The University Bridge Arch Assessment -
A New Approach

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Abstract

The University Bridge in Saskatoon is a multi-span concrete arch bridge with a service life that began in 1916. Rehabilitation of the bridge deck is currently underway and expected to be completed during the summer of 2015 with rehabilitation of the bridge arches and piers planned to occur in 10 to 15 years.

This manuscript outlines an investigation taken to evaluate a number of different arch rehabilitation strategies using numerical models and experimental data. The rehabilitation strategies considered in this investigation include: do nothing, Fiber Reinforced Polymer wrap, Galvanic Cathodic Protection, Impressed Cathodic Protection, Re-alkalization, Electrochemical Chloride Extraction, and applying a Penetrating Sealer.

Experimental data was obtained concerning properties of the concrete, pore solution, rebar, and environmental conditions within the concrete. Cores were removed for compression testing and pore solution composition analysis. Rebar was also removed for electrochemical testing, including potentiodynamic scans and long-term exposure tests. Semi-permanent probes were inserted to measure environmental properties inside the concrete related to water saturation and oxygen content. Values from these experimental data were then used in the development of numerical models.

Simulations and measured data demonstrated low moisture levels and high oxygen content within the concrete were coupled with low/insignificant corrosion rates on the reinforcing metal in most regions. However, measured data suggested high negative half-cell readings could be associated with regions of high concrete moisture (above 60% by volume) due to surface runoff and water pooling on the arches. Numerical modeling and experimental data suggest the relatively low moisture levels within the concrete could be utilized and enhanced to mitigate the corrosion of reinforcing steel. Therefore, building on these conditions, a synergistic mitigation strategy was recommended that incorporated two technologies: discrete Galvanic Cathodic Protection anodes and a Penetrating Sealer. Calculated savings due to this study revealed savings of the order-of-magnitude in the range of $2 to $4 million when compared with alternate rehabilitation strategies.

Additionally, the results of the assessment demonstrate the age of a structure has limited bearing on the remaining service life. Rather, if the underlying deterioration processes are controlled or minimized, the life of the element can be extended indefinitely so long as regular monitoring is in place to identify changes in either the environment or condition of the element that would affect the deterioration rates. As such, with the proposed rehabilitation method the City will have a system that with regular monitoring, which is already part of their City wide asset management system, will be easily capable of meeting the desired 50 year service life extension at a minimal cost impact to the overall project.

1 Introduction

In Saskatoon, The University Bridge spans the South Saskatchewan River between 25th Street on the West bank and College Drive on the East bank, refer to Figure 1. Construction on the University Bridge started in 1913 and the bridge was placed into service in 1916. Since then, multiple modifications have been made to the bridge at different times, but no significant rehabilitation of the bridge's arches has previously been undertaken.

In 2008, Arch B of the University Bridge was tested and an average carbonation penetration of 35 mm was found which had also reached the rebar in approximately 20% of the arch area. Additionally, chlorides were present from when deck drains, which had since been plugged, discharged onto the arch the concrete, but had not yet reached the stage where significant chloride induced corrosion was expected (Stantec, 2008). Delamination testing recorded 14% of the top arch surface had delaminated, and combined with half-cell testing it was concluded that the arch reinforcement may be corroding (Stantec, 2008).

A subsequent study was completed in 2012 where all arches were tested in order to capture the extent of deterioration on these elements. Results from this subsequent report identified values for delamination and carbonation depth along the top of the arch of 16% and 41 mm, respectively (Stantec, 2012). Of note is the 2008 and 2012 studies focused on the arch top and did not include arch sides or soffit as access to these elements required special equipment that was considered beyond the scope of the project at that time.

In 2013, CH2M-Hill was commissioned to develop a comprehensive rehabilitation strategy for the entire structure using available historical data and information collected as part of their program. Access using barges, lifts, and climbing, was used to collect data from all sides of the arch in order to capture all relevant information. Results were similar with the Stantec report; however, they indicated that concrete carbonation, while present, was not consistent with the delamination and spall damage on the arch.

The CH2M-Hill investigation revealed high delaminations were present in areas where carbonation had not reached the reinforcement (such as the arch top), while minimal signs of delaminations were evident where carbonation had reached the reinforcement (such as the arch

Figure 1: Elevation of the University Bridge

soffit). Areas of extensive delamination were subsequently found to be the result of debonding between layers of concrete placed during the original construction process (CH2MHill, 2013).

The City wished to have the arches service life extended an additional 50 years and with the presence of carbonation and chloride this service life expectation could not be achieved without some form of intervention. However, inconsistencies found between the arch top and soffit suggested further assessment of the arch, beyond the scope of the CH2M-Hill commission, was warranted. As such, CH2M-Hill contacted the University of Saskatchewan (U of S) to assist with the development of a detailed numerical model calibrated with field and laboratory obtained data to determine the best rehabilitation methodology for the arch.

