Engineered Solutions for Corrosion Diagnosis and Remediation in Small Bridges

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ABSTRACT

Small bridges are frequently affected by deterioration caused by reinforcement corrosion, cracking and concrete degradation. In most cases, these defects do not result from structural failures, but rather from factors such as inadequate concrete cover, leaking joints, chloride-induced corrosion, or poor construction practices. For many civil and structural engineers, diagnosing these problems (and their causes), and selecting the appropriate remediation strategies often lies outside their core expertise.

This paper presents a structured framework for the investigation and remediation of small bridges suffering from corrosion-related defects. The methodology incorporates key diagnostic testing, electrochemical assessment, and systematic evaluation of remediation options. The step-by-step process involves: (1) diagnosing the root cause and extent of deterioration, (2) assessing structural and corrosion treatment alternatives, and (3) selecting interventions based on proven performance, durability, and cost-effectiveness. A critical element of this process is ensuring that the engineers conducting the investigations are fully aware of the range of available technologies and are able to match the most effective solution to each particular scenario.

Central to the approach is the adoption of validated techniques that restore service life to the original design expectations while considering long-term maintenance requirements. Through practical case studies, the paper demonstrates how this methodology bridges the gap between inspection and solution, enabling engineers to apply technically sound, economical, and durable remediation strategies for small bridges.

1 INTRODUCTION

The remediation of small bridges affected by reinforcement corrosion presents a challenge that extends beyond conventional structural engineering. While structural assessment and analysis of concrete structures are mature and well-established disciplines, the diagnosis and treatment of corrosion-related deterioration demands a broader spectrum of expertise, spanning materials science, electrochemical engineering, and practical construction knowledge. In particular, effective solutions often depend on the ability to integrate corrosion diagnostics, assess buildability constraints, and apply electrochemical treatments (if applicable) with precision. This requires not only an understanding of electrical and electronic systems but also the capacity to evaluate long-term durability and lifecycle performance.

In practice, the fragmentation of expertise across disciplines, structural design, corrosion science, contracting logistics, and electrochemical remediation can often hinder the development of optimal repair strategies. Few individual practitioners possess the full breadth of knowledge required to navigate these complexities, and multidisciplinary teams are not always available or engaged early enough in the investigation process. As a result, many small bridges suffer from underdiagnosed deterioration and/or receive interventions that fail to address the root causes of the corrosion problems.

This paper responds to this gap by presenting a structured, engineer-accessible framework for diagnosing and remediating corrosion-related defects in small bridges. It emphasises practical, validated techniques that align with buildability constraints and long-term service life expectations, enabling engineers to make informed, defensible decisions even when specialist expertise is limited.

2 INVESTIGATION DETAILS

For the purpose of this paper, we reference a representative small bridge design commonly found across New South Wales and Queensland. This bridge design typically comprises cast in-situ headstocks supported by precast concrete piles.

2.1 Initial Investigation

The first stage of investigation involves a global visual inspection to identify the type and extent of observable concrete defects. These defects generally fall into two categories: structural deficiencies and corrosion-related deterioration. Even in the absence of visible damage, it is prudent to conduct targeted testing to assess corrosion activity within the concrete matrix. This helps determine whether preventative measures should be considered with relation to reinforcement corrosion.

Global testing typically involves visual inspection and delamination testing. Further testing and assessments are conducted by a qualified professional engineer capable of diagnosing the likely cause and extent of any defects. However, it is neither practical or cost-effective to apply all available testing methods indiscriminately. Instead, a targeted approach should be adopted based on initial findings, and one of the primary objectives of the global inspection is to establish a clear and defensible scope for further investigation.

The common defect types in concrete bridges include:

- Cracking in concrete elements
- Delamination of concrete surfaces
- Concrete spalling due to rebar corrosion

During the initial investigation, it is critical to distinguish between structural defects and material degradation. This distinction determines whether subsequent further testing requires structural engineering input or can be limited to materials investigation.

