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Rethinking Corrosion Protection Strategies: Lifecycle Perspectives on ICCP and Galvanic Systems in Reinforced Concrete

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ABSTRACT

The long-term durability of reinforced concrete infrastructure depends on corrosion management strategies aligned with the intended service life of the asset. Because structures such as bridges, tunnels, and marine facilities are rarely replaced and often remain in service for many decades, selecting an appropriate corrosion protection approach has become a critical design decision. Electrochemical protection options commonly adopted include impressed current cathodic protection (ICCP) systems using mixed metal oxide (MMO) anodes, electrochemical desalination and realkalisation treatments, and galvanic systems employing embedded zinc anodes. This paper examines the theoretical service life expectations and maintenance implications of these technologies to support rational system selection.

MMO-based ICCP systems are typically designed for an initial service life of 30 years at maximum output, before system refurbishment is required. The theoretical service life (based on anode capacity) may exceed 100 years due to reduced current demand over time. Electrochemical desalination and realkalisation provide targeted interventions that modify the concrete environment but require controlled application and monitoring. Galvanic zinc systems offer simpler installation but have a finite life, generally 10 years, limited by zinc mass and efficiency.

This paper highlights strategic considerations for rehabilitation planning that emphasise whole-of-life asset performance rather than short-term interventions that may restrict future corrosion management options.

INTRODUCTION

Reinforcement corrosion remains one of the most significant and predictable drivers of deterioration in concrete bridges, tunnels, and marine infrastructure. Its progression may be gradual, however its consequences are cumulative and unavoidable. The long-term costs include escalating maintenance interventions, reductions in structural capacity, and ultimately loss of serviceability.

Despite this, repair strategies are frequently selected based on short-term convenience, lowest upfront cost, ease of installation, ease of maintenance, and in some cases, persuasive but technically unsupported claims promoted by sales representatives. Such decisions are rarely aligned with engineering evidence, historical performance, or the long-term capability of the proposed systems. The result is a pattern of interventions that, in some cases, fail to deliver even short-term project outcomes while diminishing the asset's long-term corrosion management pathways.

Most bridges and critical infrastructure assets now operate far beyond their nominal design life. Structures conceived for 50 years routinely remain in service for 70, 90, or even more than 100 years. This widening gap between asset life and repair life creates a strategic challenge where short-lived corrosion mitigation measures may provide temporary relief, yet may obstruct, delay, or

complicate the implementation of durable corrosion protection systems which are required later in the asset's life.

This paper adopts an uncompromising whole-of-life perspective. It argues that rehabilitation decisions must be aligned with the actual service horizon of the asset, not the limited timeframe of a single project or budget cycle. The central principle is that no repair should compromise the feasibility, performance, or efficiency of future corrosion protection measures. This approach is consistent with modern sustainability commitments, and recognises that durable corrosion strategies reduce demolitions, minimise material waste, and lower embodied carbon across infrastructure's lifecycle.

CORROSION PROTECTION TECHNOLOGIES

For the purpose of this paper, the primary corrosion-protection methodologies for reinforced concrete structures are grouped into two categories. The first is electrochemical technologies which includes impressed current cathodic protection (ICCP), electrochemical chloride extraction, and electrochemical realkalisation. These technologies have been used for several decades and are supported by international standards (1–4), and have extensive global performance records across chloride-contaminated and carbonated structures. The second category is galvanic anode based systems which rely on zinc connected directly to the reinforcing steel, with proprietary backfills used to manage dissolution by-products and maintain electrical performance.

Electrochemical Technologies

ICCP systems use lightweight mixed-metal-oxide (MMO) titanium ribbon or discrete anodes with a theoretical design life of around 50 years and practical performance often exceeding 100 years due to declining current demand as steel becomes repassivated. External cabling and control components can be designed for a 30-year service life and replaced as needed, allowing the system to match or exceed the remaining life of the asset. A key advantage of ICCP is the long-term improvement in reinforcement corrosion resistance, which further reduces current demand (5).

Although some early ICCP installations experienced issues such as delamination of gunite around MMO mesh, problems with graphite-embedded discrete anodes, thin titanium wire operating at high voltages in tidal zones, grout acidification from poor encapsulation, and unreliable early-generation power supplies, the majority of systems have delivered excellent long-term protection. Recent publications (6, 7) report strong performance across Australian installations. Most historical failures were a reflection of gradual technological development. Modern ICCP systems, supported by advances in electronics and communications hardware, can now be engineered as robust, low-maintenance solutions with reliable remote monitoring and control.

Electrochemical desalination and realkalisation treatments provide service lives that depend on structure-specific conditions but share a critical advantage: they introduce no permanent hardware into the concrete. When properly designed and executed, they can deliver around 30 years of life extension while preserving full compatibility with any future corrosion protection technology.

Galvanic based systems use zinc connected directly to the reinforcing steel, typically with proprietary backfills that manage dissolution by-products and help maintain electrical performance.

