On Site Monitoring of Corrosion of Marine Structure Using Self Sacrificial Galvanic Anodes – Case Study

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***Abstract*- In recent years, focus has been shifting towards repair and rehabilitation of deficient concrete infrastructures rather than replacement, either in full or replacing the structural members. While carrying out the rehabilitation, one should keep in mind that the methodology should have cost effective strategy and durability. The deterioration caused by the corrosion of reinforcing steel in concrete structures has been recognized as one of the greatest maintenance challenges being faced by many government agencies and other private owners including the engineering contracting companies in the field of construction industry today. Technological advances have created a wide range of new product and systems, which claim to provide long-lasting protection and serviceability for these structures. Usage of different types of surface coating on rebars for the corrosion protection is no longer a proven system on account of many reasons like, reduction in bond stress between the concrete & rebar and so on. Also in the eventuality of rehabilitation of structural elements after a few years, the entire process including chipping the cover concrete, exposing the rebar, cleaning rebars, applying corrosion protection coating to the rebar, providing formwork, pumping of micro concrete, etc., becomes cumbersome and uneconomical in addition to a lot of disturbance to the occupants. However, in order to effectively address the problem it is essential to first understand the cause of the corrosion. The paper describes in detail the philosophy of the corrosion and evaluates the effect of having anodes installed in the concrete members. The paper also describes in detail investigations conducted on a corrosion damaged marine structure at main land and also at an Island, and the repair methodology suggested for the rehabilitation of the structure and executed. The repair methodology proposed included the provision of galvanic anodes. The data presented on the monitoring of the repaired marine structures through half cell potential test conducted over a period of one year from the time of completion of the repair to assess the effectiveness of the sacrificial anodes. The investigations have clearly demonstrated that galvanic anodes have proved to be an effective corrosion control technique for reinforced concrete structures.**

Keywords*- Corrosion; Galvanic Anodes; Concrete; Half Cell Potential; Rehabilitation; Marine; Methodology; Reinforcement; Cos; Micro Moncrete; Shear Connector

I. INTRODUCTION

Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, especially of the structures located in the coastal marine environment leading to the failure of the structures. It is well known that reinforced concrete is a versatile, economical and successful material. It is durable and strong, performing well throughout its service life. However, the corrosion of reinforcing steel in concrete is increasingly becoming a major durability issue leading to the failure of reinforced concrete structures as engineers maintain an aging infrastructure in recent years [1]. In the case of reinforced concrete structures affected by chlorides, the protective film in the reinforcing rods is destroyed. Hence, the reinforcing steel is passivated when sufficient chloride ions have penetrated to the reinforcement. Corrosion in the form of rust formation and/or loss in cross section of the reinforcing steel occur in the presence of oxygen and water [2].

Corrosion loss consumes considerable portion of the budget of the country by way of either restoration measures or reconstruction. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Many new systems and materials have been developed to delay the onset of corrosion and to increase durability. However it has only limited success in delaying the corrosion. In view of economical and engineering points, quantitative assessment of corrosion is also important.

This paper reviews the performance of the anodes installed in two marine structures rehabilitated using the sacrificial anodes, one at the main land in Chennai, Southern part of India, and the other at a highly corrosive environmental zone Andaman and Nicobar Islands, India. The repaired area remained intact with no signs of deterioration or formation of incipient anodes around the periphery. The results show that the anodes continue to deliver a significant current. This paper explains in detail about the usage of sacrificial anodes, which can postpone corrosion in rehabilitated concrete structures.

II. CORROSION

The corrosion of steel in concrete is an electrochemical process [3], where at the anode, iron is oxidized to iron ions that pass into pore solution and at the cathode, oxygen is reduced to hydroxyl ions. Anode and cathode from a short-circuited corrosion cell, with the flow of electrons in the steel and of ions in the pore solution of the concrete. The resulting local loss in cross section has dangerous implications for the structural safety, if the corroded steels are located in a zone of high tensile or shear stresses.

