels containing galvanized rebar. The building is expected to be completed mid-2020