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Long-term performance and life-cycle-cost benefits of cathodic protection of concrete structures using galvanic anodes

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ABSTRACT

This paper presents a market study indicating that Patch Repair without galvanic anodes (PR strategy) can lead to continued corrosion (due to the halo effect and residual chloride effect) and another major repair in about five years. Repeated patch repairs can lead to continued corrosion and eventual replacement of structures and huge life cycle cost (LCC). On the other hand, the strategy of cathodic protection using galvanic anodes (CP strategy) can enhance the service life and reduce LCC. The data on long-term depolarized potential of steel, output current from the anodes and/or visual observations indicated that the galvanic anodes were successful in controlling the chloride-induced corrosion for up to 14 and 10 years, in a jetty and industrial building, respectively. It was also found that the additional cost of galvanic anodes is only about 4% of the repair cost for the jetty structure – breaking the myth of high capital cost of CP strategy. Then, a framework to estimate the LCC of PR and CP repair strategies is developed and it is found that CP and cathodic prevention (CPrev) strategies are highly economical than the PR strategy. Also, the LCC of 30 repair projects confirmed that the use of CP strategy can lead to LCC saving of up to about 90% in about 30 years after the first repair. More importantly, the CP and CPrev strategies can enhance the service life to as long as needed by the replacement of anodes at regular intervals and at minimal cost. Also, a way forward to promote CP strategy in concrete repair industry is provided.

1. Introduction

Corrosion of steel reinforcement is one of the major deterioration mechanisms in reinforced concrete (RC) systems. The service life of the reinforced concrete system is defined as the duration in which the structure can meet the user requirements. Generally, it is represented as the summation of the initiation phase ($t_{initiation}$) and the propagation phase ($t_{propagation}$) [1]. The former is the duration during which the chloride from the atmosphere travels through the concrete cover and a specific concentration, known as chloride threshold, reaches the surface of steel rebars and initiates corrosion, see inset in Fig. 1. During the $t_{propagation}$, the rebar continues to corrode. The corrosion of steel rebars results in steel cross-sectional loss and the formation of corrosion products with more than two times the volume of the steel. This rust products applies radially outward pressure on cover concrete, and results in cracking of cover concrete. $t_{propagation}$ ends when the damage level is more than the allowable damage level. Due to presence of cracks on concrete, $t_{propagation}$ is expected to be significantly less than $t_{initiation}$. Therefore, as soon the rebar in concrete systems exhibit corrosion, structure should be repaired. However, repair of RC system is usually carried out when the structure exhibits the maximum allowable damage, a reactive approach. The life of repair depends on the adopted repair strategy and the quality of repair work.

NACE Impact Report (2016) reports that about 50% of RC structures experience a major repair within ten years after construction [2]. To repair such systems, generally, patch repair is adopted. However, many reports suggest that patch repair may not arrest the ongoing corrosion [3–5]. In addition, the corrosion can preferentially start at the interface of the parent and repaired concrete – also known as the halo effect, see Fig. 2(a) [6,7]. This halo effect can lead to premature deterioration and repeated repair within about five years [4,8]. The repair of concrete systems needs cement, polymer-modified mortar, microconcrete, epoxy adhesive, and steel rebars, which have high embodied energy and high

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List of symbols and abbreviations

C	Cost of repair excluding the cost of inspection and anodes
C_{anode}	Cost of manufacturing, supply, and installation of anodes
$C_{CP, j}$	Future value of j^{th} repair with CP
$C_{insp\text{-}zero}$	Cost of inspection at the time of 1^{st} repair
$C_{insp, i}$	Future value of i^{th} inspection
CP	Cathodic protection (with galvanic anodes)
CPrev	Cathodic prevention (with galvanic anodes)
$C_{PR, j}$	Future value of j^{th} repair without CP
CSE	Copper-copper sulfate reference electrode
$C_{total, CP}$	Total cost of repair with CP till n^{th} year
$C_{total, PR}$	Total cost of repair without CP till n^{th} year
E_{24h}	Depolarized potential at 24 h
$E_{i\text{-}Off}$	Potential of the polarised steel within 0.1 s after disconnecting from the anode
FV	Future value
HCP	Half-cell potential
i	Identification of individual inspection (i = 1, 2, 3, …)
ICCP	Impressed current cathodic protection system
j	Identification of individual repair (j = 1, 2, 3, …)
j_{max}	Maximum allowable number of repairs
LCC	Life cycle cost
n	Time elapsed from 1^{st} repair (n = 1, 2, 3, …)
n_{max}	Maximum service life extension (analysis period)
NPC	Net present cost
PR	Patch repair (without galvanic anodes)
r	Discount rate
RC	Reinforced concrete
$t_{initiation}$	Duration of corrosion initiation phase
$t_{insp, i}$	Time interval between $(i\text{-}1)^{th}$ and i^{th} inspections
$t_{propagation}$	Duration of corrosion propagation phase
t_{repair}	Duration of the entire repair phase (Desired extension in service life)
$t_{rep, j}$	Service life of j^{th} repair
$T_{insp, i}$	Time elapsed between 1^{st} and i^{th} inspection (i = 1, 2, 3, …)
$T_{rep, j}$	Time elapsed between 1^{st} and j^{th} repairs (j = 1, 2, 3, …)

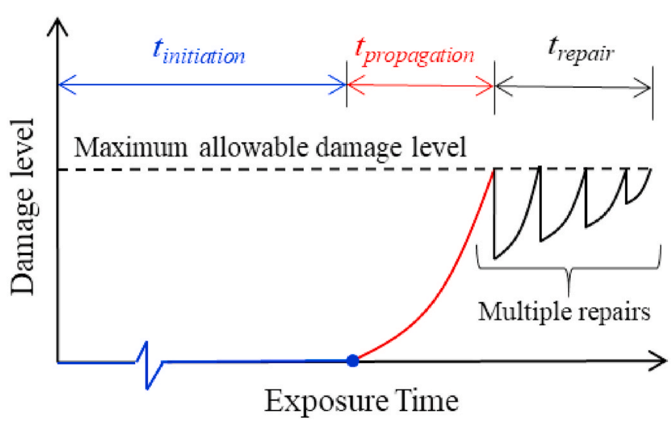


Fig. 1. Schematic showing various phases during the service life of concrete structures.

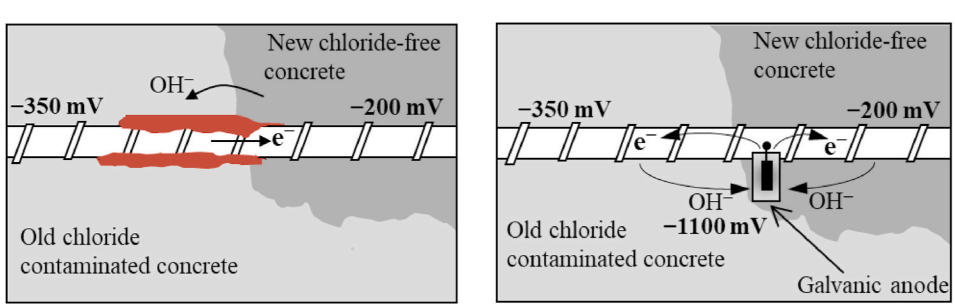
carbon footprint [9]. Therefore, implementing adequate electrochemical techniques such as cathodic protection using galvanic anodes (see Fig. 2(b)) can increase the time interval between repairs. Therefore, durable repairs can be achieved [10]. CP systems for concrete can be categorized into two: (i) impressed current cathodic protection (ICCP) system and (ii) Galvanic anode cathodic protection system [11,12]. This paper focuses on the latter system; the former will not be discussed herein.

The effectiveness of a repair can be evaluated by estimating the service life of repair, frequency of inspection or maintenance, the time required to execute the repair, aesthetics after the repair, and life cycle cost (LCC) of repair. Cathodic protection (CP) using galvanic anodes is one of the effective methods to control or prevent corrosion of rebars [13]. However, most of the repair projects do not consider using CP with patch repair because of the (i) lack of sufficient long-term field data to substantiate the claim of protection using galvanic anodes and (ii) wrong perception on the possibly high initial cost of repair with galvanic anodes and lack of consideration of LCC. It is high time that LCC is given due consideration while selecting repair strategies. This paper focuses on comparing the long-term performance and LCC of patch repairs with and without CP.

The remainder of the paper is arranged as follows. First, the working principle and assessment methods for CP in the RC systems is presented. Then, a review of literature is provided showing the lack of evidence on the long-term performance of CP in RC systems along with the concerns with the cost of repair with CP. After that, a market study of the application of CP in India is presented. Then, the details on long-term performance of CP systems on a jetty and industrial building structure are presented. Then, a model is proposed to estimate the LCC of repair. Then, the comparison of cost during the 30 years after first repair is compared. Finally, conclusions from this research are presented.

1.1. Cathodic protection systems in concrete

The principle of CP is to polarize steel (metal to be protected) from its free corrosion potential to the cathodic regime, where the corrosion is less likely to occur [14]. In atmospherically exposed concrete with steel



(a) Halo effect – when CP is not used   **(b) Prevention of halo effect – when CP is used**

Fig. 2. Patch repair with and without galvanic anodes.

rebars, a protection current to modify the micro-environment at the steel-concrete interface to inhibit pitting corrosion is sufficient [15]. The presence of the additional cathodic reaction increases the rate of formation of hydroxyl (OH^-) ions near the rebar surface – leading to the re-passivation of rebars in concrete. In addition, the negative chloride or sulfate ions are repelled from the negatively charged steel rebars [15,16].