Usually, the steel embedded in concrete becomes passivated due to the initial high alkalinity (12 < pH < 13) of the pore solution. However, the protective film is destroyed and the reinforcing steel is passivated when sufficient chloride ions have penetrated to the reinforcement or when the pH of the pore solution drops to low values due to carbonation. Corrosion in the form of rust formation and/or loss in cross section of the reinforcing steel occur in the presence of oxygen and water. The corrosion between actively corroding areas of the reinforcing steel and passive areas is of great concern because it results in very high local anodic current densities with corrosion rates of 0.5 to 1mm/year [4].

Corrosion within concrete structures is commonly caused by either the presence of sufficient concentrations of chloride ions or carbonation. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete. Fig. 1 shows the typical result of the cracking due to the expansive stresses on account of the corrosion.

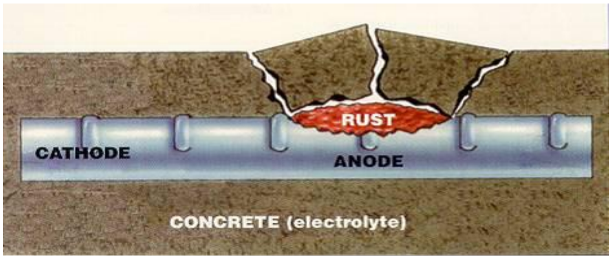

Fig. 1 Typical result of cracking

III. GALVANIC ANODES

Galvanic corrosion protection methods were originally developed in the 1820s. Over the years, galvanic corrosion protection systems have been widely used to protect underground steel structures, such as pipelines and tanks. Galvanic protection systems were first used in reinforced concrete structures in around 1960.

Embedded galvanic anodes are galvanic devices designed to neutralize or slow down new corrosion cells, which would otherwise develop around a patch, thereby extending the service life of the repair. These discrete units are designed to be attached to the rebar and incorporated within the patch repair. Based upon principles used for protecting pipelines and ships from corrosion, these anodes are “sacrificial” in nature. The anodes take advantage of the natural galvanic differences which exist between different metals.

The heart of the device is a metallic anode composed of zinc, which is cast around a pair of steel tie wires. This unit is encased within a cementitious shell. The device is shaped like a short cylinder, about 2.5 inches in diameter and 1 inch thick. The tie wires extend out on the opposing sides of the anode to enable it to be tied to the reinforcing steel. Fig. 2 shows the typical view of different galvanic anodes being used in the repair and rehabilitation of RC structures, and shows a cut-away view of a sacrificial galvanic anode.

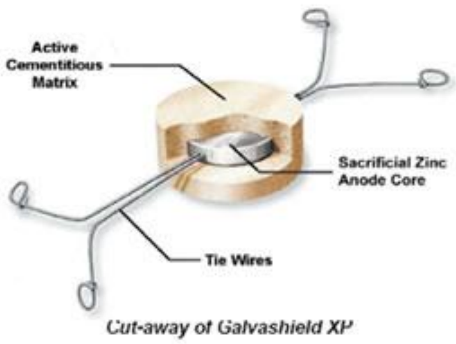

Fig. 2 Cut away section of anode

Sacrificial anodes used for galvanic protection are typically constructed using aluminum, magnesium or zinc. For reinforced concrete applications, zinc has become the most common sacrificial anode used presently. There are several reasons for the usage of zinc.

1. Zinc has high corrosion efficiency i.e. high percentages of the electrons that are discharged as the zinc corrodes are available to protect the steel.

2. As zinc corrodes, it has a relatively low rate of expansion compared to other metals including steel. This makes zinc anodes particularly suitable for application where the anodes are embedded in to the concrete structure.

3. Zinc anodes are suitable for use in prestressed and/or post-tensioned concrete because their native potential is generally not sufficient to generate atoms or cause hydrogen embitterment in a concrete environment.

Zinc anodes are covered with a precast mortar matrix saturated with lithium hydroxide (LiOH). These anodes are designed to be tied directly to the reinforcing steel to extend the life of concrete patch repairs. Because of its simplicity in installing, the sacrificial anodes both in the case of initial construction stage as well as the repair/rehabilitation after few years during the maintenance of the structural members are the better methodology in corrosion protection of the reinforced concrete members.

