Corrosion Management of Reinforced Concrete Structures – The Environmentally-Responsible Decision

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Abstract:

Corrosion mitigation and management takes many forms for reinforced concrete and masonry structures with impressed current cathodic protection (ICCP) being the foremost technique that can provide the owner with a defined and managed future for his structure.

However experiences of engineers and owners have been mixed with a common perception that these systems are high maintenance in the future.

Longevity is the main criterion for an owner with the economic value coming a close second. Preferred design lives varying from 5 years for a simple repair strategy to 120 years for a nuclear or similar type facility. Not surprisingly other mitigation products have been introduced to attempt to answer the questions raised with such a broad life expectation and pressure on cost.

However are we clear when we define design life and how does this differ from service life of the structure? We often specify design life of the system being proposed but we would argue that we should be defining the impact of that system to a proposed extension of service life of the structure in question.

If we take this step then the economics of the system being offered can quickly relate well to life cycle cost comparison and a sensitivity analysis of the technical and economic considerations. This in turn makes the case more certain for the financial heads deciding best value for an owner.

This paper provides a timeline for successful implementations of corrosion management schemes. It explains the need to monitor the performance of such mitigation solutions and the development of that monitoring to a management process where measured data inputs and impacts directly to the engineering decisions for the future of that structure.

It describes the case for an environmentally-driven discussion on acceptance of corrosion mitigation and management and how whole infrastructures can be built-up to manage multiple structures from a single online management server making a perceived high maintenance system very much a low maintenance and economically viable choice.

Keywords: Corrosion; mitigation; management; infrastructure; sustainability

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Introduction

For the corrosion engineer trying to relate the issues pertaining to mitigation and management of an already cracked and spalled structure to a first time client buyer the step to explain the full value of such a scheme is more often than not ignored and the technical merits of the anode or inhibitor or coating or repair only options become the sole factor for making the case for acceptance. For the client however evaluating the true cost of the system offered will be the over-riding concern.

It is no surprise then that repair only with no direct corrosion mitigation scheme remains the best economic case as it is the cheapest, quickest and technically least demanding to consider. It is more likely however to be the wrong decision for structure longevity given the problems associated with incipient anode formation around the repair perimeter and the developing problems with contaminated and untreated parent concrete. In other words the root problem has not gone away.

Making the case for corrosion mitigation can be long and arduous however as the client gets to grips with the perceived “alien” technical issues and product choices; this can culminate in “sticker-shock” when he reviews the likely capital costs.

So what are the issues that need explaining and how do these issues lead to the belief that the technical steps being taken are the best economic value for the owner?

For any project the considerations usually begin with the assessment and derivation of best technical solution that feeds into the evaluation of cost of the proposed system and its installation.

However the cost benefit of the solution in the form of life cycle cost analysis should also be assessed and alongside this the environmental benefit of the proposal with its economic benefit.

Another important feature of the contract process is the understanding of the transitional role of the corrosion specialist (sub-contractor) who often becomes the key performance advisor to the client following completion of the installation phase of the contract as these systems require long-term management.

In short the process should be:

1. Technical
2. Environmental
3. Cost Analysis (upfront and life cycle)
4. Future management strategy.

The Technical Case

Usually an owner will instruct an engineer to investigate a problem only when it is visually obvious and even then possibly not until the aesthetic visualisation evolves into a large repair problem and possibly added pressure from a health & safety perspective. By this point the cost of repair alone can be daunting without the consideration of corrosion mitigation alongside the repair solution.

The desired service life of the structure then becomes the issue to decide best strategy as it may not always be possible to demolish and rebuild due to cost, traffic impact or simply logistical reasons.

In Europe the approach to the type of problem shown in Figure 1 is now well documented in EN 1504-9 (4) where repair, strengthening and corrosion management are integrated into a single harmonised standard. In the USA (and used throughout the world) there is also The Concrete Repair Manual (14) to lead the engineer to a sensible strategy for solving the problems.

EN 1504-9 covers 11 principles and methods to address these issues for the long-term and these are summarised as follows:

Principle 1: Protection against ingress
Principle 2: Moisture control
Principle 3: Concrete restoration
Principle 4: Structural strengthening
Principle 5: Physical resistance
Principle 6: Resistance to chemicals
Principle 7: Preserving or restoring passivity
Principle 8: Increasing resistivity
Principle 9: Cathodic control
Principle 10: Cathodic protection
Principle 11: Control of anodic areas

Principles 1 through 6 and 8 are primarily concerned with the concrete cover and how to repair, strengthen and provide environmental resistance in the future.

