MANAGEMENT OF COASTAL BRIDGES USING CATHODIC PROTECTION AND STAINLESS STEEL REINFORCING BARS

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Abstract

Oregon Department of Transportation (ODOT) pioneered the practical application of cathodic protection (CP) for preservation of existing major historic coastal bridges and the use of stainless steel in its new coastal bridges. The intent of each is to achieve a useful life of over 120 years. Utilizing the extensive information available to the department, ODOT has made each method a standard for managing its bridges subject to corrosion. For CP, ODOT selected impressed current zinc anode system, and for stainless steel, three appropriate alloys were selected. Seven CP bridges are completed and four bridges using stainless steel reinforcement are complete. An inland highway bridge is under construction using stainless steel to resist deicing salt damage.

Introduction

The severe marine environment of Oregon's Coast Highway has forced the Oregon Department of Transportation (ODOT) to develop a method to significantly extend the service life of bridges designed for this highway. Bridges constructed in the 1950s, with no provisions for corrosion protection, were becoming severely deteriorated and requiring replacement after just forty years. Photo 1 shows the severe corrosion damage to the 40 year old Brush Creek Bridge, prompting our effort to make Coast Bridges more durable.

Photo 1: Brush Creek Bridge

Photo 2: Rocky Creek Bridge

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Photo 2 shows a 1927 bridge with similar damage that was corrected to restore it to as-original condition. Reinforced concrete bridges are the predominant choice in the Western states, due to the reduction in construction and maintenance costs achieved through the small amount of steel used. This steel, which corrodes rapidly in high-salt environments, continues to be the weak link in achieving a long service life for bridges.

Alsea Bay Bridge, a 918 m (3,011 ft) reinforced concrete arch built in 1936, deteriorated from corrosion damage to the point it could not be saved. It was planned to be replaced in 1988 with a simple, clean-looking bridge estimated to cost $20M. The public process was very contentious. Ultimately, to meet the expectations of the public, a very dramatic bridge, with a 137 m (450 ft) steel through arch for the main span was completed in 1992. It is 887 m (2,910 ft) long. It cost $44M, $24 M over the planned simpler bridge estimate. During this process, in the late 1980s, the ODOT determined it would not go through such a process again and determined to find technology that would protect the remaining Conde B. McCullough-designed arch bridges from deterioration.

One of ODOT's Bridge crews had electrical and mechanical engineers. They proposed using cathodic protection, which uses a sacrificial metal to protect steel from corroding. They were aware of this technique being that is used on vessels, pipelines and offshore oil platforms for such protection. The California Department of Transportation (CalTrans) had also just completed a research project to test thermal-sprayed zinc as an external anode for bridges.

In 1987, the crew conducted the first corrosion damage survey of the Coast Highway (US-101) bridges, both historic and non-historic, and ranked the bridges in order of needed repairs and protection. Cape Creek Bridge, 189 m (619 ft), with a main arch of 67 m (220 ft), and two levels of smaller arches, was patterned after a Roman aqueduct in France and constructed in 1931. It was at the top of the list, in serious of need of repairs for corrosion damage. It was selected as a full-scale test of cathodic protection for permanent preservation of the McCullough Coast Arch Bridges. A contract was let for the period 1990 to 1992 and cost $2.5M. Shotcrete was used as the repair concrete and an impressed current cathodic protection system was used with an arc-sprayed zinc anode. See Photos 3 & 4.

Photo 3 – Shotcrete Repair

Photo 4 – Arc Sprayed Zinc Anode

Yaquina Bay Bridge, 982 m (3,223 ft), with a main steel through arch span of 183 m (600 ft), two flanking steel deck arches, seven concrete deck arches and numerous approach spans, constructed in 1936, was selected as the next bridge. The seven concrete arches were repaired first in 1991-1994, at a cost of $13.5, followed by the southern approach deck-girder spans, in 1995, at a cost of $2M. The system used was similar to Cape Creek.

The repair of the Depoe Bay Bridge, 95 m (312 ft), with a main deck arch span of 46 m (150 ft), began while Yaquina Bay was still in progress. Depoe Bay bridge consists of two parallel structures, a 1927 bridge and a 1939 bridge joined side by side to make a four lane structure with no median. The original 1926 bridge was in seriously deteriorated condition. The work was performed 1994-1995 and cost $3.5M.