IV. CASE STUDY DETAILS

A. Description of Structure

1) Case Study 1: Main Land at Chennai Port Trust in Southern Part of India:

Chokani Finger Jetty is an existing jetty on north Groyne with a berthing face of 218m on east and west side. It is 12m wide throughout its 218m length. It is an open type piled jetty supported on piles. The main components of the jetty are as follows:

a) The jetty was built on 95 piles arranged in four rows, the intermediate rows having 22 piles in each row, the eastern row having 23 piles and the western row having 28 piles.

b) The spacing between two piles was observed as 3.330m in transverse direction and were varying between 10.00m to 11.30m in longitudinal direction except at twin pile locations.

c) Fenders were fixed by the modified pile muffs; the size of the fenders are 1.85 m to 1.9 m in longitudinal direction and 2 to 2.25 m in transverse direction and height of about 3.4 m up to the bottom of deck slab.

The following are the beam sizes on the jetty:

- Longitudinal beams: 1000mm x 400mm (excluding deck slab);
- Transverse beam: 1000mm x 750mm (excluding deck slab);
- Slab thickness: 400 mm with wearing coat;
- Top level of the deck Varies: between +4.5 to +4.15 m.

2) Case Study 2: Island at Andaman Nicobar Island:

The main components of the approach portion of the Fisheries jetty approach situated at Port Blair, Andaman and Nicobar Islands are as follows:

a) The Fisheries jetty approach was built on 78 numbers of precast driven piles consisting three rows;

b) The pile size are 400mm x 400mm;

c) The spacing between two piles was observed as 3.0 m.

The following are the beam sizes on the Fisheries jetty approach:

a) Longitudinal beams: 350 mm x 400 mm (excluding deck slab);

b) Transverse beams: 350 mm x 400 mm (excluding deck slab);

c) Slab thickness: 250 mm without wearing coat.

The cast driven piles head were broken after complete driving and the rebars were exposed. With these dowel rebars, the reinforcement of the longitudinal and cross beams were connected as per the detailing followed by in-situ concreting of beams and deck slab.

B. Test Adopted

Non destructive tests, viz., Ultrasonic pulse velocity, Rebound hammer test and extraction of powder samples for chemical analysis were carried out. In both cases, the chloride content was much more than the threshold limit of 0.6 kg/m^3. However, in this paper the post repair monitoring where the performance of the self sacrificing anodes are discussed.

The half cell potential survey was conducted before taking up the work. This method covers the estimation of electrical half cell potential of reinforcing steel in concrete, for the purpose of determining the corrosion activity of the reinforcing steel. Fig. 3 shows the typical view of half cell potential reading being taken on site.

As a copper-copper sulphate (Cu-CuSo4) electrode (reference electrode), half cell is used in this test. It consists of rigid tube of electric material that is non reactive with copper or copper sulphate, a porous wooden plug that remains wet by capillary reaction and a copper rod that is immersed within the tube in a saturated solution of copper sulphate. The solution was prepared with reagent grade copper sulphate crystals dissolved in distilled water. The solution was considered super saturated when an excess of crystal (undissolved) lies at the bottom of the solution.

Fig. 3 Typical view of onsite measurement of half cell test

In each pile, above sea level approximately 250mm x 100mm grids were marked and the piles were pre-wetted before taking the half cell potential reading. Half-cell potentiometer works on the principle of measuring voltage in the circuit of reinforcement and cover concrete using Copper Sulphate Half-Cell. This method essentially consists of measurement of the absolute potential of the concrete with reference to the reference electrode. Half Cell Potential Measurement Test (HCPT) was carried out on the RC structural elements of the selected locations on the piles. The reference guideline ASTM C-876 is presented in the following Table 1.

TABLE 1 ASTM C-876

Sl.No	Measured Potential Difference	Probability for Corrosion
1	More Negative than (-) 350 mv	High Probability of Corrosion
2	Between (-) 200 mv to (-) 350 mv	Uncertainty of Corrosion
3	More Positive than (-) 200 mv	High Probability of No Corrosion

Even though this method has serious limitations and liability to yield erroneous inferences, this method is still widely used and is being recognized to be useful with the availability of more and more authoritative reports and data.