Principles 7 and 9 through 11 target the use of corrosion mitigation products to control the corrosion processes inherent in the structure at time of repair.

The main technical challenge arises from the integration of the relevant principles to achieve a harmonised repair and protection strategy that is derived from the objectives of the owner in terms of service life expectancy or desire for service life extension in some instances.

Neither the EC standard nor the US guidelines however forces the economic case for proceeding with a rehabilitation program.

Figure 1: Bridge structure in Scotland showing localised spalling due to chloride contamination; concrete would have fallen some 30m to the ground creating structural, economic and health & safety concerns.

Figure 2 below demonstrates the effect of intervening in the corrosion process and the impact of timing on the extension to service life.

In this schematic the upper sloped line represents no intervention and the service life is defined by the maximum permissible corrosion before degradation leads to loss of structural integrity. This point will vary for structures in different environmental exposure conditions and in respect of design tolerances during construction, especially over-design of structural requirements.

Intervention during the corrosion initiation phase (that is, before there are visible signs of corrosion and its effect on the concrete cover) by proactive maintenance can often lead to significant service life extension as the point of reaching the maximum permissible corrosion limit is in itself extended in time significantly.

More often we see the intervention point represented by the reactive maintenance line where corrosion has propagated to some extent and probably lead to visible signs of degradation leading to the need to repair the structure and consider corrosion mitigation options as an add-on to that repair strategy.

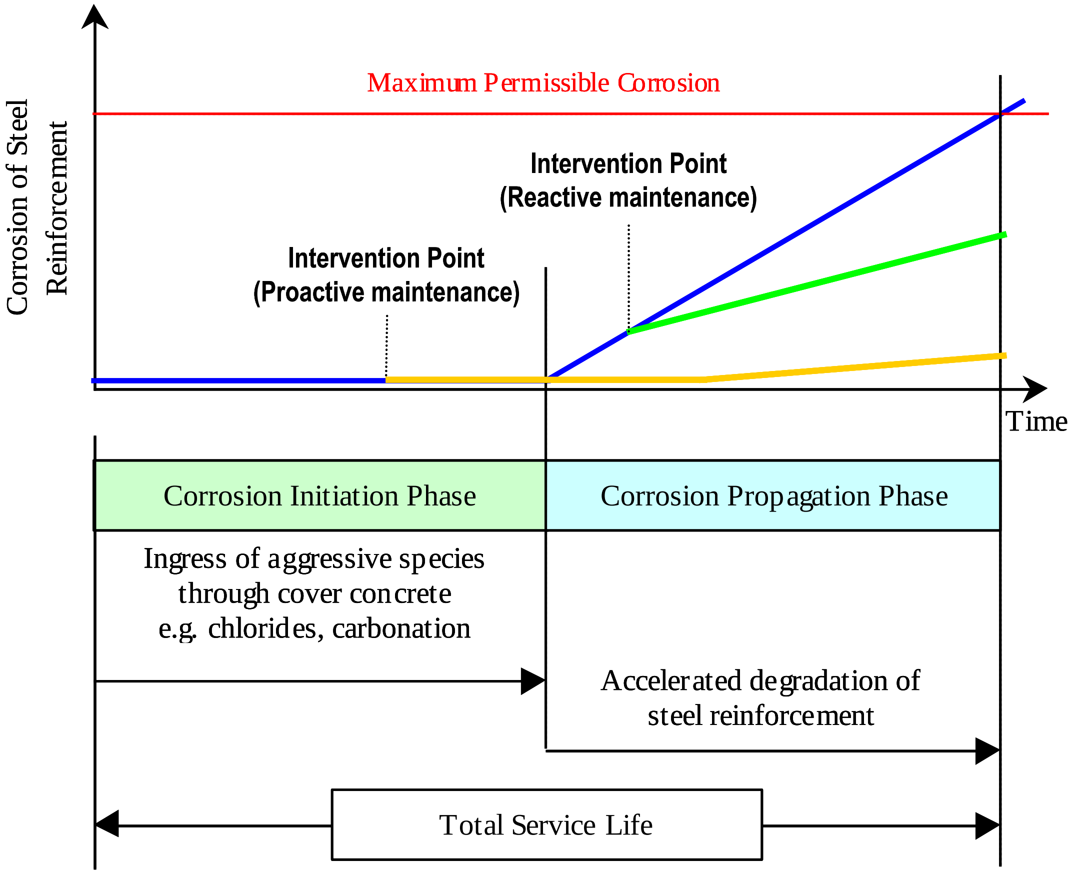

Figure 2: Schematic representation of structure service life and the impact of timing of intervention to achieve a service life extension.