The approach employed by the U of S was to develop a finite element based model that simulated the deterioration processes present within the arch. This model would then be calibrated from data obtained from site which could be used to confirm the extent of damage currently present and then predict the performance of the arch under a wide range of protection systems ranging from the current system of no protection through to complete encapsulation using advanced composite materials.

2 Arch Assessment and Model Development

The modeling objective for the University Bridge arches was to predict deterioration rates under different environmental conditions caused by the shape of the arch, shading from the deck above, and potential rehabilitation methodologies. For the purpose of the study, the model assumed service life would end when rebar corrosion resulted in delaminations that may cause concrete to detach from the arch and fall.

Primary deterioration mechanisms modeled for this assessment were corrosion of reinforcement within the concrete. Two distinct physical processes were simulated for capturing how the arch would deteriorate through time, which included:

- Transport rate of oxygen, moisture, and carbon dioxide to and from the surface of the rebar combined with transfer of ions between corrosion cells that form on the bar surface; and
- Rate of electrochemical reaction on the surface of the rebar which describe how fast the bar will corrode given the presence of various concentrations of oxygen, moisture and carbon dioxide affected by the first physical process.

These two processes are interlinked as the rate of chemical reaction on the rebar surface is correlated to the concentration of the various species present while the rate of transfer is dependent on the concentration of species. This interrelation, while complex can be easily solved with modern simulation software and modeling techniques.

However, in order to provide realistic results, the models must be calibrated using site obtained physical parameters that are incorporated into the transport and electrochemical reactions processes. Field data collected included:

- Moisture content, which is a controlling parameter for modeling transport of oxygen, carbon dioxide, chloride and the flow of ions between the anode and cathode;
- Pore solution composition, as the composition of the electrolyte in contact with the rebar effects the rate of corrosion and concrete conductivity;
- Porosity, which is used for simulating transport as this characteristic has a large effect on the rate of transport of oxygen, chloride and carbon dioxide to the rebar and ionic flow between the resulting anodes and cathodes; and
- Rebar which was tested under various pore solutions to develop a range of performance characteristics that could be used to understand how the material behaved as chemical

concentrations within the pore solution changed when chloride and carbonation were introduced.

2.1 Concrete Properties

Concrete properties were established using cores extracted from the arches and using semi-permanent probes installed into the bridge. Four cores were extracted from Arch C and Arch D, which represented an arch over land and water respectively. Additionally, one core was taken from a curtain wall above Arch C. Cores were lab tested to determine the chemical composition, which was then used within the simulations to model the corrosion processes for comparison to current rates of deterioration and to predict future deterioration rates.

Land and water arches were selected to evaluate whether differences existed in ambient moisture conditions within the arch and other features of the arch due to the presence of the river. Figure 2 identifies the locations of semi-permanent probes for measuring oxygen and moisture levels that were placed into Arch C and Arch D. Probes were positioned to determine if moisture conditions varied between interior and exterior edges of the arch and along the length of the arch due to the protective effect of the above deck and adjacent spandrel and curtain walls.

After installation, probes required several weeks to reach steady-state conditions. Once attained, measurements were recorded on a regular basis with an example reading taken from August 7th, 2014 shown in Figure 3. Results show a trend consistent throughout the measurement duration, of elevated water contents on portions of the arch closer to the exterior edge of the arch and closer to the pier, excluding one outlier that had high moisture content near the top of the arch and located towards the interior of the arch. Outliers were recognized as a potential issue that would need to be accommodated as part of the rehabilitation as these could occur due to leakage or a crack in the concrete that allowed moisture into the sensor, or the random accumulation of debris between cleaning cycles.

Results from Figure 3 revealed a microclimate is present along the arch due to the protective nature of the deck, curtain walls, and spandrel walls. This test result provided the first step in developing rehabilitation strategies that focused on controlling moisture contents with the use of sealers that would allow the concrete to dry thereby reducing corrosion rate and increasing the service life.

Figure 4 shows oxygen levels across Arch C and D taken at locations shown in Figure 2. Oxygen levels are uniform across the arch, which suggest either corrosion rates are very low and not consuming the available oxygen or the concrete does not present a significant diffusion barrier.