C. Repair Methodology

The slab and pile caps were properly supported near the pile before chipping the spalled/loose concrete from face of the piles. The heavily corroded pile liner were cut and removed from -0.20 by using under water cutting gear in case one. In the case study 2, this was not required as there was no pile liner. Fig. 4 shows the typical corroded members view pertaining to the case study 1. Fig. 5 shows the typical over all view of the jetty approach portion and a beam with spalling. All the spalled and cracked concrete or any other pre-applied mortars were removed by chipping to expose the reinforcing steel. The concrete was removed about 20mm behind the rebars. The piles/column for surface preparation were selected in such a way that no two adjacent piles/columns were chipped off at a time. In fact, every 4th pile was chipped and after the rehabilitation of these, the other piles/columns were taken.

Fig. 4 Typical view of corroded member - Case 1

Fig. 5 Typical view of corroded member - Case 2

As the concrete would have got contaminated with chloride, these chipped of surfaces were cleaned by flooding potable water using high pressure water jet equipments. The exposed rebars were also cleaned with high pressure water jet and also by means of mechanical cleaning where ever required. The existing corroded rebars were coated with zinc based protective coating. As the section needs to be increased to take care of the loading in the Case 1 and the corroded rebar diameter were reduced more than 50% in Case 2, shear connectors were provided at every 500mm c/c on the faces of piles and pile caps in staggered manner. The holes were washed well and shear connectors were anchored using polyester resin. The additional reinforcement was tied and also welded at a few places to the shear connectors so that the connectivity in the structure is ensured.

The form work for the required size & shape was kept ready and a trial was conducted before fixing the same for the micro concreting. This was done at every pile/column so that when the epoxy jointing compound was applied to the form work, the micro concrete can be completed well within the tacky stage or otherwise this would act as a debonding layer. Fig. 6 shows the typical view of the epoxy jointing compound with the sacrificial anode installation in the case study 1.

Fig. 6 View of additional rebars, poxy & rnode installed

Two component epoxy resin jointing compounds were applied, since the chloride ions were expected to be in core concrete and this membrane would arrest the ingress of chloride ion from the core concrete to the newly laid micro concrete and also act as jointing compound. The self regulating galvanic anode Galvashield XP is an amphoteric zinc block embedded within specially formulated cementitious mortar having a pore solution pH which is sufficiently high for corrosion of the anode to occur. Galvashield XP was positioned to ensure all round contact with the reinstatement material and attached to the reinforcement using the wire ties. Tightening of the wire ties was carried out using the Galvashield Fixing Tool so that no free movement is possible, thus ensuring the electrical continuity. To test electrical continuity between wire ties and reinforcement bar continuity meter, a voltmeter was used. Fig. 7 shows the closer look of the installed self sacrificing Galvanic anodes in the case study 2.

Based on the quantity of the steel provided, the required calculation was made for estimating the number of anodes to be provided. It was arrived to install 1 number per Sq. M surface area of the concrete in Case1 and 1 number per 0.75 Sq. M in Case 2. The connectivity was checked before and after installation of the self regulating sacrificial anodes. Leads were taken from the steel and also from the sacrificial anodes to the junction boxes, which were fixed on the surface of the micro concrete, so that the readings can be taken when required. Fig. 8 shows the typical view of the corrosion monitoring box.

Fig. 7 Closer view of anodes installed

Fig. 8 Typical view of corrosion monitoring box.

The members below water level were jacketed with under water micro concrete, which has anti wash & non-shrink properties. Above the water level, non-shrink free flow micro concrete was used. Both were grades of M45. As the thickness of the section to be jacketed was large, 12 mm downgraded aggregates were added at the rate of 1:1 by weight of the ready to use under-water/micro concrete. Fig. 9 shows the typical view of under-water/micro concrete and regular micro concrete done for the rehabilitated members.

