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Latest trends in corrosion control for new reinforced concrete structures and a new concept for intelligent structures

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ABSTRACT

In recent years, increased service life and structural monitoring requirements are often specified for major bridges which will be built in a marine environment.

Previously, different measures were considered to improve the durability of these new structures. These measures included the modification of concrete mix design; an increase in the cover to reinforcement; application of protective coatings; use of corrosion resistant reinforcement; and the use of corrosion inhibitors.

With the advancement of structural health monitoring, communication and corrosion technologies in recent years, advanced technologies such as the application of cathodic prevention during construction, structural health monitoring and corrosion monitoring systems are being specified. The combined use of these technologies in one application is the first step in making the new generation of marine structures “intelligent” and providing long term, cost effective monitoring and corrosion control for new structures.

This paper will review the most common corrosion prevention measures for reinforced concrete structures in the marine environment and will outline a concept for future “intelligent” structures that can incorporate under one platform and as needed, based on specific conditions, structural health monitoring, corrosion prevention and corrosion monitoring systems. In addition, this paper will also present case studies for two bridges in Finland and Australia where some of these technologies have been incorporated during the construction phase.

Key words: *structural health monitoring, corrosion, cathodic prevention, monitoring, durability, intelligent structures, marine environment, fibre optic, sensors, anodes.*

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INTRODUCTION

Today there is a significant trend towards the design of large complex bridge structures with unusual configurations. Owners are seeking to build bridges that make a design statement rather than relying on traditional simple forms of bridge design. Building these structures with complex structural elements, located mostly in harsh marine environments, would normally require incorporating structural health monitoring and corrosion control systems during the construction phase. This verifies the design assumptions; provides corrosion prevention to critical high risk corrosion members; and detects and locates damage that is difficult to identify by visual inspection alone, such as fatigue or hidden corrosion that may occur during the service life of the structure.

STRUCTURAL HEALTH AND CORROSION MONITORING

Structural Health Monitoring (SHM) is a management tool intended to deliver information on the state of the given structure. A common misconception that exists about monitoring is that it is primarily a security tool. While monitoring can play an important security role for structures where failure may have disastrous consequences, (for example, nuclear waste containment vessels, bridge decks, dams, and structures under construction) in most cases monitoring serves a more prosaic purpose: gathering information in order to anticipate maintenance needs and identification of safety concerns.[1,2] Most civil structures contain steel, either as the main structural component (bridges and skyscrapers) or as reinforcement for concrete (dams, buildings, bridges and marine platforms for example). The presence of water, pH variations, exposure to chlorine (either de-icing salts or coastal wind) are the usual suspects for degradation of concrete or corrosion of steel.[2] Therefore, monitoring the presence and concentration of these factors becomes a necessity.

Government infrastructure departments in various countries have recognized the need for improving the capabilities of current visual inspection through the development of more reliable and less expensive methodologies to assess the structural health of structures, particularly large structures such as cable-stayed bridges.

In a cable stayed bridge for example, millions of dollars are invested in fitting out the bridge with hundreds of transducers (accelerometers, displacement transducers, inclinometers, temperature gauges, corrosion sensors, etc.) for monitoring its ambient and structural static and dynamic behavior. Data from these instruments is acquired by means of a data acquisition unit and data is sent through a serial cable or wireless to a central station for processing. Finally, this information is downloaded to a computer at the monitoring station for further analysis.

SHM helps in defining the critical response of a structure to track and evaluate the symptoms of operational incidents, anomalies, deterioration, and damage that may impact the structure's serviceability and safety. SHM can achieve the goals of an effective infrastructure maintenance methodology by providing the following information:

- Knowledge on static and dynamic behaviors of civil infrastructure;
- Improved understanding of design assumptions (boundary conditions);
- Study of the performance of different design philosophies and construction techniques;
- Development and tuning of the corresponding numerical model (FEM);
- Evaluation of short-term impact due to natural hazardous events (earthquakes);
- Evaluation of short-term impact due to man-made activities (rehabilitation, retrofitting, expansion);

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- Determination of actual load carrying capacity and monitoring of long-term deformation due to operational loading;
- Monitoring of long-term deterioration due to physical aging;
- Investigation of the pattern of environmental variation and influence on measurements (temperature fluctuation);
- Providing health-related information for civil infrastructure management as a basis to optimize the allocated resources; and
- Extending the service life of structures by adequate repair and retrofit efforts.

SHM has been introduced into the regime of civil engineering as a potential and effective methodology for structural assessment. Deploying a reliable SHM system (which includes sensors, data acquisition, power supply, data transmission, data storage and mining, data processing, data interpretation and error-free-feedback systems) into civil infrastructure systems is driven by rational engineering motivations, such as the potential merit in assuring safety and in saving future cost of maintenance.

