Galvanic Cathodic Protection of Corroded Reinforced Concrete Structures

David Whitmore, P.Eng., FACI, FICRI, FCSCE, NACE CP4
Vector Corrosion Technologies Ltd.
474 Dovercourt Drive
Winnipeg, MB Canada R3Y 1G4
DavidW@Vector-Corrosion.com

J. Chris Ball
Vector Corrosion Services, Inc.
102-3822 Turman Loop
Wesley Chapel, FL 33544

ABSTRACT

Reinforced concrete structures can be designed and maintained to achieve long service lives, even in aggressive chloride environments. Unfortunately, many structures, such as bridges, piers, and wharves, show signs of active corrosion (e.g. rust staining, concrete spalling, etc.) in as little as 5 to 10 years. Left unchecked, chloride induced corrosion can lead to a major structural problems. Many severely corroded structures have been replaced at great expense and with significant disruption to the public. As an alternative to demolition and replacement, a viable option is to repair and protect the severely deteriorated structures utilizing a galvanic encasement that both structurally upgrades and cathodically protects the structure. This approach can provide an effective, low maintenance galvanic cathodic protection solution for deteriorated concrete structures.

A galvanic encasement consists of distributed galvanic anodes embedded in a concrete overlay or concrete jacket. The galvanic encasement may include additional reinforcing steel to create a one-step structural repair and protection system. This paper presents case studies on the use of galvanic encasements to repair and protect reinforced concrete structures. Long term monitoring of field projects over more than 10 years indicates that effective cathodic protection can be provided for 20 to 40+ years.

INTRODUCTION

Chloride induced corrosion of reinforcing steel in concrete is a major problem worldwide. Chlorides can be introduced into the concrete via de-icing chemicals, seawater, or in certain cases as contaminants or additives in the initial concrete mix. This leads to localized breakdown of the normally passive steel reinforcement in the form of pitting corrosion (Figure 1).

Figure 1: Chloride-induced Pitting Corrosion on Concrete Reinforcement

Corrosion leads to concrete deterioration and local patch repairs are often performed to address this concrete damage. Patch repairs are completed by removing the cracked or spalled concrete, cleaning the steel locally and filling the cavity with fresh repair mortar or concrete (Figure 2[A]). Unless all chloride-contaminated concrete around the patch is removed, however, the repair process can lead to the formation of incipient anodes (Figure 2[A]), new corrosion sites just outside the repaired area driven by the difference in potential between the steel in the chloride contaminated and chloride-free sections [1,2].

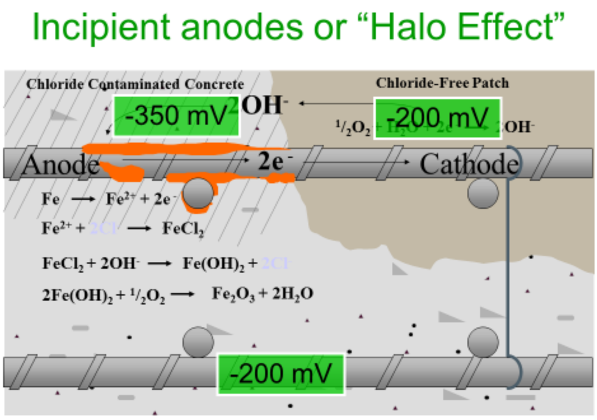

Figure 2[A]: Illustration of Corrosion around Concrete Patch Repair

Further repairs will be required and often, the whole repair process will need to be repeated several times over the remaining service life of the structure.

Installed Galvanic Anode

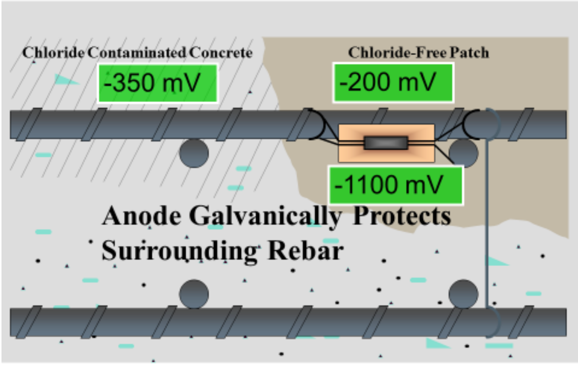

Figure 2[B]: – Illustration of Localized Galvanic Protection Protecting the Remaining Concrete Adjacent to Concrete Repair

This 'localized' problem has been eradicated by placement of discrete galvanic anodes around the perimeter of patch repairs (Figure 2[B]) which control incipient anode formation and avoid corrosion initiation [3,4]. One of the oldest monitored projects where such anodes were used has been monitored for over 16 years and is showing no signs of failure. The anodes are continuing to produce sufficient galvanic current to avoid corrosion initiation in the vicinity of the repairs, a phenomenon termed cathodic or corrosion prevention [5,6].