Fig. 9 Typical view of rehabilitted members

The surface areas of the members which are above the water levels were applied with acrylic based curing compound immediately after the stripping of formwork. After completion of all the works, the exposed jacketed surface was coated with silane/silaxone based primer, which can prevent the ingress of chloride ions and then coated with two coats of acrylic aliphatic based protective coating to prevent the carbonation in addition to addition to UV stability. Fig. 10 shows the typical view of protective coating done on the micro concreted members in the case study 2.

Fig. 10 Typical view of the protective coating

V. POST TEST PERFORMANCE

Normally the experience of the maintenance engineers is that within a year, the corrosion cracks reappear at the neighboring places. To check the performance of the repair methodology adopted, especially the provision of the self regulating galvanic anode Galvanic anode, Half cell potential survey was conducted.

In the case of case study 1, after the completion of rehabilitation of Chockani Finger Jetty in the main land half cell potential measurements were conducted on the pile immediately after the completion of the repair & rehabilitation, and after 6, 12, 18 months from the time of completion of the rehabilitation. In the case of case study 2, after the completion of rehabilitation of Fisheries jetty approach in Andaman & Nichobar Island half cell potential measurements were conducted on the pile immediately after the completion of the repair & rehabilitation after one year. Fig. 11 shows the view of the half cell potential test in progress after the rehabilitation. Care was taken to ensure that the same locations before repair were again subjected to half cell potential test to assess the efficiency of the self regulating galvanic anodes.

Fig. 11 Typical view of half cell meastuement after rehabilitation

Discussion based on the half cell readings with respect to the case study 1 is as follows. The half cell readings were taken before, after completion of the rehabilitation, after 6, 12, 18, and 24 months from the date of completion of the rehabilitation. The average values of the half cell potential reading in each location are shown in the chart respectively. The values are very low and it is evident that the system is working well in terms of corrosion protection. Also it is to be noted that the values are well within -100mv . The graphical representation are given in Fig. 12 to Fig. 15.

