SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Application of Patch Repair and Zinc Anode on RC Structures Damaged by Chloride Contamination – 3 Year Evaluation

Pinta Astuti[1,*], Rahmita Sari Rafdinal[2], Volana Anjatiana Lucia Andriamisaharimanana[3], Daisuke Yamamoto[4], Hidenori Hamada[5]

1 Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, 55183, Yogyakarta, Indonesia
2 Maintenance Engineering Group, PS. Mitsubishi Construction Co. Ltd., 104-8215, Tokyo, Japan
3 Nakabohtec Corrosion Protecting Co. Ltd., 104-0033, Tokyo, Japan
4 Department of Civil and Environmental Engineering, National Institute of Technology, Oita College, 70-0152, Oita, Japan
5 Department of Civil and Structural Engineering, Kyushu University, 819-0395, Fukuoka, Japan

ARTICLE INFO

Article history:
Received 29 April 2024
Received in revised form 24 June 2024
Accepted 7 July 2024
Available online 30 July 2024

Keywords:
Corrosion; Chloride contamination; deterioration; patch repair; Zinc anode

ABSTRACT

Combination of patch repair and cathodic protection methods was well-known as the most effective maintenance measure. This paper presented the experimental program and examined the effectivity of the intervention technique on damaged RC beams by using patching strategy and zinc anode. The electrochemical tests including potential monitoring and depolarization value were regularly measured until three years of application. The result showed that the investigation on the efficacy of a zinc anode in polarizing the potential of corroded rebar in a reinforced concrete (RC) component spanned a duration of three years. The phenomenon of high polarization is mostly observed in the vicinity of the anodes within the original concrete, whereas its occurrence in the patch repair section is constrained by intrinsic disparities in the material characteristics between the new material and the original substrate. The utilization of patch repair and zinc anode as a repair technique is deemed appropriate because the middle part may experience reduced protection as a result of patch material replacement. This is justified by the fact that the middle part already possesses a reasonably low susceptibility to corrosion.

1. Introduction

The escalating worry is around the phenomenon of corrosion in concrete structures when subjected to the corrosive effects of seawater. In order to enhance the longevity of structures, researchers and engineers have already devised repair procedures for degraded reinforced concrete (RC) elements [1-9]. The patching technique was selected for use on the most severely damaged and corroded area, considering the building material, via the use of new substance replacement. The patch repair method is a commonly employed technique for the restoration of concrete buildings to their initial state. In the rehabilitation of reinforced-concrete structures, patch restoration is a

* *Corresponding author.*
E-mail address: pinta.astuti@ft.umy.ac.id

https://doi.org/10.37934/aram.122.1.7181

common technique. However, when exposed to chloride-contaminated concrete, its efficacy is inadequate. Several prevalent issues have been identified as factors in the premature failure of patch restorations. One of the elements that contribute to this issue is the inadequate elimination of contaminating material prior to repairs, specifically in relation to chloride compounds or carbonation. Moreover, the emergence of nascent anodes in the interface between the patched and unpatched sections has been recognized as a significant concern [10,11]. Cathodic protection, in conjunction with other electrochemical restoration techniques, has the potential to provide increased efficacy and durability in protecting reinforced concrete structures afflicted by corrosion [12]. In order to maintain compatibility with the concrete substrate, it is imperative that the repair mortars adhere to a number of specifications such as chemical, electrochemical, permeability, and dimensional compatibility [5,13-16]. In the case of concrete structures where there is no visible damage, but the steel bars are subjected to corrosion, it becomes necessary to implement additional electrochemical measures to mitigate this issue. Cathodic protection is considered the most effective approach for managing corrosion current in order to prevent corrosion. Cathodic protection is widely regarded as the most efficacious method for mitigating corrosion currents and so preventing corrosion [8,13,17-27].

The utilization of cathodic protection in the United States dates back to the 1970s, with the purpose of protecting steel reinforced concrete structures that are exposed to atmospheric conditions. The use of CP in Europe was initiated in 1985, first adopted throughout many European nations [12]. Subsequently, its adoption has extended to Germany, France, and Belgium in more recent times. Several technical report on the application of the repair method to the real RC structures were found [28,29]. The Suramadu Bridge in Indonesia witnessed the latest use of cathodic protection in 2021 [30]. The Suramadu National Bridge, also referred to as the Suramadu Bridge, is a significant infrastructure project that spans the Madura Strait, serving as a vital link between Java Island, situated in Surabaya, and Madura Island, notably in Bangkalan, to the east of Kamal. The bridge in question assumes a pivotal function in facilitating interconnectivity throughout the sovereign state of Indonesia. The Suramadu Bridge, with an impressive span of 5,438 meters, has attained the esteemed distinction of being considered the longest bridge in Indonesia.

The prior study on the combination of repair methods has not adequately addressed the specific aspects of time dependence potential and depolarization value. Then, the aim of this study is to evaluate the long-term efficacy, spanning a period of three years, of corrosion protection measures implemented on badly deteriorated reinforced concrete (RC) elements. These measures involve a mix of patch repair techniques and the application of cathodic protection.

2. Methodology

2.1 Detail of Structures and Materials

The reinforced concrete beam constructions utilized in this experiment were constructed in the year 1974. The provided data in Figure 1 illustrates the cross-sectional characteristics of the beams, each having a consistent length of 2400 mm. As a component in these samples, Ordinary Portland cement was used as the binder material. The fineness modulus and specific gravity of aggregates are described in Table 1. The mix proportion of the specimens is displayed in Table 2.

