A STUDY ON REPAIRING SYSTEM OF SEVERELY DAMAGED RC BEAM BY CATHODIC PROTECTION USING A DIFFERENT KIND OF SACRIFICIAL ANODES

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A STUDY ON REPAIRING SYSTEM OF SEVERELY DAMAGED RC BEAM BY CATHODIC PROTECTION USING A DIFFERENT KIND OF SACRIFICIAL ANODES

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ABSTRACT

This research clarifies the application of different kinds of sacrificial anode cathodic protection (SACP) in the patch and non-patch repair on more than 40-years severely damaged RC beam due to chloride-induced corrosion. The most seriously damaged concrete in the middle tensile part of the beam was replaced by polymer-modified mortar as a patch repair material. Low powered SACPs were installed on the bottom surface of rebar to provide local cathodic protection and incipient anode protection. Four additional rib and smooth SACPs ∅20mm were embedded in both sides of non-patch repair concrete. Three connection patterns were demonstrated until one-month including (1) sacrificial anodes in patch repair only, (2) sacrificial anodes in non-patch repair, and (3) combination sacrificial anodes both in the patch and in non-patch repair. The results show that the polarization of steel bar occurs when the steel bars connect to sacrificial anodes in the patch or non-patch repair only. The depolarization test reveals that the combination of different kinds of sacrificial anodes in the closed distance can't reach 100 mV potential decay criterion. So, the application of a different kind of sacrificial anode in the closed area could not be a suitable repairing system.

Keywords: Repairing System, Sacrificial Anode Cathodic Protection, Patch and Non-patch Repair, Depolarization

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1. INTRODUCTION

Steel bar corrosion leads to deterioration, damage, and destruction of reinforced concrete (RC) structures, and it is a major issue in infrastructure maintenance [1]. Excessive corrosion can be dangerous and costly [2,3,4]. The annual cost of corrosion worldwide is estimated to be 3–4% of the gross domestic product (GDP) of industrialized countries [5], with US$17 billion annual maintenance investment repeatedly needed to improve bridge conditions in the USA [6].

There are several circumstantial and interconnected influences in designating which repair method to use, including weight restrictions, budget, the need for a monitoring system, maintenance requirements, traffic management during repairs, the extent and severity of the damaged, aesthetics, and technical limitation [7]. Patch repair is the most widely used but is limited to low-impact localized damage [8,9]. The most negative impact of this method is the risk of incipient anodes causing corrosion of the surrounding areas of steel bar [7]. Sacrificial anode cathodic protection has been used to limit the extent of concrete replacement and extend the service life of patch repair to RC members. They respond to the changes in the environmental conditions they are exposed to [10,11,12]. Cathodic protection applies a small current into the steel bar, forcing it to act as the cathode as opposed to the dissolving anode in an electrochemical cell [13]. It controlled corrosion in the whole area treated, thus reducing the extent of concrete repair [14]. Such an effect will be more dominant in parent concrete that has a residual level of chloride contamination as opposed to non-contaminated repair concrete or mortar [15].

In this paper, an experimental study on the repairing system by using a different kind of sacrificial anodes in patch repair and parent concrete was demonstrated on severely damaged reinforced concrete (RC) beam aged more than 40-years exposed to the natural marine environment.

2. EXPERIMENTAL PROGRAMS

2.1. Detail of structures

RC beam was used for this study has a length of 2400 mm and a cross-sectional area of 150 x 300 mm, with both suffering from chloride-induced corrosion of the reinforcement. Ordinary Portland Cement (OPC) was used as a binder of the specimens. The RC beam structures used in this experiment were cast in 1974. The average value of compressive strength and elasticity modulus of concrete after 40 years were 30.0 MPa and 29.0 GPa, respectively [16]. The deformed steel bar with a diameter of 13 mm and yield strength of 363 MPa [16] was used as tensile rebar, and non-deformed steel of 6 mm in diameter was used as compressive rebar. Two round steel bars of 6 mm in diameter as compressive bars and stirrups with a spacing of 100 mm were embedded. The detail of the specimen was depicted in **Figure 1**.

