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Stainless and Stainless-Clad Reinforcement for Highway Bridge Use

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16. Abstract

Stainless steel as concrete reinforcement has been in use for several decades. Although highly resistant to corrosion, and able to provide greater than 100 years maintenance-free service life, the main drawback to widespread use has been the cost of the material. Stainless steel reinforcement has a higher price premium than epoxy coated reinforcement, but overall the cost accounts for less than ten percent of typical bridge rehabilitation projects. To help offset the price premium of solid stainless reinforcement, stainless-clad reinforcement (SCR) is available in selected reinforcement sizes, and provides the corrosion resistance of solid stainless steel at a lower cost.

Considerations for use of stainless and stainless-clad reinforcement include locations where: future repair and maintenance would be very disruptive to traffic, requiring mitigation measures to minimize travel delay; over navigable waterways or protected wetlands sensitive to environmental impact from construction activity; the reinforcement concrete cover is less than three inches; and bridges located over high volume railway lines where access and right of way restrictions exist. Life cycle cost analysis (LCCA) should be used, including consideration of user delay costs, to provide the best choice for the traveling public.

LCCA for selected structures demonstrated a lower present value cost for the stainless steel and SCR alternative, and a break-even point when the epoxy-coated reinforced bridge deck attains 83 years maintenance-free service life. Conversely, the break-even point for the stainless and SCR alternative is when the material costs exceed 24 percent of the construction cost. The cost savings are expected to further improve when reduced concrete cover and utilization of empirical bridge deck design are incorporated.

Selective use of stainless and stainless-clad reinforcement, along with cost savings from reduced concrete cover and deck design with less reinforcement, will provide a reasonable balance between higher cost and maximizing service life. Use of stainless steel and stainless-clad steel for bridge deck construction ensures a long life with low maintenance costs, providing a more sustainable solution. The challenge remains, however, to overcome the barriers in funding the increased cost of these corrosion resistant materials.

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Executive Summary

As the national highway system infrastructure ages, the deterioration of reinforced concrete structures has become a major issue for highway agencies. The cost due to corrosion of steel and reinforced concrete structures is significant, at $3.9 billion annually (Koch, 2002). Bridge decks constructed in the 1960's in urban areas generally have had deck overlays and even replacement in less than 40 years.

Bridge deck deterioration generally results from corrosion of steel reinforcement. During the winter months, the Michigan Department of Transportation (MDOT) uses chloride-based deicing chemicals for snow and ice control. Chloride ions reach the reinforcing steel by penetrating the concrete via diffusion through pores and directly through cracks in the concrete surface. The chloride ions act as a catalyst to initiate steel reinforcement corrosion, and the corrosion by-products exert expansive forces on the concrete to cause delamination and spalling.

Epoxy-coated reinforcement (ECR) was first used in Michigan in the early 1980's as a means to extend the service life of highway structures. The epoxy coating is a barrier system intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel. It also serves to electrically insulate the steel to minimize the flow of corrosion current. With 30 years of use to date, ECR is estimated to provide at least 60 years of maintenance-free service life for Michigan bridge decks.

Stainless steel reinforcement has been in use as far back as the late 1930's. Although highly resistant to corrosion, thereby providing more than an estimated 100 years of bridge deck maintenance-free service life, the drawback to widespread use has been the material cost. One approach to reduce material costs was developed in the 1980's , using stainless steel as a cladding over carbon steel reinforcement. When material costs alone are considered, stainless reinforcement price per pound is three to five times greater and stainless-clad reinforcement nearly twice that of ECR. When considered as a portion of the construction project cost, however, stainless steel reinforcement generally accounts for less than ten percent.

Minimizing the construction cost is an important consideration, but the cost to maintain the structure over its entire service life should be evaluated, including the impact to users. With increasing focus on providing mobility in transportation, user delay costs should be considered in life-cycle cost analysis (LCCA). LCCA comparing use of ECR to stainless and stainless-clad reinforcement for selected structures resulted in a lower present value cost for the stainless and stainless-clad reinforcement alternative, and a break-even point when the ECR bridge deck attains 85 years maintenance-free service life. Conversely, the break-even point for the stainless and stainless-clad reinforcement alternative is when the material costs exceed 24 percent of the construction cost.

Considerations for use of stainless and stainless-clad reinforcement include locations where: future repair and maintenance would be very disruptive to traffic, requiring mitigation measures to minimize travel delay; over navigable waterways or protected wetlands sensitive to environmental impact from construction activity; where the concrete cover over the reinforcement is less than three inches (due to local geometric restrictions or strength limitations

of the existing substructure); and bridges located over high volume railway lines where access and right of way restrictions exist.

Selective use of stainless and stainless-clad reinforcement, along with cost savings from reduced concrete cover and deck design with less reinforcement, will provide a reasonable balance between higher cost and maximizing service life. Use of stainless steel and stainless-clad steel for bridge deck construction ensures a long life with low maintenance costs, providing a more sustainable solution. The challenge remains, however, to overcome the barriers to funding the increased cost of using corrosion resistant materials.

Action Plan

- Request approval of the report recommendations by the Executive Operations Committee

- Place recommendations for stainless and stainless-clad reinforcement use criteria in Bridge Design Manual

- Track developments in stainless and stainless-clad reinforcement production and update the frequently used special provision for newer types of stainless steel (Experimental Studies Group)

- Track stainless and stainless-clad reinforcement contract bid pricing in the Work Item Reporting System, identify and recommend appropriate Engineer's estimate bid price to Specifications and Estimates Unit in Design Division (Experimental Studies Group)

Introduction

The deterioration of reinforced concrete structures has become a major liability for highway agencies. The cost due to corrosion of steel and reinforced concrete alone is significant, at $3.9 billion annually (Koch, 2002). Bridge decks constructed in the 1960's in urban areas generally have had deck overlays and even replacement in less than 40 years.

One cause of concrete bridge deck deterioration is corrosion of the steel reinforcement, accelerated by the presence of chlorides. Chloride ions from deicing chemicals reach the reinforcing steel by penetrating the concrete via the pore water (diffusion) and through cracks in the concrete. The chloride ions initiate corrosion by depassivating and/or penetrating the iron oxide film on the reinforcement and reacting with iron to form a soluble iron-chloride complex (Fraczek, 1987). When the iron-chloride complex diffuses away from the reinforcement to an area of greater alkalinity and concentration of oxygen, it reacts with hydroxyl ions to form $Fe(OH)_2$, which frees the chloride ions to continue the corrosion process, if the supply of available water and oxygen is adequate.

The distribution of chlorides in a concrete bridge deck is not uniform. The chlorides typically enter the concrete from the top surface. The top mat of reinforcing steel is then exposed to higher concentrations of chlorides. The chlorides shift the electrical potential of the top mat reinforcing steel to a more negative (anodic) value as compared to the bottom mat reinforcement, which sets up a galvanic type of corrosion cell called a macro cell. The concrete serves as the electrolyte, and wire ties, metal chair supports, and steel bars serve as metallic conductors. An electric circuit is established. Likewise, the concentration of chlorides is not uniform along the length of the top mat reinforcement due to the heterogeneity of the concrete and uneven deicer application. These differences in chloride concentrations establish anodes and cathodes on individual steel bars in the top mat and result in the formation of microcells.