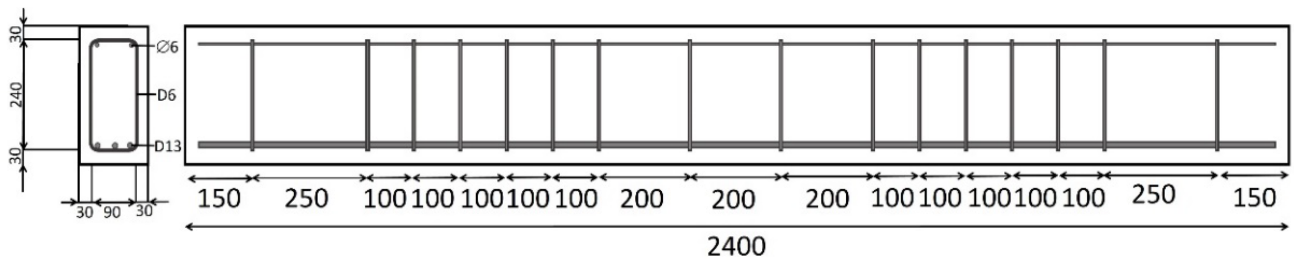


Fig. 1. Detail of the beam used in the experimental programs

Table 1
Fineness modulus and specific gravity of fine river sand and coarse-crushed stone

Aggregate	Fineness modulus	Specific gravity
Fine river sand	2.84	2.25
Coarse-crushed stone	6.63	2.75

Table 2
Detail of mix proportion of the specimen

Maximum Size of Coarse Aggregate (mm)	Slump (mm)	Air (%)	w/c %	s/a %	Unit weight (kg/m^3)				
					Water	Cement	Sand	Gravel	Admixture
20	12±2	4±1	68	47	204	300	793	964	1.2

The RC beams were first demolded and then put through one day of moisture curing before moving on to the next step of the curing process, which was air curing. Between the years 1975 and 1995, the structures that were built at Sakata Port, which is located in the most northwestern part of Japan, were allowed to remain open to the elements of the natural tidal sea environment. Before being moved to the facility at Fukuoka, Japan, the structures were kept at the laboratory at Yokosuka, Japan [31,32], Japan between the years of 1995 and 2010.

2.2 Assessment on Structure Degradation

In order to evaluate the material quality of the RC beam constructions that were employed in this experiment, the ultrasonic pulse velocity (UPV) and the rebound hammer test were both applied. According to the UPV standard that can be found in ASTM C597, the material quality is regarded to be of a satisfactory quality when its velocity falls between 4000 and 5000 meters per second and when it has an approximate compressive strength of 25 to 40 megapascals. This qualifies the concrete as having a satisfactory quality. According to the findings of the research that was conducted on the rebound hammer test, the compressive strength estimation has a value of 3,224 MPa on average after 44 years of service.

The samples show signs of rust staining, chipping and cracking, the presence of air bubbles, and exposed aggregate. In addition, there are cases in which the samples include air bubbles. As a result of the seawater splashing that the beams were subjected to, uncovered aggregate was most commonly seen on the bottom surface of the beams. On the other hand, rust stains were frequently found at the beam ends and in close proximity to the cracks. After being subjected to the elements for a period of time as long as forty years, it was discovered that the surfaces of all of the beams had developed rough textures, chips along the edges, and sporadic instances of spalling. The results of a visual inspection, the purpose of which was to evaluate the aesthetic condition of the beams, led to the conclusion that there was no significant degradation seen in reinforced concrete (RC) beams with cover thicknesses of 3 cm after a 40-year period of exposure. This conclusion may be drawn based on the findings acquired by the visual examination. The visual condition and crack pattern of the beam were presented in Figure 2 and Figure 3, respectively.