CORROSION PREVENTION FOR REINFORCED CONCRETE STRUCTURES

Reinforced concrete is a composite material that relies on the high compressive strength of concrete and the high tensile strength of steel for its mechanical performance. Steel has poor corrosion resistance and concrete has good anti-corrosion properties. The hydration process of concrete leads to the formation of hydroxides which raises the pH level of the cement to around 12.5 and provides a stable oxide layer on the steel surface, which prevents the anodic dissolution of the steel. Reinforced concrete failure is caused by the corrosion of the steel reinforcing bars as a result of the destabilization of the oxide layer. When the passivity of the steel partly or completely breaks down, either as result of carbonation or chlorides, the corrosion will start. This means that the electrochemical potential of the steel locally becomes more negative and forms anodic areas, while the other portions of the steel which have the passive layer intact will act as catchment areas for oxygen and will form cathodic areas. In spite of the development of high performance concrete from the early 1970s until today, it is evident that the application of high performance concrete in conjunction with measures such as protective coating, thick concrete cover and corrosion inhibitors is not necessarily good enough for ensuring high durability of concrete structures in marine environments. For this reason, various corrosion prevention measures have been used and specified for new reinforced concrete structures to be built in marine environments.

CORROSION PREVENTION MEASURES

Measures for corrosion prevention include: modifying the concrete mix design to decrease concrete permeability; provision of an adequate cover to reinforcement; coating application to limit chloride ingress into the concrete; use of corrosion-resistant reinforcement; addition of inhibitors to the fresh concrete; and cathodic prevention by impressed current.

Mix Design, Concrete Cover and Coating Application

The quality of concrete is of major importance in determining the durability of reinforced concrete structures. Although concrete is a dense material, it contains pores and many of these pores are interconnected to form a network of channels that allow water and oxygen, both important to steel corrosion, to penetrate into the concrete. For this reason, a low water/cement ratio will lead to either a lower number of pores or smaller pores in the concrete, both of which can lead to a reduction of concrete permeability and to conductivity of the concrete. In addition to selecting a lower cement ratio

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in the concrete, the selection of the cement type and the addition of mineral admixtures such as silica flume, fly ash and slag will play a significant role in reducing the corrosion rate of reinforcement in concrete.

An adequate layer of concrete to the first layer of reinforcing steel may under some circumstances, delay the ingress of chloride ions. The adequate depth of concrete cover is normally stated in various standards, subject to the exposure condition of the structure. The minimum depth of concrete cover must be adjusted to allow for tolerances caused by construction practices.

For dense, high quality concrete with adequate concrete cover, carbonation induced corrosion of the embedded steel is not considered to represent a major problem, however, for concrete structures in marine environments, regardless of the quality of concrete and the thickness of the concrete cover, it appears that it is only a matter of time before detrimental amounts of chloride reach the embedded steel through the concrete covers or concrete cracks and cause reinforcement corrosion and concrete spalling.

The penetration of chloride takes place through uncracked concrete mainly by capillary absorption and diffusion. When relatively dry concrete is exposed to salt water, the concrete will absorb the salt water relatively fast and wetting and drying of the concrete especially in tidal zones can accelerate the accumulation of a high concentration of salt in the concrete. Furthermore, similar areas of concrete with similar exposure conditions will have variation in the concrete deterioration process as it is very difficult to ensure homogeneity of concrete after being placed.

In certain applications where a 100 year design life requirement is specified for structures located in marine environments, the use of various chloride diffusion modelling, carbonation modelling and durability assessment of other deterioration mechanisms may lead to the theoretical development of concrete mixes and design covers that may provide theoretically a 100 year design life. There is no doubt, that the use of such concrete will lead to a substantial increase in the design life of a structure in a harsh marine environment, however there are many other factors that could not be considered in the modelling process, such as concrete cracking; the wetting and drying effect in accelerating the rate of chloride penetration; early-age exposure to seawater before the concrete has gained sufficient maturity and density; high temperatures during concrete placement; homogeneity of the concrete; workmanship problems especially in relation to concrete cover; and finally, the nature of the formation of the corrosion cell due to chloride ingress within the structure which only requires ingress of chloride to the steel level at various crack locations to start the development of unlimited numbers of corrosion cells within the concrete itself.