The RC beam was moisture-cured for one day and demoulded before being air-cured. The structure exposed to the natural tidal marine environment for 20 years from 1975 to 1995 at Sakata Port, northwestern part of Japan. In 1995–2010, the beams were kept and sheltered from the rain at Port and Airport Research Institute (PARI) laboratory, Yokosuka, Japan [17,18] before it was moved to Kyushu University site, Fukuoka, Japan. The exposure condition was presented in **Figure 2**.

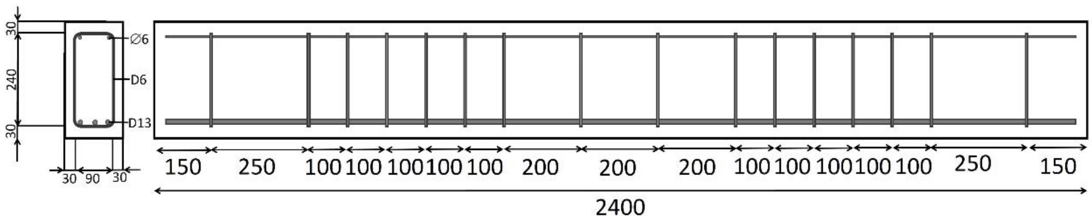


Figure 1. Detail of specimen (unit in mm)

The crack pattern, crack width, and initial corrosion map of specimens on the concrete surface after more than 40-years of exposure are presented in **Figure 3**. Longitudinal cracks occur not only in the middle tensile area but also in along of beam span with a maximum width of 0.75 mm. Transversal cracks concentrated on the middle span of the tensile area were initiated from the pre-cracking, continuous self-loading, or due to stirrups corrosion [16,19]. No concrete spalling is observed in the beam. Initial corrosion condition of the beam is recorded. Based on ASTM C 876, the corrosion probability in dry condition of the specimen is 72% area of RC-2 in uncertainty condition, and 28% in no corrosion region.

(a) (b) (c)

Figure 2. Exposure condition at (a) Sakata Port (1975-1995) [16,17], (b) PARI Laboratory (1995-2010) [20], (c) Kyushu University (2010-2016) [19]

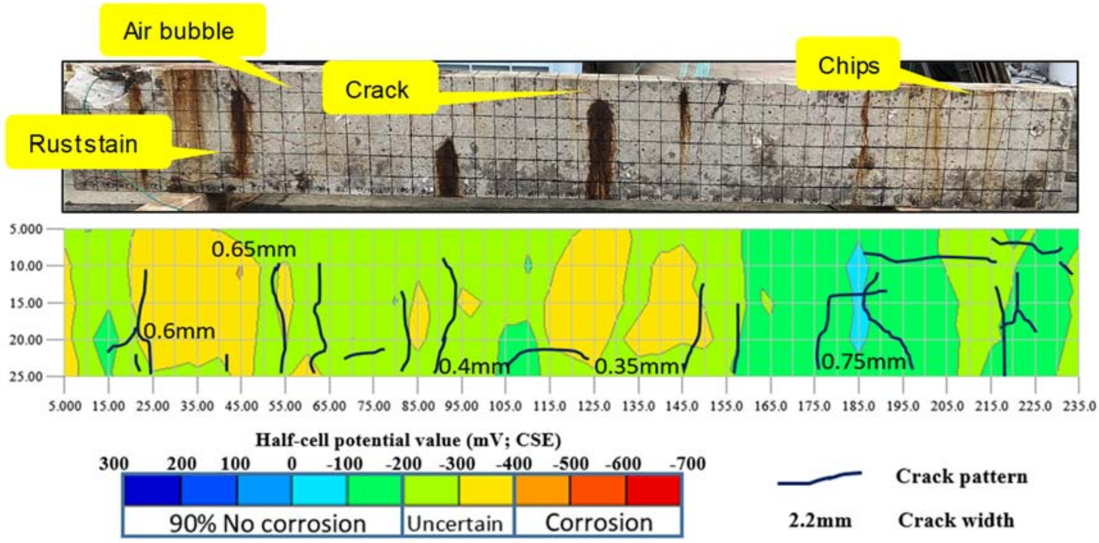


Figure 3. Deterioration condition and corrosion (natural potential) map of specimen in dry condition (unit in mm)