The corrosion products of steel reinforcing bars occupy a volume three to six times the volume of the original steel. This increase in volume induces tensile stresses in the concrete that result in cracks, delaminations, and spalls. This accelerates the corrosion process by providing an easy pathway for the water and chlorides to reach the steel. Eventually the bridge deck surface ride quality deteriorates due to the concrete spalling, and reaches the end of its maintenance-free service life, as action is required to improve the structure. Generally this occurs when a bridge deck surface has 15 percent or greater delaminations and spalls.

Most corrosion protection measures increase the service life of reinforced concrete structures by disrupting the corrosion process. Applying physical barriers to the steel surface such as epoxy coating prevents moisture, oxygen, and chloride ions from contact. Use of high resistivity and polymer modified concretes impede the electrical pathway. Placement of additional concrete cover over the reinforcement, or lowering the water-cement ratio of the concrete to reduce permeability, increases the time to corrosion. Concrete permeability can also be reduced by the use of admixtures. Corrosion inhibitors also reduce permeability and protect the passive iron oxide film on the steel surface.

Epoxy-coated reinforcing steel (ECR) was first used in Michigan in the early 1980's as a means to protect the reinforcing steel and extend the useful life of highway structures. The epoxy coating is a barrier system intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel. It also serves to electrically insulate the steel to minimize the flow of corrosion current. With 30 years of use to date, ECR is estimated to provide 60 years of maintenance-free service life for Michigan bridge decks. Stainless and stainless-clad steel reinforcement, however, provide greater than 100 years of maintenance-free service life.

A great example of stainless steel reinforced concrete durability is a pier in Progreso, Mexico. See Figure 1. Constructed between 1937 and 1941, the 6,900-foot-long pier shows almost no sign of deterioration, whereas an adjacent pier made of plain steel reinforcement in the 1960's has virtually disappeared. A total of 450,000 lbs. of equivalent type 304 stainless steel reinforcement, 1.2 in diameter, was used on the first pier because of the hot, humid marine environment and because the concrete was made of local limestone aggregate that had a relatively high porosity. The remaining service lifetime is estimated to be at least 20 to 30 years, even without any significant routine maintenance activities (Arminox, 1999, Castro-Borges, 2002).

Figure 1. Pier in Progreso, Yucatan Peninsula, Mexico, constructed in 1937-41 with equivalent type 304 stainless reinforcement. Pictures dated December 1998. Note in foreground of the right picture the remains of an adjacent pier constructed with carbon steel in the 1960's.

Objective and Scope

This report will identify the advantages and limitations of solid stainless steel and stainless-clad reinforcement for use in bridge deck construction. By examining physical and mechanical properties, design and construction criteria are recommended. Life cycle cost analysis is utilized to identify cost considerations and benefits by using superior corrosion resistant materials in bridge deck construction, and to develop a rationale for use consideration.

Stainless Steel Reinforcement

Stainless steels contain a chromium content of at least 10.5 percent by weight. Other elements, such as nickel and molybdenum, are added for improved corrosion resistance. Several different types, categories, and grades are available, determined by the chemical composition, manufacturing process, and extent of cold working. Stainless steels are grouped into five broad categories: austenitic, ferritic, duplex (austenitic-ferritic), martensitic, and precipitation hardening. These categories are based upon alloy chemistry and microstructure. The tightly adhering chromium oxide film that forms on the surface of the metal is what gives the exceptional corrosion resistance of stainless steel. After processing, the stainless steel is usually pickled (dipped in acid) to dissolve mill scale and promote formation of the oxide film (passivation).

A common stainless steel (used for many applications including tableware and diskette sheaths) is austenitic type 304. Also known as 18-8 stainless, type 304 has chromium content of 18 percent and nickel content of 8 percent. Type 316, another austenitic stainless, has molybdenum added for increased corrosion resistance. Nitrogen is added for weldability and strength, as in type 316LN. Generally austenitic stainless steels can be hardened by cold working to achieve very high strengths. Duplex stainless steel type 2205 has increased resistance to chloride stress corrosion cracking, and is used frequently in the offshore oil industry. The name specifies the chromium and nickel content, 22 and 5 percent, respectively. There are a wide variety of stainless steels to fit particular applications, with new formulations added frequently.

Stainless-Clad Steel Reinforcement (SCR).

One type of SCR consists of 0.04 to 0.16 in thick stainless cladding over carbon steel. Refer to Figure 2 for a typical cross section of SCR. Although the company is headquartered in the U.S., the product is made in the United Kingdom. According to their website, the stainless cladding tube is longitudinally seam welded, and then the carbon steel core is packed into the tube, and hot rolled for the final shape.
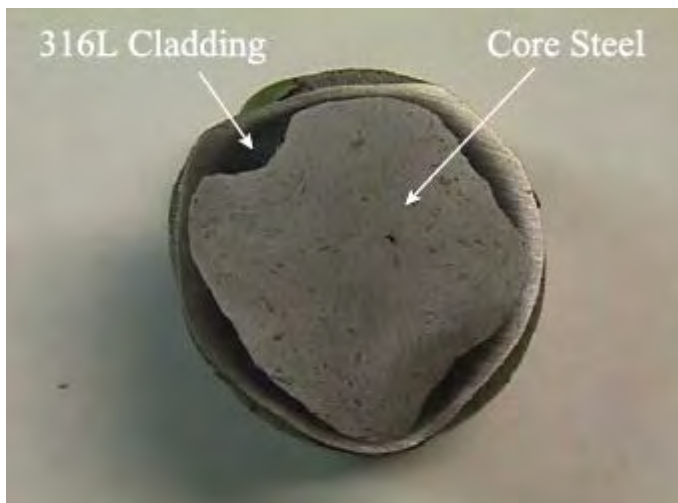

Figure 2. Cross section view of #6 (nominal ¾ in diameter) size SCR.

The SCR was evaluated by subjecting samples to bending, tensile, fatigue, and corrosion testing at MDOT facilities. The test samples provided were reputed to be from manufactured lots, but the sampling procedure was not witnessed.

Tensile testing was conducted at the MDOT in-house laboratory facility according to ASTM International (ASTM) Standard A370. During tensile testing, the #6 size SCR fractured in the grips two out of three times. The sample that fractured within the gage limits had a yield of 69 ksi and an ultimate strength of 99 ksi, meeting ASTM Standard A615 Grade 60 (60 ksi minimum yield strength) requirements. Samples of #5 sizes SCR tested also met ASTM Standard A615 Grade 60 requirements, averaging 72 ksi for yield and 108 ksi for ultimate strength.