Coating the external surfaces of concrete may in some circumstances, assist in delaying the onset of reinforcement corrosion. In a marine environment, especially in the tidal and splash areas, it is unlikely that such a measure will be effective in preventing reinforcement corrosion. The main reasons for this are the difficulties in achieving adequate bond to wet concrete and the effect of wetting and drying on accelerating deterioration of the coating.

Corrosion Resistant Reinforcement

The final and most important line of defense against corrosion is the reinforcing steel. As a measure for preventing the corrosion of steel in building concrete, various types of corrosion resistant reinforcement have been used in the past.

Epoxy coated reinforcement.

Epoxy coated rebars are carbon steel coated with stable organic coatings (epoxies) to serve as a barrier for isolating the steel from moisture, chloride ions and oxygen to prevent corrosion.

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Epoxy coated rebars were introduced in the mid 1970s in the United States as a means of extending the useful life of reinforced concrete bridge components by minimising concrete deterioration caused by corrosion of the reinforcing steel. The epoxy coatings are intended to prevent moisture and chlorides from reaching the steel.

There are various documents regarding this subject with some showing favourable performance of epoxy coated rebars especially when used in areas of low corrosion risk.

When epoxy coated rebars have been used in substructures that are exposed to a severely corrosive environment, the epoxy coated rebars did not perform well. Significant premature corrosion of the epoxy coated rebars was observed in many structures after 5-10 years from the date of construction.

The main reasons for the failure of the epoxy coated rebars are:

- Under-film corrosion because of the migration of water, oxygen and chlorides through the concrete and epoxy to the steel surface;
- Wet adhesion loss resulting in the separation of the coating from the substrate; and
- Disbondment of the epoxy coating from the reinforcing steel which starts at coating defects.

It is the authors' opinion that the use of epoxy coated rebars for corrosion prevention should not be considered. In areas of low corrosion risk, the use of carbon steel with high performance concrete and good concrete cover is sufficient to prevent any corrosion from occurring. If the oxide layer which forms around the steel is not damaged due to carbonation or chloride ingress, there should be no issues with corrosion. For the areas of high corrosion risk in marine environments, the use of epoxy coated rebars will not provide the adequate corrosion prevention to extend the life of the structure.

Galvanized steel reinforcement.

Steel reinforcing bars can be protected with a coating applied by dipping properly prepared steel bars into a molten bath of zinc.

Hot-dipped galvanised coatings for reinforcing bars have been used over the past fifty years in many countries to improve the service life of concrete structures.

Galvanizing constitutes a means to extend the service life of rebars in concrete structures that will be subjected to carbonation. A substantial increase of the service life of the structure can be achieved by using galvanised steel.

For marine structures, where the primary problem is chloride-induced corrosion, the increase in service life could be too short to justify the extra cost required for the use of galvanized reinforcement. Rapid corrosion will occur when galvanized and black steel is used in the same structure and is electrically connected in chloride-contaminated structures.

Stainless steel reinforcement.

The term stainless steel refers to a group of corrosion resistant steels containing a minimum of 12% chromium. Various alloying additions (nickel, titanium, nitrogen.etc) can be added to provide different mechanical and corrosion properties. The use of stainless steel in concrete is related to its capacity to resist corrosion in chloride-contaminated structures.

Stainless steel reinforcement has been used in various countries in structures that are located in aggressive environments. Stainless steel has been used in construction joints or critical gaps between columns and decks. There is no extensive performance data available from long-term use of stainless steel as reinforcement in concrete.

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Because of the very high cost of stainless steel reinforcement, it is not likely that the entire reinforcement for a large marine structure would be made from stainless steel. A more likely use of stainless steel would be in the outer rebar layer of a reinforced concrete element in the tidal/splash zone. Galvanic corrosion in this case between stainless steel and carbon steel should be investigated.

Corrosion Inhibitors

Corrosion inhibitors are chemicals that can be added to the concrete to decrease the corrosion rate. The inhibitors can be subdivided into three categories, anodic inhibitors, which are used to reduce the anodic reaction rate, cathodic inhibitors, which are used to reduce the cathodic reaction rate, and mixed inhibitors which are used to reduce cathodic and anodic reaction rates.

The inhibitors are used as a preventive measure for new reinforced concrete structures in aggressive environments with a known future risk of chloride-induced corrosion. Corrosion inhibitors are marketed separately as admixtures or they are present in the repair product used for conventional patch repair.

There are various questions in relation to the application of corrosion inhibitors as admixtures to reinforced concrete. Some of these questions are related to the long-term experience with corrosion inhibitors, the effect of corrosion inhibitors on concrete properties, the acceleration of corrosion when the corrosion inhibitors are used with inadequate dosage and other issues related to the leaching out and evaporation of the inhibitors from the concrete.