The average of total chloride ion concentration in the surrounding of the steel bar surface is 5.35 kg/m^3. These values are higher than the chloride ion threshold initiating corrosion of 1.2 kg/m^3 (JSCE standard specification for concrete structures – 2007 "Design") [21]. Based on JSCE standard specifications for concrete structures – 2007 "Maintenance" [22] Table C14.3.5.1 Grades of appearance and deterioration of the structure, this specimen was categorized as Grade II-1 (former acceleration stage) where corrosion-induced cracking and rust appearance are observed. The intervention methods such as surface coating, patching, cathodic protection, and electrochemical desalination are required to extend the service life of members.

2.2. Repairing design and materials

The repairing system by cathodic protection using a different kind of sacrificial anodes were implemented in this study. The repairing design of the deteriorated RC beams in the previous sub-section were presented in **Figure 4**. The polymer-modified mortar (**Figure 5(a)**) was applied in the middle of tension area with the dimension of 70 x 150 x 800 mm after replacing the chloride-contaminated existing concrete by crushing process and rust removal using an EVA (Vinyl Acetate / Ethylene) copolymer emulsion as adhesive material coating agent (**Figure 5(b)**) between parent concrete and patch repair mortar. Cylindrical ribbed sacrificial zinc anode applied for existing concrete (**Figure 5(d)**) with a diameter of 20 mm, a length of 139 mm and an approximate weight of 252 grams were installed in pre-drilled holes of 40 mm diameter in parent concrete and cementitious coating material with bentonite and $LiNO_2$ (**Figure 5(e)**) was used to cover the anodes after settling position in the hole. **Figure 5(c)** presented a rectangular sacrificial anode coated by LiOH based cementitious material installed in patch repair.

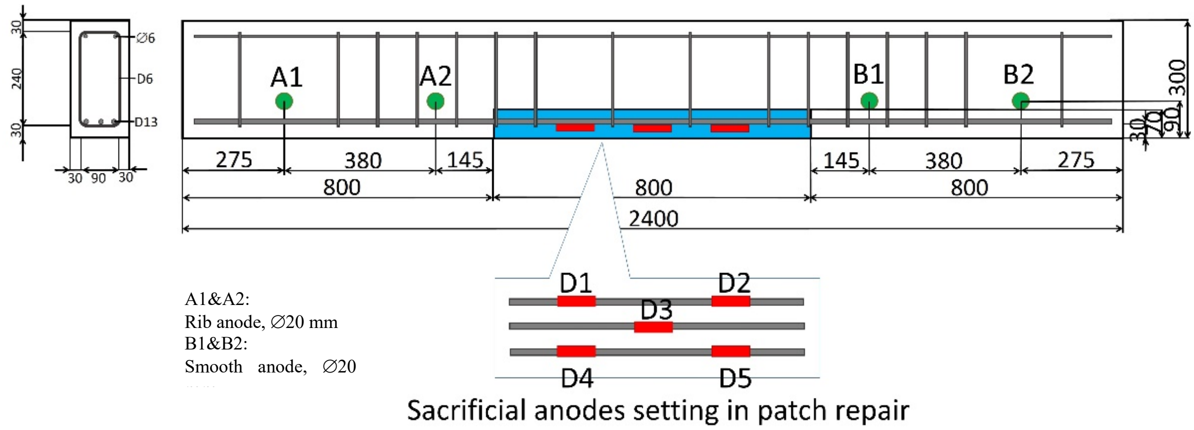
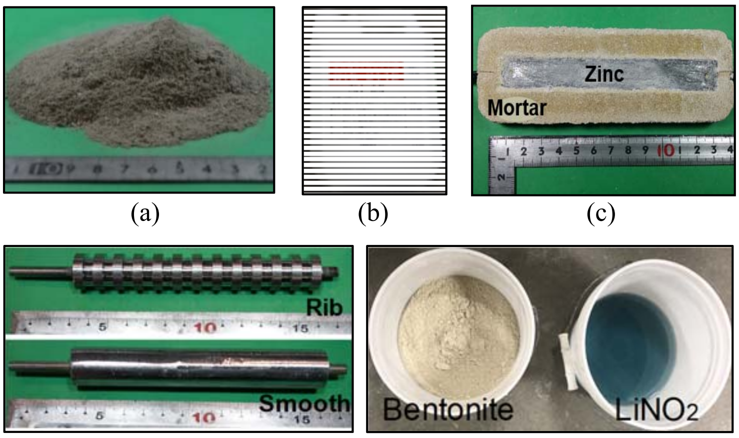