Typically, in concrete, CP is implemented by installing an anodic metal inside or on the surface of the concrete and electrically connecting it to the rebars to achieve a continuous supply of a small current (1–200 mA/m^2) with or without using a rectifier unit [17]. Then, the steel rebar becomes the cathode, and the electrically connected sacrificing metal becomes the anode. If CP is implemented during the time of construction of the structure, the applied current density for protection can be in the range of 0.2–2 mA/m^2 and the technique is termed cathodic prevention and denoted as CPrev, herein [11]. Because of less maintenance, monitoring, ease of installation, and protection against vandalism, the use of galvanic anodes for electrochemical repair of the RC systems are gaining acceptance in the last two decades [4,8,18]. The technique involves applying a permanent current through galvanic anodes in the range of 0.2–20 mA/m^2 to the steel rebars [4,19]. Zinc is a widely used galvanic metal because of its high oxidation potential against steel [20]. The corrosivity of the zinc metal is ensured by embedding it in a high pH (13–14.5) or halide-activated environment [21–23]. In the case of alkali-activated zinc anodes, zinc anodes can get passivated if the pH of the embedding mortar is in the range of 12 to 9 [24]. Then, oxides of zinc start accumulating in the mortar pores and can hinder the ion-transport from the zinc to the steel [25,26]. Therefore, a frequent inspection needs to be conducted on the installed CP system to ensure the continuous functioning of these galvanic anodes till the desired service life of anodes (say, 20–25 years).

1.2. Assessment of cathodic protection systems

Presently, EN ISO 12696 (2016) and NACE SP0290 (2007) [11,27] are used for assessing the performance of CP in RC structures. The test methods suggested in these standards mandate external electrical connections from the anodes to the steel through a monitoring box with a resistor and switch assembly. One of the most widely adopted assessment criteria for CP in concrete is verifying a 100 mV shift in the potential of steel rebar by the influence of the galvanic anodes in 24 h [28,29]. The potential shift is obtained by calculating the difference between the instantaneous-off potential ($E_{i\text{-}Off}$) and the 24-h depolarized potential of the steel rebars (E_{24h}). The $E_{i\text{-}Off}$ is the potential of the polarised steel within 0.1 s after disconnecting the anode [11]. The E_{24h} of the steel is the potential measured after 24 h from the time of disconnecting the steel from the anode. Engineers arrived at the '100 mV shift criteria' through experimental studies on the corroding pipes buried in soil [28–31]. However, in RC systems, the polarisation shift depends on the environmental conditions such as atmospheric temperature, relative humidity inside concrete, corrosion rate of steel, and level of chloride contamination [32]. Also, after the installation of CP and once the steel is protected/passivated, the use the 100 mV criteria is not appropriate for in-situ assessment because the steel being protected at that stage may not necessarily shift its potential by 100 mV if disconnected from the anode [33,34]. This is because the potential shift demand or current demand for protection is less at that stage. In short, no conclusive empirical justification is reported to adopt '100 mV shift criteria' for continuous assessment of CP in RC systems [35]. An alternative approach to assess CP systems is to disconnect the system for 24 h and checking the depolarized potential, which is essentially the half-cell potential (HCP) of the steel disconnected from the anode. These HCP values can be compared with that of a protected/pristine rebars on the same structure and the active/passive states can be defined.

1.3. Long-term performance of the galvanic anode CP system in concrete

Much literature is available to validate the short-term working of galvanic anodes for RC systems through laboratory studies [25,36–39]. Also, consistent performance (for 4 years) of submerged anodes in exhibiting a 100 mV potential shift in RC column specimens [37,38]. Another study suggested that the galvanic anodes can supply a current of ≈ 0.4–0.6 mA after about a year when the initial output current densities were 1.5–2.0 mA/m^2 [6]. The galvanic anodes made in 1990s and 2000s were designed to function for 10+ years [8]. Later, based on a 20-year data from a CP system in a bridge in the UK, it was found that the anodes could protect the structure for about 15 years until the encapsulating mortar was saturated with alkali [40]. Today, many anodes with encapsulating mortar exhibiting adequate pore structure, long-term and high pH buffer, and better ion-exchange system capabilities are available. In support of this, much literature concludes that an adequately designed galvanic anode CP system could extend the life of repair for more than 25 years; thereby, a repeated repair can be avoided [8,41,42].

1.4. Cost of repair using galvanic anodes

There is a myth that the cost of anodes can significantly increase the cost of repair. However, such myth arises because of the lack of consideration of life-cycle cost (LCC). Ideally, such cost comparisons should be made between the LCC of repair instead of the capital cost of repair. The LCC of a repair depends on the frequency of repeated repairs and the maximum number of possible repeated repairs during the desired service life [19]. The use of galvanic anodes can prevent the halo effect and help in decreasing the frequency of repeated repairs.

Life-cycle costing can be used as a reliable tool to decide on a repair strategy [43,44] and to assess the performance of various repair strategies during the service-life, in terms of costs incurred for its acquisition, operation, maintenance, and disposal [45]. Typically, the LCC of infrastructure is calculated by the discounted cash flow method that involves the calculation of the net present cost (NPC) to account for the time value of money [46]. However, this requires the knowledge of the cash flow of every operations at each instances in the future, which is not available [47,48]. A comparative LCC can be conducted by obtaining the future value (FV) of all operations using Eq. (1) and some assumptions on future cost parameters.

$$FV = \sum_{n=0}^{N} (1+r)^n \times C_1 \tag{1}$$

where, C_1 is the total cost at 1st year (can be a constant), N is the analysis period (say, desired life extension), and 'r' is the discount rate. The number of repairs within the N years of life extension could be different for different repair strategies. For example, N of 30 years can be achieved either by adopting a repair system with a life of five years for six times or another repair system with a life of 15 years for two times. LCC in these two cases would be different and must be considered before making the choices. The discount rate, r, accounts for both the nominal interest and inflation rates [49]. The LCC of infrastructure can then be calculated using Eq. (2) [47].

$$LCC = C_D + C_C + C_R + C_{DD} \tag{2}$$

where, C_D is the cost of the design of the structure, C_C is the cost of construction (acquisition and operation), C_R is the maintenance and repair cost, and C_{DD} is the cost for demolition and decommissioning of infrastructure.

A few deterministic and probabilistic models are available to evaluate the LCC of RC structures exposed to various environments in a holistic manner [48,50,51]. Peng and Stewart used deterministic LCC by considering the number of maintenance instances and the efficiency of the material to compare the economic viability of various repair materials for surface repairs on RC structures deteriorated due to corrosion [52]. In another study, Younis et al. compared probabilistic and deterministic cost models for carbonation corrosion and showed that after 100 years, the repair cost is reduced by 50% compared to a deterministic LCC model [47].

Polder et al. (2014) proposed a probabilistic cost model for estimating the LCC of ICCP systems in concrete by using failure data from 105 case studies. The frequency of the global failure of the ICCP system was excluded from the model as it was scarcely reported within the analysis period [44]. The model used the average time for replacement of ICCP systems as ≈ 15 years. This replacement can be considered as a minor repair because it does not involve the major structural repairs, which is the advantage of any cathodic protection system (including the galvanic anodes, which is the focus of the current paper). Note that a statistically significant database on the failure period of the repair strategies is required to evaluate the probabilistic maintenance time and its cost. This is not available in the case of repair using galvanic anodes. Therefore, deterministic approaches are a way forward to determine the LCC of repair of RC systems using the galvanic anodes and is adopted in this study. This paper proposes a model for analyzing the life-cycle cost and benefits of patch repair with and without CP for concrete structures.

2. Significance of the research

In 2016, the overall cost of corrosion (CoC) for various countries were estimated to be about 4 to even more than 10% of GDP, of which about 50% is due to corrosion in concrete structures. The conventional patch repairs adopted in many structures are failing in about 5 years and lead to repeated repairs and significant increase in CoC and life-cycle cost (LCC) of concrete structures. Patch repair with cathodic protection (CP) can enhance the life of repairs to about 20+ years. But cathodic protection using galvanic anodes is not being considered by many practitioners because of the myth of excessive cost implications. This is probably the first of its kind of paper with long-term field data on the performance of galvanic anodes and LCC analysis of patch repairs of RC systems with and without galvanic anodes. The long-term data and possible huge LCC savings (of about 90%) due to cathodic protection presented in this paper could be an eye-opener and can build confidence in engineers to use galvanic anodes to achieve durable repairs and extend service life of concrete structures.

3. Repair of concrete structures

3.1. Collection of data from the field

The authors interviewed a few Indian distributors of galvanic anodes for concrete structures. Following questions were asked during the interview: (i) What is the interval between the repeated repairs in structures without CP systems? (ii) How many projects they know where repair has been done using CP systems? (iii) What is the approximate number of anodes used in each project? (iv) What was the age of the structure at the time of the first repair? (v) Which infrastructure sector (jetty, buildings, etc.) the concrete structures under repair belong to? (vi) Whether the installed electrochemical repair is a CP or CPrev? (vii) Whether monitoring results from CP are available? and (viii) If monitoring results are available, can results be shared with authors for analysis and publication? The collected data was analyzed to understand (i) the number and frequency of patch repairs without CP systems, (ii) the number of projects undertaken as CP and CPrev, and (iii) the number of anodes supplied to various infrastructure sectors.