The technical focus would therefore be best served by achieving the most control over the service life and choosing the most appropriate technology to achieve that objective in accordance with the standards available. Choosing the best strategy clearly therefore requires a fundamental understanding of where one is in the corrosion process first.

To achieve this one needs to perform a good condition survey and to feed that data into the design process having established then whether and which elements of the structure are in corrosion initiation and which are in propagation as this will impact material choice and consequently make the economic case for the chosen strategy.

The Environmental Case

As the effects of global warming become more scientifically defined so the political pressures to address the underlying causes become equally pressing.

Hays and Cocke (1) summarise well the issues as they relate to the structural engineer where they highlight the tendency to tear down a structure and rebuild albeit with sustainable materials in mind is not necessarily the most climatically sensitive approach.

It is shown that the cost of demolishing and rebuilding if measured as embodied energy loss (that is the amount of energy associated with extracting, processing, manufacturing, transporting and assembling materials) is some 10x more costly than the maintenance, repair and reuse of that same structure. This equates to roughly the use of 1million gallons of car fuel versus the use of 100k gallons for a 50,000 square foot building.

Another example of energy savings is provided by Frey (2) where she quotes the case study of the Grand Central Arcade in Seattle's Pioneer Square where the rehabilitation would result in a saving of 92 billion BTU (british thermal units) or 730,000 gallons of car fuel.

This can further be explained to the use, for example, of impressed current cathodic protection (ICCP), to a saving in energy consumption of ca. 36MJ for every kg of reinforcement steel saved and a further 1MJ for every kg of concrete remaining in position (3). These figures are also understated in that author's "cradle-to-gate" approach to providing such materials as they do not account for "gate-to-site" costs.

These figures can be further developed in terms of the number of structures (buildings, parking, bridges, tunnels, stadia, utilities and so on) that undertake such a strategy on an annual basis and we can quickly reach the conclusion that the role of the corrosion engineer to the issue of global sustainability should be more prominent than it currently would appear to be.

The environmental case for maintaining structures and managing corrosion as a primary objective can be anticipated therefore to gather pace as these data become more widely known and recognised throughout the construction, and especially, repair industries.

The following case study is an example where initial thinking to demolish and rebuild the parking structure was superceded by the implementation of a corrosion management scheme dovetailed with the concrete repair and re-waterproofing strategy that follows closely the intent of EN 1504-9 (4).

Case Study: Mayorhold multi-storey car park, Northampton, UK

Built in 1973, Mayorhold MSCP is an important town centre parking facility and a key service provision from the client owner to shoppers and businesses alike and underpins the livelihood of this town.

The complex consists of 5 parking levels - designated A (basement) through E (roof) – with entry to the facility at level B. Access between levels is via flat ramps/decks upwards and spiral ramps downwards.

The revitalization of the building was undertaken after years of under-maintenance that saw the structure come perilously close to demolition.

Figure 3: View of Car Park before rehabilitation program began

The structure is a trough slab construction and conventionally reinforced through deck and within support downstand beams. Light mesh reinforcement exists between downstand beams.

Expansion and day joints were the focal point for growth of the corrosion issues.

Figure 4: Typical damage to downstand beam arising from leaking chloride-contamination from deicing salts carried in by traffic and through expansion and dayjoints.

Over various visits prior to 1999, the structure was the subject of localized repairs that were continuing to fail as a result of the corrosion process continuing. On an annual basis, new areas were also identified that required repairs and it was clear that the structure was deteriorating and that failure would ultimately occur.

Figure 5: View of reinforcement steel layout and typical corrosion condition with 32mm bars above downstand beams and steel mesh overlaying and spanning to next beam.

However, the repair areas were observed to be emerging mainly from leaking expansion joints/day joints. The downstand beams associated with these areas were in more serious condition than other mid-span beams. There was also corrosion and spalling issues associated with reinforcement in the deck surface over the beams.