Fig. 2. Visual condition on the beam surface

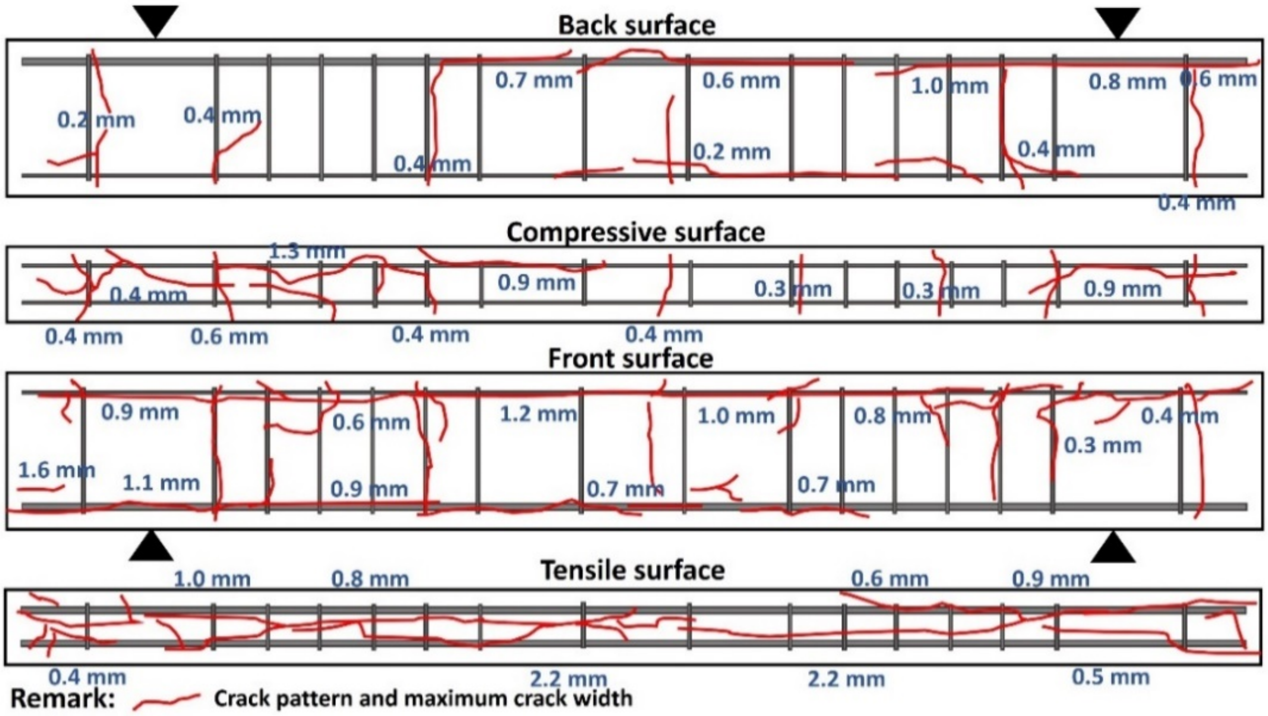


Fig. 3. Crack pattern of all specimen surfaces

It could be seen from whatever direction that one looked at the concrete, since it had developed a fissure on its surface. Each beam had cracks running parallel to the rebar down its length, and the area of medium tensile strength was where the majority of the breaking occurred. Cracks have only occurred on both sides and on the tensile surface of the other beams, there is a considerable number of cracks detected in both the compressive and tensile areas (both longitudinal and transversal direction). In the other beams, cracks have only formed on the tensile surface. It has been determined that the emergence of longitudinal cracks in the structure correlates with the positioning of both compressive and tensile rebar. Either pre-cracking that had already happened or the corrosion of the stirrups was the source of the transverse cracks that were confined in the middle span of the tensile zone. Both of these factors contributed to the failure of the structure. The fracture has a maximum width of 2.2 millimeters in its widest point. Additionally, there are air bubbles on the surface of each beam, and the diameter of these bubbles is 1.17 millimeters.

2.3 Design of Repairs

A number of cracks appeared in the center of the tensile portion, as determined by the preliminary examination. With the rush ammount on the surface of the rebar, a high risk of deterioration of implanted steel bars was determined. The presence of corrosion made this determination. As a result, the mending technique with sacrificial anode cathodic protection and patch repair was applied in order to regulate the rebar corrosion and reinforce the structures. The remediation design of the beam is depicted in Figure 4. In the midst of the 70 x 150 x 800 mm tension area, the polymer-modified mortar was applied after removing the corrosion and replacing the old concrete substrate through a crushing procedure. This was accomplished using adhesive material made from the emulsion of vinyl acetate/ethylene copolymer between the old and new substrates. Ribbed zinc anodes (diameter of 30 mm, a length of 139 mm, and a weight of 417 grams) were inserted in pre-drilled holes with a diameter of 40 mm in the old substrate, and LiOH-containing cementitious coating material was used to cover the anodes after they had settled into place.

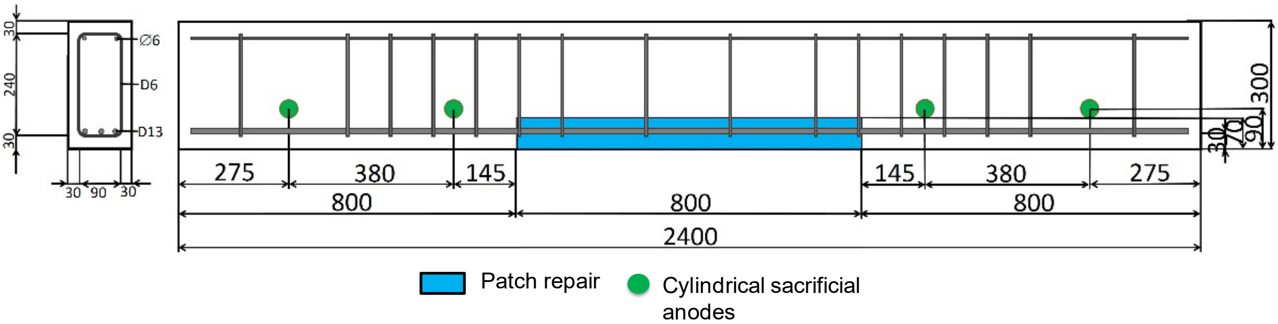


Fig. 4. Design of repair strategy

2.4 Monitoring and Evaluation Methods

The high impedance ammeter was used on a consistent basis to quantify the electric current passing through the anode. Tt is suggested that the minimum design current flow, when divided by the total surface area of the steel bar, should exceed 0.2 microamperes per square meter (EN 12696 standard). The current density, measured in microamperes per square meter, is the ratio of the current flow produced by anodes, in microamperes, to the surface area of rebar.

100 mV potential decay was chosen as the effectiveness threshold, and the depolarization test measurement was employed to investigate effectivity of anode system. The on-potential, sometimes referred to as Eon, of the rebar and the anode was calculated while the system was operating under the conditions of sacrificial anode cathodic protection. The potential known as the instant-off potential, which is also referred to as Eoff, was measured immediately after the connection was severed, and the potential known as the rest potential, which is also referred to as Ecorr, was measured twenty-four hours afterwards.