3.2. State of the concrete repair industry

As reported in literature, the patch repair without CP does not arrest corrosion or address the root cause [4,7,8]. Fig. 3 shows data from 20 structures without CP and indicate that more than 70% of the structures were re-repaired within five years after the first repair. About 30% of them were re-repaired at about 4 years after the first repair - causing huge economic burden. Maybe because of this, the number of usages of galvanic anodes has risen significantly in the recent times. Another reason for this rise is the increase in the communication about CP and its benefits among the CP manufacturers, practitioners, researchers, and consultants. However, this practice of patch repair (without CP) continues in many parts of the world and one way to change this is by obtaining field data through pilot studies.

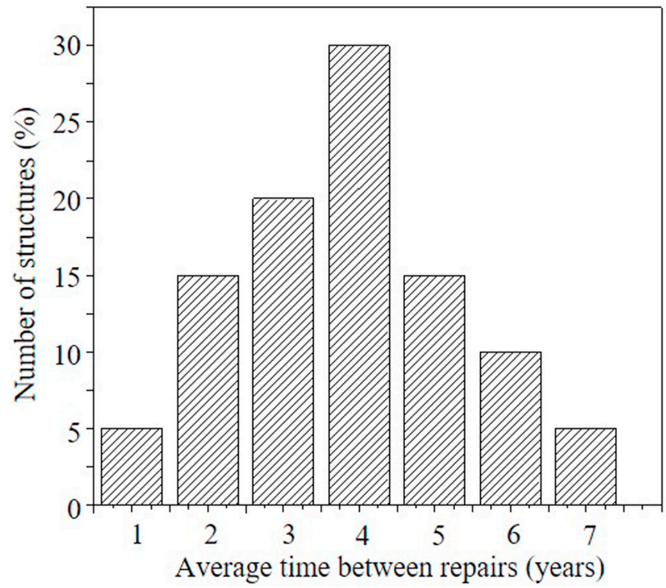


Fig. 3. Frequency of repeated repairs (data from 20 structures).

3.2.1. Indian experience with CP

Fig. 4 shows the sector-wise growth in the usage of galvanic anodes in India from 2003 to 2020 – with a total usage of ≈ 60,000 anodes in reinforced concrete structures in India. About 60% of these anodes

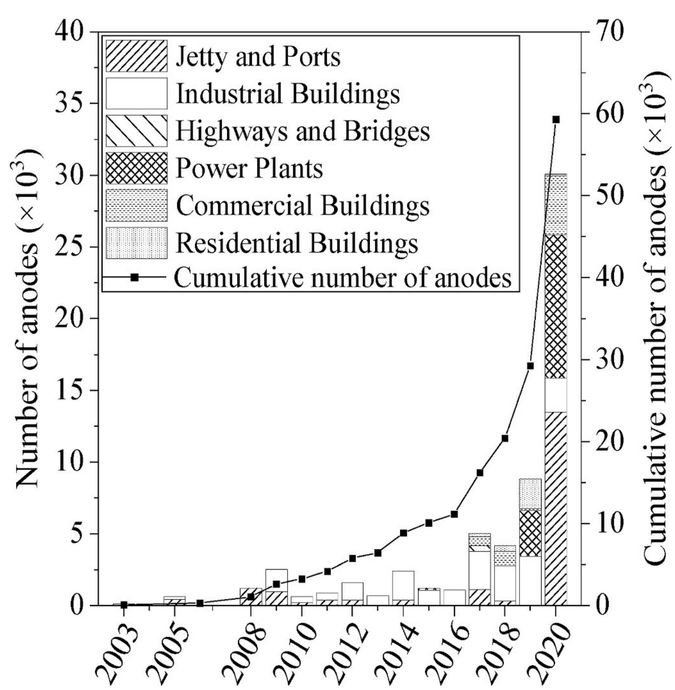


Fig. 4. Acceptance of galvanic anodes to repair RC systems from 2003 to 2020.

(33,000 anodes) were used in 2020 — an exponential growth in the usage of galvanic anodes. The usage of CP systems varies from sector to sector. For example, from 2003 to 2020, the industrial buildings, jetties and ports used ≈ 20,000 anodes each. The highway and bridge sector consumed least number of anodes (about 400 anodes were used in two projects in the year 2016). This indicates that significant efforts are needed to promote the use of CP systems in highways and bridges. This is of utmost importance because the Indian Bridge Management Systems (IBMS) has recently identified about 6000 bridges for immediate repair [53]. The LCC of those bridges can be significantly reduced if CP systems are used while repairing the bridges with corrosion as a root cause of distress.

Overall, only about 70 projects in India have used galvanic anodes in the repair work, which is miniscule while considering the huge number of ongoing repair projects across the country. Similar could be the case in many parts of the world – highlighting a dire need to promote CP technology across the world and save structures from deterioration. The authors believe that the use of galvanic anodes in RC systems was/is limited because of the following: (i) lack of experienced CP professionals in construction sector, (ii) wrong belief that the introduction of CP in repair industry could reduce the market share of repair chemicals, and (iii) lack of knowledge of the life-cycle benefits of CP.

Even today, only a few firms in India practice the use of good galvanic anodes for concrete repair. About more than a decade ago, a few practitioners in India started pilot studies with CP in concrete repair projects. In these, minimum number of galvanic anodes was determined using an approximate calculation and without considering the actual surface area of the steel, concrete resistivity, exposure condition, etc. For example, a standard practice of one anode per m^2 of concrete surface area was considered, which may not be sufficient to passivate the steel rebars, but adequate to suppress ongoing corrosion. Also, in India, one recently constructed port facility has used cathodic prevention systems, which is a very positive signal indicating that engineers are now realizing the importance of CP and CPrev technologies for concrete structures.

3.2.2. Worldwide experience with CP

Fig. 5 shows the sector-wise distribution of CP usage worldwide from 2003 to 2018. Fig. 5(a) shows that 62% of cathodically protected structures belong to industrial facilities with aggressive environments (e.g., chemical manufacturing plants and industrial effluent treatment plants). Other buildings (e.g., government, heritage, and institutional buildings, public parks, and shopping complexes) and jetties and ports used about 15% of the total anodes used. Fig. 5(b) shows the sector-wise distribution of various repair projects with cathodic prevention (CPrev). It is observed that 28%, 25%, and 18% of structures with CPrev are residential, industrial, and commercial buildings, respectively. However, cathodic prevention and protection are least employed in power plants, highways and bridges ranges from about 4 to 10%.

In general, the long-term performance data of CP systems from many of these structures are not available because the clients hesitate to facilitate field measurements. Based on the available documentation, data collected, site visits, and possible access to the structure, the authors have selected two of the infrastructure (a finger jetty and an industrial building) to present the long-term performance of CP systems.

4. Long-term performance of cathodic protection in concrete structures

This section presents two case studies on the performance of CP systems on (i) a finger jetty and (ii) an industrial building exposed to the marine environments. The details about the field investigation, methodology of repair, and the results on the long-term performance are discussed next.

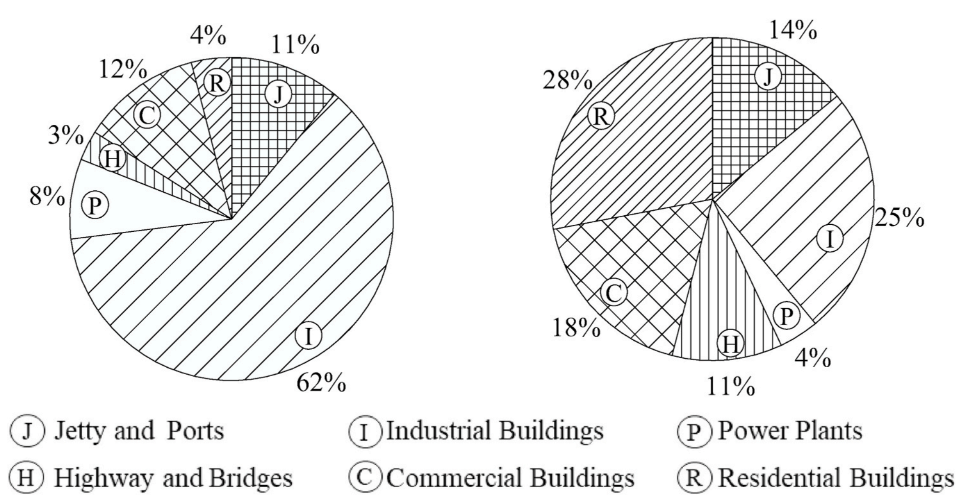
4.1. Case study 1 - finger jetty in Chennai, India

4.1.1. Field investigation

Fig. 6 shows the photograph, schematic, and layout of finger jetty constructed in 1992 and located at Chennai city in the East Coast of India. As shown in Fig. 6(b), the typical tidal variation is 0.7 m and the mean sea level (MSL) is below the pier cap indicating that the top portion of the pier and pier cap experiences severe wet-dry exposure to seawater. After about 14 years of service, although M35 concrete was used, significant corrosion of rebars was observed in the piers at the splash zone (see Fig. 7(a)). In 2005, the jetty structure was visually investigated, and chloride tests were conducted (as per ASTM C1152) on the cylindrical concrete core samples extracted from the structure. An average chloride concentration in concrete at the rebar level was found to be greater than 0.6% by weight of the binder, which is significantly higher than the chloride threshold of the uncoated steel rebar in concrete [54]. Based on the visual inspection and chloride concentrations determined, it was decided to repair and strengthen the piers and pier caps immediately.