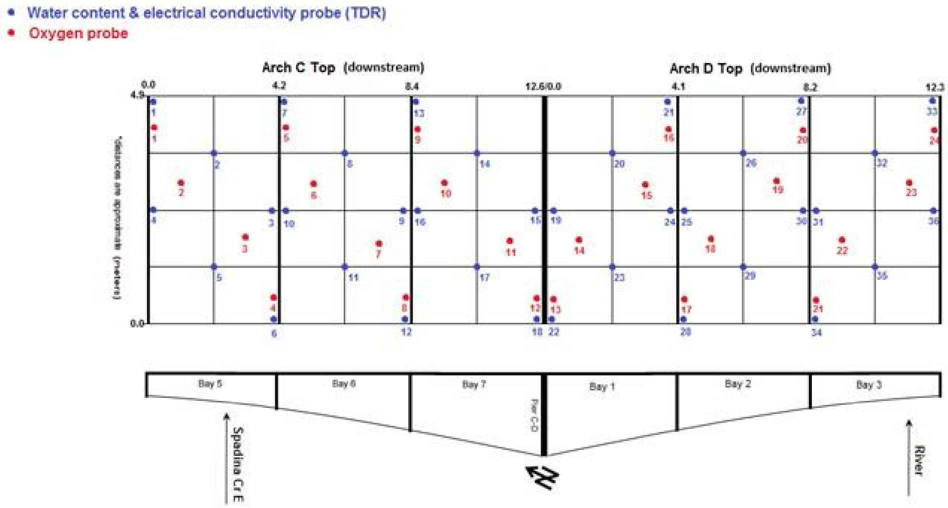

Figure 2. Layout of semi-permanent probes on Arch C and Arch D.

Considering the moisture contents measurements shown in Figure 3, and that no corroding reinforcement was found, the likely conclusion is that a combination of insufficient moisture and low corrosion rate is minimizing the oxygen consumption rate thereby reducing the need for oxygen to be transported to the bar. The low moisture content and high oxygen transport capacity of the concrete is significant when alternative rehabilitation strategies are considered.

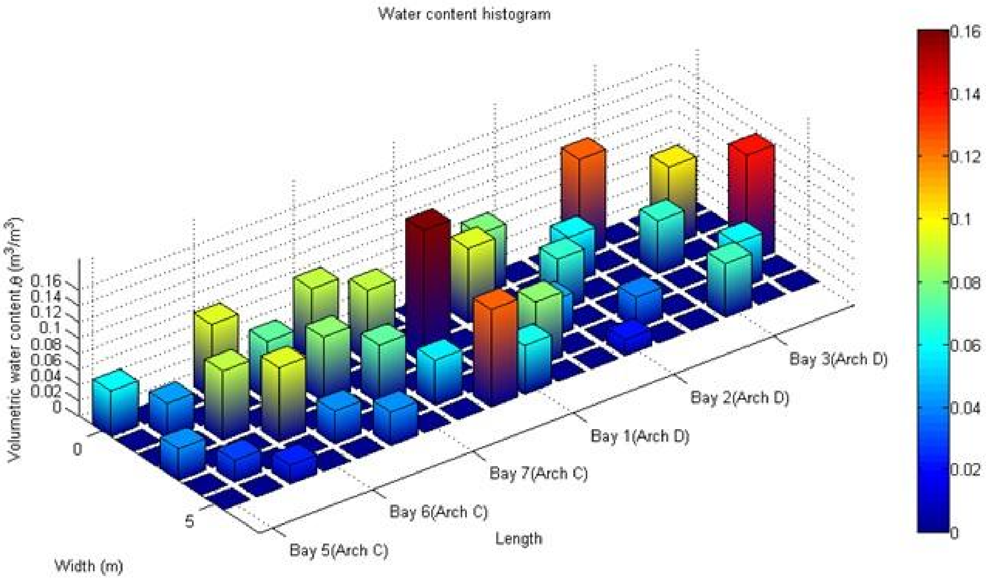

Figure 3. Measured moisture levels across on Arch C and Arch D (August 7, 2014).