In general, it appears that if inhibitors are used in suitable concentration, they may delay the initiation of corrosion; however there is no established evidence that the commercial inhibitors available at present are able to reduce the corrosion rate after the initiation of corrosion.

Cathodic Prevention

Steel embedded in alkaline-free chloride concrete is in the passive condition. This passivity breaks down when the level of chloride content exceeds the threshold and pitting corrosion can initiate.

Cathodic prevention is an electrochemical technique that involves the application of a small electrical current using anodes that have been embedded in the concrete during construction. This system can be applied to an entire structure or to selected elements of a structure with the aim of preventing reinforcement corrosion when chloride penetration from the environment takes place during the service life of the structure. The basic philosophy of cathodic prevention is that a much smaller cathodic prevention current is required to prevent pitting corrosion compared to a higher current requirement to suppress ongoing corrosion.

The conditions for pitting initiation and propagation were pointed out by Pourbaix who during the 1970s introduced the concept of “imperfect passivity” and “perfect passivity” intervals. The different domain of potentials is shown below. As can be seen from the graph, for cathodic prevention, a modest lowering of the steel potential can produce a significant increase in the critical chloride level. The free corrosion potential of steel ranges from –200mV to 0mV versus saturated calomel electrode (SCE). Pitting corrosion can take place if the chloride level exceeds 0.4% weight by weight of cement.

If a cathodic prevention current is applied to steel in chloride-free concrete, this will allow the steel to remain passive even when the chloride reaches a considerably high content. The cathodic prevention current produces hydroxide ions at the steel surface and causes the chloride ions to move toward the anode away from the steel.

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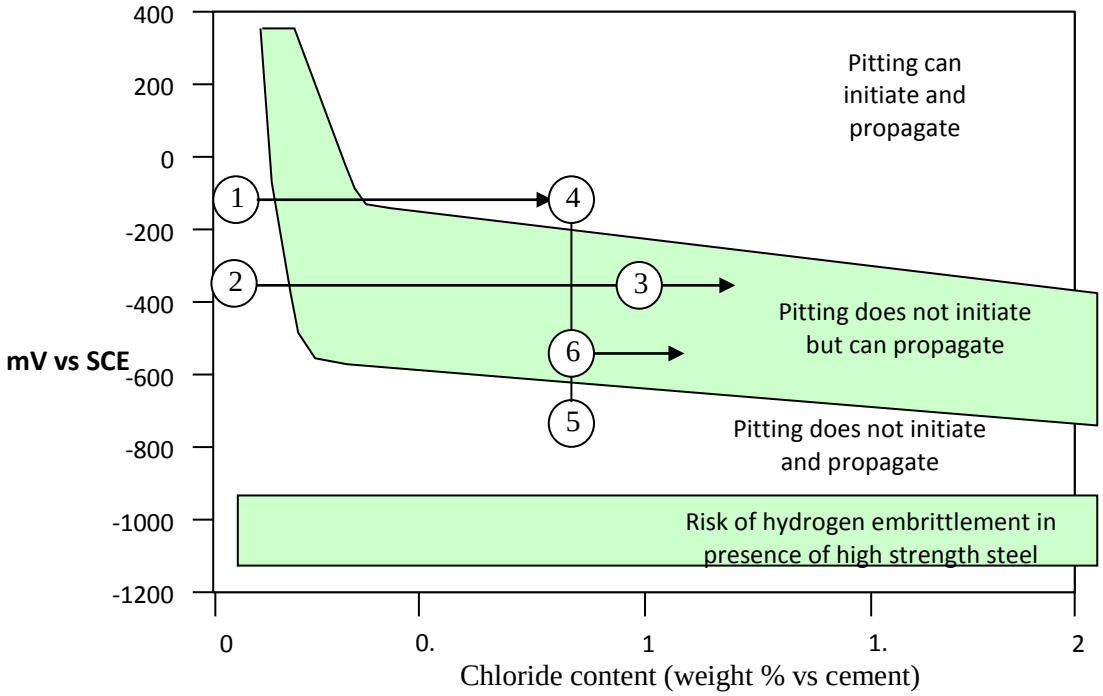


Figure 1: Graph showing cathodic prevention: (1→2→3→); cathodic protection restoring passivity (1→4→5→); and cathodic protection reducing corrosion rate (1→4→6→)

When cathodic prevention is applied, the initiation of a new pit is prevented but pitting can propagate. For this reason cathodic prevention has to be applied before corrosion initiates and must be maintained throughout the service life of the structure. If pitting corrosion has initiated, the current capacity typical for cathodic prevention will no longer be sufficient and cathodic protection current would be required.