They perform reliably within their design life in low-resistivity environments such as overlays and jackets. Their limitations become clear when installed in drilled holes for global bridge protection, where long-term performance demands large zinc masses and still may not deliver adequate current in moderate- to high-resistivity concrete or aggressive marine environments. This inherently restricts their suitability for whole-of-structure, long-term protection.

Galvanic systems are unlikely to consistently achieve recognised cathodic protection criteria over their service life, though they can provide localised corrosion mitigation under favourable

conditions. They are most appropriate where ICCP is impractical or undesirable, for example, structures with limited remaining life, elements with poor electrical continuity, and residential buildings where long-term ICCP maintenance cannot be guaranteed. In such cases, galvanic systems can be a practical and defensible option. Where these constraints do not apply, embedding short-lived zinc anodes into structures expected to remain in service for 50–100 years is neither technically nor ethically defensible, as finite zinc mass and limited service life cannot support whole-of-life corrosion-protection requirements.

Galvanic systems include both traditional zinc anodes and hybrid anodes that provide a brief impressed-current phase before reverting to galvanic operation. Their performance record in Australia has been inconsistent, with variable outcomes across projects. A defining characteristic of all galvanic systems is the permanent embedment of zinc within the concrete. Some systems do not operate effectively from the outset in higher-resistivity environments, and those that do typically provide protection only in proportion to the available zinc mass. Across the industry, zinc-based anodes generally achieve around 10 years of service life, with protection diminishing from partial to negligible as the zinc is consumed

LONG-TERM PERFORMANCE

Presenting selected performance information for ICCP, electrochemical treatments, and galvanic systems, although not the central focus of this paper, is necessary to establish a whole-of-life perspective on how each performs over time. This context leads directly to the core discussion of this paper which is the suitability of these systems for rehabilitating structures expected to remain in service for 100 years or more.

Impressed current systems can be engineered to operate for the full life of the asset, with routine replacement of cabling and power supplies at roughly 30-year intervals. Electrochemical realkalisation and desalination can be repeated after 20–30 years without restricting future treatment options, as they leave no permanent hardware in the concrete or any associated repair mortars (with variations in resistivity to the parent concrete). In contrast, all galvanic-based systems require the permanent embedment of zinc anodes that must eventually be removed often through substantial demolition after their limited service life of approximately 10–15 years, with some systems providing negligible protection from the outset due to the inherent limitations of zinc in aggressive environments such as bridges, tunnels, and wharves.

SERVICE LIFE CONSIDERATIONS

When evaluating corrosion protection strategies for reinforced concrete structures, it is tempting to focus on short-term considerations such as convenience, perceived cost savings, or the promise of ‘maintenance-free’ operation. For infrastructure expected to remain in service for 100 years or more, these considerations are secondary. One of the key obligations of engineers, asset owners, and society is to ensure that today’s interventions do not compromise tomorrow’s options.

The comparison between electrochemical technologies and galvanic-based systems makes this requirement clear. Impressed current cathodic protection can be engineered to match the full service life of long-span bridges and major infrastructure, with predictable replacement of external components at manageable intervals. Electrochemical realkalisation and desalination can be repeated after 20 to 30 years without destructive extraction of permanent anodes, preserving full compatibility with future technologies. These approaches extend service life without constraining future rehabilitation pathways or imposing recurring demolition cycles.

Galvanic-based systems, when used on assets intended to last a century, require the permanent embedment of zinc anodes that must be removed and replaced every 10 to 15 years, often through destructive intervention. In aggressive environments, some systems provide negligible protection from the outset. The repeated embedment and removal of sacrificial materials is incompatible with the long-term stewardship of assets designed to serve multiple generations. It introduces unnecessary waste, embodied carbon, and structural disturbance for a level of performance that does not align with claims often made to asset owners.

From a sustainability, environmental, and social responsibility perspective, the rule should be unambiguous: no repair methodology should be adopted if it significantly inhibits future corrosion protection or requires cyclical removal of embedded materials throughout the life of the asset.

From a carbon footprint perspective, every unnecessary demolition cycle adds avoidable embodied carbon, material waste, and structural disruption. Repair methodologies that require recurring extraction and replacement of embedded components compound this carbon burden over the life of the asset. Long-life electrochemical systems and reversible treatments minimise embodied carbon by reducing intervention frequency and preserving the structural fabric. Sustainable corrosion management is inseparable from lifecycle carbon performance, and the most sustainable solution is the one that avoids repeated demolition and maintains compatibility with future rehabilitation pathways.

CONCLUSION

Long-life infrastructure demands long-life thinking. Rehabilitation strategies must preserve future options, avoid recurring demolition, and must aim to minimise environmental burdens. Electrochemical systems and reversible treatments align with these obligations, while short-life galvanic-based systems do not. From a carbon and sustainability standpoint, the priority is to reduce intervention frequency and avoid embedded materials that require cyclical removal. These steps are essential for lowering embodied carbon and protecting the structural fabric.

This position is not a rejection of galvanic systems. They have well-defined and appropriate applications as outlined in the paper. The distinction is simply that short-lived technologies cannot be relied upon for infrastructure expected to remain in service for many decades. Sustainable stewardship creates value only when today's interventions protect tomorrow's possibilities.

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