Similar galvanic anodes have been used in either a grid configuration or as elongated chains parallel to the main steel reinforcement to control low level steel corrosion in yet undamaged reinforced concrete elements which were shown to be at risk of corrosion or where incipient anode formation was considered to be a risk. This application is known as corrosion control where corrosion cannot initiate at new locations and locations where corrosion is already occurring is gradually reduced. These have also shown consistently good performance [7].

Continuous monitoring of field projects and further laboratory investigation has led to a better understanding of the performance and capability of galvanic anodes in a variety of environments. It is now recognised, for example, that chlorides are repelled away from the steel concrete interface owing to the negative charge which is imposed on the steel. This is aided by the cathodic reaction (1) and the migration of the alkali cations Na^+, K^+ & Ca^{++} to the steel which enhances the alkalinity around the steel. As a result, the chloride to hydroxide ratio $[Cl^-/OH^-]$, the primary parameter that determines the corrosivity of the electrolyte, decreases substantially, the passive film is reinstated and steel corrosion subsequently ceases.

$$\tfrac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^- \qquad (1)$$

PERFORMANCE OF GALVANIC ANODES

Specially designed galvanic anodes were first installed in the late 1990's to provide cathodic prevention (corrosion prevention) in concrete patch repairs. One of the first monitored installations was on a pier cap of a bridge in the UK (Figure 3).

Figure 3: Embedded Galvanic Anode Installation on a Bridge Pier Cap

A total of 12 anodes were installed at approximately 600mm centres along the perimeter of the repairs. The pier cap suffered from corrosion due to chloride contamination of up to 2% Cl^- by weight of cement at the depth of the steel. The galvanic anodes were connected to the steel via a junction box allowing monitoring of the current. Figure 4 summarises the mean current density delivered by the anodes to the steel. The range is comfortably within the 0.2-2.0 mA/m^2 current density suggested for cathodic prevention over the entire 15-year period (Figure 4). More importantly, there is no evidence of corrosion initiation either within or around the periphery of the patch repair. Removal and examination of two anodes showed that over half the zinc mass was still available for continued protection such that the service life of the anodes is likely to be 25 to 35 years.

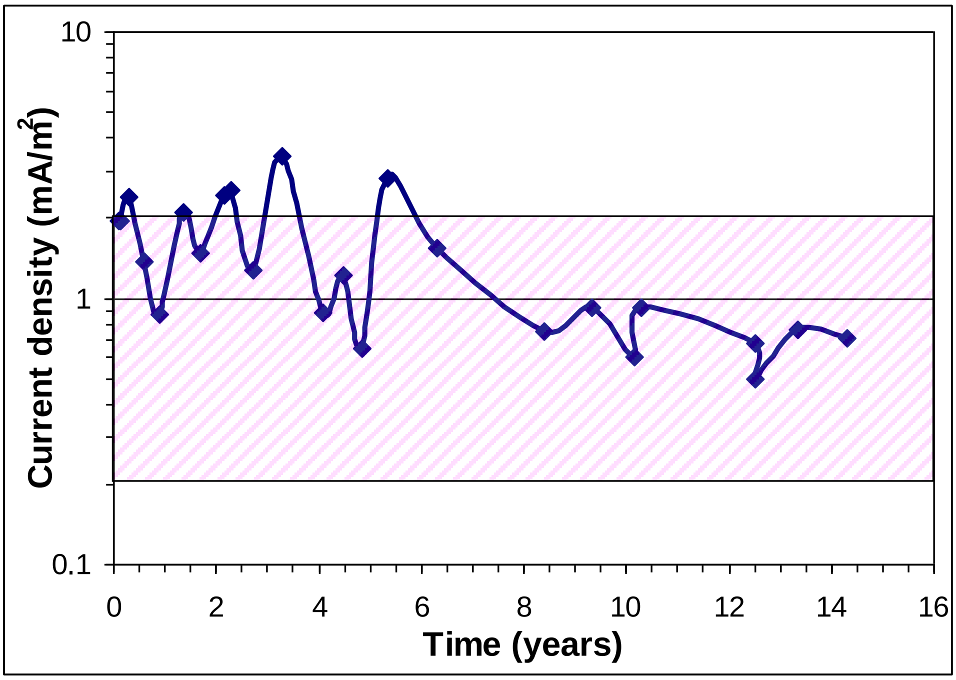

Figure 4: Current density to the reinforcing steel (mA/m^2) plotted vs time. Shaded area indicates current density for cathodic prevention (corrosion prevention) as per EN12696 (0.2 to 2.0 mA/m^2)