4.1.2. Methodology of the repair using galvanic anodes and subsequent inspections

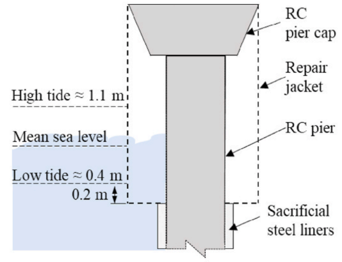
Fig. 7(b) shows the photograph (taken in 2005) of a pier under



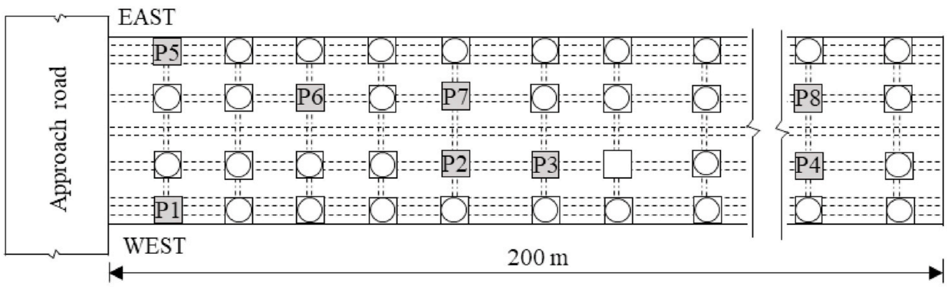
(a) Cathodic protection **(b) Cathodic prevention**

Fig. 5. Distribution of usage of the galvanic anodes in various repair works worldwide from 2003 to 2018 (Courtesy: Vector Corrosion Technologies, Canada).

(a) Repaired piers of finger jetty (Photograph taken in 2019)

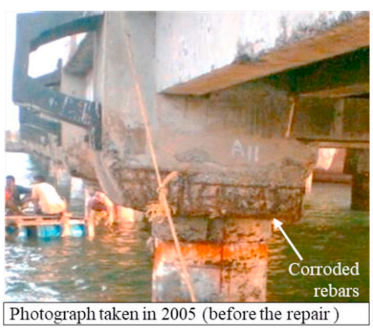


(b) Elevation of the piers and jacket repair

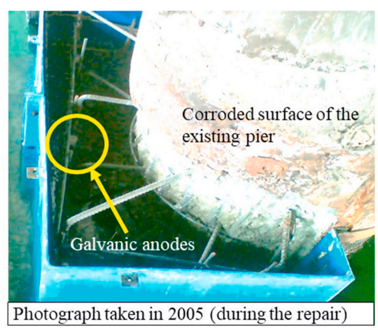


(c) Layout of the finger jetty (Monitoring boxes were installed on the shaded piers only)

Fig. 6. Repaired finger jetty in Chennai, India.



(a) Piers with corroded rebars (with circular cross-section)



(b) Setup for concrete jacketing with additional rebars and galvanic anodes

(d) Piers after repair (with rectangular cross-section)

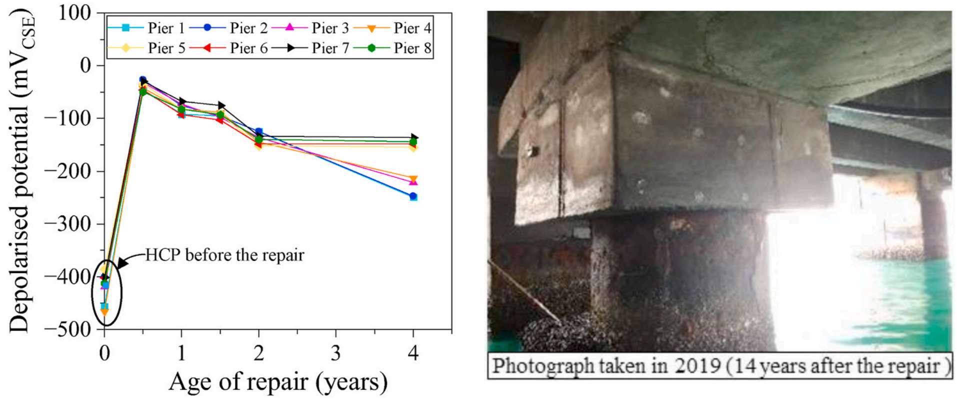
Fig. 7. Repair of finger jetty using galvanic anodes.

repair. The sacrificial steel liners were removed for up to ≈ 0.2 m deep from the bottom of the pier cap. The rebars were coated with anticorrosive zinc coating. Also, one anode was installed for every 1 m^2 of concrete surface. About 10 m^3 of prepackaged repair concrete (denoted as 'microconcrete', herein) was used for repair. Also, about 10 tons of additional reinforcing steel was used. An epoxy-based polymer adhesive was applied to the existing concrete surface – to enhance the bond between the microconcrete and substrate concrete. Considering the high chloride contamination at the rebar level and significant loss of steel cross-section, the repair using galvanic anodes was recommended. For this, the continuity of all the rebars in the piers was checked using a high impedance multimeter to ensure the functioning of CP systems. A total of about 1400 galvanic anodes were installed in various structural elements (pier, pier cap, longitudinal beams, and slabs). Fig. 7(b) shows the additional reinforcement and galvanic anodes installed in one of the piers. Fig. 7(c) shows the piers after repair using the CP. To monitor the performance of galvanic anodes, monitoring boxes were installed in eight piers [see the shaded piers in Fig. 6(c)].

From 2005 onwards, depolarized potential of steel and output current from the anodes (I_{output}) were obtained from the piers. During depolarization tests, the anode-steel circuits are disconnected and allowed to depolarize for 24 h, then HCP of the steel rebars are measured (as per ASTM C876 procedures[55]) and defined as the depolarized corrosion potential (E_{24h}). After obtaining the E_{24h}, the steel-anode circuits are reconnected for the CP system to resume its function. The E_{24h} of steels were monitored at about every six months until 4 years after the installation of anodes. After that, frequent visual inspections were carried out. In 2019, after 14 years from the 1st repair with CP, the monitoring boxes were found to be degraded and even missing in some cases; and hence, E_{24h} could not be measured and only I_{output} was measured.

4.1.3. 14-Year long performance of galvanic anodes

Fig. 8(a) shows the E_{24h} of steel rebars in the piers before and after the repair. Note that the starting data point (inside the ellipse) of each curve is the HCP of the steel rebars before the installation of anodes and are more negative than −350 mV_{CSE}, which indicate high probability of corrosion. After six months of repair, E_{24h} were more positive than −100



(a) Depolarized corrosion potentials obtained from piers of finger jetty

(b) CP protected pier after 14 years

Fig. 8. 14-year long performance of repair using galvanic anodes in Finger Jetty.

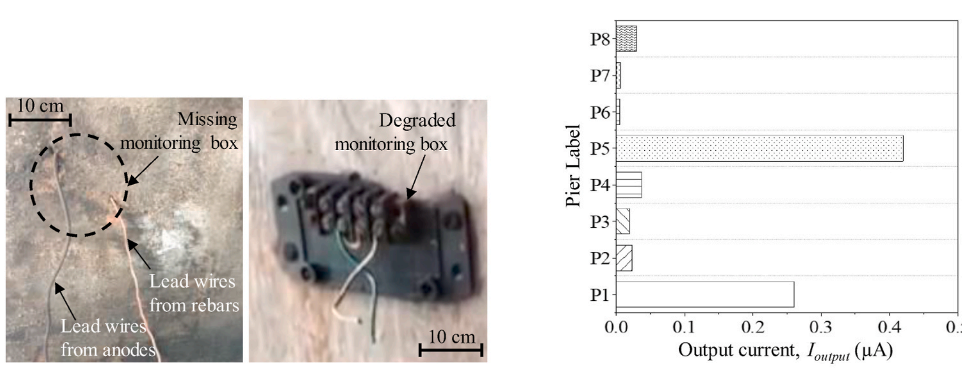
mV_{CSE}, which indicate re-passivation of rebars within about six months of installation of galvanic anodes. E_{24h} were monitored for about four years and were found to be more positive than −270 mV_{CSE}. This indicates that the probability of corrosion was less than 10% (as per ASTM C876 2015). Due to contractual agreements and other constraints, regular monitoring was possible only until 4 years after the installation of anodes. Later, after 14 years of first repair, a visual inspection was conducted, and no significant corrosion-induced cracks were observed on the concrete surfaces. Fig. 8(b) shows a photograph of one of the pier caps with cracks 14 years after the repair — indicating good protection of embedded steel for more than 14 years.