Moreover, the areas of heavy trafficking associated with Entry level B, Ramp B-C and Level C itself were worse than the Basement Level A where traffic rarely descended and on Levels D and E where trafficking was much lighter. In addition, Roof level E was also protected over time with a deck waterproofing system.

The evidence of deterioration was therefore more specific than general (although growing in scope) and this lead to the client instigating testing works to assess the feasibility of designing a corrosion management strategy that could meet the technical and economic needs of the parking structure.

In 1999, the first phase of investigation began on Levels B and C and revealed high chloride and corrosion to the reinforcement over a significant portion of these levels. This was repeated in 2003 and over a four year period it was determined that the problem was accelerating in the high chloride areas.

Figure 6: Half-cell testing of parking decks

The principle techniques employed to determine the condition as well as to determine the acceleration effects were:

1. Chloride depth analysis at 25mm increments to 3 depths
2. Carbonation testing with phenolphthalein to fresh concrete surfaces
3. Half-cell potential contour mapping and interpretation to ASTMC876:99 (5).
4. Delamination sounding
5. Visual records

The following data was taken at the same test location on Level B driving lane and is representative of the corrosion condition to that level. The condition was also typical extending to Level C.

Table 1: Comparative summary of test data from Level B showing change in condition over different survey years.

Year of testing	Chloride to 25mm	Chloride to 50mm	Chloride to 75mm	Most –ve potential	Most +ve potential
1999	1.82	2.32	1.28	-396	-206
2003	4.48	4.85	3.96	-560	-285

Chloride content is expressed as percentage by weight of cement

Corrosion Potential is expressed as mVCSE (copper/copper sulphate electrode)

The data above clearly demonstrate the extent to which deterioration was accelerating given the increasing chloride at all depths as well as the more negative shift in corrosion potential. This acted as the basis for the type of corrosion mitigation techniques employed.

Typically other levels demonstrated chloride content less than 1wt% for Levels A and E with Level D showing chloride levels varying from very low (<0.1wt%) to medium at less than 2wt% with corrosion potentials reflecting this lower activity.

Carbonation levels were low throughout with the deterioration mainly attributed to chloride contamination of the cover concrete.

The corrosion management strategy was designed to arrest corrosion immediately with important control considerations that would avoid deterioration in the future.

Concrete repairs were defined and carried out together with the significant use of electrochemical corrosion mitigation techniques, namely, surface-applied corrosion inhibitors and impressed current cathodic protection methods to control the effects of corrosion.

The repairs were to the deck surfaces above the rib positions and at every 5th rib soffit position (including downstand beam) arising from the leaking of day joints.

Armed with the visual and electrochemical inspection results from the 2 test regimes in 1999 and 2003, criteria were developed to identify the most appropriate corrosion mitigation techniques in specific circumstances. This had the intention of targeting the most appropriate technical solution whilst still being acutely aware of the most appropriate economic solution for the client.

The criteria were based in principle on the chloride depth and corrosion potential contour mapping information but with the underlying intention not to mix and match solutions on the same parking level but to utilize the most appropriate technique to achieve the 25-year life extension desired by the Client.

The criteria and system package solutions applied were:

1. Half-cell potentials more positive than -200mVCSE and chloride content less than 1% by wt of cement would receive no corrosion mitigation treatment.

2. Half-cell potentials more negative than -200mVCSE and chloride content less than 1% by wt of cement would receive surface-applied corrosion inhibitor throughout. This was also applied to support columns.

3. Half-cell potentials more negative than -200mVCSE and chloride content greater than 1% by wt of cement would receive MMO titanium ribbon impressed current cathodic protection system.

4. In addition to 1) through 3) above, the top deck (Level E) would receive a decking system (solvent-free elastic polyurethane overcoated with a flexible epoxy seal coat) on all top surfaces to provide a tough, crack-bridging, waterproof but flexible surface to the deck with good color stability and weather, abrasion and slip resistance.

5. Intermediate decks exposed to less weathering received a solvent-free epoxy resin decking system with all the stated exposure durability characteristics.

6. Moreover, a decorative and anti-carbonation coating system was applied to soffits and downstand beams.

This yielded the following strategy on a level-by-level basis:

Level A: Limited concrete repairs and deck waterproof coating
Level B: Extensive concrete repairs, ICCP system and deck waterproof coating
Level C: As Level B
Level D: Limited concrete repairs, surface applied corrosion inhibitor and deck waterproof coating
Level E: No concrete repairs but new deck waterproof coating.