3. Results

3.1 Current flow of Anodes

After a period of time in which patches were fixed and anodes were inserted, anodes were ultimately linked to the rebar. This process took a total of 28 days. Figure 5 presents the temporal variations in current flow and protective current density induced by sacrificial anodes, as well as the corresponding air temperature, throughout the course of a one-year observation period. The presented data illustrates the correlation between the flow of current and the protective current density produced by sacrificial anodes, in conjunction with variations in air temperature. These graphs illustrate the link that exists between the temperature of the surrounding air and the amount of protective current density that is produced by the sacrificial anodes. It has been established that the repair method has protective current densities that are greater than the 10 mA/m^2 as the minimum design limit based on EN 12696. This is the case because the remedial measure have protective current densities that are higher than the minimum design limit.

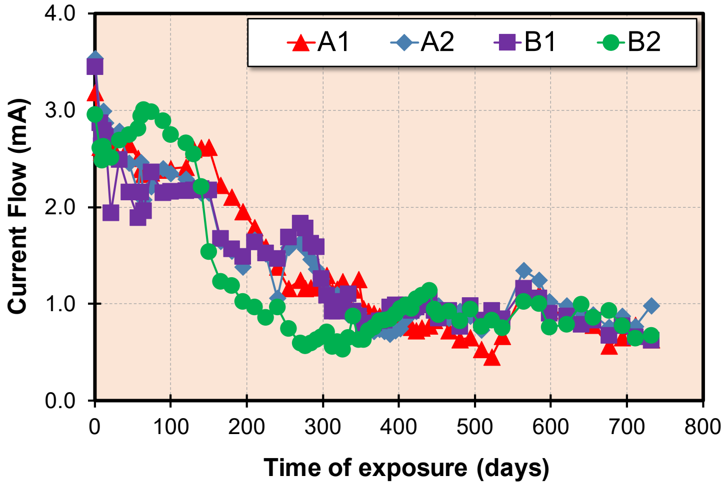
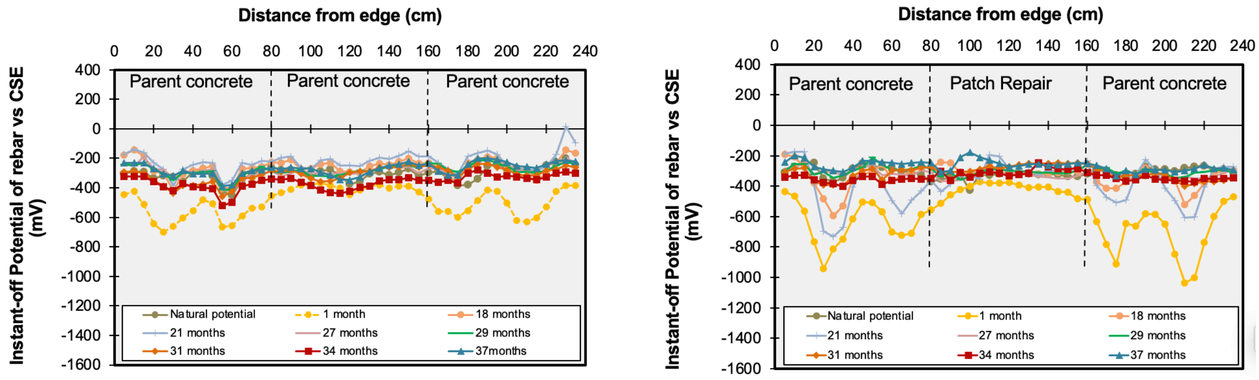


Fig. 5. Current flow of sacrificial anodes

3.2 Rest Potential and Instant-off of Steel Bars

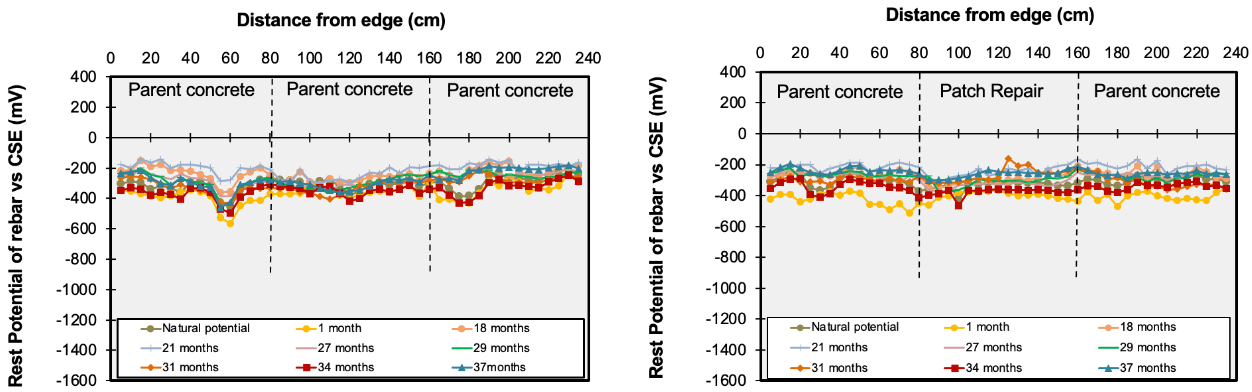
In order to assess the efficacy of sacrificial anode cathodic protection, various measurements were taken to analyze the potential of rebar and sacrificial anodes at different stages: during connection (on potential), immediately after disconnection (instant-off potential), and after a 24-hour period of disconnection (rest potential). These recordings were made to evaluate the potential of utilizing sacrificial anodes as a means of cathodic protection. After a period of 37 months, the recorded potential values of all sacrificial anodes experienced a transition to a noble value ranging from about -1000 mV to -600 mV. Additionally, the remaining potential of the anodes was seen to be between the range of -1400 mV to -1000 mV. The observed behavior of the rebar, characterized by rapid fluctuations in potential upon activation and deactivation, indicates that the sacrificial anodes exerted a discernible impact on the surrounding potentials at a radius of about 200 mm from the anode location for the whole 37-month monitoring period. The finalized data on the instantaneous-off potential is illustrated in Figure 6. The tensile bar exhibited a higher degree of polarization compared to the compressive bar, mostly because to its proximity to the anode during installation.

