Considerations Necessary to Estimate the Service Life of Epoxy Coated Reinforcement in Bridge Decks

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March 7, 2005

ABSTRACT

This paper discusses various issues relevant to the performance of bridge decks containing epoxy-coated reinforcing steel. The corrosion protection provided to bridge decks built with coated reinforcing is due to several phenomena. The epoxy coating reduces corrosion by: 1) forming a barrier to chloride ions at the anode (corroding) sites, 2) forming a barrier to oxygen at the cathode (non-corroding) sites, and 3) by increasing the ionic resistance path between the anode and cathode locations. This is best performed by damage-free, coated bars that are electrically isolated from other uncoated steel within the concrete.

Accelerated laboratory testing using the various test methods, including the Southern Exposure test, has been widely used by many researchers to assess the corrosion resistance of epoxy coated reinforcing in projects funded by the FHWA and state transportation agencies. Epoxy coated reinforcing has consistently shown good to excellent corrosion resistance in severe accelerated testing. Even damaged, non-specification bars show improvements in corrosion resistance, and much improved performance is achieved when testing quality epoxy coated bars used in both top and bottom bar mats.

Coating both top and bottom mats in bridge decks is beneficial since this discourages the cathodic reaction (oxygen reduction) which is an essential part of the corrosion process. By coating the bottom mat, electrical connections between the top bars and bottom bars are limited and the corrosion rate of the top (anode) bars is slowed since oxygen is not reduced at the bottom mat. This is the contrast to uncoated bottom mat systems where the large surface area of this mat readily serves as a cathode.

More time is needed to assess the service life extension of bridges built with epoxy coated reinforcing because so few problems have been seen to date in bridges where this technology has been installed properly. Field problems with epoxy coated steel reinforcing in bridge decks have been primarily limited to decks with black bar bottom mats or where lack of concrete cover or cracking have contributed to early corrosion.

Based on a review of laboratory and field data, the service life extension of bridge decks containing electrically discontinuous bars and those with both top and bottom coated mats is greater than in decks that only have the top steel mat coated. This effect is far more important to the service life extension than is loss of coating adhesion. This paper discusses some of the published literature that highlight the potential benefits of installing quality epoxy coated bars, minimizing coating damage, and electrically isolating epoxy-coated bars in bridge decks.

INTRODUCTION

Large volumes of research and literature have been published on the testing and performance of epoxy-coated reinforcing (ECR) steel. Most laboratory and field trial research has shown epoxy-coating to be an effective corrosion protection system. When considering the wide range of factors that are known to affect actual performance, field performance of bridge decks with ECR has been good, especially when both top and bottom mats of reinforcing bars are coated. Recently, theories have been proposed that the extension in the service life of decks achieved through the use of ECR may be shortened since poor bond of the epoxy has been observed on bar samples cored from older structures. However, correlation between corrosion protection and the adhesion of the coating is not well established. In fact in Brown and FHWA's recently released report, no correlation between adhesion and corrosion protection could be established. Loss of adhesion does not eliminate the potential benefit of coated reinforcing since the coating may still delay corrosion initiation and slow the propagation rate of corrosion. The durability and service life of coated reinforcing in bridge structures is much more complex than assuming the benefits of coated reinforcing are exhausted when adhesion is lost. In fact, while epoxy-coated reinforcing steel has been widely used for 25 years, it is still too soon to fully assess its long-term benefits, since most bridges of that age are still performing very well regardless of whether the steel is coated or not.

The purpose of this paper is to review and discuss previous research and highlight some of the many factors that should be considered when deciding if epoxy coated reinforcing is beneficial for use. The findings appear consistent within the literature and are supported by field performance to date. Primary discussions relate to the effect of the exposed cathode area on the performance of epoxy-coated reinforcing steel in bridge decks and the importance of good quality control in the manufacturing and installation of coated reinforcing.

Early Development and Research of Epoxy-Coated Reinforcing Steel

The United States National Bureau of Standards (NBS) conducted tests on a range of epoxy and other organic coatings for corrosion protection of reinforcing bars in 1973 (Clifton; et al. 1974). Based upon the findings of this project and additional research in the early 1980's, widespread use of epoxy-coated bars for reinforced concrete structures exposed to chloride developed. A few early demonstration bridges were built in the mid-1970's and more widespread use of epoxy-coated steel began in 1980. It is estimated that the United States currently uses almost a million tons of ECR each year, about 10 percent of all reinforcing bars used. Early bridge decks were cast with epoxy top mats and uncoated black steel in the bottom mats. Field measurements by Clear on several bridges in Kentucky and Virginia found that electrical contact between the top coated reinforcing mat and the bottom uncoated mat existed on most bridges. (Clear et al. 1983) It was known by corrosion specialists that corrosion currents could develop between the top bars were chloride was present (anode) and the bottom black (cathode) bars and the corrosion rate of steel in concrete is primarily controlled by the cathodic reactions[1]. Therefore, limiting the exposed bare metal area in the bottom mat, thereby, reducing the cathodic area will reduce the corrosion rate of the top anodic steel. This was confirmed by Clear and Virmani in 1983 in their non-specification bar study. In this study, poor quality, bars that did not meet specifications were tested in