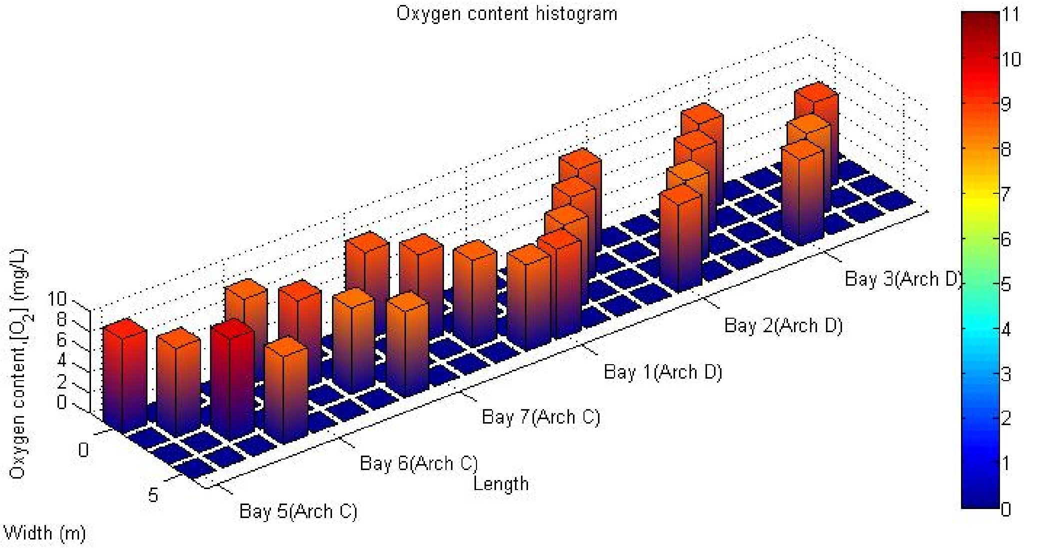

Figure 4. Measured oxygen concentrations across on Arch C and Arch D (August 7, 2014).

2.2 Rebar Corrosion Properties

Rebar samples from the arch, columns, and curtain wall were electrochemically tested using a potentiondynamic scanner in the laboratory to determine corrosion parameters of the arch rebar. Testing was performed on reinforcement embedded in concrete and then rebar bar was extracted, prepared, and tested in nine artificial pore solutions of different pH and sodium chloride concentrations that were selected to simulate the future condition of the arch concrete as the structure ages. Additionally, long-term exposure tests were conducted to evaluate the behavior of the corrosion rate over periods of weeks.

Potentiodynamic scans are an electrochemical test that expose the metal being evaluated to a range of potentials while measuring the corrosion current being produced. The resulting plot is used to determine three parameters for modeling, which include: exchange current density, reversible potential, and Tafel slope. These parameters represent the corrosion kinetics that describe the rate of rebar corrosion when exposed to different chemical composition pore solutions and corrosion potentials. This range is important when simulating corrosion of reinforcement within concrete as different corrosion cells are created on the bar/concrete interface which are each at different corrosion potentials and hence different corrosion rates. Therefore, they interact with each other and create larger corrosion cells that in effect produce areas of cathodic protection countered with areas of high corrosion rates that ultimately result in delaminations and spalls that control the service life of the element.

Figure 5 shows the results of a single potentiodynamic scan of rebar removed from Arch C in a simulated pore solution with a pH of 13.5. Three areas are identified in this figure as follows:

- Negatively sloped red line – This line represents the cathodic Tafel slope, which indicates material is plating out of solution and onto the prepared specimen. Net corrosion or section loss is not possible in this region;
- Positively sloped red line – This line represents the anodic Tafel slope, which indicates that metal is being consumed (corroding); and
- Above the positively sloped red line – This part of the anodic branch indicates that a passive film has developed which has caused rate of corrosion to remain constant while the corrosion potential increases. This feature is an important facet of this rebar as modern reinforcement does not exhibit this leveling off of corrosion rate with increasing corrosion potential. Therefore, under certain circumstances, the rebar in the arches