Another essential component of the initial assessment is identifying the type of piles supporting the bridge (whether they are steel or concrete). This informs the strategy for inspecting the underwater sections of the piles, particularly in tidal zones. Where barnacle growth is normally present, selective removal from sample piles is recommended to assess the condition of the underlying material.

The initial global inspection of a small bridge can typically be completed within one day and may require boat access for substructure evaluation. Upon completion of this stage, the next step is to define the scope and methodology for detailed testing, based on the findings of the initial assessment.

2.2 Detailed Investigation

The most common scenario for detailed testing for a reinforced concrete bridge will involve the following test methods:

- Delamination testing (hammer tap survey)
- Concrete cover and reinforcement configuration measurement
- Chloride concentration testing at depth
- Concrete carbonation testing
- Electrical continuity testing
- Half-cell potential mapping
- Resistivity testing
- Compressive strength analysis
- Inspection of rebar at breakout location

The above tests are the most common for concrete elements on small bridges. These tests can be supplemented with additional testing such as petrographic analysis in case cracking due to ASR (Alkali-Silica Reaction) is suspected. In case of major cracks not caused by rebar corrosion, structural assessment would be required in conjunction with the above scope of testing.

3 TESTING PROCEDURE

3.1 Delamination Testing (Hammer Tap Survey)

Delamination testing by hammer is effective during a specific stage of the corrosion process. In the early initiation stage of reinforcement corrosion, chloride ingress or carbonation may depassivate the steel, but the corrosion products have not yet generated sufficient expansive pressure to fracture the concrete cover. At this stage, no acoustic change is expected, and hammer sounding cannot identify areas at risk. Conversely, in the late propagation stage, once corrosion has advanced to the point of significant cracking and cover separation, delamination becomes visually evident and hammer sounding provides little additional diagnostic value. The technique is therefore most useful during the intermediate phase of propagation, when subsurface cracking and incipient debonding have developed but before spalling is externally obvious. In this window, changes in acoustic response can reliably indicate zones where corrosion-induced cracking has progressed to cover separation.

3.2 Concrete Cover and Reinforcement Configuration Measurement

The concrete cover to reinforcement is typically measured using a rebar locator. In addition to determining cover depth, these instruments can identify the spacing and layout of the reinforcement. To confirm the accuracy of the instrument readings, selective verification can be carried out by drilling small diameter holes directly above detected reinforcement to physically confirm by caliper the actual cover depth and bar position. This verification step is important, as reliable information on both cover and reinforcement layout underpins several aspects of durability assessment.

From a corrosion risk perspective, the concrete cover and reinforcement configuration provide insight into the potential influence of carbonation depth or chloride ingress on the embedded steel. Areas with lower concrete cover are more susceptible to early depassivation and may reach the corrosion initiation threshold sooner. Accurate data on cover and bar arrangement therefore assists in interpreting exposure conditions and assessing the likelihood and distribution of corrosion activity across the structure.

These measurements are also critical when electrochemical treatments such as impressed current cathodic protection or galvanic anode systems are being considered. The available cover depth and reinforcement spacing directly influence the feasible anode type, geometry and placement. Adequate separation between the anode and the reinforcement is essential to achieve uniform current distribution, avoid localised over polarisation, and ensure long term system performance. Reliable data on both concrete cover and reinforcement configuration therefore supports the selection and detailed design of electrochemical treatment systems.

3.3 Carbonation Testing

Carbonation is the reaction between atmospheric carbon dioxide and the calcium hydroxide present in the cement paste. This reaction forms calcium carbonate and progressively reduces the pore solution pH from its natural alkaline state (typically >12.5) to values around 9. At this lower pH, the passive oxide film protecting the reinforcing steel becomes unstable, and corrosion initiation becomes possible once moisture and oxygen are available.