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[1] For corrosion cell to develop in steel, two reactions must occur simultaneously in an electrically continuous element, the first is the anodic reaction where iron is oxidized liberating electrons. The second is the cathodic reaction here the liberated electrons are consumed in a reaction with oxygen and water to form hydroxide ions. The site where these occur is known as the anode and cathode respectively and both must develop for corrosion to occur.

poor quality concrete. The bars were exposed outdoors for two years. The bars had at least 25 holidays per foot, and they failed bend testing. The bars were intentionally damaged to produce bare areas of 0.24 % and 0.86 %, while the specification at the time allowed up to 2% bare area. The results of this FHWA study showed that even this poor quality coated reinforcing reduced the corrosion rate by 11.5 times when an epoxy-coated top mat and black bottom mat were used and by 41 times when both the top and bottom mats were coated. The good performance of the non-specification, damaged bars was attributed to the reduced cathodic bare area limiting the oxygen reduction reaction that controls the rate of metal consumption at the cathode and to the high electrical resistance of the coating (Clear 1983, Virmani 1983). While the good performance of the non-specification, damaged bars clearly demonstrated the good corrosion protection of coated reinforcing and the importance of controlling the cathodic reaction, it allowed a cavalier attitude within the engineering community reflected in the phrase “if it’s green, it’s good”. Little effort was made to improve the quality of coated reinforcing and little inspection of the coating quality was performed in the field. Large areas of bare steel, coating gaps, numerous holidays, construction damage and long-term outdoor exposure were common place and allowed by inspectors through the mid-1980’s.

Performance of Epoxy-Coated Reinforcing in Marine Structures

The engineering community awoke to the need for better quality control when corrosion of coated reinforcing in the substructure of the Long Key Bridge was found in 1986. The Long Key Bridge was built in 1979 and 17 of 101 piers showed corrosion by 1988 and 31 of the 101 piers showed corrosion by 1991 (Manning 1996). The corrosion was first noticed in areas of low concrete cover (25 mm) but progressed to bars with more cover over time. The chloride content of the concrete was very high and reached almost 20 lbs/cu. yd. at a depth of 3 to 4 in. after only 8 years of exposure (7-Mile Bridge). The corrosion was limited to 2 to 8 feet above the mean high water mark, close to the cathode, where oxygen is available. Studies of the failure at the University of South Florida showed that the coating was debonded from the bars and that the corrosion was aggravated by bending, coating defects and macrocell corrosion (Zayed 1989, Sagues 1990). The researchers postulated that imperfections in the bars were aggravated by fabrication, handling and exposure to sea air in the construction yard. It was also found that disbondment could occur in chloride-free concrete (Sagues 1994). Therefore, some of the bar coating was already partly debonded when the bars were installed and the debonding progressed as a result of long-term moisture exposure.

However, similar Florida Department of Transportation (FDOT) marine structures with ECR did not show similar distress. Test piles at Matanza Inlet were installed in 1979 and when examined 9 years later were found to be corrosion free. This was explained by the fact that the bars were essentially defect-free when they were installed (Manning 1996). A single pile with uncoated reinforcing in this project was heavily corroded and the concrete cracked. The FDOT report (Brown 1982) noted that the uncoated reinforcement had begun to corrode only five months after the pile was installed.

A U.S. Navy study of ECR’s in a severe marine tidal zone environment found that although the black bar specimens were significantly deteriorated, similar deterioration was not observed in the specimens containing epoxy-coated bars after 7 years (Burke 1995). Another study tested over 100 specimens containing bent “U” shaped epoxy-coated bars in a marine exposure site at Treat’s Island in Maine (Bremner et al. 1995). In this marine exposure, the epoxy-coated reinforcing performed significantly better than the black reinforcing bars.

Field Performance of Bridge Decks

Many field studies have been conducted on bridges containing epoxy-coated bars. These studies have principally found to-date that structures containing epoxy-coated bars are more durable than those with black bars. The number of bridges containing epoxy coated reinforcing being evaluated is numerous. Several early bridges built with ECR being evaluated were complied by CRSI and are listed in Appendix A. The studies are too numerous to describe in sufficient detail and many have been summarized by others (Manning 1996). The following introduces several studies.

A report written by West Virginia Department of Transportation staff compared the performance of fourteen individual ECR bridge decks between 18 and 20 years old with survey results from black bar decks of similar age, traffic and wear (Kessler and Lipscomb, 1994). The chloride content was measured and found to be similar in both types of deck and in some cases bridges from each grouping were within 10 miles of each other on the same highway. Fewer spalls and lower delaminated area were noted in the ECR decks surveyed compared with the black bar reinforced decks presented for comparison. The better performance of the ECR decks was attributed directly to the epoxy coating on the reinforcing steel. This report concluded that surface cracks were present in decks with both types of reinforcement but those in the ECR decks did not appear to be related to reinforcement deterioration and that, despite the increased access of water to the reinforcing steel provided by cracks, the damage related to corrosion was greatly reduced in decks with ECR compared to decks with uncoated reinforcing steel.