The #6 size SCR samples were bent 180° around a 3.75 in mandrel, which was more severe than the MDOT minimum 4.5 in bend radius. The first sample had cladding separate between the ribs, as shown in Figure 3. Two other samples were tested, and no openings were observed in the cladding around the outside edge of the bend. It is unlikely that cladding will separate with larger bend radius. The #5 size SCR samples were bent around a 2.188 in mandrel, tighter than the MDOT specification minimum 2.5 in radius requirement for stirrups and ties. No opening of cladding was observed on any of the three bend test samples.

Figure 3. Cladding defect at outside of 3.75 in bend radius with #6 size SCR. Note the standard bend radius is 4.5 in for this size. The remaining #6 size samples and all #5 size samples passed bend testing.

According to the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications 5th Edition, subsection 5.5.3.1, fatigue need not be considered for multi girder superstructures. However, the possibility of the stainless cladding to separate from the core steel was investigated. The fatigue life of a detail is considered infinite when the cyclical stress range is less than the constant amplitude fatigue limit (CAFL), the allowable fatigue stress range for more than 2 million cycles on a redundant load path structure. The stainless cladding longitudinal seam weld is considered a stress category B′ detail, with a CAFL of 12 ksi (LRFD Table 6.6.1.2.5-3). Over a 75 year period this represents approximately 1,035 trucks per day (single lane). The MDOT structures lab Materials Testing Systems Model 400 uniaxial tensile testing machine was used to load a #6 size SCR at a stress range of 12 to 24 ksi, at a loading rate of nine cycles per second. After completion of 2,000,000 cycles, the sample was found by inspection to

have no defects or cladding separation. Since the stress range used in the testing was greater than the 12 ksi fatigue limit, it is unlikely that the seam weld will separate over its service life. Samples of the #6 size SCR were cut and mounted into the MDOT structures lab wet-dry cycling tank to determine effects of corrosion of the exposed cut ends. Three sample shapes were used; one straight, one with a cladding defect (1/4 in hole drilled through the cladding), and one bent section. The corrosion test was modified from ASTM Standard G44 by using a high pH 12 solution of 3.5 percent salt water to simulate concrete pore water contaminated with chlorides, and a neutral pH 7 solution of 3.5 percent salt water to simulate the breakdown of the passive steel surface. The cut ends were sealed with 3M Scotchkote® 214 epoxy. The exposure duration was for 90 days, with constant wet-dry cycling ratio of 2:1. This meant that the samples were submerged for 40 minutes and dried for 20 minutes per hour, 24 hours a day, for a total of 2,160 wet-dry cycles. See Figure 4.

Figure 4. Corrosion test equipment and sample configuration for stainless-clad reinforcement testing.

At the end of the 90 day corrosion test, samples were removed, cleaned, and examined. The most corrosion and loss of core steel section in the samples occurred as expected in the neutral pH tank. Samples mounted in the high pH tank, simulating the concrete environment that would passivate the steel, had the least corrosion damage and loss of section. The maximum pitting corrosion observed on the ends did not penetrate further than 0.060 in. Measurements were obtained using a depth micrometer. See Figure 5. The epoxy coating did not protect the cut ends from corrosion, but it is anticipated that end corrosion would have little impact on the expected maintenance-free service life.

Figure 5. Magnified cross section (20x) of #6 size SCR showing pitting corrosion of the carbon steel. Note the stainless cladding in the upper right corner of the picture is unaffected (saw marks are visible).

Stainless and Stainless Clad Reinforced Bridge Decks in Michigan

The earliest deck built using stainless steel reinforcement was constructed in 1983. This structure, S03 of 63103, I-696 over Lenox Road, Ferndale, Michigan, was constructed with 63,000 lb. of type 304 stainless steel reinforcement for the eastbound deck, and epoxy coated reinforcement for the westbound deck. The cost was $4.33/lb. adjusted in 2011 dollars.

A visual inspection was made in April 2008, where photos and crack mapping were collected for both decks, and no deterioration of the stainless steel reinforced deck was observed. The epoxy coated reinforced deck showed minor deterioration, as evidenced by asphalt patches at the bridge side of the expansion joint. See Figure 6.

Figure 6. Stainless steel reinforced bridge deck surface, S03 of 63103, I-696 over Lenox Road, Ferndale, Michigan, in April 2008.

In 1999, S09 of 82104, M-8 (Davison Freeway) under Oakland Avenue, was constructed using type 304 stainless steel reinforcement. In order to retain the existing roadway approach geometry, the bridge deck was constructed with a thickness of 7 in, and concrete cover of 1.5 in over the top mat steel reinforcement. The approach geometry and cover restrictions were the primary reason stainless reinforcement had been selected for this deck. This restriction also required the use of 759 stainless steel mechanical reinforcement splices due to part-width construction.

Similarly, in 2004, the bridge deck on S27 of 82022, I-94 over Greenfield Avenue, was reconstructed using stainless steel reinforcement. In order to retain the existing roadway approach geometry and maintain the existing deck thickness, the bridge deck was constructed with a thickness of 8 in, and concrete cover of 2 in over the top mat steel reinforcement.

The first attempt at using SCR was in 2001. The Federal Highway Administration (FHWA), through the Innovative Bridge Research and Construction (IBRC) program, provided funding. This three lane bridge, R12-4 of 33045, westbound I-496 over CSX Railroad and Holmes Road in Lansing, Michigan, is over 550 ft. long. To reduce dead load on the existing substructure, the deck thickness was limited to 8 in (2 in clear cover). The adjacent bridge, R12-3 of 33045, eastbound I-496 over CSX Railroad and Holmes Road, was constructed with ECR.

The SCR was a proprietary product made in a foreign country. The federal regulation in Title 23 United States Code, Section 635.411, Material or Product Selection, prohibit funding proprietary products, but provides specific exemptions. The exemption under §635.411 (a) (3) states *"Such patented or proprietary item is used for research or for a distinctive type of construction on relatively short sections of road for experimental purposes."* Additionally, a Buy America waiver was required for the SCR manufactured in the United Kingdom. Title 23 USC Section 313 outlines the allowable exemptions to Buy America. Because the SCR was not *"…produced in the United States in sufficient and reasonably available quantities and of a satisfactory quality [§313 (b) (2)],"* a Buy America waiver was granted by the FHWA for the project. No U.S. steel manufacturer produced SCR, although one company was in the developmental stage at the time.

Some weeks after the order was placed, the manufacturer notified MDOT that the #4 size reinforcement was not available, and they would substitute with #5 size reinforcement at no additional cost to the contractor. As the delivery date approached, the manufacturer notified MDOT that they could not guarantee delivery of all SCR by the time stipulated. Because the bridge project was part of a larger corridor reconstruction of I-496, supply became a critical issue to the contractor. A meeting was held with MDOT, the contractor, and consultant overseeing the project, and it was decided to cancel the SCR order.