The time-dependent trends of the polarization effects of tensile rebar were seen in Figure 7. These effects were measured based on the distance between the sacrificial anode and the edge of the beams. The observed trends were determined based on the varying distances between the sacrificial anode and the edges of the beams. The effects accessible to the user were defined by the distance between the sacrificial anode and the edge of the beam. The experiment revealed a shift in the rest potential of the rebar towards a more noble value with time.



(a) (b)

Fig. 6. Instant off potential of steel bar at (a) compressive bar and (b) tensile bar until 37 months

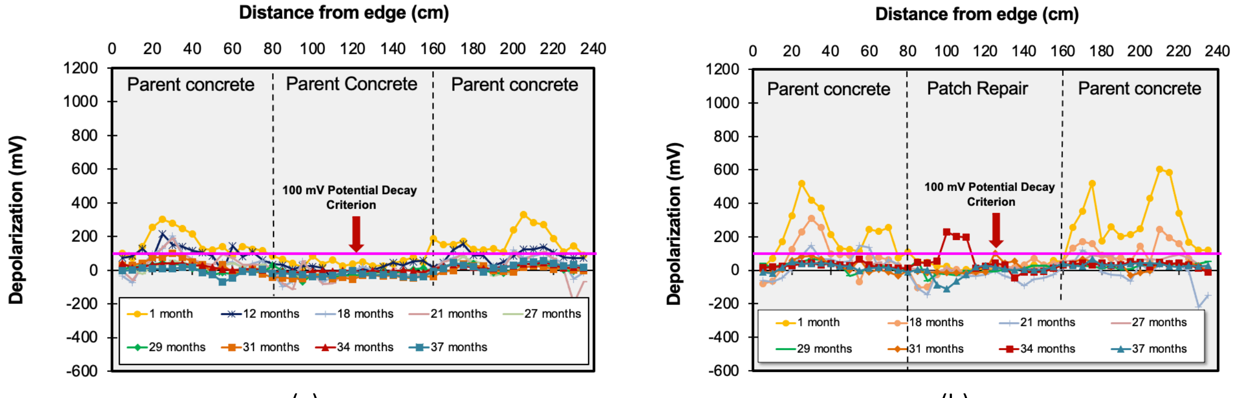


(a) (b)

Fig. 7. Rest potential of steel bar at (a) compressive bar and (b) tensile bar until 37 months

3.3 Depolarization Value

The determination of depolarization value involves the utilization of the discrepancy between the instantaneous off potential and the resting potential. In the assessment of cathodic protection's efficacy, it is customary to employ a threshold of 100 millivolts (mV) as the criterion for possible degradation. The depolarization test data up to 37 months post-exposure were exhibited. The results indicate that the depolarization test value of the rebar in the original concrete of both specimens has the potential to exceed 100 mV. The utilization of sacrificial anodes was shown to be an effective strategy in mitigating corrosion in concrete structures polluted with chloride. The depolarization value is depicted in Figure 8. However, depolarization is limited in patch repairs because the material properties of patch repairs differ from those of non-patch repairs. An additional method for assessing the effectiveness of sacrificial anode systems might involve employing potential mapping to analyze spatial fluctuations, rather than just relying on a 100 mV potential drop. The incorporation of sacrificial anodes into the primary concrete structure is anticipated to exert a significant impact on the electrical potentials of the reinforcing bars, extending beyond the immediate area of the anode. The amplitude of this impact must be at least equal to half the distance between the positions of the anodes. This alternate criterion is consistent with the conclusions made by prior scholars.

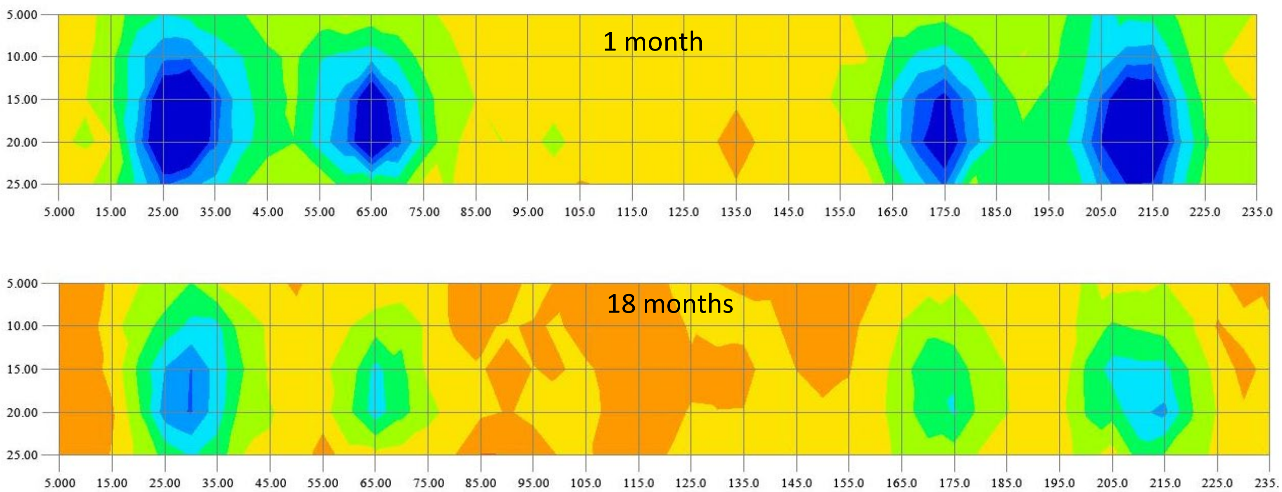


(a) (b)