GALVANIC CATHODIC PROTECTION

Historically, cathodic protection systems required an impressed current power supply to provide sufficient current to the reinforcing steel. This is no longer the case as properly designed galvanic encasements using high output, long life distributed galvanic anodes can provide sufficient current density to polarize the reinforcing steel and meet all NACE Cathodic Protection (CP) criteria.

This portion of the paper describes four projects where long term cathodic protection has been provided galvanically to bridge abutments, decks and columns.

a) Ohio DOT Bridge Substructure
b) Ontario Ministry of Transportation Bridge Deck
c) New York State DOT Marine Columns (Tidal / Splash Zone)
d) Florida DOT Marine Substructures (Above Tidal Zone)

Ohio DOT Substructure

This bridge was repaired in July, 2005 with a galvanic encasement. The ODOT bridge substructure repair included re-facing the abutments of multiple bridges with distributed embedded galvanic anodes designed to provide cathodic protection (Figures 5 & 6[A]) for the steel in the entire abutment. The bridge has been monitored as part of an ODOT technology evaluation program since May, 2005. (Figure 6[B]).

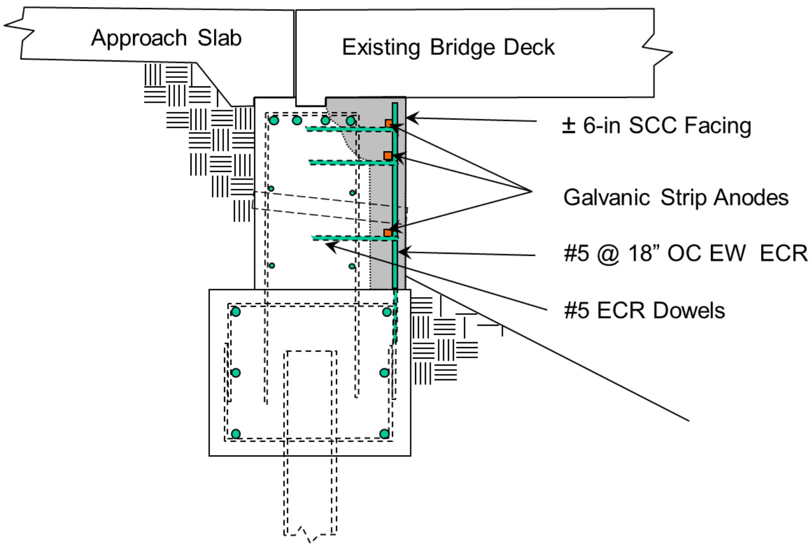

Figure 5: Galvanic Encasement of Abutment

Figure 6[A] –Galvanic Distributed Anodes Installed Across Face of Abutment

Figure 6[B]: Distributed Anode System Monitoring Cabinet

The monitoring program included the installation of dataloggers to monitor the current flowing from the galvanic anodes to the reinforcing steel as well as the temperature of the concrete itself (Figure 7). In addition to the dataloggers, current, potentials and polarization was measured manually when personnel visited the project site (Figure 8).