A study conducted by the Michigan Department of Transportation evaluated the relative performance of bridge decks reinforced with black bars, galvanized reinforcement and ECR. Three decks were examined in which adjacent spans were reinforced with each of these reinforcements. In addition, nine additional ECR decks were also evaluated, four that had epoxy coating on the top mat and five that had epoxy coating on both mats. (McCrum et al. 1995) The most recent survey of the decks discussed in this report was conducted 15 years after their construction and minimal concrete deck deterioration had occurred to that date. However, enough corrosion of the reinforcing steel had occurred so that the performance of the reinforcement between the types of reinforcement could be differentiated. This performance was evaluated based on the visual appearance of sections of rebar obtained in cores taken from the bridge decks, and it was determined that the epoxy coated bars were in better condition than the other types of bars investigated. The performance of the ECR was superior particularly where cracks have accelerated chloride ingress. This report also suggested that the performance of ECR in similar conditions is best when both top and bottom mats are coated.

Six bridge decks containing ECR were examined in Indiana by researchers from Purdue University as part of a FHWA sponsored project. These decks ranged from 11 to 18 years of age. Four of the six bridges had chloride content at the steel depth above the accepted corrosion threshold and despite this fact, no sign of corrosion or coating disbondment was observed in the pieces of reinforcement extracted from the decks. (Hasan et al. 1995)

In June 1995, 32 papers on epoxy-coated bars were presented at a 2-day ASTM workshop. Many of the papers reviewed the findings of field surveys of structure containing ECR and these are discussed below. Some other notable studies on the field performance of ECR bridge decks are also presented.

Bars were extracted from three coastal bridges in North Carolina in 1985 (Reaves 1995). The investigation included visual inspection of the bridge bents, and the extraction of cores in tidal, splash and dry zones. The conclusion reached was that despite the harsh marine environment, epoxy-coated bars are providing adequate corrosion protection.

Field inspections were conducted by Caltrans on bridges that were 7 to 10 yrs of age. These all showed acceptable durability. Texas DOT stated that epoxy-coated bars are not a panacea for corrosion problems and suggested areas for improvement (Wolf 1995). TxDOT suggested that every step in the coating, transport, and placement procedures is crucial. They also stated that appropriate concrete mixtures must be used. In addition, TxDOT is developing its own specifications for epoxy-coated bars and currently require all coating applicators to be pre-qualified and monitored.

A paper discussed cores removed from a coastal structure in Georgia (Griggs 1995). When cores were removed from honey-combed concrete in the tidal area, corrosion of the epoxy-coated bars was observed. In similar locations that were not honey-combed, the adhesion of the epoxy-coating was reduced; however no corrosion was observed.

Kansas Department of Transportation studied the deck ratings of 213 structures built since 1978 containing coated bars (McReynolds et al. 1995). All of the structures were found to be in excellent condition. Minnesota DOT studied several structures (Rowecamp 1995). Twenty years after construction, the first bridge deck constructed shows no sign of distress. Four of these early bridges were evaluated in detail in August 1995 (Krauss et al. 1996). Two of the decks had extensive cracking and large amounts of chloride at the bar depth. Chloride ingress into full depth deck cracks caused corrosion of the uncoated bottom reinforcing mat steel and bottom deck spalling. Corrosion of some epoxy bars was noted at crack locations and small areas of delaminations had occurred. The coating adhesion ranged from excellent to poor.

Recently, Michael Brown of Virginia Polytechnic Institute, performed research on epoxy coated and black reinforcement from bridge decks in Virginia (Brown 2002). Eight decks with epoxy-coated reinforcement and two decks with black steel were sampled. The core samples removed from the black bar decks had very little chloride compared to the decks sampled containing the epoxy coated steel. The cores containing the epoxy bars had chloride contents at the 12 mm depth that ranged from 1.1 to 6.5 times the threshold for corrosion of black reinforcing (0.75 kg/cu m), compared to the average chloride of samples taken from the black bar decks of only 0.2 to 0.6 percent of threshold. The cores were then cyclically ponded in the laboratory with 3 % NaCl solution for 2 days, followed by 3 to 5 days of drying. After 22 months of exposure, 27 of 28 black bar steel specimens had cracked and only 21 of 113 epoxy coated bar specimens had cracked. The chloride at the bar level was measured on the samples that cracked. The chloride at the bar level of the 27 of 28 black bar specimens that cracked averaged 7.12 kg/cu m and the chloride level at the bar level of the 21 of the 113 epoxy coated bar samples that cracked averaged 9.15 kg/cu m. The chloride at the bar depth of 16 uncracked epoxy bar samples were also measured and found to have an average of 9.78 kg/cu m with 3 of the 16 bars having chloride contents at the bar depth of over 12 kg/cu m without cracking. The average chloride content at the epoxy-coated bar depth could not be determined in this study since so many epoxy-coated bar samples did not crack.