Fig. 8. Depolarization value of steel bar at (a) compressive bar and (b) tensile bar until 37 months

3.4 Protection Development

The Figure 9 presented the development of protection by using the combination of patch repair in the middle tensile part and sacrificial zinc anode in both side the parent concrete. The findings suggest that the utilization of patch repair materials, such as polymer modified mortar, does not undermine the effectiveness of sacrificial anodes placed within the original concrete around the repaired area. This conclusion is supported by the structural repairs standard BS EN 1504 (2015). However, BS EN ISO 12696 (2012) states that polymer modified mortar is not advised for use with sacrificial anodes because of its high resistivity. On the contrary, it is anticipated that the use of such materials would increase the longevity and durability of the repair. Because of their greater resistance to current flow, sacrificial anodes can more efficiently direct corrosion-causing ions away from the original concrete's rebar. Nevertheless, this method of restoration can be implemented under the assumption that adequate protection is provided for both sides of the parent concrete. It should be noted, however, that the middle section may have limited protection owing to the replacement of old concrete material, as it already has a relatively low risk of corrosion.



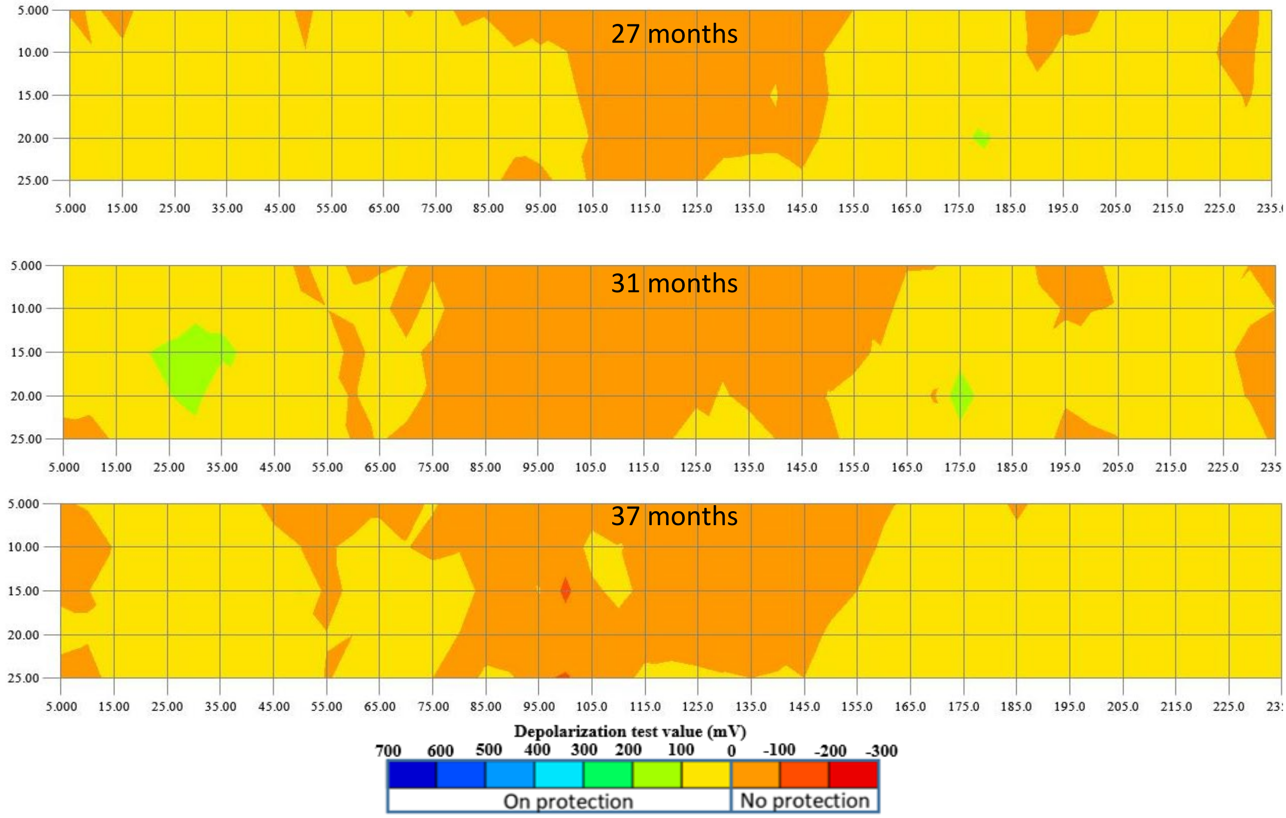


Fig. 9. Development of protection condition indicated by time dependency depolarization map

4. Conclusions

The effectiveness of a zinc anode in polarizing the potential of rebar in a corroded RC component was investigated until three years. The phenomenon of high polarization is observed mostly in the vicinity of the anodes within the original concrete, rather than in the patch repair region. This discrepancy can be attributed to intrinsic disparities in the material characteristics between the patch repair material and the original concrete. The repair method by using patch repair and zinc anode is acceptable due to the middle section may have limited protection owing to the patch material replacement, as it already has a relatively low risk of corrosion, so it can be applied in the real deteriorated structure.