CASE STUDY 1 – HALFCELL POTENTIAL VALUES

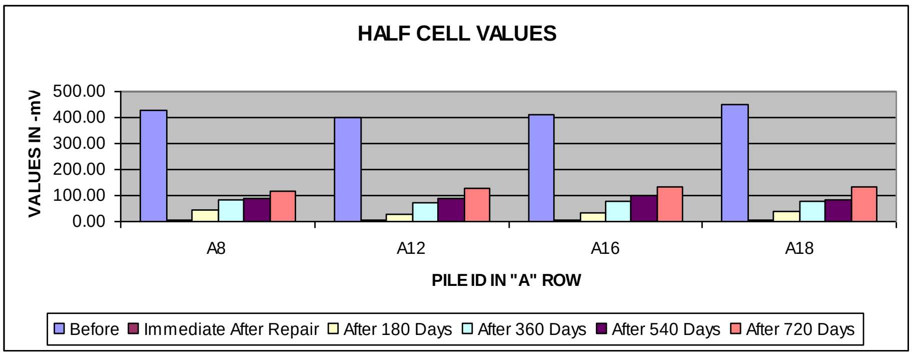

Fig. 12 Half cell values in “A” row

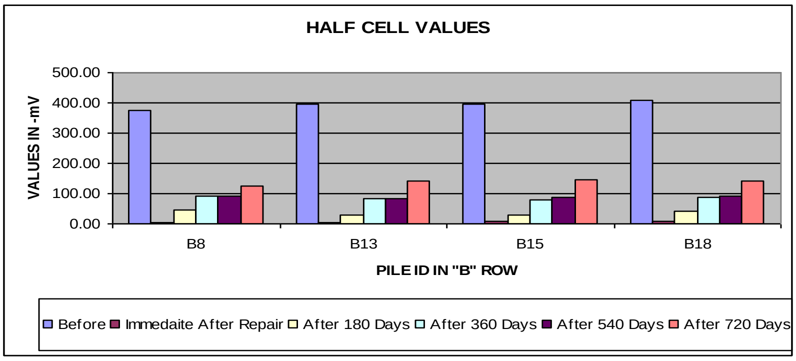

Fig. 13 HalfCell values in “B” Row

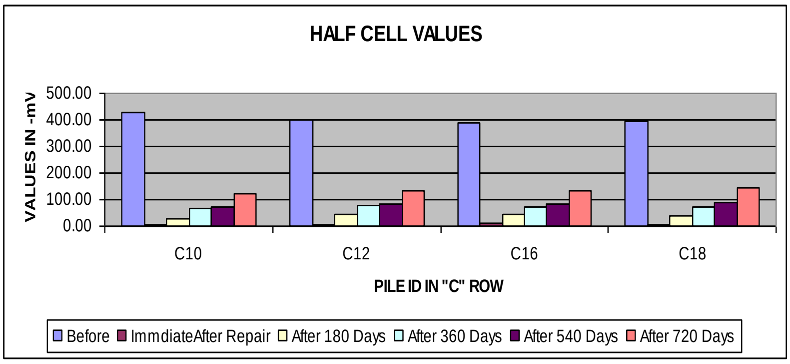

Fig. 14 Half cell values in “C” row

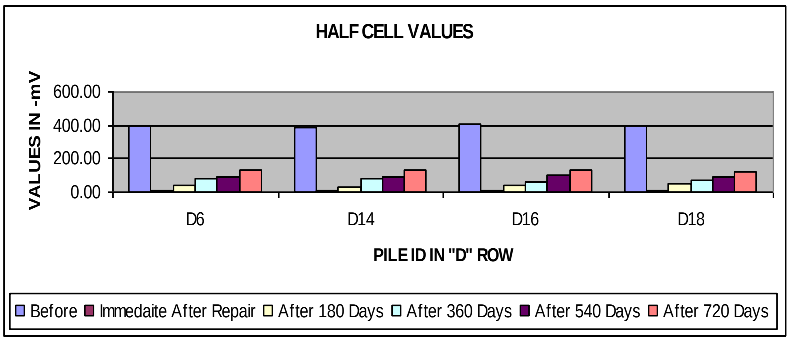

Fig. 15 Half cell values in “D” row

With respect to the case study 2, the half cell readings were taken before and after completion of the rehabilitation and at interval of one year from the date of completion of the rehabilitation, are shown below in the chart. The half cell potential reading values show values more positive than -200 mV at the end of 1 year and as per the recommendations of ASTM C-876 the rehabilitated structural members have high probability of no corrosion. The graphical representation is presented in Fig. 16. Hence, it is clearly evident that the self regulating galvanic anode system is performing well in terms of corrosion protection.

CASE STUDY 2 – HALFCELL POTENTIAL VALUES

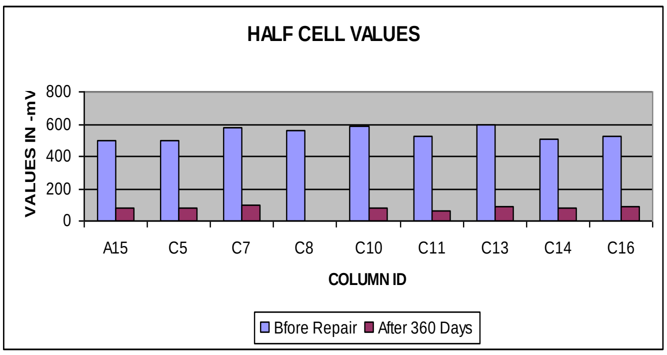

Fig. 12 Half cell values in selected columns

VI. CONCLUSION

The above said real time projects have not shown any distress on account of corrosion. The experience of the marine engineers is that normally after the repair of the corrosion affected marine structures with the normal anti corrosive surface coating on the rebars gives way after a year i.e. the corrosion reoccurs resulting in repairment. In the case of self regulating sacrificial anodes i.e. the galvanic protection system is serving well and from the half cell potential readings, this may continue to perform well for a few more years without any problem. In addition to that, even if the corrosion reoccurs after say 5 years, it is required only to cut open the particular place to install another piece of self regulating anode rather than redoing the entire operation.

Thus it is concluded that the galvanic protection using the self regulating sacrificial anodes are technologically and commercially a viable system to be adopted in general.

VII. ACKNOWLEDGEMENTS

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