Levels B through D are monitored for performance as well as selected early detection points to the downward spiral ramps.

Repairs were conducted with a proprietary pre-bagged rapid setting mortar with high early strength characteristics.

The consideration of repair material resistivity was made with the decision to firstly provide robust concrete repairs and allow the ICCP to provide its protection to the unrepaired areas. Over time, as the steel within the repair patch requires additional protection, the resistivity change would allow passage of current and allow protection to proceed.

The MMO titanium ribbon anode however was set into slots in the deck with a non-polymer modified but rapid setting mortar to allow flow of current to occur from initial energization.

A policy of utilizing embedded monitoring of all system packages in a representative manner for the structure was also adopted. To achieve this, the half-cell contour plots were used to place corrosion potential and corrosion rate devices to provide performance data for deck, downstand beam and trough steel on the levels that received direct corrosion mitigation treatments.

The approach taken with the repair and protection scheme can be tracked to one or more principles contained within BS EN 1504-9. The only principle not represented in the scheme is Principle 4 for structural strengthening that was not a requirement.

Table 2: Summary of EN1504 principles with choice of repair and corrosion management strategy

Part 9 Principle	Objective	Technique Chosen	Area of Structure
1	Protection against ingress	Waterproof membranes and anti-carbonation coatings	Throughout top surfaces and soffits
2	Moisture control	Waterproof membranes; new expansion joints	Throughout
3	Concrete restoration	Concrete repairs	Where delaminated
5	Physical resistance	Coatings	Throughout
6	Chemical resistance	Coatings	Throughout
7	Preserving or restoring passivity	ICCP and inhibitors	Levels B, C and D
8	Increasing resistivity	Coatings	Throughout
9	Cathodic control	ICCP and inhibitors	Levels B, C and D
10	Cathodic protection	ICCP	Levels B and C
11	Control of anodic areas	ICCP and inhibitors	Levels B,C and D

All wiring associated with the ICCP and monitoring systems was hidden within the deck either in the anode slots or sawcut into the deck and dropped through the termination boxes on the soffits. These were then transferred to zonal enclosures in 2-compartment trunking that was also used to house the lighting cabling.

The system installed integrates all corrosion mitigation choices in a single controllable network management system. Boxes containing specific electronics for ICCP power, control and monitoring as well as SACI and early detection monitoring were discreetly hidden within the trough ends.

A single network management access unit controls the whole installation and is conveniently sited in the parking management suite.

Access and control is remote and accessible from a secure internet facility that will allow not only growth of the client's infrastructure management but also can integrate other features, such as lighting and security on the same network.

Figure 7: Control and monitoring electronics fitted neatly between downstand beams and protected against damage

Expansion joints were upgraded on both the top deck and intermediate decks with state-of-the-art technology with attention to finishing and sealing details.

Having established the structural integrity and future condition of the parking facility, the functionality and aesthetic end product was also a main consideration.

The deck coating systems were chosen not only for their durability and mechanical features but also for their aesthetic and safety features. The parking garage was a dark and dismal structure previously but with the ability to enhance the colour regime within the structure and upgrade the lighting system, the appearance of the structure has been transformed.

Addition of new roller shutters secures the parking facility at nights. Moreover fully interactive help points linked to a help desk have been added to newly installed pay-on-foot machines. CCTV has also been installed and the parking facility patrolled to augment security.