The carbonation reaction occurs only in the presence of moisture, as carbon dioxide must dissolve into pore water before reacting with calcium hydroxide. Consequently, the rate of carbonation is strongly influenced by the concrete’s moisture condition. In very dry concrete, insufficient pore water slows the reaction. In fully saturated concrete, the pore water blocks the ingress of carbon dioxide, again limiting the rate. The most favourable conditions for carbonation occur at intermediate moisture

levels (typically around 50–70% relative humidity) where sufficient moisture is present for the reaction, but not enough to impede gas diffusion.

In well constructed structures made with dense, good quality concrete and/or protected by coatings or membranes, carbonation progresses slowly and may take many years or decades to reach the depth of the reinforcement. Conversely, concrete with low cover, high permeability, or exposure to alternating wet–dry cycles may experience significantly faster carbonation rates. Measuring carbonation depth therefore provides valuable insight into the likelihood that the reinforcement has reached or is approaching the corrosion initiation threshold.

Carbonation depth can be assessed on site by spraying a pH indicator solution, commonly phenolphthalein, onto freshly broken or fractured concrete surfaces. The uncarbonated alkaline concrete will show a distinct change in colour, while carbonated zones remain colourless. Alternatively, carbonation can be measured in the laboratory using extracted core samples, where controlled cutting and testing allow for more precise determination of carbonation profiles.

3.4 Electrical Continuity of Reinforcement

Testing for reinforcement continuity is carried out for two primary purposes. The first is to determine whether potential mapping can be meaningfully performed. Electrical continuity of the reinforcement is essential for potential mapping, as discontinuous steel will produce misleading or non interpretable corrosion potential gradients.

The second purpose relates to the feasibility of applying electrochemical treatment systems. Electrochemical methods such as impressed current cathodic protection, or electrochemical realkalisation or electrochemical desalination require the reinforcement to be electrically continuous so that current can be distributed uniformly throughout the steel network. If significant discontinuities exist, achieving full continuity across the structure can be technically difficult, intrusive and costly. In cases where these is inadequate electrical continuity, electrochemical treatment may not be practical or cost effective.

Continuity testing is typically performed by measuring the electrical resistance between selected reinforcement bars at various locations. Low resistance values indicate good electrical continuity, whereas high or unstable readings suggest discontinuities or isolated steel segments.

3.5 Potential Mapping

Potential mapping is typically undertaken at selected locations across the structure to assess the corrosion activity of the embedded reinforcement. It is one of the most informative diagnostic tests available, as it can detect corrosion activity during the initiation stage, before cracking or delamination become evident. In addition, potential mapping provides an overall assessment of areas exhibiting differing levels of corrosion risk. This is particularly informative for the piles and headstocks of small bridges to ascertain the corrosion risk profiles at different exposure conditions.

Accurate interpretation of potential mapping results is essential. While standard criteria provide a useful baseline, calibration against the actual structure is often beneficial (10). This can be achieved by verifying a small number of locations through physical inspection allowing the measured potentials to be correlated with the true corrosion condition of the reinforcement.

The results are commonly interpreted in accordance with ASTM C876 80 (1) and ACI Committee 222 (1985) guidance (2).

Under ASTM C876 80, the probability of corrosion based on potentials measured relative to a Copper–Copper Sulphate Electrode (CSE) is:

- More positive than –200 mV (CSE): <5% probability of corrosion
- Between –200 mV and –350 mV (CSE): approximately 50% probability of corrosion
- More negative than –350 mV (CSE): >95% probability of corrosion

The ACI 222 (1985) criterion further notes that a potential difference greater than 0.100 V between adjacent grid points usually indicates active corrosion. Large potential gradients tend to be associated with localised corrosion (pitting) and higher corrosion rates.

When applied correctly and interpreted with appropriate engineering judgement, potential mapping provides a powerful tool for identifying corrosion activity, prioritising areas for further investigation, and informing the selection of suitable remediation strategies.