Solid stainless steel reinforcement Type 304L was substituted for the SCR. As part of the experimental work plan, a corrosion monitoring probe was installed on the top mat reinforcement of the eastbound bridge deck (ECR) to indicate when deterioration occurs. Because the deck concrete cover was reduced to 2 in, it is anticipated that the ECR deck service life will be shortened by 10 to 15 years. The probe was made from ASTM Standard A615 Grade 60 steel, epoxy coated with 3M Scotchkote® 214 Epoxy Resin, and manufactured by Rohrback Cosasco Systems. See Figure 7.

Figure 7. Rohrback Cosasco Corrosometer Model 650-T-50 corrosion probe tied to top mat reinforcement of R12-3 of 33045.

The probe functions by measuring metal loss through corrosion by electrical resistance. As the probe metal corrodes the electrical resistance increases. The readings indicate the relative resistance ratio of the probe to the temperature compensating reference circuit. When plotted over time, the slope of the curve gives the corrosion rate in mils per year (equation 1).

$$Corrosion\ Rate\ (mils\ per\ year) = \frac{\Delta\,dial\ reading}{\Delta\,time\,(days)} \times 0.365 \times probe\ span \qquad \textbf{Equation 1}$$

The resistance ratio readings have mostly remained at or below the initial reading, indicating that the probe steel has not corroded, and by association, the ECR in the top mat (Table 1). If 1 mil (0.001 in) of corrosion byproducts is sufficient to crack concrete, then a 35 year service life corrosion rate of 1/35 mils per year would correspond to an increase of 40 units above the baseline level. The baseline level of 187 was determined by the 99th percentile normal distribution of eight years' data.

Table 1. Corrosion probe resistance ratio readings for Corrosometer Model 650-T-50 (probe span = 25).

Date	Probe Reading	Date	Probe Reading
4/12/2002	185	5/4/2007	182
8/6/2003	180	11/8/2007	184
8/3/2005	171	4/17/2008	169
11/14/2005	187	11/20/2008	185
6/2/2006	168	10/15/2009	182
10/31/2006	176	11/08/2010	180
Baseline (99th percentile) Probe Reading			187

The next attempt to use SCR was for a bridge carrying I-94 over the Galien River in Berrien County, Michigan, a dual structure sharing a common abutment. Each structure has a 60 ft. clear roadway width comprised of three 12 ft. lanes and two 12 ft. shoulders, and is 195 ft. long. The primary reinforcement was #5 size (5/8 in nominal diameter); with the temperature and distribution steel of #3 size (3/8 in nominal diameter). Because the smallest available SCR was #5, solid stainless steel was used for the #3 reinforcement. The manufacturer of the SCR stockpiled inventory at a U.S. facility which resulted in timely delivery. The manufacturer had provided end caps for the SCR as shown in Figure 8. The mixture of solid stainless reinforcement and SCR will provide equivalent maintenance-free service life as a deck constructed entirely with solid stainless reinforcement.
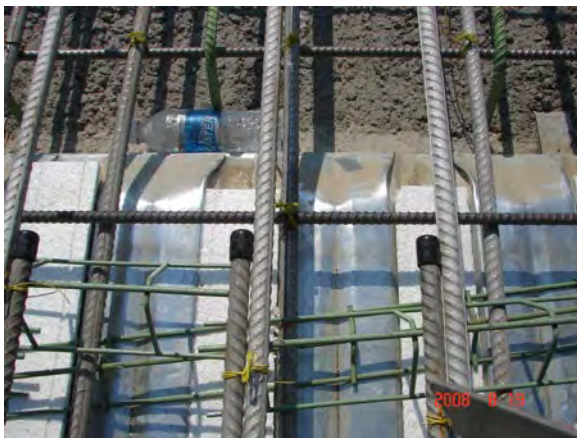

Figure 8. SCR (#5 size) with end caps shown. The smaller reinforcement shown (#3 size) is solid stainless.

A recent use of stainless steel reinforcement was on the twin structures carrying I-94 over Riverside Drive in Battle Creek, Michigan. This dual structure shares a common abutment.

Each bound is a single span, 69 ft. length, 63 ft. -5⅝ in out to out width, with a 60 ft. -2⅝ in clear roadway, supported by 33 in depth prestressed concrete spread box beams.

The bridge deck reinforcement was a low carbon duplex stainless steel (ASTM Standard A276 type 2304) that consisted of replacing nickel and molybdenum content with chromium. The chemical composition lowered the material cost by an estimated 30 percent, based on a quotation from the manufacturer of $2.80/lb. FOB (free on board) destination, not including fabrication and installation. The contractor's bid price to furnish and install the stainless steel reinforcement was $3.74/lb., consistent with historical pricing, but not reflective of the traditional costs to furnish and install reinforcement. The labor costs for fabrication and installation is typically $0.32/lb. (Craftsman Book Company, 2011)

One year later, the same stainless steel reinforcement type (and manufacturer) was used on a bridge project on M-37 over the Pine River, Wexford County, Michigan, but with the contractor's bid price (fabricated, furnished, and installed) of $2.70/lb.

As of December 2011, ten bridge decks have been constructed with stainless steel reinforcement, and one with stainless steel and SCR. See Table 2 for a summary.

Table 2. Location and cost summary of bridge decks built with stainless steel reinforcement.

Structure	Location	Year Built	Stainless reinforcement Type	Bid Price $/lb.	Bid price $/lb., inflation adjusted 2011	Quantity (lb.)	Stainless reinforcement Cost ($)[†]	Bridge Construction Cost ($)[†]	Percentage of Construction Cost (%)
S03 of 63103	WB I-696 over Lenox Rd., Ferndale and Royal Oak	1983	304	$2.00	$4.33	35,769	$71,538	$1,494,833	4.79
S09 of 82104	Oakland over Davidson	2000	316	$3.63	$4.55	100,300	$363,966	$1,940,230	18.8
R12-4 of 33045	WB I-496 over Holmes Rd. and CSX RR	2001	304L	$3.88	$4.73	139,400	$540,574	$3,710,000	14.6
S19 of 82191	I-75 under London-Moore, Detroit	2002	316LN	$3.00	$3.60	55,392	$165,799	$1,489,286	11.1
S22 of 82191	I-75 under Champaign, Detroit	2002	316LN	$3.00	$3.60	72,983	$218,454	$1,489,287	14.7
S01 of 82194	I-75 under Cicotte Ave., Detroit	2002	316LN	$3.00	$3.60	45,095	$134,977	$3,889,109	3.47
S27 of 82022	I-94 over Greenfield Road, Detroit	2004	304	$3.50	$4.00	156,888	$549,106	$1,585,773*	34.6
B01 of 11015	I-94 over Galien River, Berrien County	2008	304 solid 316LN clad	$5.00 solid $1.75 clad	$5.01 solid $1.76 clad	72,306 solid 95,266 clad	$361,530 solid $166,715 clad	$3,947,690	13.4
S05 of 13081	EB and WB I-94 over Riverside Drive, Battle Creek	2010	2304	$3.74	$3.74	62,771	$234,764	$2,715,143	8.64
B01 of 83011	M-37 over Pine River, Wexford County	2011	2304	$2.70	$2.70	94,071	$253,992	$1,856,394	13.7

All structures built in 2002 and before had a dissimilar metals isolation requirement for stainless steel. This requirement was removed in 2003.