During the 2019 visit, it was found that all the monitoring boxes and lead wires were naturally damaged/degraded (see Fig. 9(a) for a typical scenario). Also, many of the monitoring boxes and lead wires were missing (say, degraded/damaged and fallen into the seawater below). Hence, E_{24h} could not be measured and only the I_{output} was obtained from Piers 1 to 8 (see Fig. 9(b)). The I_{output} from a galvanic anode in Piers 1 and 5 were 0.25 and 0.42 μA, respectively, which are significantly higher than the I_{output} from galvanic anodes in other piers. Piers 1 and 5 are located in the outer wing of the finger jetty and experience the incoming tides to higher level than the internal piers. Also, the outer piers have been experiencing higher temperature (during summer) and more severe splashing, whereas the inner piers always experienced lower temperature (under shade) and less severe splashing. Therefore, the I_{output} required for the outer piers could be higher than that for the inner piers. Fig. 8(a) shows that the rebars are passivated within the first six months after the installation of anodes; also, the I_{output} would be less for the anodes connected to the passivated steel, which is the case for Piers other than P1 and P5. In case of P1 and P5, the I_{output} required to protect the steel is high, the same is provided by the anodes, and no corrosion-induced cracks were visible – hence, it can be concluded that the steel is protected from corrosion. Due to the high I_{output}, the anodes in P1 and P5 have shorter residual life than in other piers and may have to be replaced soon. Frequent monitoring (say, once in every 2 years) of I_{output} from the Piers 1 to 8 can help in developing a preventive maintenance strategy and protecting the steel inside the piers for as long as desired – with minimal life cycle cost implications.

4.2. Case study 2 - industrial building

4.2.1. Methodology of repair using galvanic anodes and subsequent inspections

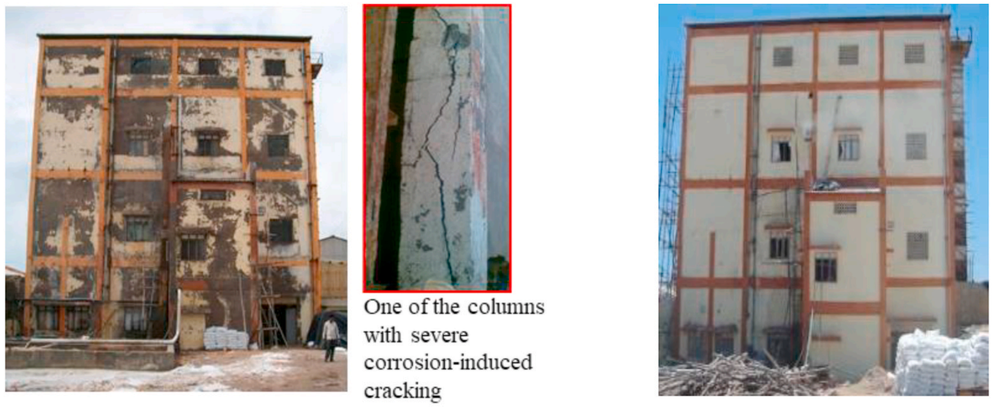
Fig. 10 shows the photograph of a four-storey industrial building (salt processing unit) built in the early 1990s near a seashore in Tamil Nadu, India. Due to the high chloride and humidity levels, significant corrosion and concrete spalling were observed in about 15 years of service (see Fig. 10(a)). Because of this severe and visible corrosion conditions, the various columns, slabs, and beams were cathodically protected using a total of about 2800 anodes. Fig. 11(a) shows the layout of the structural frame of the building. Monitoring boxes were installed at the following members in various floors: (i) Ground floor: Beams B5–C5, and A3-B3, (ii) 1st floor: Column C4, (iii) 2nd floor: Column C1, Beam B2–B3, and (iv) 3rd floor: Beam C2–C3. At these locations, E_{24h} was measured at every six months until four years after the installation of anodes.



(a) Missing, naturally degraded/damaged monitoring boxes

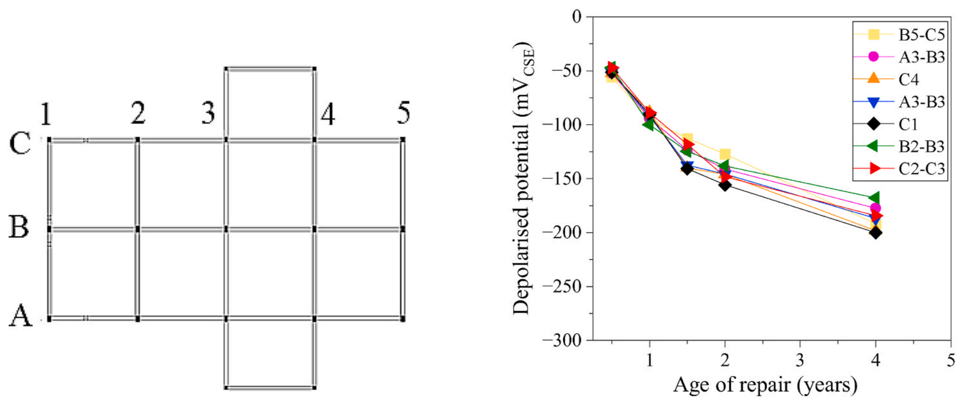
(b) Output current data collected in 2019

Fig. 9. Condition of monitoring boxes and the output current of anodes, at the end of 14 years after repair.



(a) Before repair **(b) After repair**

Fig. 10. Industrial building (salt processing unit) before and after the repair in 2008.



(a) Layout of the structural members **(b) Variation of depolarized potential**

Fig. 11. Depolarized potential (E_{24h}) obtained from the industrial building elements.

4.2.2. *4-Year long performance of galvanic anodes*

Fig. 11(b) shows the variation of the E_{24h} of steel rebars after the installation of anodes. At the end of six months, E_{24h} was about −50 mV$_{CSE}$, which indicates that the galvanic anodes have passivated the steel rebars. At the end of 4 years, the E_{24h} reached from about −50 mV$_{CSE}$ to about −200 mV$_{CSE}$, which indicate that the steel rebars were still in passive state. Due to contractual agreements and other constraints, regular monitoring was possible only for 4 years after installing anodes. However, to check the long-term performance of galvanic anodes, a visual inspection of the industrial building was conducted at the end of 10 years after repair. It was observed that the structural elements did not exhibit any corrosion-induced cracking. However, in 2018, the salt processing procedure was changed, and the building was demolished. But this is a very good case study showing that galvanic anodes can protect the steel rebars from corrosion for more than 10 years, even in chloride-rich environments. However, clients are hesitant to adopt repairs using galvanic anodes due to the myth of the high cost of anodes instead of considering the effect of galvanic anodes on the LCC of the structure.

5. Effect of repairs with and without galvanic anodes

Fig. 12 shows the difference between the patch repairs with and without galvanic anodes. In case of repair without CP, the steel rebars can corrode due to two mechanisms: (i) new corrosion due to the halo effect and (ii) continued corrosion due to the possible residual chlorides in the residual corrosion products (say, residual chloride effect; if rebars are not undercut and cleaned well, which is usually the case in many repair projects). The former results in an increase in the length of corroding region on the rebars and the area of repair region. The latter results in a reduction in the cross-sectional area of rebars in the already corroded portions. Use of CP can arrest corrosion due to both these mechanisms, which is depicted in the schematics in Fig. 12.

Fig. 12(a) shows that when patch repaired without anodes, the length of the corroded regions of rebars and the area of repair region continues to increase. The structural capacity of the RC systems continues to decrease during the life of patch repair without CP; necessitating more frequent repairs with increasing areas of repair region. Also, as shown in the last schematic in Fig. 12(a), this can lead to severe ongoing corrosion in short period of time (say, n_1 years after first repair) requiring the addition of even splice rebars. These will have significant impact on the LCC after 1st repair. On the other hand, Fig. 12(b) shows that when an RC system is repaired with galvanic anodes, the corrosion due to both the halo effect and residual chloride effect is arrested or controlled. The schematics corresponding to “in-between” indicate that the repair region do not increase (anodes prevent halo effect), cross-sectional area of rebars do not decrease (anodes stop corrosion due to the residual chloride effect). When the anode is found to be consumed completely (say, after n_2 years after the 1st repair; $n_1 < n_2$), they can be replaced with new anodes at a lower cost than the repair cost in the case of patch repair without CP. However, it should be noted that the locations of all anodes must be identified to enable easy replacement.