LABORATORY STUDIES OF EPOXY-COATED REINFORCING

Extensive research has been performed on the corrosion resistance of epoxy-coated reinforcing making it one of the most researched materials for extending the durability of bridge decks. Much Federal and State research money has been expended to fund these studies. Accelerated testing techniques have been devised to expose the reinforcing and the coating to extremely severe conditions. The laboratory results all show a clear benefit for using epoxy-coated reinforcing. However, professionals debate how to use the accelerated test results to predict field service life. The NBS development study and the FHWA non-specification bar study have already been mentioned. Several other major studies merit mention.

1988 CRSI Bent Bar Study

CRSI sponsored an accelerated corrosion study in 1988 (Kenneth C. Clear Inc. 1991). The bars were bent and obtained from eight different manufacturers. The bars were cast in concrete and subjected to 70 weeks of southern exposure (SE) cycling consisting of 4 days of ponding with salt solution and 3 days of drying at 100 deg. F. This SE testing has been widely accepted and used in many major research projects, sometimes with modifications. The bars are tested in concrete and the corrosion current between the top anode bars and bottom cathode bars are measured directly, allowing the metal loss from corrosion to be estimated. After 70 weeks, all the black uncoated samples were heavily corroded. None of the epoxy-coated samples had visible signs of corrosion or cracking. The slabs were then continuously ponded with tap water and some of the epoxy-coated reinforced slabs showed in increase in corrosion while other coated samples did not. Follow up testing showed that the bars having high initial electrical resistance properties and few defects performed better than bars having defects and lower resistance properties.

This study also demonstrated that coated bars bent around a six bar diameter (6D) mandrel provided excellent long-term corrosion protection during the accelerated test program when bending-induced cracks and holes had been repaired with epoxy repair material. The 6D bent bars certainly had suffered significant adhesion loss from the bending operation, yet the coating provided corrosion resistance. This good performance for the bent bars was related primarily to the lack of holidays, tears or holes in the coating and indicates that adhesion loss is not the primary criteria governing the corrosion resistance of epoxy-coated bars.

FHWA New Breed Bar Study

A five year research study was funded by FHWA in 1992 with the goal to identify reinforcement bars that will provide excellent corrosion resistance of up to 75 years or longer. The 1993-1998 research program involved testing over 52 different organic, inorganic, ceramic, and metallic coatings on steel bars, as well as solid metallic bars. Based on the results of screening tests, twelve bar types were selected for the 96-week in-concrete testing. The 141 reinforced concrete slab specimens using twelve different bar types were exposed to a very severe 96-week test program of alternating SE testing (12 weeks) and continuous ponding (12 weeks) and the results were published in a 1998 FHWA report titled *Corrosion Evaluation of Epoxy-Coated, Metallic-Clad and Solid Metallic Reinforcing Bars in Concrete. (McDonald et al. 1998).*

It was concluded that the best ECR performance was obtained when the bars were tested in a straight condition, with 0.004 percent damage in uncracked concrete using an ECR cathode in the bottom mat. It was also found that there was a clear relationship between the mat-to-mat resistance values of the ECR's and their corrosion performance. Better corrosion protection was provided by those coating systems that had high electrical resistance, that is, the corrosion was strongly dependent on the amount of damage in the coating and if the cathode bars were coated.(McDonald et al. 1998).

In this study extensive screening tests used to select the bars for the in-concrete tests. These screening tests included solution immersion tests in high and low pH, chloride-containing and chloride-free solutions and cathodic debonding tests in a high pH solution. However, solution tests and coating bond strength were not good predictors of performance in concrete. There was no consistent trend found between the level of macro-cell current density and the extent of coating adhesion loss. The coating adhesion, as tested by solution immersion and cathodic disbonding tests, appeared to be a poor indicator of long-term performance of the coated bars in chloride contaminated concrete after 96 weeks of SE testing.

Coating the bottom mat of steel made a large difference in the corrosion performance. When a black bar bottom mat was tested, the performance of the epoxy-coated bars was sometimes poor; whereas, if an epoxy-coated bottom mat was tested the slabs exhibited a corrosion rate over 100 times less than that with black bars.

FHWA New Breed Bar Study Extension

The 1993-1998 FHWA study was extended to allow long-term natural weathering exposure testing of 31 post-Southern Exposure (SE) test slabs that contained ECR, black bars, and stainless steel bars and were not autopsied during the research project. The test slabs had been exposed to the very aggressive 96-week SE and continuous ponding test. The SE test slabs were stored outdoors for an additional five years [FHWA-HRT-04-090].

The chloride content in the slabs was extremely high at the end of the 96 week laboratory testing and at the 1-in. bar depth averaged about 0.8 percent by weight of concrete (17.8 kg/cu m). Even at the sixth week of testing, the chloride concentration at the bar depth was high and some slabs exceeded 5 lb/yd^3 [0.137 percent or 1,370 parts per million (ppm)] which was greater than three times the known chloride threshold (300 to 350 ppm or 1.2 to 1.5 lb/yd3) for uncoated ASTM A615 reinforcing steel. Uncracked slabs containing uncoated reinforcing initiated corrosion within the first 3 weeks of testing.

The chloride content at the bar depth was about 25 times higher than the threshold for corrosion of black steel at the end of the 96 weeks of lab testing and prior to placing the test slabs outdoors. At the end of the additional 5 year outdoor exposure, some bottom mat bars corroded due to a high level of chloride that penetrated all the way to the bottom mat of steel.