Figure 4. Repair design

The performance of different kinds of sacrificial anodes in the same structures at a close range is still unclear. Therefore, three experiments of the appropriate timing of sacrificial anode application were conducted to simulate the behavior of the system. In the first experiment, a rectangular sacrificial anode was installed in the steel bar inside the patch repair. In this paper, different kinds of sacrificial anodes were embedded in the patch and non-patch repair at the same time. Rectangular sacrificial anodes were embedded in the patch repair. Rib (A1&A2) and smooth (B1&B2) cylindrical sacrificial anodes ∅20 mm were installed in the left and right part of non-patch repair concrete.



(a) (b) (c)

(d) (e)

Figure 5. Materials for repair: (a) polymer modified mortar, (b) coating agent, (c) sacrificial anode in patch repair, (d) rib and smooth sacrificial anodes ∅20 mm for non-patch repair, and (e) bentonite and $LiNO_2$

2.3. Testing method

Half-cell potential test of rebar according to ASTM C876-15 was conducted by the calomel-saturated electrode (CSE) and high impedance multimeter (voltmeter setting) on every 50 mm square grid at the compressive and tensile rebar position after one hour of pre-wetting to evaluate the potential of the steel bar. On-potential (E_{on}) of rebar and the anode are measured under sacrificial anode cathodic protection. Instant-off potential (E_{iof}) is checked immediately after disconnection, and the rest potential (E_{corr}) is measured at 24 hours after interruption of the steel bar and the anode.

3. RESULTS AND DISCUSSION

3.1. Connection pattern

Three sacrificial anodes connection pattern, as explained in **Figure 6**, were demonstrated in this study. Sacrificial anodes in patch repair only were connected to the steel bar as the first pattern shown in (a). The second pattern describes sacrificial anodes in non-patch repair connected to the steel bar shown in (b). The last pattern, all sacrificial anodes both in the patch and in patch repair were connected to steel bar shown in (c). Each pattern was observed during one month of exposure. A similar pattern by a different type of sacrificial anodes and backfill material were done in the previous study [20, 23].