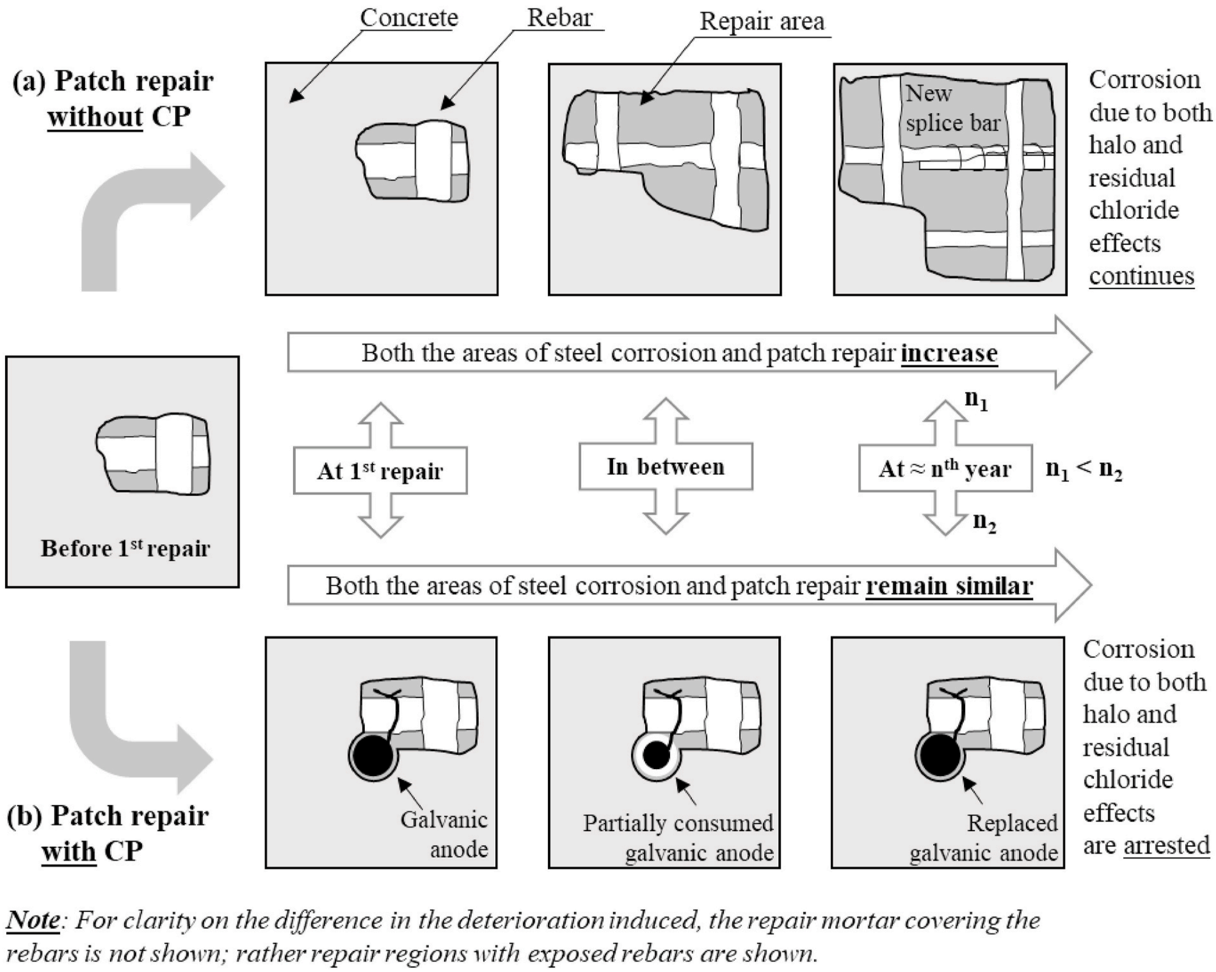


Fig. 12. Differences in the areas of repair region and steel corrosion in case of patch repairs with and without CP [Not drawn to scale].

6. Life-cycle-cost (LCC) analysis of repairs

To compare the life-cycle-cost (LCC) of conventional patch repair with and without galvanic anodes, the individual costs associated with the various repair materials/systems/activities are required. Herein, the patch repair without and with cathodic protection are denoted as "PR" and "CP", respectively.

6.1. Framework for estimating the LCC of repairs

The LCC of the repair is calculated considering the costs associated with all the possible future repeated repairs and inspections during the repair life; the costs of construction and demolition are not included. Fig. 13 shows a flowchart showing the framework for estimating the LCC of repairs in the following four major steps: (S1) Capital cost of repair, (S2) Future value (FV) of subsequent inspections, (S3) FV of subsequent repairs, and (S4) Cumulative FV of repairs and inspections, which is LCC of repairs. Following is a discussion on these major steps.

S1: Capital cost of repair is the sum of the cost of the first repair work and the cost of inspection prior to that ($C_{insp\text{-}zero}$). For example, the cost of 1st repair for PR and CP strategies are calculated using Eq. (3) and Eq. (4), respectively (see S1 in Fig. 13).

$$\text{Capital cost of PR, } C_{total,PR} = C + C_{insp-Zero} \tag{3}$$

$$\text{Capital cost of CP, } C_{total,\ CP} = C + C_{anodes} + C_{insp-Zero} \tag{4}$$

where, C is the sum of the cost of all the repair heads, such as (i) cleaning and preparation of the surface of steel and concrete at the repair region, (ii) additional steel, (iii) formwork, (iv) bonding agent for concrete surface, (v) repair concrete, (vi) other costs (if any), and C_{anodes} is the cost of anodes (including shipment, installation, and monitoring).

S2: FV of subsequent inspections until the End of Life (EoL) or the 'LCC analysis period' are calculated using Eq. (5) (see B2 in Fig. 13).

$$C_{insp,\ i} = (1 + r)^{T_{insp,\ i}} \times C_{insp-zero};\ i = 1, 2, 3, \ldots \tag{5}$$

where, r is the discount rate, $T_{insp,\ i}$ is the time elapsed from the 1st to i^{th} inspection. Frequency of inspections of infrastructure varies based on the suggested duration prescribed by the governing code of practice or client.

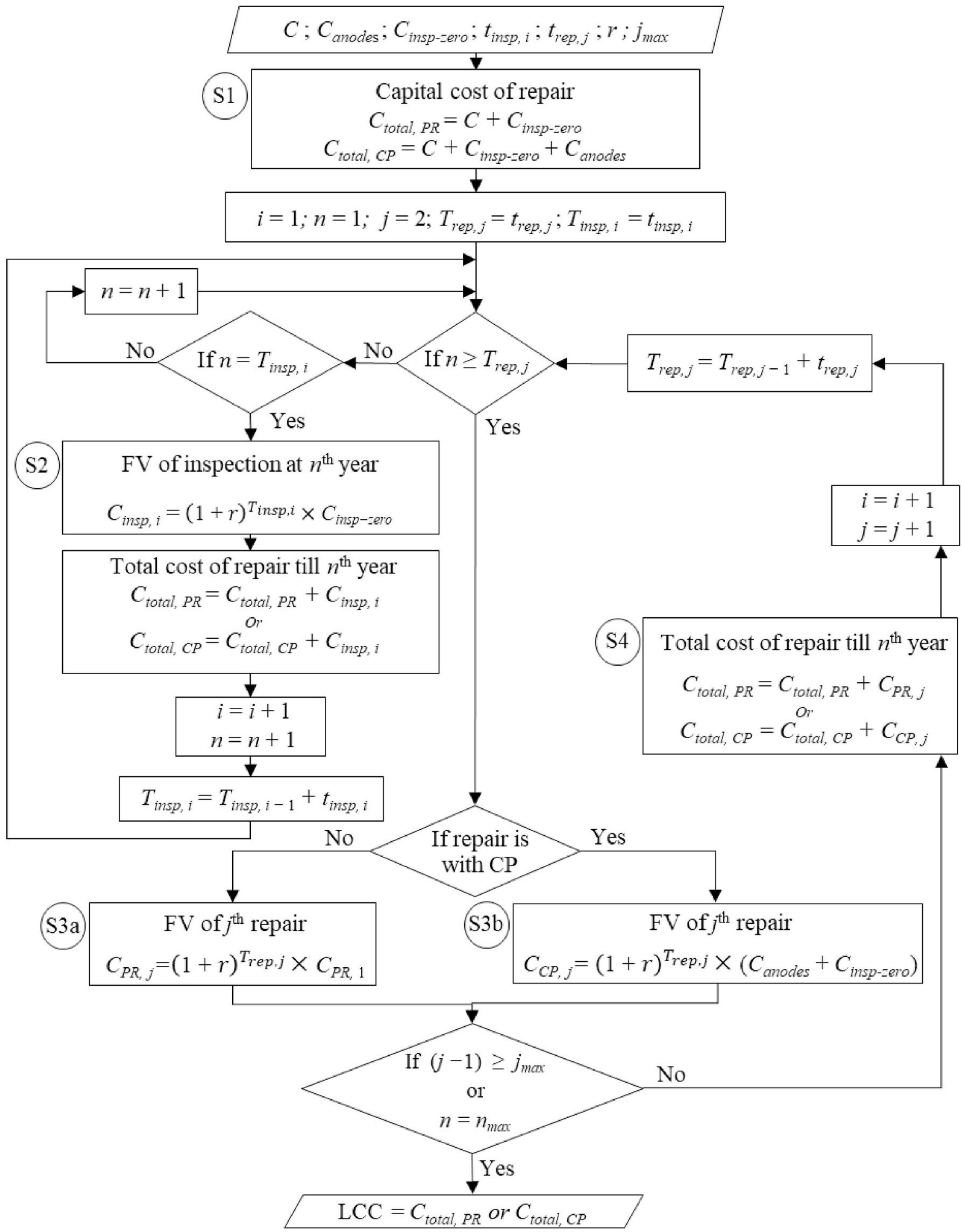
S3: FV of subsequent repairs are calculated using Eq. (6) and Eq. (7), respectively (see S3a and S3b in Fig. 13).

$$C_{PR,\ j} = (1 + r)^{T_{rep,\ j}} \times C_{PR,\ 1};\ j = 2, 3, 4, \ldots \tag{6}$$

$$C_{CP,\ j} = (1 + r)^{T_{rep,\ j}} \times \left(C_{anodes} + C_{insp-zero}\right);\ j = 2, 3, 4, \ldots \tag{7}$$

where, $C_{PR,\ j}$ is the sum of the various head-wise costs of j^{th} patch repair and the inspection costs; whereas $C_{CP,\ j}$ is the sum of the cost of anodes, and the inspection prior to the j^{th} repair. Note that in case of CP strategy, the patch repair is needed only once and hence, the repair costs (for $j > 1$) include only the cost of anode replacement and not cost of patch repair; this significantly reduce the LCC of CP strategy. $C_{PR,\ 1}$ and $C_{CP,\ 1}$ are calculated in S1.