The use of cathodic prevention for prestressed steel will eliminate the risk of hydrogen evolution because a lower current is required to prevent the initiation of pitting corrosion. A typical operating current for cathodic prevention ranges from 2-5 mA/m² of steel. The design for a cathodic prevention system, system monitoring and operation is similar to cathodic protection. The main difference is related to the lower current density requirement and the ease of installation during construction.

In recent years, cathodic prevention has been applied to the high risk corrosion areas of many marine structures. This technology appears to offer a technically sound and cost effective solution for various applications. It is essential to note that cathodic prevention would require permanent monitoring of the system for the life of the structure. This requirement is becoming more and more acceptable as for any large new marine structure; there are existing maintenance programs for various services that can easily incorporate corrosion prevention monitoring.

INTELLIGENT STRUCTURE CONCEPT

Various individual systems for structural health monitoring, corrosion monitoring and corrosion control exist using data loggers and manual or remote corrosion control systems. The shortcomings from the installation of different types of individual systems within a bridge structure are the complexity and the cost of maintaining these different systems with their unique hardware and software requirements during the life of the structure. In addition, coordinating the data from such systems in one single report with the relevant data assessment and relevant damage detection and alarm functions could be difficult.

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A new application for marine structures has been developed recently, where all components of structural health monitoring, corrosion control and corrosion protection and prevention can be combined in one system. All the hardware components, such as sensors, corrosion probes, anodes, traffic control equipment and reference electrodes can be incorporated into one centralised system. There is one user interface which is accessed via the internet. This combines all corrosion and structural health monitoring and performance data into a simple and comprehensive report that is generated automatically and is capable of providing all the essential data regarding the health of the structure.

CASE STUDY 1: STRUCTURAL HEALTH AND CORROSION MONITORING

Crusell Bridge is a new landmark in Helsinki, the capital of Finland. It crosses the bay separating a new residential area of Jätkänsaari, built on the former West Harbour site, from Central Helsinki. It is a dual-spanned, asymmetrical cable-stayed bridge with a total length of 175 m and inclined pylons 49 m tall, commissioned by the City of Helsinki's public works department. Construction began in the autumn of 2008, and was completed in August 2011.



Figure 2: Crusell Bridge in Helsinki

The superstructure of the bridge is a longitudinally prestressed concrete beam, and horizontally the bridge is a composite structure. This type of structure is unique in Finland. The composite structure makes it look very thin and light.

The design challenges for this bridge are related to the asymmetrical arrangement of the cables, the narrow steel pylons and composite details on the structural elements. The bridge was designed completely using 3D modeling techniques allowing the product model to be utilized throughout the construction process. Extensive use was made of the building information modeling (BIM) for the whole construction process from fabrication to quality control, and for construction planning using 4D animation. Modeling supported lean construction practices during the project. It was a learning experience for everybody involved due to many new solutions and techniques implemented. Therefore

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the structural monitoring is also more extensive during construction and now during the normal operation of the bridge than in previous Finnish bridge building projects.

Structural Monitoring System

There are a total of 92 different sensors installed within the bridge:

- 1 pc weather sensor, top of the pylon;
- 2 pcs 3D accelerometers, in pylon and deck;
- 2 pcs boltable strain sensors, under deck;
- 1 pc displacement sensor, in expansion joint;
- 1 pc traffic camera with video, in pylon;
- 2 pcs corrosion rate sensors (ladder type), in deck;
- 14 pcs corrosion potential sensors (reference electrodes), in deck;
- 6 pcs fiber optic strain sensors, in pylon leg;
- 4 pcs fiber optic temperature sensors, in pylon leg;
- 16 pcs fiber optic strain sensors, in pylon;
- 8 pcs fiber optic temperature sensors, in pylon;
- 24 pcs fiber optic strain sensors, in deck; and
- 11pcs fiber optic temperature sensors, in deck.

The sensor configuration is a mixture of electrical, electrochemical and optical sensors.

Electrical sensors such as weather sensors, accelerometers, displacement and boltable strain sensors offer either unambiguous serial data or specific electrical responses to excitation signals from the data acquisition system. The fiber optic sensors are based on Bragg grating technology and rely on changes in the scattering light wavelength when the fibre in which the grating is located, is under physical strain. The electrochemical sensors display the potential value of the steel reinforcement bar in concrete against MnO_2 reference electrodes. The corrosion rate is periodically measured from each segment of the ladder sensor using galvanostatic pulse method.

Monitoring Data

The automatic continuous monitoring system was commissioned in April 2010, prior to that there were periodical measurements made during the construction. All sensor information can be monitored online via web interface.