[†]Not adjusted for inflation.

*Project scope was for deck reconstruction only, not complete bridge replacement, therefore a higher percentage results.

Use Considerations

Selection of the proper stainless steel for a given application depends on the particular service environment to which the material will be exposed, and the desired mechanical properties. The ASTM Standard A276 specifies chemical composition of most stainless grades. For stainless used as concrete reinforcement, ASTM Standard A955 specifies the required mechanical properties and corrosion resistance.

A study reviewing bridges with corrosion resistant reinforcement notes that the most common types State Departments of Transportation have used are stainless 316LN austenitic and 2205 duplex (Hartt, 2006). Some properties of stainless steel reinforcement types allowed by MDOT special provision are listed in Table 3. Magnetic permeability is shown for information as it can indicate the relative success of performing a magnet test on reinforcement as quick field verification. The chloride threshold is an indicator of qualitative corrosion performance as compared to mild steel. A higher chloride threshold indicates more corrosion resistance. Typically the time to corrosion is estimated with consideration of the timeframe for the chloride concentration at the reinforcement depth to reach the chloride threshold level.

Table 3. Some properties of stainless steel reinforcement types permitted by MDOT special provision.

Stainless reinforcement Type*	Classification	Magnetic permeability (mild steel = 200)	Chloride Threshold (lb. /yd^3 concrete)
241 (XM-28)	Austenitic	0 to 1	19 (est.)
304, 304L	Austenitic	1 to 8	19 (a)
316, 316LN	Austenitic	0 to 1	31 (a)
2205	Duplex	60 to 120	> 22 (b)
2304	Duplex	100 to 200 (est.)	> 22 (est.)
Mild steel	n/a	200	1.2

* refer to ASTM Standard A955, Table 2 for further information. L = low carbon content. N = nitrogen added for strength. Sources: (a) McDonald et. al., 1998; (b) Ji et. al., 2005; (est.) = this author's estimate.

Using stainless steel and SCR requires no modification to current bridge deck design standards. Solid stainless reinforcement is available in 60 and 75 ksi yield stress, while SCR is available in 60 ksi yield stress. The development and lap lengths are the same as for uncoated reinforcement. To reduce the stainless steel quantity required for deck reinforcement, 75 ksi design yield stress, or empirical deck design as allowed by the AASHTO LRFD Specifications could be used. In some cases the steel reinforcement required in an empirical bridge deck design can be reduced by up to 30 percent. Stainless steel and SCR are marginally heavier than standard reinforcement, so the nominal weight is adjusted by a factor of 1.02 when computing quantities.

Other design considerations for stainless steel and SCR may include use of a thinner deck cross section in cases of geometric or dead load restrictions. For instance, some structures built in the 1960's carrying local roads over urban depressed freeways were constructed in Michigan with a 7-½ in minimum thickness parabolic crown deck. Many cross streets and service drives along freeways intersect the carried routes. Reconstruction to current design requirements of 3 in concrete cover and a linear 1.5 percent cross slope would entail a deck thickness of 9 in at the centerline and greater thickness at the edges. The greater deck thickness would require

reconstruction of the approach pavements, and depending on the location, possibly the entire intersection. The increased dead load also would limit the structure's live load capacity, since most bridges of the era were designed for smaller truck loads than current design standards. In some cases the additional dead load would require the strengthening or replacement of substructure components. Using stainless and SCR in the deck would allow for the existing deck and approach profiles and substructure to remain unchanged, at a significant cost savings.

In estimating the cost of solid stainless steel and SCR, current prices should be obtained from suppliers. The stainless steel reinforcement material price premium and volatility is due to the nickel and molybdenum content, since these individual components are up to ten times the cost of chromium. Solid stainless steel and SCR costs are sensitive to bar length, diameter and the waste when cutting from relatively short stock bars. In addition, prices may vary significantly between suppliers.

A direct cost comparison of stainless steel reinforcement to ECR was made on a bridge deck square foot basis, using actual construction costs from the bridge projects listed in Table 2. The costs include furnishing, fabricating, and installing the reinforcement. The plot shows an increased material cost of $17.43/SFT in 2011 dollars. In all cases, the stainless steel reinforcement was directly substituted on a one to one basis for ECR. See Figure 9.