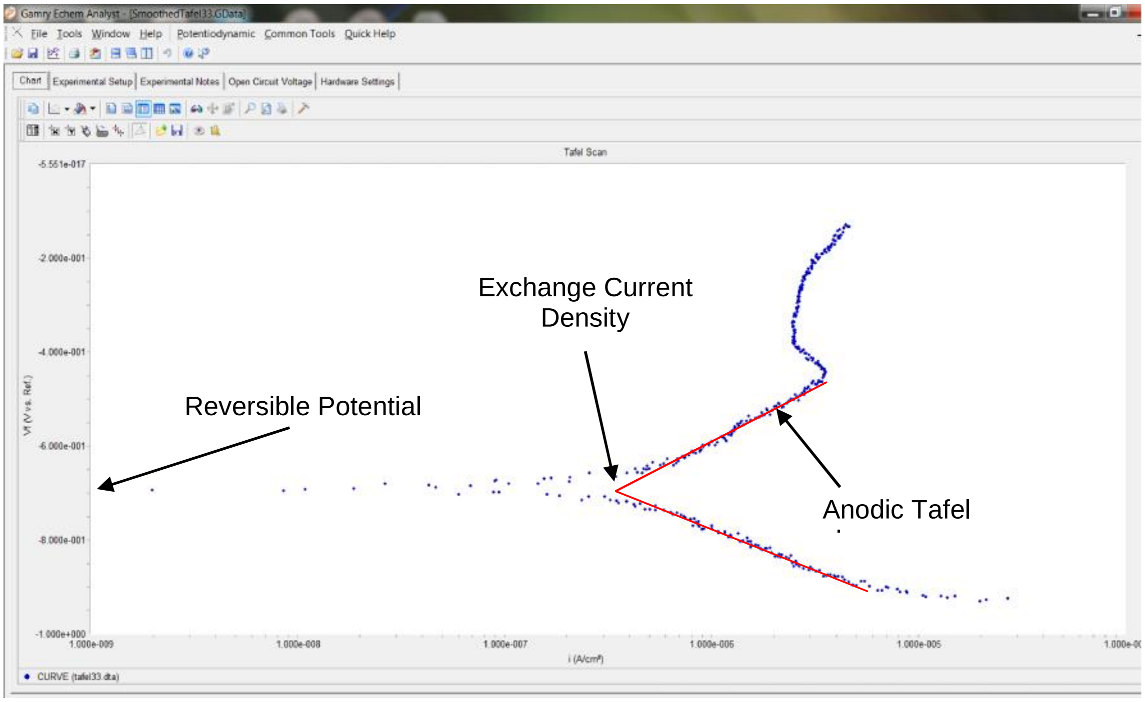

Figure 5: Potentiodynamic scan of rebar in concrete from the University Bridge using a Calomel reference electrode

appears to have the potential for a low corrosion rate that has been visually substantiated with extracted bars which had minimal corrosion by-product present on the surface.

Results from these tests provided the necessary input values used in the numerical model for simulation of the corrosion processes as oxygen, moisture and carbonation changes through time.

Long-term exposure tests were conducted and the results showed no increase in the corrosion rate due to time-delayed penetration of chloride at the conditions tested over a period of two weeks. The conditions tested included three different values of pH (13.5, 12.0, and 8.5), and three different chloride concentrations (0 M, 0.01 M, and 0.2 M).

3 Numerical Model

Several numerical models were developed to analyze the arch rehabilitation strategies. This section discusses the general development and results from the main deterioration models utilizing the electrochemical and physical data obtained from laboratory and semi-permanent probe measurements as input parameters. The importance of these models is that they are not site specific and can be used on any type of structure exposed to chloride or carbonation to model the performance of the element under a wide range of environmental conditions.

Figure 6 shows the logic diagram illustrating the flow of information between various algorithms within the model. Six components were developed that combine to form the overall model used to simulate the build-up of rust on the reinforcing bar surface and ultimately when the concrete would detach and form a delamination. A detailed description of each component is given below:

- Electrochemical measurements. Parameters included exchange current density, reversible potential, and Tafel slope;
- Electrochemical kinetics. Given electrochemical measurements, the rate of corrosion can be calculated using Tafel kinetics for a given pore solution composition. This rate of corrosion affects rust thickness and mass transport of ions being consumed and produced at the rebar surface;
- Physical measurements. Porosity of the concrete is input to the model to simulate the rate of mass transfer of species such as carbon dioxide, oxygen, and sodium chloride,

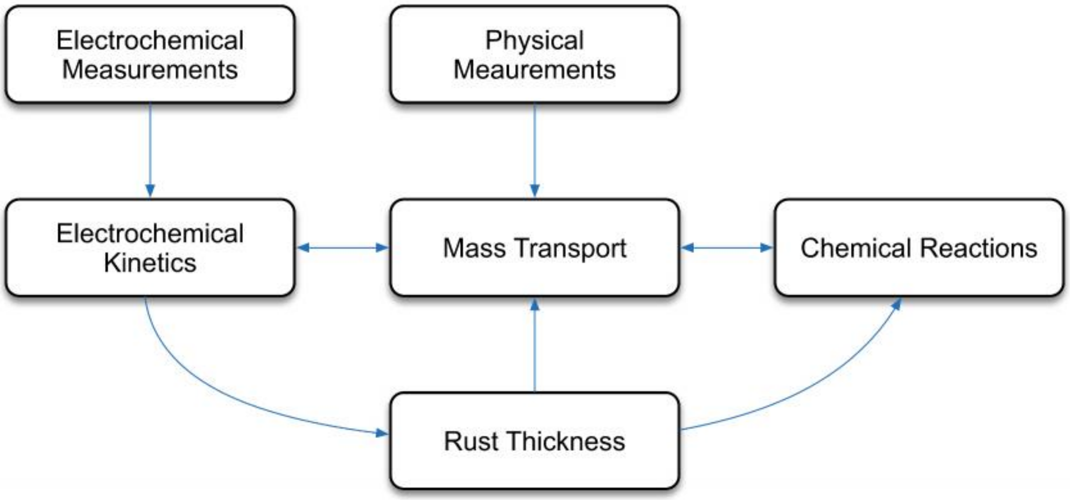

Figure 6. Flowchart showing the flow of information in the model predicting the thickness of rust on the University Bridge arches over time.

into the concrete and towards the rebar. This variable was modified as the corrosion process consumed or created various species that changed the local porosity of the concrete around the bar;

- Mass transport. The rate at which species are transported towards and away from the rebar is coupled with multiple phenomena. For example, if mass transport is limited due to low moisture, then corrosion cells that occur between different bars or separated along one bar become less likely. Additionally, mass transport will determine the time required for chloride from the concrete surface to reach the rebar and increase the corrosion rate. Mass transfer is affected by chemical reactions and rust thickness, as rust blocks pores and reduces porosity;
- Rust thickness provides a good indication of the life of the reinforced concrete, as it relates to the quantity of corroded rebar and possibility of delaminations and spalling. As mentioned previously, it effects, and is affected by, multiple other components in the model; and
- Chemical reactions, such as carbonation of the concrete, consume and produce species undergoing mass transport within the concrete. Carbonation decreases the pore solution pH, which in turn increases the electrochemical kinetics, and carbonation may cause precipitation of calcium carbonate.