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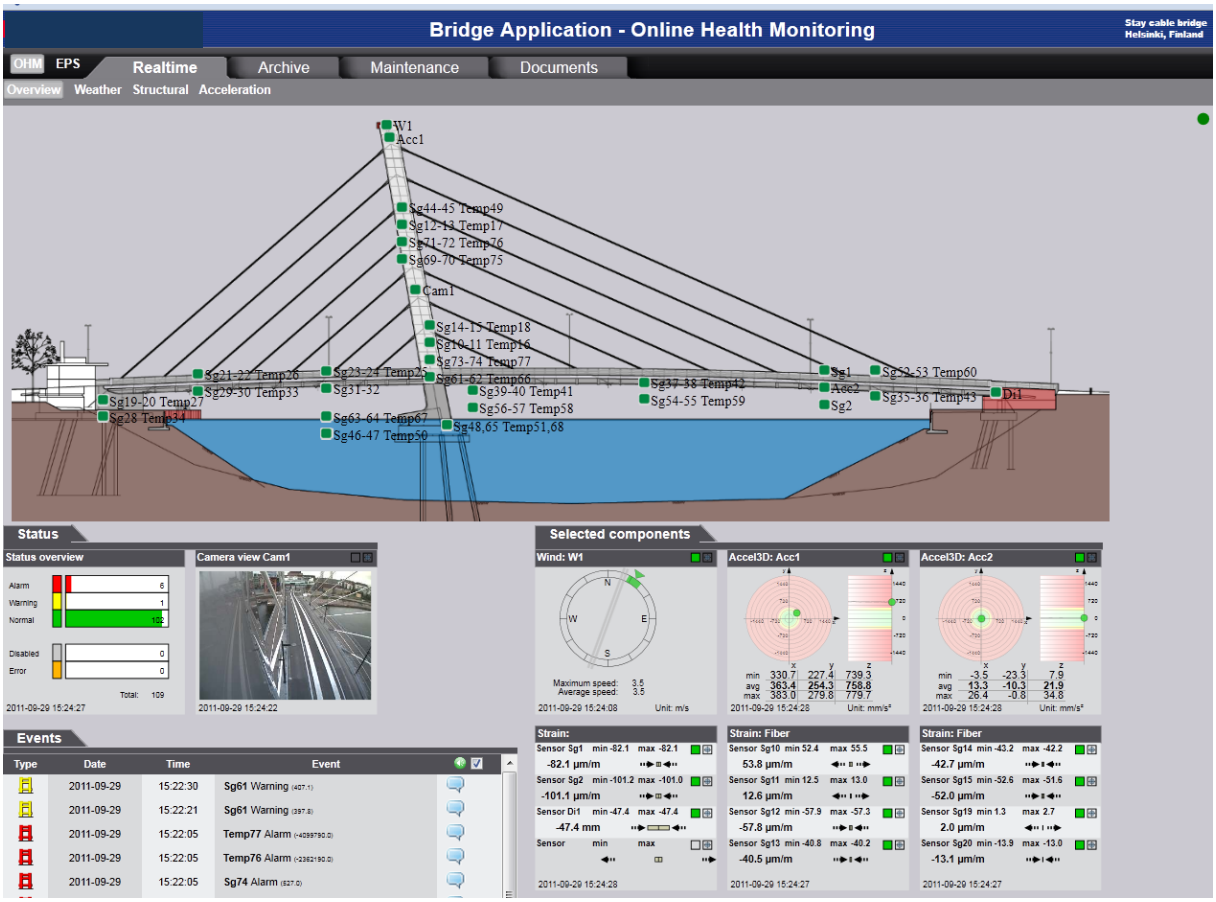


Figure 3: User interface main page of the online structural monitoring system

CASE STUDY 2: CATHODIC PREVENTION

SeaCliff Bridge is a recently constructed two-lane bridge between Clifton and Coalcliff along Lawrence Hargrave Drive (LHD), New South Wales, Australia. The bridge is located in an unusually severe marine environment as it faces the open ocean and is subject to splashing in high sea swells, putting it at a very high risk of chloride-induced corrosion. This case study discusses the design, installation and monitoring of the cathodic prevention system on the SeaCliff Bridge.