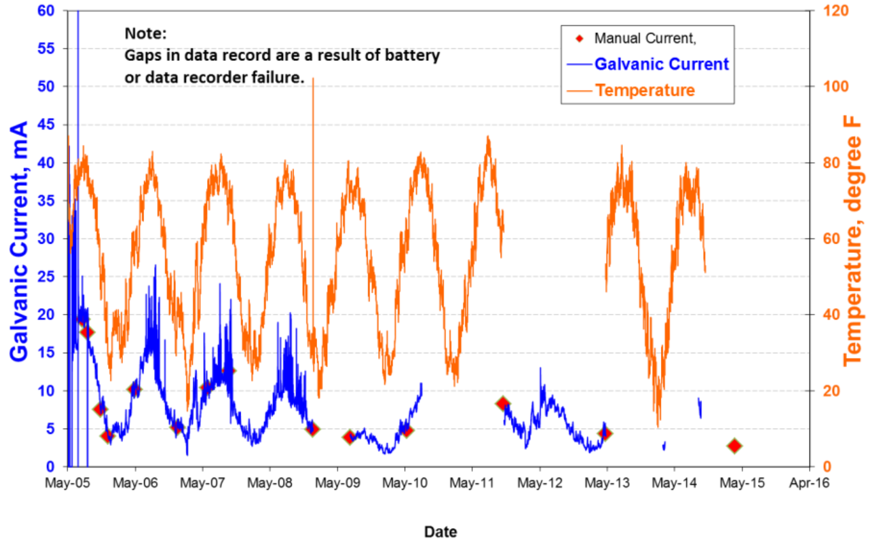

Figure 7: Ohio DOT Galvanic Current and Temperature History

Galvanic current data collected at regular intervals can be integrated to precisely calculate the consumption of the galvanic anodes. The calculated anode life is approximately 35 years. This calculation includes an anode utilization factor of 0.8 and an anode efficiency factor of 0.9.

Ohio DOT: Galvanic CP Data

Date	Temp	mA/m2	Polarization
5/6/05	(C)	37.7	(mV)
8/16/05	31	12.9	333
12/7/05	11	3.2	339
5/1/06	14	7.5	335
5/30/07	26	7.5	446
12/09/08	4	3.3	470
5/11/2010	12	3.3	485
10/16/2011	22	6.6	488
4/22/2013	21	3.3	425
3/24/2015	2	2.2	381

Figure 8: Ohio DOT Galvanic CP Polarization Data

The performance data indicates that the installed galvanic cathodic protection system is performing well. The following cathodic protection criteria are satisfied:

- Cathodic polarization shift exceeds 100 mV,
- the polarized instant-off potential has generally been more negative than -850 mV vs CSE, and
- Polarization of the reinforcing steel is requiring less current density over time. Calculated service life is now more than double the design service life as the average current density has been significantly less than the design current density.

The abutment is in very good condition 10 years after the galvanic encasement was completed. Prior to completing this galvanic encasement, this type of abutment was being repaired every 5 to 7 years.

The performance of this galvanic encasement installation verifies the system has been providing galvanic cathodic protection for over 10 years. Service life calculations indicate there is sufficient zinc for the system to provide corrosion protection for 35 years.

Ontario Ministry of Transportation (MTO) Bridge Deck Overlay

Due to long-term exposure to de-icing chemicals the bridge deck of the North Otter Creek Bridge (MTO) was chloride contaminated and required repair. In 2003, the Ontario Ministry of Transportation (MTO) decided to place a galvanic cathodic protection overlay on the bridge deck.

Figure 9: Bridge Deck after Milling

The bridge deck was prepared by milling off a portion of the existing concrete cover. As a result the majority of the existing reinforcing steel was to remain in chloride contaiminated concrete. A ‘distributed’ galvanic cathodic protection system consisting of elongated galvanic anodes placed in rows and connected to the existing reinforcing steel was installed. The galvanic anodes consisted of a zinc core encased in a low resistivity alkali-activated mortar shell and were prefabricated to fit the dimensions of the deck. (Figure 10)

A carbon fiber grid was installed to reduce shrinkage and minimize cracking of the 2.5 inch (60 mm) thick silica fume deck overlay (Figure 10).

Figure 10: Installation of Distributed Galvanic Anodes and Carbon Fiber Grid prior to Concrete Overlay

MTO Galvanic CP Bridge Deck Overlay

Date	Temp C / F	Current (mA)	Current/m2 (mA/m2)	Polarization (mV)
Oct. 3, 2003	7 / 45	169	6.5	273
May 10, 2004	20 / 68	99	3.8	271
Jan. 18, 2005	-20 / -4	14	0.55	142
July 27, 2005	20 / 68	47	1.8	313
Nov. 17, 2005	0 / 32	30	1.1	276
Apr. 19, 2006	10 / 50	38	1.4	330
July 26, 2006	25 / 76	43	1.6	353
Apr. 11, 2007	-3 / 27	27	1.0	201
Aug. 23, 2007	22 / 71	41	1.5	501
Jan. 10, 2008	0 / 32	29	1.1	322
May 12, 2009	21 / 70	38	1.4	285
Sept. 25, 2010	19 / 66	35	1.3	305
June 7, 2012	22 / 71	46	1.8	278
Nov. 7, 2013	4 / 39	29	1.13	388
Oct. 6, 2015	13 / 55	28	1.1	423

Figure 11: MTO Galvanic CP Bridge Deck Overlay Performance Data

The bridge deck has been monitored since 2003 and remains in good physical condition. The galvanic cathodic protection overlay is providing over 100 mV polarization and is meeting the NACE cathodic protection standard for cathodic protection (Figure 11) even though the anodes are in a dry environment beneath the silica fume concrete overlay and bridge deck waterproofing system installed on top.