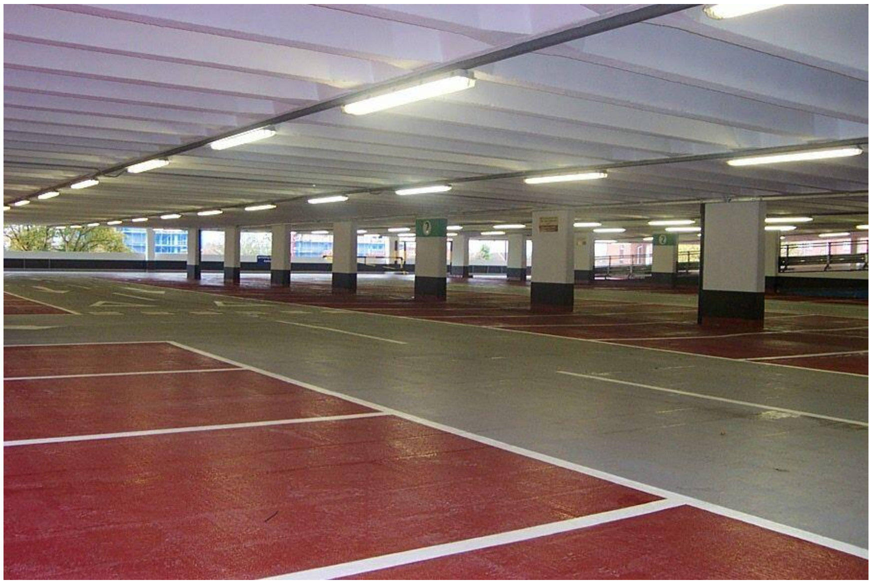

Figure 8: Enhancement of social aspects through better lighting and colour-coding of parking and pedestrian features gives the parking structure added sustainability credentials

The internet corrosion management facility is especially comforting to the owner as it offers the opportunity to continually assess the performance of the parking facility and reinforce the wisdom of his investment in a structure that looked initially to be more likely to be a candidate for demolition than a structure ready to face the next 25 years as a working and profitable asset to the town.

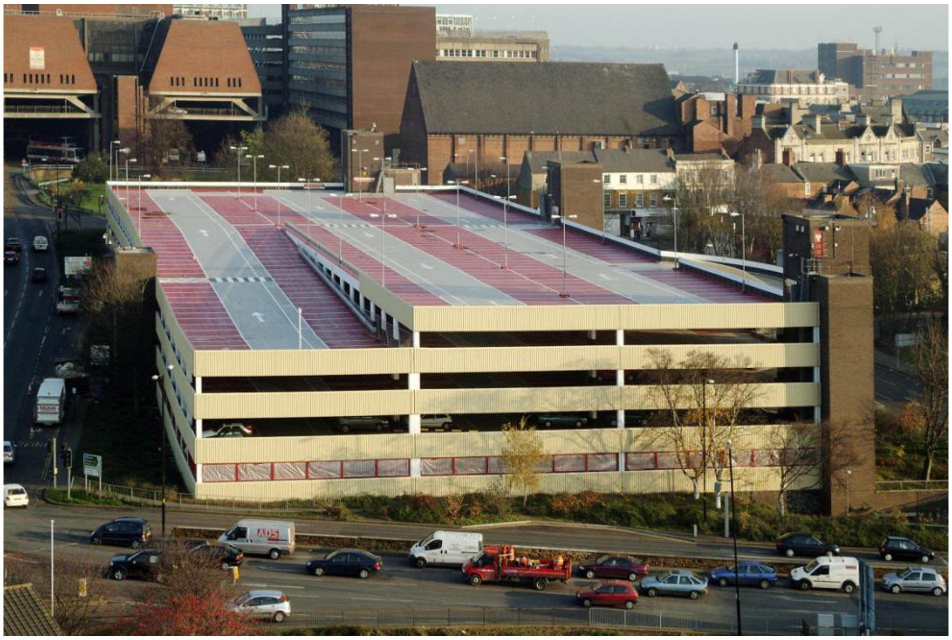

Figure 9: Aerial view of completed parking structure ready for the next 25 years

The Economic Case

In terms of cost we would argue that the greatest cost is in taking no action followed by delayed intervention followed by proactive intervention; this of course depends on how one calculates the total cost of these strategies.

Taking no action may seem on first consideration as the low cost option as it has “only” cost the owner the amount of first build on the face of it and none of the costs of interactive maintenance. However one needs to also consider the costs in outage terms for downtime closures, engineering costs for surveys to justify taking no action, health & safety costs and what of the environmental costs if the structure has to be demolished and rebuilt (see later for discussion of the latter point) and re-repair costs when the problem re-emerges in the future.

In other words how many rehabilitation strategies consider the life cycle costs over the period of service life expectancy? We would suggest not many and certainly not enough.

The economic impact of preferring the route of intelligent repair and corrosion management rather than demolition and rebuild can be developed from the data available from an online embodied energy calculator (6) for the above case study.

The car park had around 10,000 m^2 of concrete with an equivalent 11,000 m^2 of steel reinforcement and a further 10,000 m^2 of coatings. The demolition and rebuild route would have cost an equivalent of 156 billion BTU for the existing building, demolition and rebuild or the equivalent of 1.36million gallons of fuel (US$3.4million in saved fuel equivalent at today’s US pump prices).