3.6 Resistivity Testing

Resistivity is a fundamental material property that reflects the ability of concrete to resist the flow of electrical current or ionic movement when subjected to an electrical field. It is expressed in ohm centimetres (Ω·cm). Materials with high resistivity are poor conductors, while those with low resistivity conduct electrical current more readily. In concrete, resistivity is governed largely by its microstructure, particularly the size, distribution and connectivity of capillary pores. A dense pore network with limited interconnection reduces permeability and results in higher resistivity.

For reinforced concrete structures, resistivity measurements provide valuable insight into the corrosion risk of embedded reinforcement. Low resistivity concrete facilitates ionic transport and generally corresponds to a higher likelihood of corrosion activity, especially when chlorides or carbonation are present. Conversely, high resistivity concrete restricts ionic movement and is typically associated with a lower probability of corrosion.

For bridges and infrastructure located in marine environments, resistivity data is an essential factor for the feasibility and selection of electrochemical protection systems. Galvanic anode systems rely on natural potential differences to drive protective current, and their performance decreases significantly as concrete resistivity increases. In practice, galvanic systems are generally ineffective in concrete resistivity greater than 50 kΩ·cm (5).

Impressed current cathodic protection (ICCP) systems, by contrast, can operate effectively in medium resistivity environments. However, in high resistivity concrete, ICCP may require design modifications such as reduced anode spacing to ensure adequate current distribution and long term performance (3).

Overall, resistivity testing of concrete provides a critical link between material condition, corrosion risk, and the feasibility of electrochemical remediation strategies.

3.7 Compressive Strength Testing

Compressive strength testing is not generally considered essential from a durability assessment perspective, as the strength of the concrete does not directly indicate its susceptibility to carbonation, chloride ingress, or reinforcement corrosion. However, when compressive strength is known, it can provide supplementary value in the selection of compatible repair materials.

For concrete remediation work, compressive strength data can assist in choosing a repair mortar with mechanical properties that are compatible with the parent concrete. While durability related properties such as resistivity and permeability are more critical for long term performance, a repair mortar with strength characteristics broadly aligned with the existing concrete can help minimise differential movement and improve the overall bond between the repair and the substrate. In some cases, selecting a repair material with resistivity similar to the parent concrete may also contribute to more uniform electrochemical behaviour across the repair interface.

Compressive strength testing requires the extraction of concrete cores and subsequent laboratory testing. This process is highly intrusive, causes localised damage, and requires reinstatement. For this reason, compressive strength testing is typically reserved for situations where structural capacity must be confirmed or where specific information is needed to support the selection of repair materials. In most durability investigations, it is not an essential test and is often omitted unless there is a clear justification.

3.8 Inspection of Reinforcement at Breakout Locations

Inspection of reinforcement at breakout locations provides direct visual confirmation of the steel condition and is valuable for correlating non destructive test results with actual in situ conditions. This test is inherently destructive and should therefore be undertaken selectively, typically only where the overall corrosion assessment remains uncertain or where verification is required to validate interpretations from potential mapping, resistivity, or other diagnostic methods.

Breakouts allow assessment of key parameters such as the presence of corrosion products, cracking patterns around the reinforcement and concrete quality adjacent to the steel. Another objective is to verify the accuracy of cover measurements from non-destructive testing.

When used judiciously, these rebar inspections help to anchor the broader dataset and ensure that conclusions drawn from non destructive testing accurately reflect the true condition of the reinforcement.

4 INTERPRETATION OF RESULTS

Following the completion of site testing and the receipt of laboratory results, an experienced engineer can determine the underlying causes and extent of the observed defects. This step is critical, as accurate diagnosis forms the foundation for selecting an appropriate and effective remediation strategy.

When testing is carried out in a structured, comprehensive, and methodical manner, the resulting dataset typically provides a clear and coherent picture of the condition of the structure. In such cases, the interpretation process becomes more straightforward, and the results naturally guide the next stage of decision-making, namely, the selection of the most suitable remediation option.