New York State DOT Marine Columns (Splash Zone)

In 2006, New York State DOT completed a project on the Robert Moses Causeway to Long Island, NY (Figure 12[A]). The project included installation of galvanic cathodic protection jackets to protect the tidal and splash zone of 764 columns (Figure 12[B]).

Figure 12[A]: Alkali-activated Distributed Galvanic Anodes for Pile Protection on the Robert Moses Causeway

Figure 12: FRP Concrete Placement and Jacket Elevation at High Tide

Monitored jackets have met cathodic protection criteria by providing greater than 100 mV polarization. NYSDOT specified a 35 year design service life for the column jackets. Service life calculations based on data from monitored jackets predicts that the system contains enough zinc to last over 70 years.

Florida DOT Marine Columns (Above Splash Zone)

These Florida DOT marine bridges located in south Florida and the Florida Keys were suffering from corrosion due to chloride contamination from storm surges and atmospheric exposure (Figure 13).

Figure 13: Deteriorated Columns and Removal of Damaged Concrete

Florida DOT has utilized other corrosion protection options such as arc-sprayed zinc and zinc mesh jackets on this type of structure in the past with limited success. These projects utilized distributed alkali activated galvanic anodes installed inside stay-in-place forms (Figure 14).

Figure 14: Installation of Alkali-Activated Galvanic Anodes and Jacket

The stay-in-place form can be fiberglass or PVC with PVC having the advantage of being modular and providing greatly improved durability and bonding with the concrete column.

Figure 15: Installed PVC Galvanic Cathodic Protection Jacket with Monitoring Station

As with all FDOT projects, monitoring provisions were provided when the column jackets were installed such that the long-term performance and effectiveness in providing cathodic protection could be verified (Figure 15).

FDOT has used zinc mesh galvanic jackets to protect reinforcing steel in the splash zone. Research has shown these jackets to be effective if they are kept wet but the zinc mesh will become more passive and generate less protective current for each foot of elevation above the high tide line. Since these columns are fully above the high tide line activated zinc anodes were specified and installed (Figure 16).

Figure 16: Installed Above-Water Alkali-Activated Galvanic Cathodic Protection Jackets

The alkali-activated galvanic cathodic protection jackets are installed and are being monitored by FDOT. Monitoring parameters include potentials, current, polarization and service life. Due to the number of monitored columns, the raw data is too voluminous to present herein. Since the first columns were completed in 2012, the jacketed columns have met or exceeded the NACE cathodic protection criteria by polarizing the reinforcing steel more than 100mV.

	mA	On (mV)	Off (mV)	Pol. (mV)	Notes
Static/native		-458			
On	725				
16 hrs	228	-997	-825	-367	vs static
20 days	98	-931	-652	-238	4 hours
90 days	72	-912	-657	-293	21 hours
118 days	n/a	-905	-667	-205	vs static
270 days	54	-867	-664	-236	2 hours
594 days	67	-924	-679	-330	14 hours

Figure 17: Long Term Monitoring of Alkali-Activated Galvanic Cathodic Protection Jacket in the Florida Keys

CONCLUSIONS

- Alkali-activated discrete galvanic anodes installed in the 1990’s remain active and have provided Corrosion Prevention (Cathodic Prevention) current densities to reinforcing steel adjacent to patch repairs for over 15 years. Examination of anodes verify there is sufficient zinc remaining to last 25 to 30 years. As such, alkali-activated discrete galvanic anodes in patch repairs provide a low cost and simple to monitor approach which can significantly extend the service life of localized concrete repairs.

- Galvanic anode systems can be designed to meet cathodic protection criteria by polarizing the reinforcing steel by 100mV or greater.

- Galvanic cathodic protection systems can be designed to provide low maintenance cathodic protection for 20 to 40+ years.

- Current densities required to polarize the reinforcing steel typically decrease over time as hydroxide ions are generated at the steel / concrete interface and the steel becomes more passive. As a result, actual service life may be greater than the calculated design service life since the average current density may be less than the design current density.

- Galvanic cathodic protection systems can be designed to provide long-term cathodic protection to structural concrete components in a range of environments including:
    - Bridge substructures in temperate, de-icing salt environments,
    - Bridge decks in temperate, de-icing salt environments,
    - Bridge piles in marine tidal / splash zones, and
    - Bridge columns in tropical, marine environments above the tidal zone.

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