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Figure 4: SeaCliff bridge, NSW Australia

Design Concept

The design of the system was performed in accordance with relevant standards, including AS 2832.5-2002.[3]

Activated mixed metal oxide titanium mesh ribbon anode was used as the anode material, to be embedded in the concrete during construction. The anode was specially manufactured to provide a 100 year design life operating at 110 mA/m^2. The specifications of the mesh ribbon anode are as follows:

- Width: 23.7 mm
- Thickness: 1.3 mm
- Current output: 5.28 mA/m

The pile caps and pier columns of SeaCliff Bridge were divided into multiple electrical zones to account for the following variables of the structure:

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- Environmental exposure
- Construction stages
- Geometry of the structure
- Maximum current output of power units
- Current distribution

The zoning of a typical pier is described in Table 1.

Table 1
Electrical zoning of SeaCliff Bridge

Zone	Description	Environmental Exposure
1	Pile caps and pad footings	Buried
2	Columns: lower two sections	Splash area
3	Columns: middle two sections	Lower atmospheric
4	Columns: upper two sections	Upper atmospheric

One control unit was installed for each bridge. Within each control unit, there is a sufficient number of separately controllable rectifiers for supply of DC current to each zone.

An important part of the design process is selecting the best location for the components external to the concrete. The junction boxes, conduit, cabling and control units were specifically located to allow relatively easy future maintenance, whilst ensuring the components are not visible to the public (for aesthetic purposes) and are protected from potential vandalism.

Monitoring

The performance of the system is monitored by a combination of 37 Silver/Silver Chloride (Ag/AgCl) reference electrodes with a design life of 20 years and 41 activated MMO Titanium reference electrodes with a design life of 100 years. The reference electrodes were installed during construction of the piers in representative locations throughout the structure to obtain a comprehensive set of data for future monitoring. This included ensuring some reference electrodes were close to and remote from the positive connection to monitor for over and under protection.

Ag/AgCl reference electrodes can be used to measure the absolute potential of the steel reinforcement and for potential decay measurements. They allow the system to be assessed according to all the protection criteria in the standards, and therefore allow the monitoring engineer to make informed decisions on current output required to maintain protection levels.[3] This is especially critical during the first few years of system operation. However, as their design life is limited, and the structure itself is designed for at least a 100 year service life, it is important to include reference electrodes that will monitor the system past the first 20 years. Activated MMO Titanium references can be used very effectively for potential decay measurements, allowing the engineer to assess the system based on the 100 mV decay criterion.

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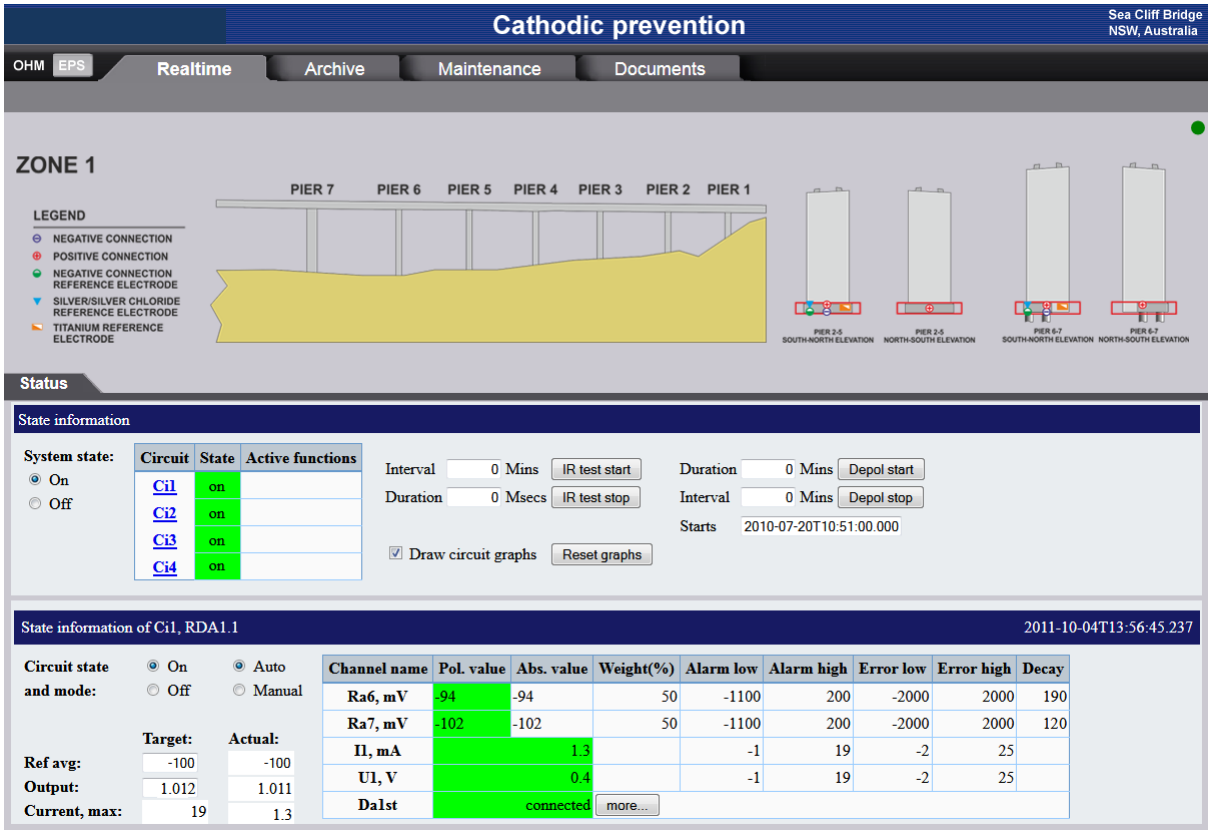