5 REPAIR SELECTION

For infrastructure, the selection of an appropriate and workable repair strategy is the stage which demands the highest level of engineering judgement and professional experience. Making sound recommendations requires a thorough understanding of the diagnostic test results, combined with detailed knowledge of available repair technologies and a clear appreciation of their advantages, limitations, and long term performance characteristics. Reliance on sales driven product selection or choosing solutions simply because they require minimal monitoring or maintenance often leads to poor outcomes and, in many cases, premature failure.

While a detailed comparison of all repair systems is beyond the scope of this paper, reference is made to published performance data for both impressed current cathodic protection (ICCP) systems and galvanic based systems installed on numerous similar bridges across Australia (4,5). In general, the primary decision lies between two broad categories:

1. Conventional patch repair and protective coatings, and
2. Electrochemical treatment systems.

Conventional patch repair and protective coating systems for bridge elements may be suitable where reinforcement continuity is poor or where deterioration is primarily driven by low concrete cover, often in combination with carbonation. If carbonation is widespread but the concrete matrix remains largely sound, electrochemical realkalisation may be considered, however, this technique has not yet achieved broad adoption in Australia.

Where chloride induced corrosion is not the primary cause of deterioration, and carbonation is not extensive across the structure, conventional patch repair using a polymer modified repair mortar combined with an appropriate protective coating remains the default repair approach.

Where chloride contamination is the principal cause of corrosion, the selection becomes more constrained. Galvanic anode systems may be suitable in situations where reinforcement continuity is

poor. In such cases, localised galvanic anodes can be installed within patch repairs to mitigate the risk of incipient anode formation.

In all other circumstances involving chloride contaminated concrete, ICCP or electrochemical chloride extraction (desalination) should be considered, as these are the only technologies with established global and local standards (6,7,8,9) and a proven track record of effectively addressing chloride induced corrosion in reinforced concrete structures. Chloride extraction, however, is generally ineffective in tidal and splash zones or where chlorides have penetrated well beyond the depth of the reinforcement.

ICCP remains the most versatile and reliable technology for halting chloride induced corrosion across a wide range of exposure conditions.

For the immersed portions of marine structures, galvanic anodes installed directly in the water are often the most practical solution, particularly for smaller bridges, as they avoid restrictions associated with fishing, diving, or marine operations that may arise with submerged ICCP anodes. In many cases, the optimal long term solution for bridges affected by chloride induced corrosion is a combined approach: galvanic anodes for the submerged elements and ICCP for the concrete components above water. For areas like the deck sofit, normally silane based penetrating sealer is the most common option for corrosion prevention.

6 CONCLUSION

The investigation and remediation of corrosion affected small bridges requires a disciplined, evidence based approach that extends beyond traditional structural assessment. The framework presented in this paper demonstrates that when diagnostic testing is carried out systematically, beginning with a global inspection and progressing through detailed electrochemical and materials evaluation, the resulting dataset provides a clear foundation for selecting appropriate and durable repair strategies.

A key outcome of this structured methodology is the ability to distinguish between defects that can be addressed through conventional repair techniques and those that demand electrochemical intervention. By integrating cover measurement, chloride and carbonation assessment, potential mapping, resistivity testing, and selective breakout verification, engineers can reliably diagnose the root causes of deterioration and evaluate the feasibility of available treatment technologies.

Ultimately, the effectiveness of any remediation strategy depends on matching the correct technology to the specific deterioration mechanism, exposure environment, and material condition. This paper reinforces that durable, economical outcomes are achieved not through defaulting to familiar or low maintenance solutions, but through informed engineering judgement grounded in validated diagnostic data. By adopting this structured approach, practitioners can bridge the gap between inspection and solution, delivering interventions that restore service life, align with buildability constraints, and provide long term value for small bridge assets.

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