The test results confirmed that the black bars produced the highest mean macrocell current among the various combinations of test variables regardless of slab configuration and the stainless steel bars exhibited negligible mean macro-cell current density. The macro-cell current density of straight top-mat ECR's varied from 7 to 40 percent of the highest black bar case depending on the size of the initial coating damage and the type of bar in the bottom mat. ECR used in the top mat alone increased the corrosion current density to no more than 50 percent of the black bar case even when the coating was damaged and the top bars were connected to the black bar bottom mat. When straight ECR's in the top mat were connected to ECR's in the bottom mat, the mean macro-cell current density was no greater than two percent of the highest black bar case and approached the corrosion resistant level of stainless steel reinforcement. Autopsy of ECR slabs exhibiting negligible macro-cell current density revealed steel in excellent condition with no signs of corrosion. However, ECR samples exhibiting high macro-cell current densities showed coating deterioration and exhibited numerous hairline cracks or blisters in conjunction with reduced adhesion, coating bond loss and underlying steel corrosion. Epoxy coated reinforcing that maintained high electrical resistance and low corrosion currents provided excellent corrosion protection during this most severe laboratory and outdoor exposure testing.

CORROSION OF REINFORCING STEEL IN CONCRETE

When chloride penetrates the concrete cover, the potential of the steel becomes more negative. In bridge decks, it is not uncommon to have 300 to 400 mV (copper-copper sulfate) potential differences between different locations on the top mat of steel and between local areas of the top mat of steel and the bottom mat of steel. This large potential difference can result in rapid corrosion of the embedded reinforcing steel.

The corrosion of steel has been described using two processes, the anodic reaction where rust forms and the cathodic reaction where oxygen is reduced. The fact that different half-cell potentials exist on corroding concrete structures clearly shows that separate anode and cathode areas exist. The corrosion of reinforcing steel in concrete is controlled by the amount of chloride at the bar surface, the conductive and ionic paths, and the availability of oxygen. If either the anodic or the cathodic reactions are controlled, corrosion is controlled. The following discussion highlights the importance of the cathodic reaction on corrosion from work reported in ASTM STP 818, published in 1983.

Berman (34) and Hausmann (35) showed that, for corrosion of steel rebar to occur in a saturated, aerated $Ca(OH)_2$ solution, the threshold concentration of CL^- was 0.02 to 0.3M or 700 to 1000 ppm. If the solutions were saturated with nitrogen instead of oxygen, the threshold level increased to above 1M. These results show the critical nature of oxygen in supporting corrosion.

Clear (52) at Federal Highway Administration, demonstrated the important effect of the cathode. Steel placed in a highly chloride-contaminated concrete block did not evidence corrosion until this small block was cemented to the top of a larger reinforced slab and the two steels were connected. Then rapid corrosion occurred, at a rate of 9 mpy. Bridge deck structures usually contain two different depths of steel reinforcing, which are commonly electrically connected. Different chloride levels often exist at the two depths and a macroscopic active anode/passive cathode cell can occur.

To complete the corrosion cell, current flow within the concrete from anodic to cathodic areas must occur. The ionic resistance of concrete or the coating on the reinforcing will directly affect the corrosion rate. With reduced concrete permeability to oxygen and the presence of a coating, oxygen transport to the cathodes will reduced and the corrosion rate at the anode will also be reduced. One of the best predictors of corrosion performance of reinforcing steel in concrete is the AC resistance between the top and bottom mats of steel in test slabs [Pfeifer, 1993].

Research has shown that the control of oxygen will restrict corrosion even when sufficient chloride is present. The excellent performance of bare reinforcing steel submerged in marine environments is an example. The excellent performance of submerged reinforced concrete structures can be easily rationalized on the basis of the restricted supply of oxygen. Review anodic polarization curves for steel in concrete show that the restricted oxygen (diffusion-limited) line is shown at active but very low potentials. Under completely submerged conditions, oxygen can only be supplied by diffusion and generally the corrosion rates of reinforced concrete submerged in seawater are very small even though chloride is readily available.

This discussion is important for understanding partly how epoxy coatings protect reinforcing steel in concrete subjected to deicers or chloride. While the anodic locations (coating defects in chloride containing concrete) may depassivate in the presence of chloride, the rate of corrosion can be controlled by the cathodic (oxygen reduction) reaction. For steel corrosion in concrete, both anode and cathode reactions must occur in balance. It has been estimated that the anode reaction may be 10 to 100 times more efficient than the cathode reaction. Thus, for every 1 square mm of steel acting as an anode there must be 10 to 100 square mm of cathode area, depending on the amount of oxygen present (Allied Bar coaters, Cardiff, UK literature). Coatings inhibit oxygen and chlorides and increase the electrical resistance within the corrosion cell, significantly reducing the rate of corrosion. Therefore, epoxy coatings that limit the cathodic reaction should also more effective in controlling corrosion of nearby anode areas. When epoxy coated bars are electrically continuous with black reinforcing bottom mats, the cathode area is large and allows the anodic reaction to occur more freely. However, if the bars are electrically discontinuous, such as having a coated bottom mat, the cathodic reaction is controlled and the rate of corrosion at the anode will be slow. This explains the improved corrosion performance observed, in both accelerated tests and in-situ bridge deck assessments, when both top and bottom deck bars are coated versus when the bottom bars are not coated.