Acknowledgement
The authors would like to express their gratitude to the PARI, Japan for providing the RC beams utilized in this experimental study. The authors would like to extend their gratitude to all members of the Kyushu University laboratory who contributed to our research and offered valuable input.

References
[1] Lozinguez, Eric, Jean-François Barthélémy, Véronique Bouteiller, and Tiffany Desbois. "Contribution of Sacrificial Anode in reinforced concrete patch repair: Results of numerical simulations." *Construction and Building Materials* 178 (2018): 405-417. https://doi.org/10.1016/j.conbuildmat.2018.05.063
[2] Tashan, Jawdat. "Flexural behavior evaluation of repaired high strength geopolymer concrete." *Composite Structures* 300 (2022): 116144. https://doi.org/10.1016/j.compstruct.2022.116144
[3] Bertolini, Luca, Bernhard Elsener, Pietro Pedeferri, Elena Redaelli, and Rob B. Polder. *Corrosion of steel in concrete: prevention, diagnosis, repair*. John Wiley & Sons, 2013. https://doi.org/10.1002/9783527651696
[4] England, Highways. "BA 35/90 Inspection and Repair of Concrete Highway Structures." *The Highways Agency, London, UK* (1990).

[5] Ali, M. Shafqat, Eileen Leyne, Mohammad Saifuzzaman, and M. Saeed Mirza. "An experimental study of electrochemical incompatibility between repaired patch concrete and existing old concrete." *Construction and Building Materials* 174 (2018): 159-172. https://doi.org/10.1016/j.conbuildmat.2018.04.059
[6] Ali, M. Shafqat, Eileen Leyne, Mohammad Saifuzzaman, and M. Saeed Mirza. "An experimental study of electrochemical incompatibility between repaired patch concrete and existing old concrete." *Construction and Building Materials* 174 (2018): 159-172. https://doi.org/10.1016/j.conbuildmat.2018.04.059
[7] Ali, M. Shafqat, Eileen Leyne, Mohammad Saifuzzaman, and M. Saeed Mirza. "An experimental study of electrochemical incompatibility between repaired patch concrete and existing old concrete." *Construction and Building Materials* 174 (2018): 159-172. https://doi.org/10.1016/j.conbuildmat.2018.04.059
[8] Astuti, Pinta, Rahmita Sari Rafdinal, and Yasutaka Sagawa. "Application of sacrificial anode cathodic protection for partially repaired RC beams damaged by corrosion." Organizing Committee of 4th International Symposium on Concrete and Structures for Next Generation, 2019.
[9] Wang, Yan-Shuai, Kai-Di Peng, Yazan Alrefaei, and Jian-Guo Dai. "The bond between geopolymer repair mortars and OPC concrete substrate: Strength and microscopic interactions." *Cement and Concrete Composites* 119 (2021): 103991. https://doi.org/10.1016/j.cemconcomp.2021.103991
[10] Ghoddousi, Parviz, Mostafa Haghtalab, and Ali Akbar Shirzadi Javid. "Experimental and numerical analysis of the effects of different repair mortars on the controlling factors of macro-cell corrosion in concrete patch repair." *Cement and Concrete Composites* 121 (2021): 104077. https://doi.org/10.1016/j.cemconcomp.2021.104077
[11] Rodulfo, Perla, Boyu Wang, Rishi Gupta, Loveleen Sharma, and Phalguni Mukhopadhyaya. "Relationship between electrical Conductivity, Half cell Potential, Linear polarization resistance and Macrocell current of cementitious repair materials." *Construction and Building Materials* 401 (2023): 132733. https://doi.org/10.1016/j.conbuildmat.2023.132733
[12] Ducasse-Lapeyrusse, Jean, Véronique Bouteiller, Elisabeth Marie-Victoire, Myriam Bouichou, Guillaume Damien, Victor Martinet, Camille Annede-Villeau, and Olivier Lesieutre. "Assessment of the Impressed Current Cathodic Protection system after 4 years operation: Case study of the Saint-Cloud Viaduct (France)." *Case Studies in Construction Materials* 18 (2023): e02023. https://doi.org/10.1016/j.cscm.2023.e02023
[13] Astuti, P., R. S. Rafdinal, H. Hamada, Y. Sagawa, D. Yamamoto, and K. Kamarulzaman. "Effectiveness of rusted and non-rusted reinforcing bar protected by sacrificial anode cathodic protection in repaired patch concrete." In *IOP Conference Series: Earth and Environmental Science*, vol. 366, no. 1, p. 012013. IOP Publishing, 2019. https://doi.org/10.1088/1755-1315/366/1/012013
[14] Afriansya, Rahmad, Evelyn Anabela Anisa, Pinta Astuti, and Martyana Dwi Cahyati. "Effect of polypropylene fiber on workability and strength of fly ash-based geopolymer mortar." In *E3S Web of Conferences*, vol. 429, p. 05006. EDP Sciences, 2023. https://doi.org/10.1051/e3sconf/202342905006
[15] Astuti, Pinta, Laode Abdul Zakri Radio, Farah Salsabila, Afdhal Kresna Aulia, Rahmita Sari Rafdinal, and Adhitya Yoga Purnama. "Corrosion potential of coated steel bar embedded in sea-water mixed mortar." In *E3S Web of Conferences*, vol. 429, p. 05028. EDP Sciences, 2023. https://doi.org/10.1051/e3sconf/202342905028
[16] Talib, Mohd Khaidir Abu, Siti Nor Hidayah Arifin, Aziman Madun, Mohd Firdaus Md Dan, and Faizal Pakir. "Effect of Rice Husk Ash (RHA) as a Pozzolan on the Strength Improvement of Cement Stabilized Peat." *Journal of Advanced Research in Applied Mechanics* 114, no. 1 (2024): 83-93. https://doi.org/10.37934/aram.114.1.8393
[17] Astuti, Pinta, Khalilah Kamarulzaman, and Hidenori Hamada. "Non-destructive investigation of a 44-year-old RC structure exposed to actual marine tidal environments using electrochemical methods." *International Journal of Integrated Engineering* 13, no. 3 (2021): 148-157. https://doi.org/10.30880/ijie.2021.13.03.018
[18] Astuti, Pinta, Rahmita Sari Rafdinal, Daisuke Yamamoto, and Hidenori Hamada. "Corrosion rate of deteriorated steel bar protected by sacrificial anode cathodic protection." In *AIP Conference Proceedings*, vol. 2482, no. 1. AIP Publishing, 2023. https://doi.org/10.1063/5.0110419
[19] Astuti, Pinta, Rahmita Sari Rafdinal, Daisuke Yamamoto, Volana Andriamisaharimanana, and Hidenori Hamada. "Effective use of sacrificial zinc anode as a suitable repair method for severely damaged RC members due to chloride attack." *Civil Engineering Journal* 8, no. 7 (2022): 1535-1548. https://doi.org/10.28991/CEJ-2022-08-07-015
[20] Astuti, P., R. S. Rafdinal, A. Mahasiripan, H. Hamada, Y. Sagawa, and D. Yamamoto. "Potential development of sacrificial anode cathodic protection applied for severely damaged RC beams aged 44 years." *Journal of Thailand Concrete Association* 6, no. 2 (2018): 24-31.
[21] Pedeferri, Pietro. "Cathodic protection and cathodic prevention." *Construction and building materials* 10, no. 5 (1996): 391-402. https://doi.org/10.1016/0950-0618(95)00017-8
[22] ISO, BSEN. "12696 (2012) Cathodic protection of steel in concrete." *British Standards Institution* (2012).