Big Creek Bridge, 72 m (235 ft), with a main through arch span of 37 m (120 ft), constructed in 1931, was in seriously deteriorated condition and was scheduled to have been replaced at about the same time as the Alsea Bay Bridge. However, the endangered Oregon Silverspot Butterfly, had halted that project. ODOT proposed restoring and preserving the bridge, instead. This was accepted, with the requirement that the contractor not set foot on the area more than five feet away from the bridge in order to not adversely affect the butterfly habitat. The contractor built a platform for his equipment and easily performed the work. ODOT, with concurrence of the State Historic Preservation Office, included a design for altering the bridge portal to prevent continuing impact damage of over-height trucks to the overhead cross-bracing. The work was completed in 1998 at $2.5M.

Cummins Creek, 56 m (185 ft), with a main deck arch span of 35 m (115 ft), constructed in 1931, was completed next, in 2002, at a cost of $1.7M. This was the first bridge in which ODOT used cathodic protection on the bridge rails. Prior to this, the rails were left unprotected, partly because there was concern that if significant work was done to the rails, they would have to be replaced with crash-tested rails. By now, the issue had been solved by an agreement to replace the rails with replicas that have sufficient embedded steel to meet the required loading.

Rocky Creek (Ben Jones) Bridge, 110 m (360 ft), with a main deck arch span of 49 m (160 ft), constructed in 1927, was restored and preserved in 2003 at a cost of $4.8M. This bridge was named in honor of the "father" of the Coast Highway. This bridge was in the worst condition of any bridges on the Coast, but carried a frontage road, the old highway, not US-101. The deck needed complete replacement. This required replacement of the rails due to the difficulty of properly reattaching them. Rather than designing a replacement rail to match the original drawings, we designed them using structural steel within the concrete to make them much stronger than the originals. We precast them in sections to both reduce costs and ensure accuracy, and applied full cathodic protection to them, as well as to the bridge. The deck also had reinforcing steel meeting current standards, while maintaining the dimensions of the original deck, which had a 22 ft roadway clearance between rails.

Rogue River (Isaac Lee Patterson) Bridge, 609 m (1,898 ft) with seven concrete deck arch spans, constructed in 1932, is currently undergoing restoration and cathodic protection. The project is estimated to cost $20M. This includes the normal repairs, plus the new rail treatment of highly strengthened precast structural steel rails within the historically accurate concrete exterior, and a new $2M deep foundation under one of the bridge piers, which has been seriously undercut by the river. All of this work is being performed while keeping the bridge open to US-101 traffic. Design is starting on the next projects, Ten Mile Creek, almost identical to Big Creek and the southern seven arch spans, and the approaches of the 1627 m (5,339 ft) Coos Bay (Conde B. McCullough) Bridge. It is a $24M project that is planned to start in 2007.

	BRIDGE	Total Cost	CP Cost	No. of CP Zones
1	Cape Creek	$ 2.4 M	$ 75 /m^2 (7/sf)	26
2	Depoe Bay	$ 4.5 M	$108 /m^2 (10/sf)	14
3	Yaquina Bay	$13.5 M	$108 /m^2 (10/sf)	55
4	Big Creek	$ 2.5 M	$ 86 /m^2 (8/sf)	5
5	Cummins Creek	$ 1.7 M	$ 97 /m^2 (9/sf)	6
6	Rocky Creek	$ 4.8 M	$161 /m^2 (15/sf)	10
7	Rogue River	$20.0 M	$ 65 /m^2 (6/sf)	51

Conventional corrosion protection techniques, such as epoxy coating of reinforcing steel, offered an extension of twenty years in service life, but would still require complete bridge replacement once corrosion had become a problem. With limited funds for bridge replacements, adding twenty years to a forty year bridge design is not a cost effective investment in bridge life. ODOT set an objective to at least double the expected service life of bridges designed for the coast environment. This brought us back to the root issue, the search for materials which intrinsically have a useful life of 120 years or more in a high-salt environment.

Corrosion Resistant Metals

To extend the service life of coastal bridges, ODOT elected to replace the corrosion-susceptible reinforcing steel with a material that has the same mechanical properties, but is highly resistant to salt-induced corrosion. Other industries, maritime shipping, aerospace, petrochemical and nuclear, in particular, have already gone through this process and have been using a number of metals with the strength, ductility and corrosion resistance that would meet this objective. ODOT considered titanium and nickel-based alloys, but rejected them for the high-cost of the base element. High chrome (at least 11%) iron-based alloys, stainless steels, could provide the required properties: Tensile Strength>= 620 MPa (90 KSI), Yield Strength>= 414 MPa (60 KSI), Elongation>= 12%, Bend Ratio=4 x diameter, and Corrosion Rate< 5 mils/year.

With the help of the Stainless Steel Institute of North America (SSINA) and the Nickel Development Institute (NiDI), ODOT investigated the five families of alloys generically referred to as stainless steels for potential application. As noted in Table 2, the austenitic and duplex families appear well suited for use as reinforcing steel in the coast environment.