IMPROVING QUALITY CONTROL

In response to the marginal performance of epoxy-coated bars in the Florida Keys bridges, considerable activity began to improve the coating quality and integrity of ECR. This resulted in an industry sponsored quality control program for ECR manufacturers, more stringent ASTM and DOT specifications, and improved training on handling and installing ECR to reduce coating damage.

The CRSI Plant Certification Program for applicator plants producing fusion-bonded epoxy-coated reinforcing steel was established in 1991 to improve the quality of manufactured bars. It is a voluntary program that defines an acceptable level of quality control and its requirements are stricter than the ASTM specifications. The program requires written QA/QC policies and procedures. Tests are conducted on the bars prior to coating to ensure that they are satisfactorily prepared and include: determination of the suitability of the bars to be coated, checking for contaminants on the bar surfaces, measurement of the anchor profile of the blasted bars and ensuring that the abrasive meets quality requirements. Several new quality test procedures were developed for underfilm contamination, mill scale and chloride on the blasted bars. Prior to coating, the bar temperatures are checked to verify that the bars are at a suitable temperature for coating. The coating powder is also checked to determine if it is stored at correct temperatures, used within its recommended shelf life, and has met the required ASTM prequalification tests.

During the coating process, the bars are checked to determine if they are coated properly and that there is an adequate gel and cure time. After coating, holiday, thickness, and bend tests are conducted. Stricter bend testing and thickness control was required. Cathodic disbondment testing is also required to evaluate initial adhesion. The program also limits the amount of time epoxy-coated bars are left exposed to moisture and the sun. This program has resulted in advancement in holiday detection equipment and calibration of thickness gages, the development of target blast media working gradations, installation of alarms and temperature recorders in powder storage rooms, and significant improvements in the daily inspection checklists and record keeping. Plants must also implement employee training programs and education in quality control. Prior to implementation of the certification program, it was not uncommon for inadequately prepared bars to be coated. Some bars had steel surface contamination levels of 40 to 60 percent. The reduction of this problem has significantly improved the adhesion of the epoxy-coating to the reinforcing bars and reduced damage due to fabrication bending.

Certified plants are audited at least once per year in an unannounced audit. Since 1997, certified plants have averaged less than 0.23 holidays per foot and control of coating thickness has greatly improved. Improved blasting and cleaning procedures by certified plants have reduced the average contamination levels to less than 15 percent. Chloride contamination of the blasted bar surfaces have been eliminated or reduced to a trace. CRSI's plant certification program has been well-received and 33 applicator plants in North America are certified. Several State Departments of Transportation require their suppliers of epoxy-coated reinforcing bars to be certified under CRSI's program.

Efforts have been made to reduce damage to the coating during installation with tighter specifications and the use of padded vibrators, coated bundle ties, and covered storage on dunnage. Training courses are routinely held and CRSI has been active in promoting proper handling procedures for coated reinforcing.

Most state specifications now require all visible damage to the coating be repaired prior to placing concrete. However, damage to the coating due to field handling and the abrasion due to concrete placement and the use of internal vibrators is an area that can still be improved (Herman and Jirsa 1997).

MORE DEMANDING REQUIREMENTS IN ASTM SPECIFICATIONS

ASTM Specification A775/A775M prescribes acceptance tests and procedures for bendable epoxy-coated reinforcing. Prescriptive requirements in the specification detail the minimum requirements for the level of quality that should be attained. CRSI reports that the following areas were considered by ASTM. Changes to the ASTM A775 specification to improve ECR quality are listed in the Appendix.

> *During the late 1980's in response to concerns about the Florida Keys bridges, a task group within the ASTM Subcommittee on Steel Reinforcement initiated a critical evaluation of the A775/A775M specification. The task group's goal was to develop proposed revisions to the specification which would translate into higher quality epoxy-coated bars. The task group's efforts focused on:*
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> - *Minimize the number of holidays in the coating.*
> - *Reduce the limit on the number of permissible holidays.*
> - *Require the repair of all damaged areas of coating which are incurred to the point of shipment of the coated bars to the jobsite.*
> - *Reduce the limit on the total amount of damaged coating — all of which has to be repaired before the coated bars are shipped to the jobsite.*
> - *Incorporate criteria in the specification to enhance adhesion of the coating to a bar.*
> - *The frequency of conducting acceptance tests.*
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> (Gustafson 1997)

APPENDIX A

Table 1 presents the latest available performance data for the first bridge decks in 14 States in which epoxy-coated bars were used. In the 1970's, many State DOT's specified epoxy-coated bars only in the top mat of reinforcement. Research has shown long-term performance is enhanced when all reinforcement is epoxy-coated. Current practice is to require both mats to be epoxy-coated.