Figure 5: User interface zone page of the remote control and monitoring system

Installation

The installation procedures and quality assurance testing are briefly described below.

Prior to the installation of the cathodic prevention system, the electrical continuity of the steel reinforcement was tested in accordance with AS2832.5.[3] Where discontinuity was identified, the adjacent steel was welded to establish adequate continuity. All of the cages were tack welded for construction purposes, and therefore continuity was generally found to be satisfactory.

The steel reinforcement cages were constructed in two halves in an area near the bridge construction site. Once each half of the cage was completed the cathodic prevention components were installed and fully tested. Following this, each half of the cage was lifted by crane to the location of the bridge pier where it was welded to the adjacent connecting sections of the structure. The CPrev components were adjusted as required and final testing undertaken. Following final inspection and acceptance of test results, concrete was poured into this section. Cathodic prevention technicians were present during all stages of the works including the concrete pour and vibration, to ensure no damage would occur to the CPrev components.

The cathodic prevention system involves the use of mesh ribbon anode grid attached onto the reinforcing cage with specially designed insulating cementitious material prior to pouring. The anode grid assembly for the precast elements is made of an array of parallel mesh ribbon anode grids supported by the composite cementitious spacer above which the anode elements are secured by means of plastic fixings. The assembly is positioned on the reinforcing steel and fixed by plastic ties. A titanium bus bar is welded to each anode strip to connect them together. The main characteristics of this assembly is that by varying the degree of expansion, the width and the spacing between the

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parallel strips, the current output of the anode assembly can be easily varied to match the variations of the steel density of the concrete structure.[4]

Reference electrodes were fixed to the steel cages at the designated locations. All cables were embedded in concrete and terminated in a junction box above each pier. The four junction boxes for GD2 Bridge were installed in the service tunnel. The seven junction boxes for GD3 Bridge were fully concealed in the barricades adjacent to the pedestrian walkway. All junction boxes are relatively easily accessible for future maintenance. The cables from each junction box were then terminated in the appropriate GD2 and GD3 control units in the service tunnel.

The installation was fully integrated into the bridge construction, and does not affect the bridge aesthetics.

A comprehensive testing schedule was implemented for this project, to ensure all components were installed in accordance with the specification. These tests included short circuit tests between anode ribbon and steel reinforcement, continuity checks of all connections, thorough inspections prior to concrete pour and temporary energising of each section following concrete pour. One of the most essential steps in the installation process was the final inspection prior to concrete pour to ensure no short circuit could occur during the concrete pour or vibration of the concrete. This included cutting or folding back any tie wire that could potentially move during this process and ensuring every anode and conductor bar strip was adequately fixed.

CONCLUSIONS

The two case studies presented in this paper are an excellent example of innovative technologies incorporated into two new bridge marine structures.

In the Crusell Bridge in Finland, a corrosion monitoring system and a structural health monitoring system were incorporated during construction. The structural health monitoring system includes a combination of electrical and optical sensors and secured online monitoring with alarm function and data analysis.

The SeaCliff Bridge in Australia includes a corrosion prevention system which was installed during construction for the high corrosion critical elements of the bridge. The system is monitored using secured online monitoring with alarm function and automatic data processing and system adjustment.

This concept of incorporating corrosion prevention, corrosion monitoring and a structural health monitoring system into the construction of a new marine structure is the first step in making the new generation of these structures “intelligent”.

An intelligent marine structure is a structure that is equipped, as individually required, with an integrated structural health monitoring, corrosion prevention and corrosion monitoring system that can provide real active corrosion control to all high corrosion risk areas of the structure. It can also detect structural deterioration and corrosion activity, coordinate data automatically and provide early warning of potential failure and regular information regarding the health of the structure.

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