The repair and protection route would be the equivalent of 10% of that cost saving some US$3.1 million.

The capital cost of this route would have cost around $10million in demolition and rebuild costs compared to the actual cost of $3million to perform the rehabilitation strategy.

In total, without accounting for the social sustainability effects, then this project saved the equivalent of US$10.1million to perform the rehabilitation task. Put into perspective for the corrosion management aspects of the project these cost US$1.07million to perform with ongoing annual management costs of US$10,000 to avoid repeating the repair processes any time in the next 25 years.

In life cycle cost terms over a 25 year period then this can be summarised as:

Option 1: Demolition and Rebuild Cost with first maintenance after 15 years for a period of 10 years.

Option 2: Cost of Repair scheme only over 25 years (assumes re-repair and new repair 5 times in period and rewaterproofing 2 times in period).

Option 3: Cost of Repair scheme and Corrosion management over 25 years (one off solution with 25 year corrosion management on the internet and re-waterproofing 2 times in period).

No allowance is made for non-monetary benefits (eg. increased pedestrian usage to the shopping facility due to improvements in lighting and safety, service life extension or social improvements) and no allowance is made for purchase or acquisition costs for land and so on.

Table 3: Summary Life Cycle Cost Analysis (LCCA) for Options 1 through 3 derived from NIST(7).

Option	Life Cycle Cost Analysis Value US$million	Environmental Cost US$million	Total LCCA US$
1	15.0	3.4	18.4
2	8.9	1.1	10.0
3	6.0	0.4	6.4

As we see from the figures above the LCCA demonstrates that even if we discount the environmental impact fully then the rolling out of the cost analysis over a 25 year period with modest re-repair assumptions then the use of corrosion management is fully justified.

If however the client is environmentally sensitive (which many public bodies are increasingly being) then the adoption of a corrosion management becomes irresistible at ca 1/3rd of the demolition/ replacement cost and almost 60% of the iterative re-repair cost.

In addition we could argue both a legal and emotional comfort that Option 3 provides with the generation of annual performance reports missing from the other 2 options that would be unlikely to be monitored, thereby enhancing the resaleability of the asset.

The Timeline for Corrosion Monitoring and Management

In 1989 the author presented a paper to the 4th APCCC (8) where the technology and principles for adopting corrosion rate monitoring for reinforced concrete was introduced.

Up to that point in time ICCP systems were the only systems to require monitoring in order to make control decisions.

In broad terms this remains the case with no other corrosion mitigation technique requiring monitoring.

However that does not mean to say that ICCP is the only technique to be monitored as technology and especially corrosion rate monitoring has evolved since 1989 to become not only a reliable method of monitoring with embedded probes but has become automated in its data acquisition and reporting over the internet (9-13) for reinforced concrete and historic masonry structures.

The first corrosion rate monitoring system (9) was installed in 1989 for the new construction of the reinforced earth approach walls at the UK terminus of the Channel Tunnel for assessment of corrosion of the galvanised earth straps and assessment of the effects of stray current corrosion that may arise from the leakage of current from the catenary lines as trains pass.

This system is still functioning well and is interrogated manually on intermittent visits.

From that point in time over 80 installations have been installed to the author's knowledge that have adopted corrosion rate monitoring for the performance management of ICCP, surface-applied corrosion inhibitors, silane treatments, waterproofing membranes and simple concrete repairs. To date none of these installations have been the subject of re-repair as knowledge has enhanced the ability to either control the corrosion processes or provide early and economic intervention to avoid the cost of re-repair.

However after 20 years this technology is still by no means accepted as the norm and it is almost certainly the case that more repair schemes progress without any monitoring of performance than adopt monitoring technology.

Conclusions

As clients and engineers become more environmentally aware as they consider the most effective rehabilitation schemes for reinforced concrete structures then we hope we have laid the foundation here for the corrosion engineer to be the central pivot of the team to devise such a scheme.

The technical, environmental and most importantly the economic cases are strong for adopting corrosion management strategies rather than demolition/ rebuild or constant re-repair policies.

This situation we contend is also true for new construction (13) as it is for preserving existing structures.

In that sense we have a new role as not only corrosion engineers but environmental/ preservation engineers and in that we perform a valuable service to both the client and the public at large as more and more structures become corrosion controlled and managed.

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