Family	Advantages	Disadvantages
Ferritic	Relatively Low Cost, Resistant to Chloride Stress-Corrosion Cracking	Poor Fracture Toughness, Only Mildly Corrosion Resistant Not Heat Treatable
Austenitic	Highly Corrosion Resistant, Especially to Chloride Induced Pitting , Can be Work Hardened, Very Ductile	Susceptible to Chloride Stress-Corrosion Cracking at High Temperature and Stress, Not Heat Treatable
Martensitic	High Strength, Can be Hardened by Heat Treating	Only Mildly Corrosion Resistant
Duplex	Extremely Corrosion Resistant, Especially to Chloride Pitting, Chloride Stress Corrosion Cracking, High Strength, Ductile	
Precipitation-Hardening	High Strength, Can be Work Hardened and Age Hardened, Ductile	

Table 2: Comparison of Stainless Steel Alloy Families

The literature describing stainless steels focuses on their performance in environments that are extreme in comparison to embedment in concrete in salt water. An example of this is the characterization of austenitic alloys as being susceptible to Stress Corrosion Cracking (SSC) in a chloride environment. The test environment used is 42% or 45% boiling magnesium chloride, at a temperature of 154°C (309°F). In a sea water environment, neither the chloride concentration nor the temperature can reach a point where SSC becomes a concern.

Research on stainless steel as a reinforcing material has concentrated on demonstrating its resistance to chloride induced corrosion. Austenitic structure stainless steels, such as American Iron and Steel Institute (AISI) types 302, 304 and 316, and duplex structure stainless steels, such as AISI 2205, have been examined in long term tests by Treadaway, Cox and Brown,[i] Pastore and Pedeferri,[ii] and Flint and Cox.[iii] Their conclusions confirm that the austenitic and duplex alloys are very corrosion resistant in highly concentrated chloride environments. Pastore and Pedeferri offered the only direct comparison of a duplex alloy, 23Cr4Ni, with 316 and 304.

The alloys 316, XM-19 (Nitronic 50) and duplex 2205 all have 3% molybdenum for increased resistance to chloride induced pitting and stress corrosion cracking. Alloys

316N, 316LN, XM-19 have nitrogen added for increased strength and resistance to chloride-induced pitting and crevice corrosion. A similar long term test, by Rasheeduzzafar, Dakhil, Bader and Khan,[iv] compared mild steel, galvanized steel and stainless steel clad reinforcing bars. Of the four studies, this was the only one that compared stainless steel and epoxy coating.

Epoxy performed as well as stainless clad bar except in extremely high concentrations of chloride. The failure mode for the epoxy bar was intense corrosion at discontinuities in the coating, followed by progressive cracking of the coating by corrosion products and further corrosion. Through progressive disbonding of the epoxy, the carbon steel ultimately corrodes, as if not protected.

A comprehensive study, performed by Wiss, Janney, Elstner and Associates,[v] under contract with the Federal Highway Administration, evaluated a wide variety of corrosion resistant metals and clad or coated mild steels to meet a 100 year design life in reinforced concrete bridges. This study concludes that solid stainless rebar has an expected life of 100 years, despite concrete cracking. It further recommends the use of type 316 over type 304 for marine structures and bridges where closure for repair would present problems.

ODOT performed extensive testing of stainless steel clad reinforcing. In Materials Testing Institute Method MTI-4 extended corrosion testing, it performed at the level of a solid bar, except at extreme chloride concentrations. In mechanical testing, the sample bar was subjected to a 180 degree bend around a mandrel four times its diameter. The bar was then straightened and pulled to failure. The clad bar became two distinct metals, yielding separately, as shown in Photo 5.

Photo 5: Clad Reinforcing

As a consequence, ODOT has narrowed its focus to solid reinforcing bars until this phenomenon is studied thoroughly and determined as not adverse to the clad bar's performance as tensile reinforcing for bridges. Table 3 shows that the mechanical properties of certain stainless steels are very similar to those of mild steel.[vi] The ductility, indicated by elongation, is significantly better. Their corrosion life is three to eight times greater.