4 Model Details

Simulations used two separate finite element models to predict deterioration rates within the arches. The first model used a very simple geometry shown in Figure 7 with all of the chemical, kinetics, and mass transport processes included. The geometry represents a single bar embedded in concrete with transport of oxygen, carbon dioxide, chloride, and moisture from a single surface to the bar. Using the principle physical processes that control corrosion, results were produced which were then used in the finite element model represented in Figure 8 which described a more complex portion of arch geometry.

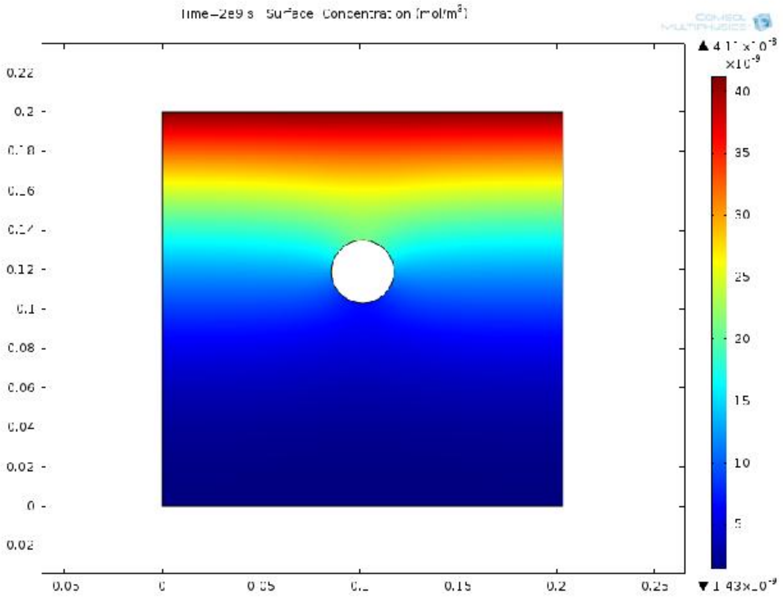

Figure 7. Simple geometry model of a single bar embedded in concrete combined with complex physical processes – Current picture demonstrates the development of carbonation within the concrete after 100 years of service life.

This approach was used as implementing a high geometric complexity with a high complexity of physical processes resulted in a model with an extremely high computation demand that was inefficient for considering a wide range of options. The selected approach allowed a high degree of control over both the complexity of the physical deterioration processes and the geometry of the element being evaluated. This allowed evaluators the ability to simulate a wide range of operating conditions to determine the effect of various rehabilitation treatments that are discussed in the subsequent sections.

5 Rehabilitation Strategies and Field Testing Program

The previous simulations matched the visual evidence that the current arch had not sustained significant deterioration due to corrosion as the current moisture conditions were sufficiently low to protect the arch from carbonation and chloride induced corrosion. However, simulations did reveal future carbonation damage would result if moisture levels in unprotected areas of the arch were not lowered as these areas were currently inactive, but only due to the low carbonation levels currently present.

Several strategies for rehabilitation were considered that included moisture control, cathodic protection, encapsulation, and combinations.   Using the finite element model previously developed, the effects of each rehabilitation were simulated to determine whether they would achieve the service life extension desired. Results of the simulations for each option are discussed as follows:

- Moisture Control – For this scenario, a silane sealer was used and the evaporation of moisture from the concrete was simulated. Results indicated a high degree of protection