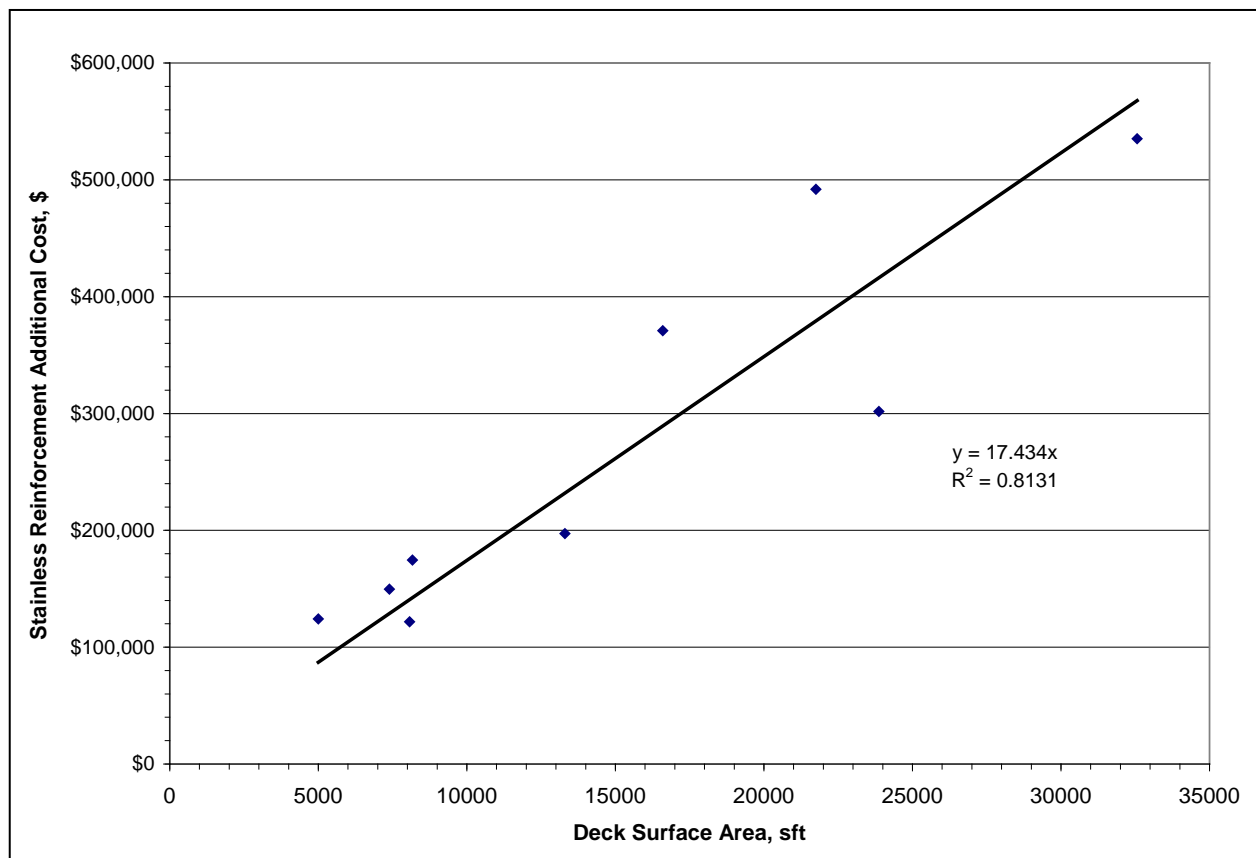

Figure 9. Cost premium of stainless steel reinforcement in relation to deck surface area in 2011 dollars. The cost premium is based on an ECR cost of $0.96/lb. (taken from the MDOT weighted average item price report for 2011).

When specifying stainless steel and SCR, mill scale removal and surface passivation are required. The mill scale has a lower corrosion resistance than the parent metal, allowing for eventual pitting corrosion to form at lower chloride threshold levels. Passivation allows for the tightly adhering chromium oxide film to form that gives stainless steel its corrosion resistance.

For project level quality assurance, MDOT requires the supplier to provide mill certificates for each lot that shows the material is in conformance to specifications. Samples of each bar size are collected for acceptance testing. Since stainless steel reinforcement is generally cold rolled, the amount of cold working can have a significant influence on the yield strength, tensile strength, and elongation, and can vary by lot. Visual inspection confirms mill scale removal. The appearance of austenitic stainless steel is different than ASTM A615 steel, as austenitic stainless has a dull grey finish to it (Figure 10). Duplex stainless, however, is more similar in appearance to ASTM A615 steel, albeit possessing a slight grey color, and will be magnetic because of its ferritic grain structure. A simple field test for solid austenitic stainless steel can be performed by placing a magnet onto the bar surface. Austenitic stainless steel will be non-magnetic, although it can be made weakly magnetic through cold working.

Figure 10. The solid stainless steel reinforcement installed on westbound I-496, R12-4 of 33045, has a dull grey color.

One important advantage that stainless and SCR has over ECR is in handling and storage. ECR requires extra care in transport, handling, storage, and placement. Coating damage has to be repaired in the field, adding expense and time to the project. There is little concern over rough handling of solid stainless or SCR, since both solid and clad surfaces will resist gouges, nicks and cuts. The SCR is furnished with end caps to protect the exposed mild steel core.

Contact between dissimilar metals was prevented for the earlier bridge projects that used stainless steel reinforcement by placement of insulating spacers between the stainless reinforcement and other metals, including shear developers and beam flanges. Some reports have shown that galvanic coupling of stainless steel with carbon steel in concrete can be neglected (Qian, 2005; Cui et al., 2008). A report issued by the Ontario Ministry of Transportation revealed that no distress of the structure is likely from galvanic coupling of

stainless and carbon steel during the service life (Hope, 2001). In fact, because the stainless steel acts poorly as an anode, the coupling effect of stainless to carbon steel is less than that for passive carbon steel to active (corroding) carbon steel in concrete. Therefore coupling stainless and carbon steel will not increase the risk of steel corrosion in concrete.

Other States' Use of Stainless Steel and SCR

Several States' Departments of Transportation (DOT) have implemented selective use of stainless and SCR in their bridge projects. The Virginia Department of Transportation (VDOT) issued a design memorandum for the use of corrosion resistant steel reinforcement, which includes stainless steel and SCR (VDOT, 2010). The memorandum outlines selection criteria based on functional classification of the route, and the structural component(s) that would use it. There are three types of corrosion resistant reinforcement, namely:

1. Solid stainless steel reinforcing bars conforming to ASTM STANDARD A955/A955M – UNS designations: S24000, S24100, S30400, S31603, S31653, 31803, S32101;
2. Stainless reinforcing steel clad bars conforming to AASHTO designation: MP 13M/MP 13-04; and
3. Low Carbon/Chromium reinforcing steel bars conforming to ASTM Standard A1035/A1035M (MMFX-2). [For more information on MMFX-2, refer to MDOT Research Report R-1499, available at http://www.michigan.gov/mdot/0,1607,7-151-9622_11045_24249---,00.html.]

The locations where VDOT permits the use of corrosion resistant reinforcement are mostly confined to the deck slab and concrete diaphragms, parapets, and pier caps under joints.

A survey of state agencies' use of stainless steel and SCR was conducted by Maine DOT through the AASHTO Subcommittee on Materials (AASHTO website, 2009). See Table 4.

Table 4. Stainless steel reinforcement and SCR use by select DOT agencies.

State DOT	Specification reference	SCR allowed	ASTM STANDARD A955 stainless steel types allowed
Virginia	Design Memorandum	Y	S24000, S24100, S30400, S31603, S31653, S31803, S32101
Pennsylvania	709.1(f)	N	S24100, S30400, S31653, S31803
New York	Bridge Manual Section 15.12, and Construction Sections 709-12 and 709-13	Y	All ASTM STANDARD A955 types
Michigan	03SP706(B) and Design Manual section 7.04	Y	S24100, S30400, S30403, S31600, S31603, S31653, S31803, S32304
Oregon	Special provision U00530	Y	S20910, S24100, S31653, S31803, S32304
South Dakota	Special Provision	N	S31803
Florida	Special Provision	Y	S31603, S31803
Maryland	Special Provision	N	S31653, S31803
Minnesota	Draft Specification	N	S20910, S24100, S30400, S31603, S31653, S31803, S32201, S32205, S32304

Life Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is used when determining the appropriate strategy for rehabilitation of roads and bridges. LCCA provides a way to quantify the costs of different rehabilitation scenarios over the anticipated service life period, so that alternatives can be compared uniformly. One way is to compare the equivalent uniform annual cost (EUAC) of various strategies, because the alternative with higher initial cost may actually possess the lowest life cycle cost on an annualized basis.

Typically the EUAC cost is determined from all future cost impacts, including reconstruction, maintenance, and rehabilitation, and compared (Equation 2). This EUAC gives a better picture of agency costs to maintain the structure over the intended service life; for example, stainless steel reinforcement will increase the bridge construction cost by two to eight percent as compared to ECR, but will reduce future maintenance costs and bypass a rehabilitation cycle. The EUAC is calculated from the net present value (NPV) of the expenditure and annualized over the analysis period.

$$EUAC = NPV\left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \quad \text{(Equation 2)},$$

Where:

NPV = Net present value of the expenditure (cost), includes all future costs

i = Real discount rate (DR), a measure of the "opportunity cost", or time value of money. It represents the real interest rate from which the inflation premium has been removed.

n = Number of periods, generally years, between the present and future time.