Steel (alloy)	Tensile Strength MPa (ksi)	Yield Strength MPa (ksi)	Elongation % in 5 cm (% in 2 in)	Thermal Expansion (ppm/°C)	Corrosion Rate (mils/yr)
Austenitic					
304	579 (84)	290 (42)	55	17	5
Nitronic 33	>690 (100)	414-552(60-80)	~50	17	5
316	579 (84)	290 (42)	50	16	2
Nitronic 50	>690 (100)	414-552(60-80)	~50	16	2
316N cold worked	>690 (100)	414-552(60-80)	<50	16	2
Duplex					
2205	620 (90)	448 (65)	25		2
Mild Steel					
A36	552 (80)	248 (36)	48	12	15
1020	414 (60)	345 (50)	15	12	15

Table 3: Mechanical Properties of Specific Alloys

Stainless Steel Specification

Oregon developed its specification for use of stainless steel based on the yield strength and corrosion rates shown in this table. It is an "allowable" specification, in that it allows the contractor to choose Nitronic 50, 316N cold worked or the duplex alloy 2205, and to choose which source(s) to use.

To confirm these alloys could be produced, ODOT worked with the three specialty steel mills that had produced stainless steel rebar: Al Tech (now Dunkirk Specialty Steel, a subsidiary of Universal Steel) in Dunkirk, NY; Republic Engineered Steels, in Baltimore, MD; and Talley Metals (a subsidiary of Carpenter Technologies) in Hartsville, SC.

ODOT required production samples and plant capability data to demonstrate that a mill could produce sufficient quantities of bar and at uniform properties to ensure that supplies would not hold up construction schedules.

ODOT also worked closely with FHWA's Division Bridge Engineer and Corrosion Expert to ensure FHWA could support the concept of doubling the life of a coastal structure through the use of stainless steel and that the specification format would be acceptable for use with federal aid funding.

After confirmation that that these mills were the only suppliers within the U.S. that could readily produce stainless steel rebar that would meet Buy America Act requirements and that each mill could produce at least one of the allowable alloys, these mills were designated in the specification as the only approved sources. The contractor is free to choose which one(s) to use. While the cost of stainless steel was five times that of conventional mild steel, its cost was only 15% of the bridge cost. This raised the project cost approximately 12%, while doubling the life of the bridge.

Stainless Steel Projects

The development of the "market" for production-ready stainless steel reinforcing was done in conjunction with similar efforts by the Ontario Ministry of Transportation, and concurrently with the design of the replacement Brush Creek Bridge. The following photographs summarize the sequence of construction of this bridge, which used type 316N solid stainless steel reinforcing in the deck, rails, cross beams and spread-slab girders. The designer, Robert Kaspari, selected an arch structure for corrosion protection, seismic resistance and for aesthetic purposes as a "gateway" structure between the Pacific Ocean and the popular Humbug Mountain State Park.

Photo 6: Construction

Photo 7: Stainless Bars in Crossbeam

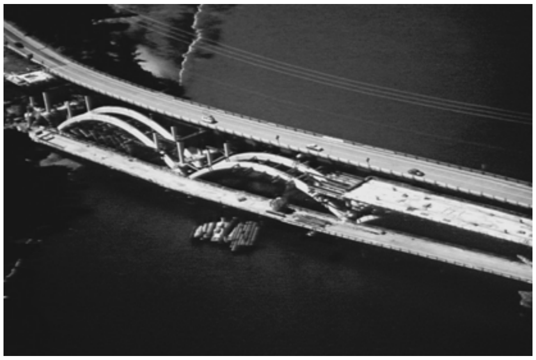
Holm II, of Stayton, OR, is the Contractor, and this was their first arch bridge and the first concrete arch bridge on the Coast Highway since Conde B. McCullough's arch bridges in the 1930s. Humbug Mountain directs the sea-air at the bridge site, where it condenses on the undersurfaces of the bridge. Microsilica concrete was used throughout for corrosion protection. The deck also gained abrasion resistance, yielding an extremely durable bridge.

Photo 8: Deck Ready for Concrete

Photo 9: Stainless Bar Supports

The specification required type 316 stainless steel for rebar chairs, bolsters, tie-wires, and inserts to eliminate the possibility of corrosion initiation on the bars in contact with them. The tie-wire needs to be annealed "dead soft at size" to permit it to be twisted by hand. Microsilica concrete requires cool temperatures and wet curing, or it develops shrinkage cracks. Holm II placed the deck at night and used sprinklers on burlap for curing. Some shallow hairline cracks were still experienced, but were sealed with methacrylate.

One advantage of the stainless reinforcing was very evident during construction. It was immune from the extensive damage, inspection and recoating required with epoxy coated rebar. And there was no concern that walking on the bar, or aggregate contact with the bar during placement, would make the bar susceptible to corrosion. As a result of the success with Brush Creek Bridge, replacement of three additional bridges on the Coast Highway utilized stainless steel reinforcing. The most significant was the three arch spans on the Haynes Inlet Slough Bridge, designed by James Bollman.