[23] Carmona, J., P. Garcés, and M. A. Climent. "Efficiency of a conductive cement-based anodic system for the application of cathodic protection, cathodic prevention and electrochemical chloride extraction to control corrosion in reinforced concrete structures." *Corrosion Science* 96 (2015): 102-111. https://doi.org/10.1016/j.corsci.2015.04.012

[24] Cheung, Moe MS, and Chong Cao. "Application of cathodic protection for controlling macrocell corrosion in chloride contaminated RC structures." *Construction and Building Materials* 45 (2013): 199-207. https://doi.org/10.1016/j.conbuildmat.2013.04.010

[25] Jeong, Jin-A., Chung-Kuk Jin, and Won-Sub Chung. "Tidal water effect on the hybrid cathodic protection systems for marine concrete structures." *Journal of Advanced Concrete Technology* 10, no. 12 (2012): 389-394. https://doi.org/10.3151/jact.10.389

[26] Zhu, Ji-Hua, Zhi Wang, Mei-ni Su, Tamon Ueda, and Feng Xing. "C-FRCM jacket confinement for RC columns under impressed current cathodic protection." *Journal of Composites for Construction* 24, no. 2 (2020): 04020001. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001006

[27] Byrne, Aimee, Niall Holmes, and Brian Norton. "State-of-the-art review of cathodic protection for reinforced concrete structures." *Magazine of Concrete Research* 68, no. 13 (2016): 664-677.

[28] Krishnan, Naveen, Deepak K. Kamde, Zameel Doosa Veedu, Radhakrishna G. Pillai, Dhruvesh Shah, and Rajendran Velayudham. "Long-term performance and life-cycle-cost benefits of cathodic protection of concrete structures using galvanic anodes." *Journal of Building Engineering* 42 (2021): 102467. https://doi.org/10.1016/j.jobe.2021.102467

[29] Kamde, Deepak K., Karthikeyan Manickam, Radhakrishna G. Pillai, and George Sergi. "Long-term performance of galvanic anodes for the protection of steel reinforced concrete structures." *Journal of Building Engineering* 42 (2021): 103049. https://doi.org/10.1016/j.jobe.2021.103049

[30] Sonjaya, Hadi Gunawan, and Rahmita Sari Rafdinal. "TEKNOLOGI ZINC CARTRIDGE DAN TI-WIRE SENSOR SEBAGAI TEKNOLOGI PROTEKSI KATODIK DAN PEMANTAUAN KOROSI BAJA TULANGAN BETON PERTAMA DI INDONESIA." *Jurnal HPJI (Himpunan Pengembangan Jalan Indonesia)* 9, no. 1 (2023): 31-40. https://doi.org/10.26593/jhpji.v9i1.6443.31-40

[31] Hamada, H., N. Otsuki, and M. Haramo. "Durabilities of concrete beams under marine environments exposed in port of Sakata and Kagoshima (after 10 yearsexposed)." *Technical Note of the Port and Airport Research Institute* 614 (1988): 3-43.

[32] Yokota, H., T. Akiyama, H. Hamada, A. Mikami, and T. Fukute. "Effect of degradation of concrete on mechanical properties of reinforced concrete beams exposed to marine environment (for 20 years in Sakata)." *Report of the Port and Airport Research Institute* 38, no. 2 (1999).