S4: Cumulative FV of repair is obtained by adding all the $C_{PR,\ j}$ costs until the time when the number of repairs is equal to the maximum allowable number of repairs (say, $j = j_{max}$) OR until the end of 'LCC



Symbols: C : Cost of repair excluding the cost of inspection and anodes; C_{anodes} : Cost of manufacturing, supply, and installation of anodes; $C_{insp\text{-}zero}$: Cost of inspection at the time of 1st repair; $C_{insp,\, i}$: FV of i^{th} inspection; $C_{PR,\, j}$: FV of j^{th} repair without CP; $C_{CP,\, j}$: FV of j^{th} repair with CP; $C_{total,\, PR}$: Total cost of patch repair till n^{th} year; $C_{total,\, CP}$: Total cost of patch repair with CP till n^{th} year; i : Identification of individual inspection; j : Identification of individual repair; j_{max} : Maximum allowable number of repairs; n : Time elapsed from 1st repair; n_{max} : Maximum possible service life extension; r : Discount rate; $t_{insp,\, i}$: Time interval between $(i\text{-}1)^{th}$ and i^{th} inspections; $t_{rep,\, j}$: Service life of j^{th} repair; $T_{insp,\, i}$: Time elapsed between 1st and i^{th} inspection; $T_{rep,\, j}$: Time elapsed between 1st and j^{th} repairs

Fig. 13. Generalized framework to calculate LCC for repair with and without CP.

analysis period', whichever is shorter. This cumulatiuve C_{PR} is defined as $C_{total,\ PR}$ and is the LCC of the PR strategy. The $C_{total,\ CP}$ for the CP strategy can also be calculated in a similar manner (see S4 in Fig. 13). Using this framework, the LCC of the various repair strategies can be compared for selecting a suitable repair strategy. Next section demonstrates this through the case study of the CP repair of a jetty structure in Chennai, India.

6.2. Case studies - comparison of LCC of PR, CP and CPrev strategies

6.2.1. Input data for LCC of CP repair of finger jetty

As discussed earlier, in 2004, the finger jetty in Chennai was repaired using CP strategy (i.e., patch-repaired with anodes) and was one of the early CP pilot projects in India. Fig. 14 shows the distribution of various costs associated with this CP repair work. Repair concrete (micro-concrte) used for patch repair constitutes a significant majority (about 66%) of the repair cost. On the other hand, the total cost of the CP system (galvanic anodes and monitoring boxes) was only about 3% of the total cost of repair and is negligible considering the cost of micro-concrete. This disproves the myth that the use of CP would add significantly to the cost of repair and also emphasizes that the LCC (instead of capital cost) should be considered for selecting a repair strategy.

6.2.2. LCC of repairs of finger jetty

The LCCs of the following three repair strategies for the jetty in Chennai, India were compared:

- **PR strategy** - Patch repair without CP and repeated every 5th year (see Fig. 3)
- **CP strategy** - Patch repair with galvanic anodes and repeated replacement of galvanic anodes at every 15th year (see Case Study 1), and
- **CPrev strategy** – Installation of galvanic anodes at the time of construction and repeated replacement of anodes at the end of the design life of the galvanic anodes, i.e., 30 year.

Note that the CP strategy was actually adopted for the structure and the PR and CPrev strategies are hypothetical in this discussion. In these three strategies, the LCC was stopped if one of the following two

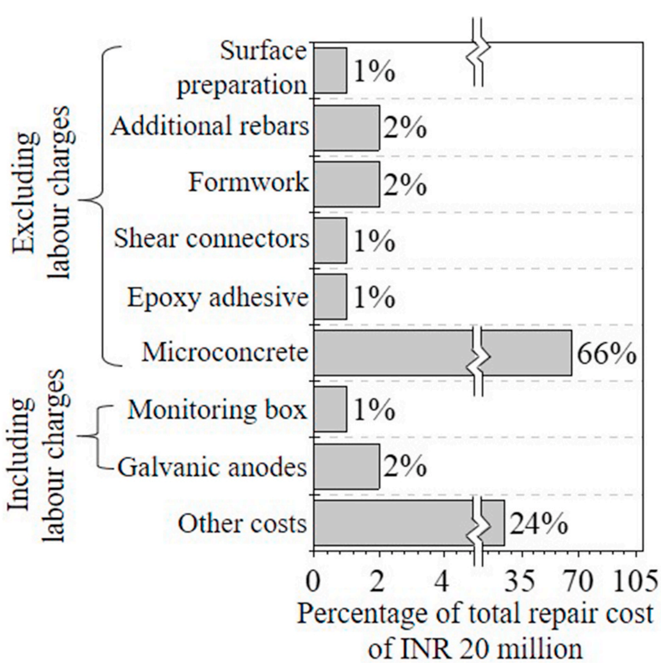


Fig. 14. Head-wise cost of repair with CP at finger jetty, Chennai, India.

conditions were satisfied: (i) maximum number of repairs are five (j_{max} = 5) and (ii) LCC analysis period is 75 years. For LCC calculation, the discount rate, r, is assumed to be 7% [56]. Fig. 15 shows three cash flow diagrams (step function) showing the variation of the cumulative FV for PR, CP, and CPrev strategies (i.e., $C_{total,\ PR}$, $C_{total,\ CP}$, and $C_{total,\ CPrev}$). For the ease of comparison, the LCC at each year is normalized to the maximum cumulative cost spent for CP repair ($C_{total,\ CP}$ at 90th year (i.e. 75 years after 1st repair). Note that the first repair in both the PR and CP strategies were done at 15 years after construction. Each unfilled square marker along the step function graph represents the repeated patch repair. Each unfilled circular and triangular markers along the step function graph represents the repeated replacements of galvanic anodes in CP and CPrev strategies, respectively.

This paragraph compares the capital cost of PR, CP, and CPrev strategies (see S1 in Fig. 13). Note that the hypothetical CPrev is assumed to be implemented at the time of construction and the cost was about 0.2% more than the cost of PR or CP repair (see Close-up A in Fig. 15). At the time of 1st repair (in 15 years after construction), the cumulative cost of PR and CP repairs were about 25 times more than the FV of CPrev – indicating significant advantage of choosing CPrev option in the long-term. However, most often engineers tend to cite the constraints associated with construction budgets and do not opt for CPrev strategy, leading to significant repair costs later. For the jetty structure in study, the cost of 1st CP repair was obtained and is about 4% more than the cost of the hypothetical PR repair (see Close-up B in Fig. 15). Therefore, capital cost of CPrev < PR < CP and is not a correct comparison to base the selection of repair strategy. The comparison of costs of repair should be made based on LCC during the analysis period or the desired extension of service life.

In this paragraph, the LCCs at 45 and 90 years of service are discussed. Until 45 years of service (i.e., 30 years after the first repair), the PR strategy would require six repeated patch repairs. During this time, the structure may experience significant deterioration because of the continued steel corrosion (due to halo effect and residual chloride effects) until End of Life (EoL). At 45 years of service, if CP strategy is adopted for repair, then the anodes need to be replaced twice; if CPrev strategy is adopted, then anodes need only one replacement. Also, in comparison with the FV of PR strategy, the adoption of CP and CPrev strategies can reduce the cumulative FV (at 45 years of service) by 90 and 98%, respectively. In addition, it is estimated that the cumulative FV (at 90 years of service) of CP strategy is about twice that of CPrev strategy. This indicate that the longer the LCC analysis period, the more will be the LCC of CP strategy when compared to CPrev strategy. Also, note that the PR strategy is not able to provide a total service life of more than about 45 years; whereas both CP and CPrev stratgies are able to provide a total service life of more than 90 years.

In other words, the adopted CP strategy in the jetty structure is expected to provide 45+ years of additional service with about half the LCC of PR strategy; and further life extension is possible with repeated replacement anodes for as long as needed. Ideally, if the galvanic anodes are replaced as required and repeatedly, the CP and CPrev strategies can arrest steel corrosion for as long as needed. However, it should be noted that the CPrev strategy is possible only for structures that are yet to experience corrosion. For corroding structures, CP is the only appropriate option — among the PR, CP, and CPrev strategies under study. This detailed study on LCC shows that the adoption of either CP or CPrev can lead to huge savings in term sof LCC, see Fig. 15. Further examples of such huge savings in LCC are shown next.