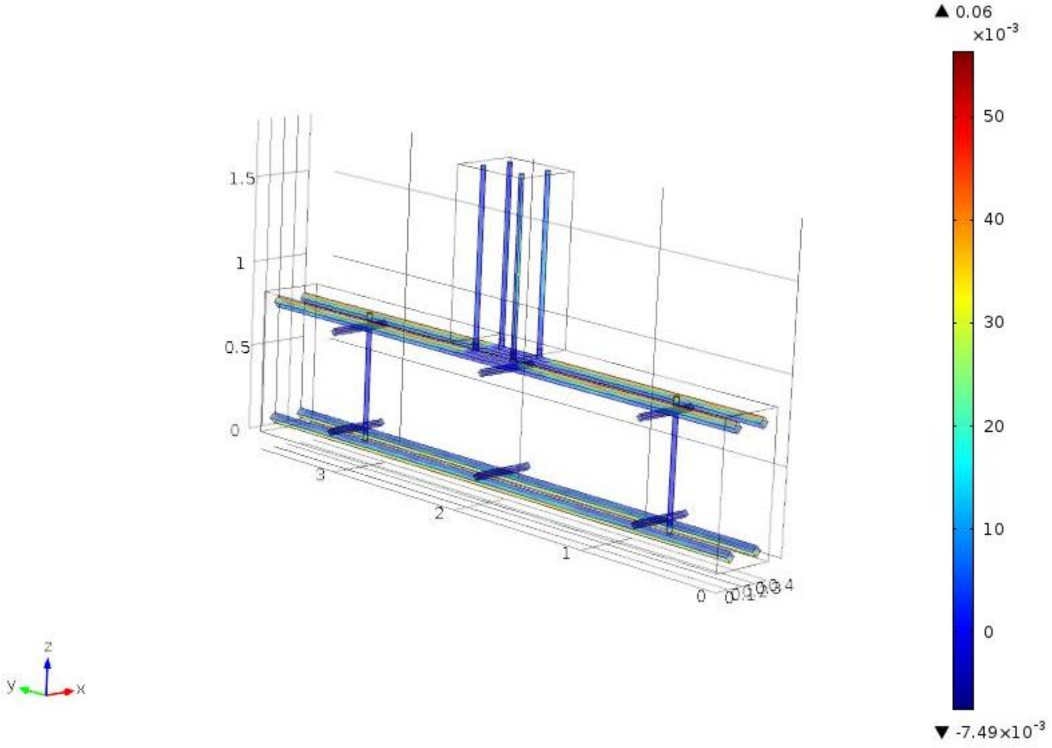

Figure 8. Complex geometry model of the arch and column interface combined with relationships of the physical processes produced from the simple physical model. Current picture demonstrates bar rust thickness after approximately 100 years for rebar in concrete with a cover of 40 mm and subjected to relative humidity of 95%.

would be provided, however, there was some uncertainty related to localized cracks allowing moisture into un-protected areas or the accumulation of debris allowing moisture to be held against the surface. Therefore, repeated silane applications, improved runoff, and debris removals were recommended combined with the use of discrete galvanic anodes to control localized corrosion cell formation in the event that moisture was present;

- Cathodic Protection – Both Impressed Current Cathodic Protection (ICCP) and Galvanic Cathodic Protection (GCP) were simulated. These systems were found to provide a high degree of protection, however, due to the low moisture contents currently present in the concrete a humectant would need to be applied to ensure electrical continuity between the anode and reinforcement so that proper protection could be achieved. A high degree of risk was identified with ICCP in ensuring the arch and connecting elements were properly connected so that stray current or partial protection was avoided;
- Encapsulation – Epoxy encapsulation was simulated as this option had been presented as a permanent solution to corrosion on the arches. Results of the simulation are shown in Figure 9, which exhibited a potential for oxygen concentration gradients and high rates of corrosion occurring at the termination of the epoxy encapsulation. This result is caused by oxygen depletion within the arch due to the cathodic reduction of oxygen into ions. If the encapsulation is 100% effective, then the corrosion rate will drop to near zero. However, at termination points, oxygen can flow in from the unprotected areas allowing corrosion processes for a certain distance into the protected area to continue. Under this scenario, chemical concentrations within the protected area become acidic due to unbalanced reactions thereby producing a high rate of corrosion and concrete delamination/spalls. This damage then results in further penetration of oxygen which progressively deteriorates the encapsulation system.