Table 1 First Use of Epoxy-Coated Reinforcing Bars in Bridge Decks Deck Condition and Grading[1]

State DOT	Coated Bars in Top or in Top and Bottom Mats[2]	Bridge Opened	Initial Grade-Year	Latest Grade-Year	Deck Maintenance Caused by Rebar
Illinois	Top	1977	N/A	7-1997	0
Indiana	Top & Bottom	1976	7-1976	6-1997	0
Iowa	Top	1975	8-1975	7-1997	0
Kansas	Top	1977	8-1977	8-1997	0
Kentucky	Top	1975	7-1981*	7-1997	0
Maryland	Top & Bottom	1974	9-1974	7-1996	0
Michigan	Top & Bottom	1976	8-1980	7-1997	0
Michigan	Top & Bottom	1976	8-1980	6-1996	0
Michigan	Top & Bottom	1976	8-1980	7-1997	0
Minnesota	Top	1973	8-1973	7-1996	0
Missouri	Top	1974	9-1974	7-1996	0
Nebraska	Top	1975	9-1975	7-1997	0
Nebraska	Top	1976	N/A	8-1997	0
Ohio	Top	1974	8-1985*	7-1997	0
Pennsylvania[3]	Top	1973	6-1989*	5-1997	0
West Virginia	Top	1973	9-1973	6-1997	0
Wisconsin	Top	1975	9-1975	7-1996	0
Wisconsin	Top	1976	9-1976	8-1996	0

1. Data compiled in January 1998.
2. "Mat" refers to the layers of reinforcing bars; "Top" for the orthogonal grid of bars near top surface of deck and "Bottom" for the grid near bottom surface of deck.
3. Acknowledged as the first use of epoxy-coated reinforcing bars in a bridge deck.

N/A = not available
FHWA Grade 0 to 9.9
* Initial grade unknown
Grade of 9 = new condition
Grade of 8, 7, 6 and 5 = very good to satisfactory

Summary of Selected Bridge Deck Studies (CRSI)

State	No. of Bridge Decks Surveyed	Average Age at Survey (years)	Year of Survey	Average Concrete Cover (in.)	Average Cl Content (lbs/yd^3)	Average Corrosion* (percent)	Average Coating Disbondment**	Average Total Delaminations (ft^2)	Spalls or Patched Areas (ft^2)	Comments
California	4	8.8	1992	2.7	5.0	12	24	6.7	0	Minor corrosion on the extracted ECR segments; coating disbondment at both corroded and non-corroded areas; more corrosion at heavily cracked and shallow cover locations.
Indiana	6	11.5	1993	3.0	2.73	0	0	Some	0	No corrosion; no disbondment; minor delamination on three decks (area not reported) indicated by maps in published report; cause of delamination unknown.
Kansas	2	10	1988	NR	0.55	0	NR	5.5	0	Detailed survey performed on only two decks. In 1995, the state analyzed the inspection data for 757 decks containing ECR and six had a condition rating of 6 (<1%) indicating possible problems with the reinforcing steel.
Michigan	12	13.2	1988 1989 1992	3.1	3.50	20	NR	<1% on one deck and none on the other 11	0	11 out of 12 decks had no delaminations, spalls, or patched areas indicating good performance of ECR when exposed to an average Cl content of 3.0 lbs/yd^3 at 13.2 years of service.
Minnesota	11	15-20	1992	NR	NR	11	NR	0	0	Concrete cores were taken at cracked locations on purpose (worst case) to examine the condition of extracted ECR segments; out of nine ECR segments, only one showed minor corrosion.
New York	14	9.6	1990	2.7	4.0	35	NR	0.14	0	Out of 14 bridges, only one had a delamination (2 ft^2) at 7/8-inch depth, but the ECR in this bridge was located at 2-inch level indicating the delamination not related with ECR corrosion; out of 54 ECR segments extracted, only (6%) three showed bar corrosion.
Penn 1	11	7.8	1984	2.35 (only two decks)	0.5 (only two decks)	No cores with ECR taken	No cores with ECR taken	0	0	Chloride concentrations below threshold level and not delaminations and spalls, etc.
Penn 2	4	10.7	1986	2.63	1.64	4.6[1]	4.6[1]	2[2]	0	1. Pennsylvania rated the extracted ECR segment condition and apparent corrosion from 0.0 (very poor) to 5.0 (new condition and no corrosion). The data for PA 2 is on the rating scale instead of average percentage. The average visual rebar rating was 4.6 which is close to 5, new condition and no corrosion. 2. Pennsylvania did not report the area but reported a total of two delaminations in the four surveyed bridges, one was associated with an expansion dam.
Virginia	2	10-16	1987 1990 1993	2.75	1.44	None	None	0	0	There was no indication of significant corrosion or coating disbondment even though the initial condition coating was poor and numerous holidays and bare area were present.
W. Virginia	14	17.3	1993	NR	3.28[3]	ND	ND	3	4[4]	3. This is the average chloride concentration for the area between 1/2 inch from the deck surface and the rebar level instead of at the rebar level reported by other states. 4. There were three small circular spalled areas, 13 to 19 mm (1/2 to 3/4 in.) deep and are not associated with ECR corrosion. A fourth spall was associated with a 0.1 m^2 (1 ft^2) delamination.
Ontario	2	9	1988	NR	3.25	Minor	NR	0	0	Ontario has performed an additional survey on 11 barrier walls, three sidewalks, six end dams, and two exposed decks. The report is currently being prepared.
C-SHRP	19	10.7	1990-1991	2.47	3.38	27	2.7[5]	[6]	[7]	5. The average value of dry knife adhesion is 2.7. A rating scale of 1 (coating well bonded), 3 (coating some what easy to remove), and 5 (coating easily removed or totally disbonded) was used. 6. Out of 19 structures surveyed, one deck had 0.2 m^2 (2 ft^2) of delamination and another had less than 1% delamination. The remaining 17 structures have not delaminated. 7. Some patching was found on one of the decks; the area of patching was not reported; the origin of the distress and when the patching was done was unknown.