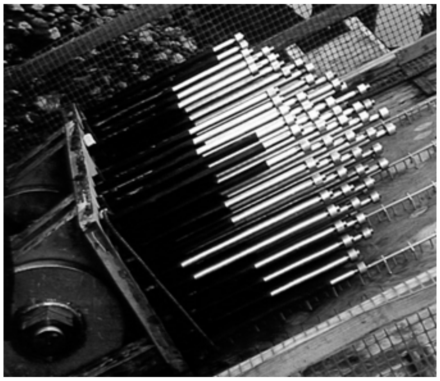


Photo 10: Haynes Inlet Slough Bridge

Photo 11: Arch Rib Hinge

The Haynes Inlet Bridge is shown in Photo 10. The bridge was constructed in two stages, each capable of carrying two lanes of traffic. Stainless steel reinforcing was used in the deck and superstructure. Microsilica concrete was used throughout, as in the Brush Creek Bridge.

To continue the decreasing height theme of the arches on the nearby McCullough Bridge, two-hinged arches were needed to permit very shallow arches. The hinges would be underwater during low tide, so would have to be extremely resistant to corrosion in sea water. The duplex alloy, 2205, was selected for the plates. These were fabricated by Oregon Iron Works, using slabs provided by Allegheny-Ludlum. The pins are Nitronic 60 stainless steel to resist galling. The studs, which attach the hinges to the concrete, are 316LN, threaded into blind holes to ensure full development.

The studs are wrapped with polyethylene tape to prevent contact with the conventional steel reinforcing used in the piers and arch ribs. The use of stainless reinforcing followed the pattern of Brush Creek. At this time, the three sources available were Al Tech, Talley Metals and Slater Steels, which replaced Republic.

A significant difference was the specification of 518 MPa (75 ksi) yield strength for the reinforcing in this bridge, to reduce the quantity, and therefore the cost, of the stainless reinforcing. The Contractor, Hamilton Construction, of Springfield, OR and the Fabricator, Farwest Steel, of Eugene, OR, selected 2205 alloy reinforcing from Talley Metals. Talley, with the help of their parent, Carpenter Technologies, pioneered the process of producing the higher strength reinforcing bars.

Farwest saw a significant advantage in using mechanical couplers to both tie the reinforcing mats in the two bridge decks together and to simplify the placing of the large bars in the stems of the cast-in-place deck-tee-beams. Erico produced Lenton couplers fabricated from 2205 to the same dimensions as their carbon steel couplers, and then proof-tested them with number 10 and 11 reinforcing bars of 2205 alloy with 518 MPa (75 ksi) yield. ODOT accepted the test results and permitted the use of the 2205 couplers under the same quality assurance conditions as for conventional bar.

Photo 12: Stem with 2205 Reinforcing

Photo 13: Erico 2205 Coupler

ODOT now has four bridges completed which use stainless steel, a fifth in design and two more planned. The unit costs experienced are shown in the next table.

Project	Brush Creek	Haynes Inlet
Year Completed	1998	2003
Stainless Steel used in	Deck, Beams	Deck, Beams
Alloy	316N	2205
Yield Strength	414 MPa (60 ksi)	517 MPa (75 ksi)
Stainless Quantity	42185 kg (93,000) lbs	319334 kg (704,000 lbs)
Lump Sum Price	$ 333,660	$ 1,610,000
Stainless Unit Price	$ 3.58	$ 2.28
Mild Steel Quantity	153,000 lbs	1,320,000 lbs
Lump Sum Price	$ 187,017	$ 900,000
Mild Unit Price	$ 1.16	$ 0.69
Total Bridge Cost	$2,259,382	$11,055,398
Stainless Reinforcing Percent of Bridge Cost	14.8 %	14.5 %

Table 4: Comparison of Reinforcing Steel Costs

CONCLUSIONS

The cost for using stainless steel in specific corrosion-prone components of a bridge is less than 15% of the structure cost, but provides at least a 200% return on that investment. This is the basis for ODOT's policy of using it to manage the investment in coastal bridges. We believe that NOT using stainless steel in a corrosive environment, marine or high deicing salt use, is more expensive considering life-cycle cost. Stainless steel should be used in carefully considered locations and bridge components.

As these projects have progressed, additional bridge owners have come to recognize the value of stainless steel, improving both the cost and availability of alloy reinforcing bars. As a result, a distributor of stainless steel reinforcing bars and hardware, Salit Specialty Rebar, now exists to support this increased demand.

A number of Transportation Agencies have now used stainless steel reinforcing, and can share their results. Several very experienced ones are the Ontario Ministry of Transportation, the Ohio Department of Transportation and the Garden State Turnpike

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Below is a description of the cultural resource the McCullough arch bridge are to Oregon.