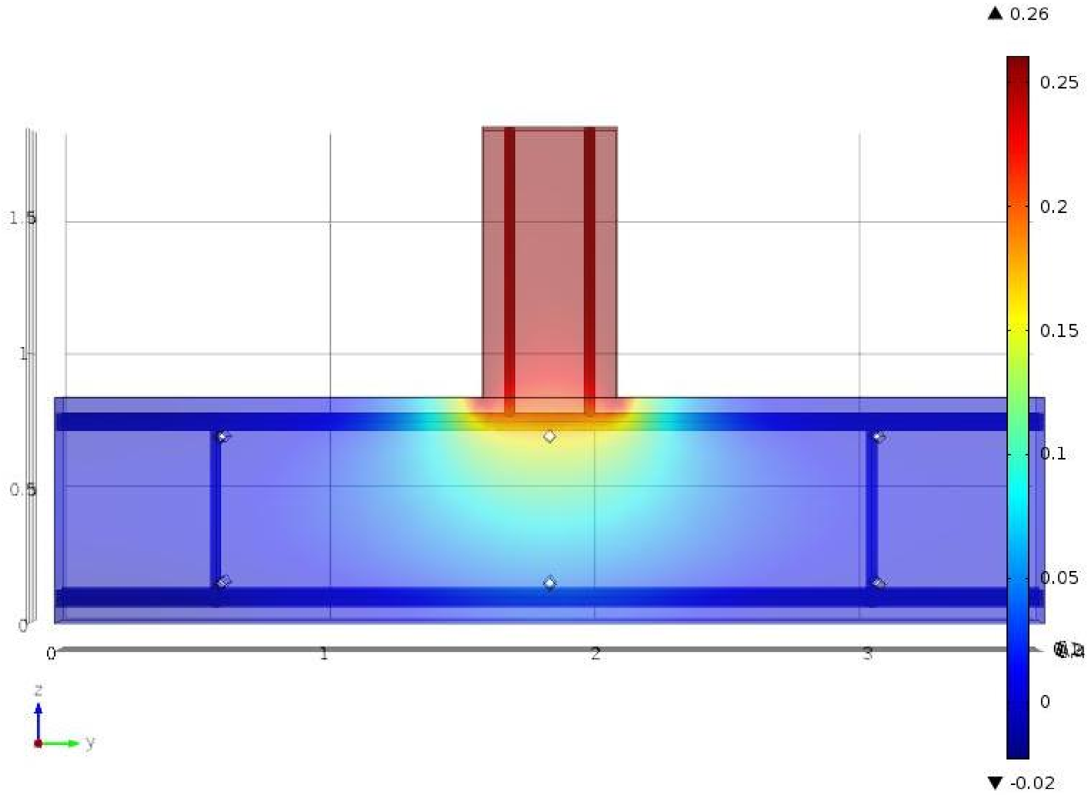

Figure 9. Simulated oxygen concentration gradients for encapsulation rehabilitation option.

Given the area of the arch and number of interfacing elements, this option was deemed to represent a high potential failure risk unless a secondary protection system was installed at the interfaces. As such, a sub-alternative was created which incorporated GCP at the interfaces to protect against this scenario occurring;

- Combinations:
    - Sealer plus GCP – This scenario was considered as a means to mitigate the risk of random cracks and debris accumulation allowing moisture to by-pass the sealed surface. Since moisture conditions within the concrete would normally be quite low until a crack would occur, the GCP would effectively be disconnected from the surrounding concrete and would only become active when moisture infiltrated. Therefore, it was found that this combination provide a high degree of long-term protection, however further testing was required to determine if the GCP would remain passive in the concrete; and
    - Encapsulation plus GCP – As discussed previously, the GCP may be added into the termination areas to control the corrosion rates produced by oxygen concentration cells being formed. The addition of GCP would help mitigate corrosion at termination areas, however, a high consumption rate would result in regular replacement of the anodes to provide the necessary protection and service life targets.

Using the simulated performances, preliminary costs were developed using the silane sealer with GCP located in areas where moisture ingress could occur. This option was considered the reference option as it was the least costly of the solutions and would allow the City to stage the implementation over a period of time and monitor to determine the effectiveness of the repair.

Table 1 displays the estimates comparison for the various rehabilitation strategies evaluated. It is obvious from this table that the reference rehabilitation strategy, which is based on a sealer with the addition of GCP, was significantly lower in cost than any other system. As such, the sealer with GCP was selected for field-testing, which is currently being implemented during the summer of 2015.

Field testing was implemented for several reasons as follows:

- Validate that moisture reduction within the arch will occur to the levels necessary to achieve an environment that corrosion cannot progress;
- Develop a sealer application rate and frequency as the protected nature of the arches is unique and lends itself to potentially reducing both the recommended application rates and frequency which translates to lower operating costs; and
- Develop an optimal GCP anode distribution pattern and confirm the anode consumption rate as the targeted low moisture contents is significantly different than normal applications for this product.

Table 1. Order-of-magnitude cost estimates of rehabilitation strategies to extend the life of the University Bridge arches for another 50 years. Cost estimates taken from sources: * private correspondence; ** BRE Projects (2015); *** (Wipf, Klaiber, Rhodes, & Kempers, 2004)

Rehabilitation Strategy	Cost Relative to Silane Sealer with Targeted Discrete Galvanic Anodes
Impressed Cathodic Protection*	$3,500,000
Electrochemical Chloride Extraction**	$2,500,000
Realkalization**	$2,000,000
Galvanic Zinc Strip Anodes*	$2,250,000
Polymer Wrap without Fiber***	$4,000,000

6 Conclusions

The numerical simulations and field program conducted for the University Bridge produced recommendations that identified potential savings between $2 and $4 million. Simulations were based on an approach to deterioration modeling that can be adapted for any type of structure, material, environment, or deterioration process to produce realistic and reproducible results.

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