6.3. 30 case studies on saving in LCC

Table 1 shows the cost data for the 30 repairs with CP strategy in various sectors, such as jetty and ports, highway and bridges, industrial building. Using these data, LCCs of the 30 structures were calculated as per the framework proposed in Fig. 13. Fig. 16 shows the time-variant saving in LCC with the adoption of CP strategy over PR strategy for

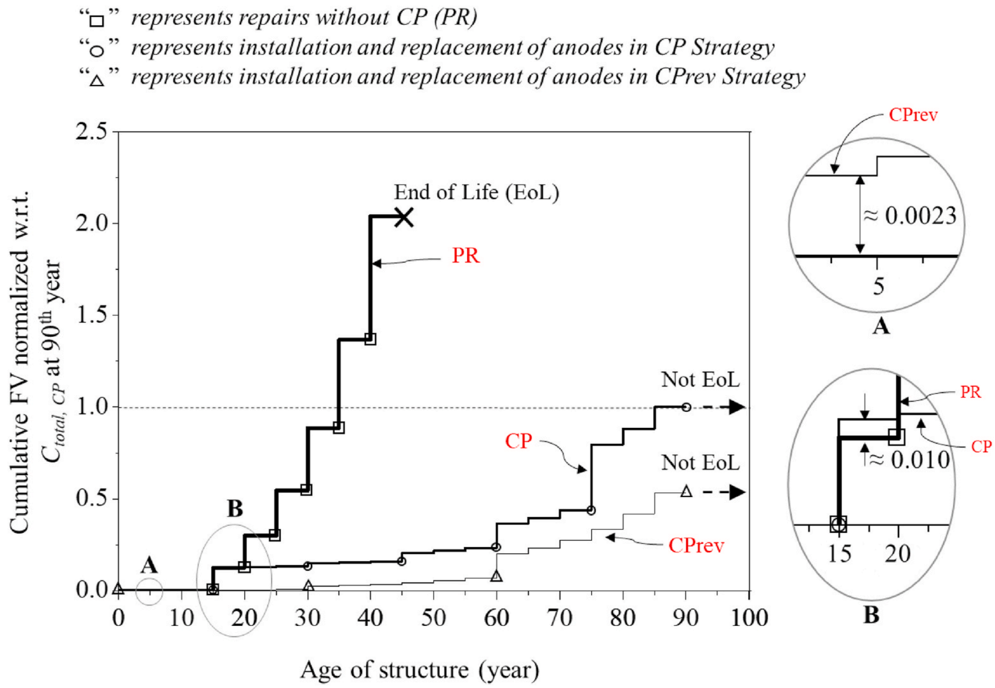


Fig. 15. Life-cycle cost of PR, CP, and CPrev strategies for the repair of Jetty in Chennai, India.

the 30 case studies. It shows that at the end of first repair, employing a CP strategy instead of PR strategy would lead to ≈7% more capital cost (mainly due to the additional cost of the anodes). Most often, engineers tend to decide against the CP strategy because of this small increase in capital cost. Considering only capital cost is not a suitable approach; and the decision on repair strategies must be made based on LCCs. As shown in Fig. 16, at the end of 5, 10, 15, and 30 years from 1st repair, the LCC saving with adoption of CP strategy is about 55, 75, 80, and 90%, respectively. After 20 years of repair, the rate of increase in LCC saving decreases and LCC saving becomes asymptotic to the time axis. Note that the LCC beyond 30 years after first repair is not calculated because the structures with PR strategy experience multiple patch repairs without arresting corrosion and reach their End of Life typically at about 30 years after first patch repair. Thereafter, they get either demolished or

Table 1
Various cases studies on concrete structures with repair using CP in India.

Type of structure	Location (State/Union Territory)	Year of anode installation	Number of anodes	Total cost of anodes at the time of repair (INR)
Jetty 1	Lakshadweep islands	2005	440	264,000
Jetty 1	Tamil Nadu	2008	1390	959,100
Jetty 2		2008	790	545,100
Jetty and approach bridge	Maharashtra	2009	1200	1,050,000
Jetty 3	Lakshadweep islands	2009	500	345,000
Jetty 4		2009	460	317,400
Jetty and fender columns	Gujarat	2010	225	249,975
Jetty deck slab beams 1	Goa	2011	400	376,800
Water treatment plant	Maharashtra	2014	1500	1,350,000
Industrial building 1	Gujarat	2015	40	52,000
Industrial building 2		2016	210	220,080
Staircase in a building	Puducherry	2016	86	193,500
Bridge 1	Gujarat	2017	240	289,920
Residential building		2017	453	449,829
Bridge 2		2017	61	61,000
Industrial building 3		2017	250	300,000
Public building		2018	180	199,980
Office building 1	Maharashtra	2018	910	1,274,000
Pipe rack 1	Gujarat	2018	600	720,000
Industrial building 4		2018	220	225,060
Industrial building 5		2018	200	220,000
Wastewater treatment tank		2019	131	236,455
Office building 2	Tamil Nadu	2019	50	50,000
Pipe rack 2	Gujarat	2019	500	600,000
Industrial building 6		2019	1316	2,500,400
Industrial building 7		2019	200	220,000
Water-treatment plant		2019	2837	6,388,924
Cooling tower		2020	9000	15,138,000
Jetty deck slab beams 2		2020	10,000	12,000,000
Office building 3		2020	60	181,740

replaced. Therefore, for corroding infrastructure, the CP repair strategy is clearly more economical than the PR strategy. Also, this paper discusses only the direct costs; if the indirect costs are considered, then the advantages of adopting CP or CPrev strategies over PR strategy would be further enhanced. However, data to estimate indirect costs were not available, hence kept out of scope of this paper.

7. Way forward

Conventional PR strategy alone may not arrest the corrosion due to halo effect and residual chloride effects – resulting in continued corrosion of structures leading to multiple and less durable repairs and eventual replacement of structures in a few decades. Adoption of CP strategy (patch repair with galvanic anodes) is a viable and cost-effective option to extend the service life for multiple decades. Based on the experience in India, the authors suggest the following as the way forward for promoting CP strategy in the concrete repair industry: (i) to perceive galvanic anodes as a product that augments the performance of other concrete repair products rather than as a competitor, (ii) emphasize on the electrochemical advantages of CP strategy in stopping further corrosion/damage and the possibility of enhancing service life to as long as needed by less expensive replacement of anodes (iii) give more emphasize on the LCC benefits of CP strategy over the capital cost benefits alone of PR strategy, (iv) allow pilot studies on CP strategy in concrete repair works with provision for long-term monitoring of performance, (v) incorporation of good performance based specifications for CP strategy in the documents governing repair activities, especially in the public sector, and (vi) enable industry-supported academic research on CP strategies and use the performance data of anodes to enhance the codal specifications, in addition to the scholarly publications.

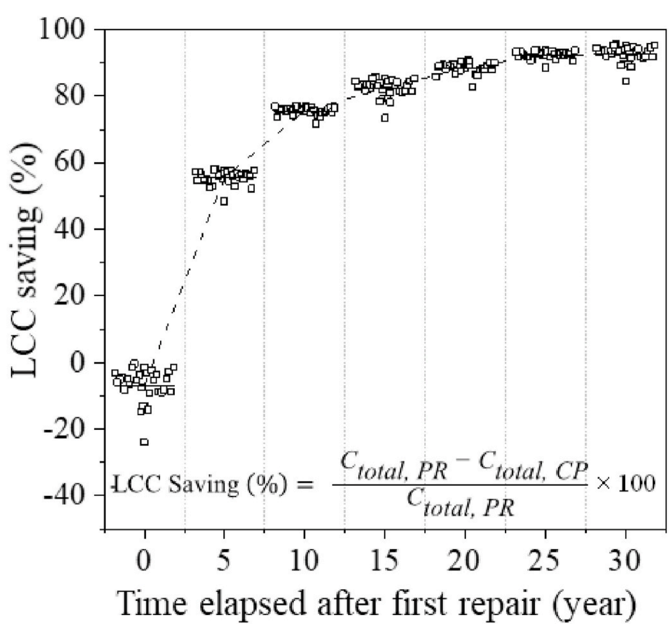


Fig. 16. LCC saving due to CP strategy.

8. Summary and conclusions

A market study was conducted on the performance and life cycle cost (LCC) of cathodic protection using galvanic anodes (CP strategy) in reinforced concrete (RC) structures in India and worldwide. It was found that CP is commonly used in coastal structures such as jetties and ports and ignored in many other structures, such as highways, railways, buildings. Therefore, significant efforts are required to promote the use of CP systems in highways, bridges, and buildings for durable and economical repairs. For this, long-term performance and cost data from a jetty and an industrial building structure were inivestigated. The long-term electrochemical data and visual observations concluded that galvanic anodes can arrest steel corrosion for at least 14 years in chloride-rich environment. Also, a framework to estimate the life cycle cost (LCC) was developed and the differences in LCCs between patch repair (PR), CP and cathodic prevention (CPrev) strategies for the jetty structure were evaluated. The comparison of the capital cost of repair without and with CP for 30 case studies shows that employing CP strategy instead of PR strategy would lead to ≈ 7% more capital cost. However, comparison of LCC of repair for 10 and 30 years of service life extension shows that CP repairs can save about 55% and 90%, respectively, as compared to the LCC of PR. In addition, PR strategy allows continued corrosion (due to halo effect and residual chloride effect) and could not extend service life beyond 30 years after first repair; whereas, CP and CPrev strategies can enhance the service life to as long as needed by the replacement of anodes at regular intervals and at a minimal cost of about 5% of the cost of first repair. Also, the LCC of CP strategy (at 90 years) is just about half that of PR strategy (at 45 years). This paper provides technical and economic advantages of adopting CP strategy in all the repairs, where corrosion due to halo effect and residual chloride effect are possible and multiple decades of life extension is desired.

CRediT authorship contribution statement

Naveen Krishnan: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft. **Deepak K. Kamde:** Conceptualization, Investigation, Writing – review & editing, Visualization. **Zameel Doosa Veedu:** Investigation, Formal analysis, Writing – review & editing. **Radhakrishna G. Pillai:** Conceptualization, Writing – review & editing, Visualization, Funding acquisition. **Dhruvesh Shah:** Conceptualization, Resources. **Rajendran Velayudham:** Conceptualization, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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