Sensitivity analysis can be done to account for the uncertainty in LCCA parameter estimation, such as variance in the real discount rate (DR), user delay costs, and ECR service life estimates. The DR may be a significant parameter because of its influence in computing present value of future costs. This report references the real discount rates provided by the White House Office of Management and Budget, Appendix C of Circular A-94 (OMB website, 2011).

With increasing focus on providing mobility in transportation, user delay costs must be considered. The Michigan State Transportation Commission policy states:

> *"During the project scoping process, the Department shall consider the impact on motorists, including motorist delay cost, when determining the type of project rehabilitation to be used. Determination of when the work should take place (i.e. days, nights, weekends, off-season) and use of incentives/disincentives shall be made prior to the start of design and calculated as part of the cost of the project (Policy 10015, 1996)."*

To compare alternatives to using ECR in bridge decks, the reinforcement service life needs to be reasonably estimated. There have been many reports that have provided an estimation of ECR service life, and some are summarized below:

- Deck cores analyzed in a Virginia DOT research study on bridge decks between two and twenty years old revealed that in Virginia the epoxy debonded from the steel in as little as four years. In addition, the authors pointed out that none of the other laboratory or field studies on ECR concluded that the ECR would not corrode (Weyers et. al., 2000).
- One laboratory study estimated that ECR would provide long-term corrosion protection of 46 years (Spectrum News, 2001).
- A Federal Highway Administration (FHWA) report compared A615 black bar, epoxy, metallic, and metallic clad bars to estimate service life. Bridge decks constructed with uncoated carbon steel reinforcement have an estimated service life of 9 years, and bridge decks constructed with ECR have an estimated additional service life of 27 years. In contrast, a bridge deck constructed with stainless steel reinforcement has an estimated service life of 75 to 100 years (McDonald, 1998).
- Researchers at Iowa State University analyzed cores from 80 bridges and in conjunction with developing models of chloride infiltration through the bridge deck and the corrosion threshold of ECR, estimated service life for Iowa ECR bridge decks of over 50 years (Fanous, 2000). However, another researcher reviewed the findings and concluded that the original authors made critical errors in service life estimation by inappropriate survey techniques, lab evaluation, and methods of analysis (Weyers, 2006).
- Concrete specimens with ECR and black steel reinforcement were subjected to freeze-thaw cycling and impressed current accelerated corrosion testing to simulate the varying ages of bridge decks. The ECR corrosion rates from the 160 day accelerated corrosion test were 2.5 times lower than uncoated steel. The authors recommended a service life of 65 years based on the 2.5 multiplier (Harichandran et. al., 2010).
- Michigan has used ECR in bridge decks for over 30 years. An internal MDOT study estimated the deterioration curve for the time to poor condition (NBI deck condition rating of 4, item 58A) for uncoated reinforcement using Markov transition probability matrix analysis. The results from analyzing NBI deck condition data covering an inventory of over 1,000 bridge decks indicated that it would take an average of 35 years to reach poor condition. This model was then used to extrapolate ECR bridge deck estimated time to poor condition of 70 years (Boatman, 2010).

A computer program was developed by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST), called BridgeLCC 2.0. According to the user manual, the LCCA used in the program was based on ASTM Standard E917 *"Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,"* and a cost classification scheme developed by NIST. The program allows for basic and advanced modes, including Monte Carlo simulation (Ehlen, 2003).

A basic LCCA was completed using BridgeLCC 2.0 for alternative rehabilitation strategies on the bridge B01-3 and -4 of 11015, EB and WB I-94 over the Galien River, Berrien County. This bridge was constructed in 2008 using stainless and stainless-clad reinforcement in the deck. The bridges are twin structures, each carrying two lanes of I-94 traffic with a width of 61 ft. - 2 in and length of 195 ft. The average daily traffic for this corridor is 55,900 vehicles, with 24 percent commercial trucks. The analysis period was defined as 100 years.

The median service life for the ECR bridge deck was chosen at 60 years to coincide with current MDOT forecasting. Based on estimates in published literature, a service life of 100 years was

selected for the stainless steel reinforced bridge deck. In this analysis, the construction cost is not broken down by element (deck, substructure, etc.), but a lump sum cost is given instead for each alternative. Because ECR was not used to construct this bridge deck, the construction cost for the ECR deck alternative was estimated by substituting the stainless and SCR pay items with the ECR bid price from the project. Rehabilitation costs recurring over the service life are based on the MDOT estimate of $70/SFT for deck replacement cost, and the additive cost of $17.43/SFT (see Figure 9) for the stainless steel reinforcement alternative. The sensitivity analysis accounted for the uncertainty in the service life, estimated at +/- 20 percent, and +/- 100 percent for the inflation adjusted discount rate. See Table 5.

Table 5. B01 of 11015 life cycle cost analysis summary, with costs in present value dollars (2011).

Bridge deck reinforcement type	Epoxy	Stainless Clad/ Stainless
Bid price for reinforcement per lb.	$1.00	$3.21*
Initial construction cost	$3,587,016	$3,947,690
Rehabilitation recurrence interval (variance +/- 20%)	60 years	100 years
Rehabilitation cost**	$1,004,000	$271,000
Work zone user delay cost (ADT = 55,000)	$432,000	$121,000
Real discount rate (variance +/- 100%)	2.7%,	2.7%
Salvage value	$0	$0
Life cycle cost	$4,591,000	$4,219,000
EUAC (over 100 year period)	$49,350	$45,350

* Calculated from bid prices of stainless and stainless-clad reinforcement at $5.00/lb. and $1.75/lb. respectively, and a ratio of 45/55 percent based on the steel reinforcement quantities.
** Deck replacement costs are $70/SFT for ECR and $87.43/SFT for stainless steel reinforcement.

The analysis result was independent of the discount rate (all cases favored the alternative), and indicated a break-even point when the ECR bridge deck achieves a service life of 81 years, which is considered unlikely (Clemena, 2002). Conversely, the break-even point for the stainless and SCR alternative is when the material bid price exceeds 20 percent of the initial construction cost. Table 6 summarizes LCCA results from eight bridges built with stainless steel reinforcement.

Table 6. LCCA results of several bridges showing the break even scenario (LCCA savings at $0) both in years of service life and material cost. The analysis included user delay costs.

Bridge ID (see Table 2)	Life Cycle Cost Savings using stainless steel reinforcement	ECR maintenance-free service life break-even point (LCCA savings at $0), in years after construction	Stainless steel reinforcement break-even point (LCCA savings at $0) as percentage of construction cost
S09 of 82104	$229,880	71	28%
R12 of 33045	$458,750	75	24%
S19 of 82191	$199,080	100+	22%
S22 of 82191	$211,820	95	26%
S01 of 82194	$233,860	100+	8%
S27 of 82022	$174,090	58	44%
B01 of 11015	$372,000	81	20%
S05 of 13081	$201,890	100+	16%
Average	**$260,200**	**85**	**24%**

Sustainability

Sustainability is generally defined as meeting the needs of people today, without consuming the resources needed by people in future generations. Service life and sustainability are clearly interrelated. AASHTO LRFD Specifications define service life as *"The period of time that the bridge is expected to be in operation"* (subsection 1.2). For purposes of sustainability, service life can be considered as the period of time that the bridge is expected to be in operation with proper maintenance, but without any major rehabilitation. Increasing the rehabilitation interval from 50 years to 100 or more years would greatly reduce the resources needed on an annual basis.