* This column represents the observed corrosion on the extracted ECR. A report of 12 percent corrosion means that 12 out of 100 ECR segments had some corrosion, which may be due to chlorides or may have been present at the time of construction as some ECR segments showed corrosion where the chloride level was lower than the threshold for black steel.

** This includes the disbondment caused by holidays in the coating on the ECR segments. A report of 24 percent disbondment means that 24 out of 100 segments could be disbonded with a knife. In reality it means that the epoxy coating on 24 out of 100 segments had deteriorated over 8.8 years

NR- Not Reported, ND- Not Determined

Metric Conversions: 1 in= 25.4 mm, 1 lb/yd^3= 0.6 kg/m^3, 1 ft^2= 0.0929 m^2

APPENDIX B

(Excerpted and modified from Gustafson 1997, CRSI)

The following revisions have been adopted in the A775/A775M specification during the period beginning with the 1989 edition and continuing through the current 2004 edition.

1. **Coating Thickness** — raised the lower value of the permitted range of thickness to 7 mils (0.007 in.) from 5 mils (0.005 in.). Lots having 5 percent of measurements below 5 mils shall be rejected.

2. **Surface Preparation** — require readings of 1.5 to 4.0 mils (0.04 to 0.10 mm) for the roughness depth of the blasted bar anchor pattern. Require the use of multidirectional high-pressure dry air knives to remove dust, grit and other foreign matter from the bar surface.

3. **Coating Continuity** — an in-line holiday detection system is required that counts the number of holidays on each bar. The accuracy of the in-line system is to be verified by checking with a hand-held detector. Reduced the limit on the allowable number of holidays to an average of one per foot (three per meter) from two per foot. Eliminated the allowable 2% bare area of damaged coating.

4. **Coating Flexibility** — Revised the requirements for conducting bend tests of coated bars; require a 180° bend except the bend angle for the large bars, bar sizes #14 and #18 (#43 and #57), is 90°; maximum time for completion of test is 15 seconds for bars to size #6 (#19), and 45 seconds for bar sizes #7 through #18 (#22 through #57). Previously, the bend angle was 120° and the test had to be completed within 90 seconds. Conduct a bend test on at least one bar of each size every four production hours.

5. **Coating Adhesion** — Evaluate production-coated bars by a cathodic disbondment test. The test is described in the mandatory Annex A of the specification. Conduct test on at least one bar every eight production hours. Test data are to be furnished to purchaser upon request.

6. **Permissible Amount of Damaged Coating and the Repair of Damaged Coating** — all damaged coating incurred during handling and fabrication, to the point of shipment to the jobsite, must be repaired. Damaged coating on a bar is permitted to be repaired if the amount of damaged coating does not exceed one percent of the total surface area in each one foot (0.3 meter) length of the bar. The limit on the amount of repairable damaged coating does not include sheared or cut ends of bars that are required to be coated with patching material. Repaired areas of damaged coating shall have a minimum coating thickness of 7 mils. Previous requirements allowed up to 2 percent are area.

7. **Storage** — Require implementation of protective measures if coated bars are stored outdoors for more than two months before being shipped to the jobsite. The date the bars are moved outdoors must be marked on each bundle.

8. **Three Major Revisions Have Been Adopted in Mandatory Annex A — the Annex Prescribes Requirements for the Coating Material (Prequalification)**

a. **Chemical Resistance** — the requirements were revised to more accurately model the concrete environment to which epoxy-coated bars are exposed. Test requires immersion of coated bar specimens in distilled water, in a 3M aqueous solution of $CaCl_2$, in a 3M aqueous solution of NaOH, and in a solution saturated with $Ca(OH)_2$. Specimens are evaluated for blisters, softening, bond loss, if holidays developed, and the presence of undercutting.

b. **Cathodic Disbondment** — A coated bar specimen is immersed in 3% NaCl electrolyte solution; duration of test is 168 hours; average coating disbondment radius not to exceed 0.16 inches (4 mm).

c. **Salt Spray Resistance** — Evaluation of resistance of the coating in a hot, wet corrosive environment; salt spray 5% NaCl; duration of test is 800 ∀ 20 hours; average coating disbondment radius not to exceed 0.12 inches (3 mm).

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