Highway road and bridge construction account for over 13 percent (17.5 million metric tons CO_2 equivalent) of the total construction industry annual greenhouse gas (GHG) emissions (U.S. EPA, 2009). Put in another context, the 17.5 million metric tons of CO_2 equivalent GHG emissions represents the consumption of 782,000 gallons of fuel. Note that this total includes only fossil fuel combustion and electricity use. Other life cycle components, such as emissions from the production and transport of the materials used or waste disposed, are not included and would add to the total impact. One report analyzed diesel and gasoline equipment use for several construction project categories. By collecting extensive data from work sites over a large variety of highway construction projects, the researchers found that bridge projects have the highest average equipment use of 20,527 hours over the project lifetime (Kable, 2006). Average fuel consumption for equipment use is estimated at 1.2 gallons per hour. Therefore fuel consumption and GHG emissions for equipment used on a bridge project is estimated at 24,600 gallons and 516,000 lb. CO_2 equivalent. The average passenger automobile emits 0.916 lb. of CO2 per mile traveled (EPA, 2000). For a construction zone of one mile length, this net reduction in CO2 emissions would correspond to the equivalent of 560,000 vehicles, or for a stretch of highway with an ADT of 56,000 vehicles per day, the daily emissions over a ten mile portion of the highway. Thus elimination of a rehabilitation event over the life cycle of the structure has the potential to save substantial greenhouse emissions.

A new bridge deck with stainless steel reinforcement and SCR may require some minor work after 100 years of maintenance-free service life. Beyond that timeframe the deck would be rehabilitated rather than reconstructed, salvaging or leaving the stainless steel reinforcement in place, as the expected concrete deterioration mechanism would shift from corrosion of reinforcement causing spalling to concrete damage from traffic wear and freeze/thaw action. The stainless steel reinforcement and SCR would additionally be expected to last several decades beyond the rehabilitation.

Conclusions

Stainless steel and SCR are highly resistant to corrosion and can provide more than 100 years of bridge deck maintenance-free service life. The obvious drawback to more frequent use has been the material cost. When considered as a portion of the construction cost, however, stainless steel and SCR generally accounts for ten percent or less of the total, not including offsetting cost savings from reduced concrete cover requirements.

Minimizing the construction cost is an important consideration, but the cost to maintain the structure over its entire service life should be evaluated, including the impact to users. LCCA for selected structures demonstrated a lower present value cost for the stainless steel and SCR alternative, and a break-even point when the ECR bridge deck attains 85 years maintenance-free service life. Conversely, the break-even point for the stainless and stainless-clad reinforcement alternative is when the material costs exceed 24 percent of the construction cost. The LCCA improves further when the cost savings realized from reduced concrete cover and utilization of empirical bridge deck design are incorporated.

Appendix A contains the MDOT Bridge Design Manual subsection 7.04.02, Stainless Steel Reinforcement, summarized here, which list the criteria bridge designers and scoping engineers should consider for use of stainless steel and SCR:

1. When the additional expenditure for solid stainless reinforcement and SCR, including cost savings from reduced cover requirements, is no more than eight percent of the programmed structure cost.
2. For structures on interstate and highway routes where future repair and maintenance would be very disruptive to traffic, and where mobility analysis defines the project as significant, and mitigation measures to minimize travel delay are needed.
3. For bridges located over navigable waterways or protected wetlands sensitive to environmental impact from construction activity.
4. Where the deck cross section is less than nine inches, due to local geometric restrictions or in widening projects where the dead load is limited to the capacity of the existing substructure. The standard cover requirement of three inches can be reduced to two inches.
5. For bridges located over high volume railway lines where access and right of way restrictions exist.

Use of stainless steel and stainless-clad steel for bridge deck construction is justified through life cycle cost analysis, ensures a long life with low maintenance costs, and provides a more sustainable solution. The challenge remains, however, to overcome the barriers to funding the increased cost of using corrosion resistant materials.

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Appendix A

Excerpt of Michigan Bridge Design Manual

Section 07.04.02 Stainless Steel Reinforcement

7.04.02

Stainless Steel Reinforcement

(11-28-2011)

A. Criteria For Use

As an alternative to epoxy coated reinforcement, stainless-clad and solid stainless steel reinforcement should be selectively used in bridge deck construction. Designers will need to examine whether the additional expenditure is warranted for enhanced durability of the structure. The designer should consider use of stainless-clad and solid stainless reinforcement under one or more of the following circumstances.

1. The additional expenditure for stainless-clad and solid stainless reinforcement, including cost savings from reduced cover requirements, should be no more than eight percent of the programmed structure cost.

2. For structures on trunkline roads where future repair and maintenance would be very disruptive to traffic and where mobility analysis defines the project as significant and mitigation measures to minimize travel delay are needed (See Work Zone Safety and Mobility Policy).

3. Over navigable waterways or protected wetlands sensitive to environmental impact from construction activity.

4. Where the deck cross section is less than 9 inches, due to local geometric restrictions or in widening projects where the dead load is limited to the capacity of the existing substructure.

5. Bridges located over high volume railway lines where access and right of way restrictions exist.

7.04.02 (continued)

When using stainless-clad or solid stainless steel reinforcement for new bridge deck construction, the designer should consider using empirical deck design when that type of design reduces the amount of steel reinforcement.

Combine stainless-clad reinforcement with solid stainless reinforcement to optimize the material costs.

B. Cost

In estimating the cost of stainless-clad and solid stainless steel reinforcement, current prices should be obtained from suppliers. Stainless-clad and solid stainless steel reinforcement costs are more volatile and variable than for carbon steel and are sensitive to bar length, diameter and the waste when cutting from relatively short stock bars. Prices may vary significantly between suppliers.

C. Detailing and Availability

Stainless-clad and solid stainless steel reinforcement is similar to normal carbon steel reinforcement in the design, detailing and construction process. Use stainless-clad and solid stainless steel reinforcement in both reinforcement mats in the bridge deck, and in other locations as warranted. Dissimilar metals contact, whether with epoxy coated reinforcement, uncoated reinforcement, or galvanized steel, is not considered detrimental when embedded in concrete. The standard cover requirement of three inches can be reduced to two inches.

Stainless-clad reinforcement is available in standard U.S. customary sizes of #5 or greater, with maximum lengths of 40'-0", and available in Grade 60. Solid stainless steel reinforcement is available in all standard sizes and lengths, and available in both Grade 60 and Grade 75.