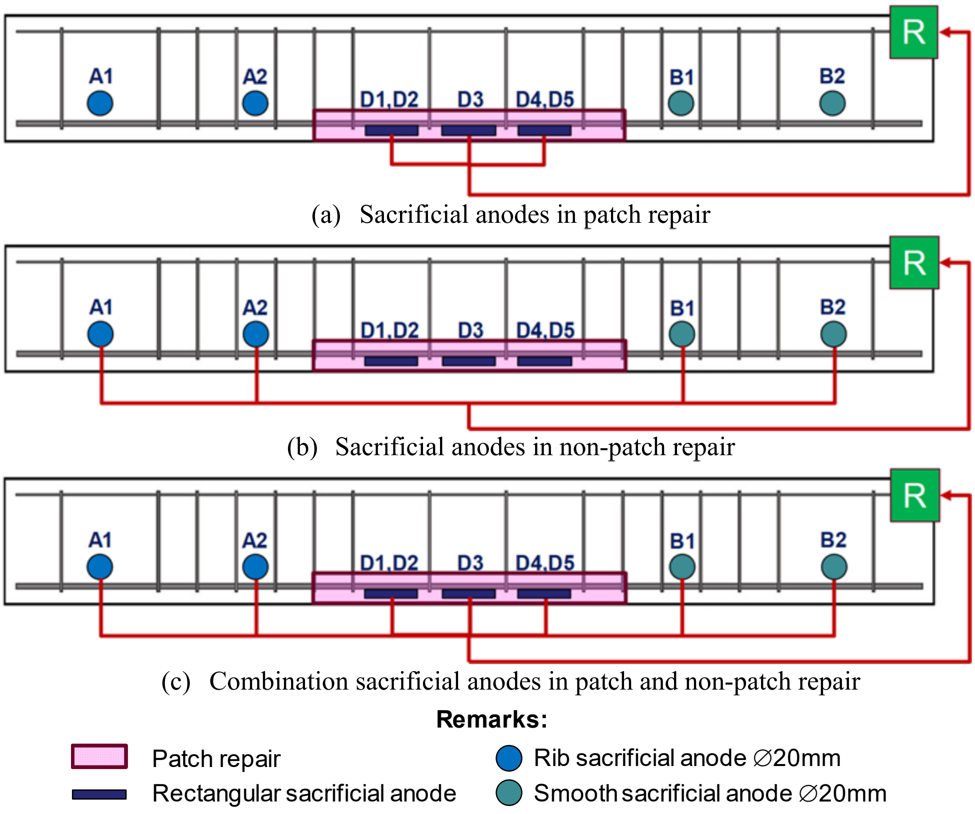


Figure 6. Connection pattern of sacrificial anodes and steel bar

3.2. Current flow of sacrificial anodes

The current flow of each sacrificial anode in the three connection pattern was presented in **Figure 7**. It shows that the current flow of sacrificial anode both in patch and non-patch repair is 0.7~0.8 mA. However, the current flows increase to 1.3~1.4 mA and 0.8~0.9 mA for the sacrificial anode in patch and non-patch repair, respectively. So, the combination anodes stimulate incremental of current flow.

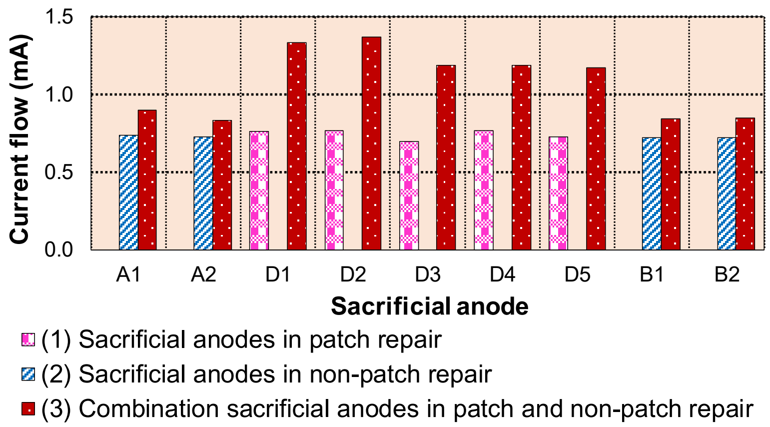


Figure 7. Current flow of sacrificial anodes

3.3. Polarization effect of aodes

The potential development of steel bar after one-month of connection, including instant-off potential, rest potential, and depolarization test value is presented in **Figure 8**. The potential of rebar and sacrificial anodes during connection (on potential), immediately after disconnection (instant-off potential), and rest potential after 24-hours of disconnection (half-cell potential) were recorded in this experiment. The polarization of the sacrificial anode effect can be presented by using instant-off potential data. The rest potential is used to understand the corrosion probability based on ASTM C 876. The effectiveness of cathodic protection is categorized based on 100 mV potential decay criterion.

From the first pattern when sacrificial anodes in patch repair are connected to a steel bar, the polarization only occur in the patch repair area. It is confirmed by depolarization value that it can reach 100 mV potential decay only in the patch repair area. The second connection pattern also shows that the steel bars in non-patch repair are polarized by the application of sacrificial anodes in non-patch repair. The depolarization value shows that the protection is concentrated in the surrounding of a sacrificial anode setting position. It may due to electrochemical incompatibility between polymer modified mortar as patch repair material and existing concrete [19,23,27]. The first and second connection patterns perform well to protect the steel bar in its area. The third pattern reveals the less polarization effect of steel bar due to combination different kinds of sacrificial anodes in the patch and non-patch repair. The polarization only occurs around A1 and none in other sacrificial anodes.

The protection condition of each connection pattern is illustrated as a depolarization map of the steel bar and it was presented in **Figure 9**. Although the current flow of sacrificial anodes is generated from combination sacrificial anodes, it is not clear the current circulation from anodes to steel bar. So, the protection trend is unfavorable.

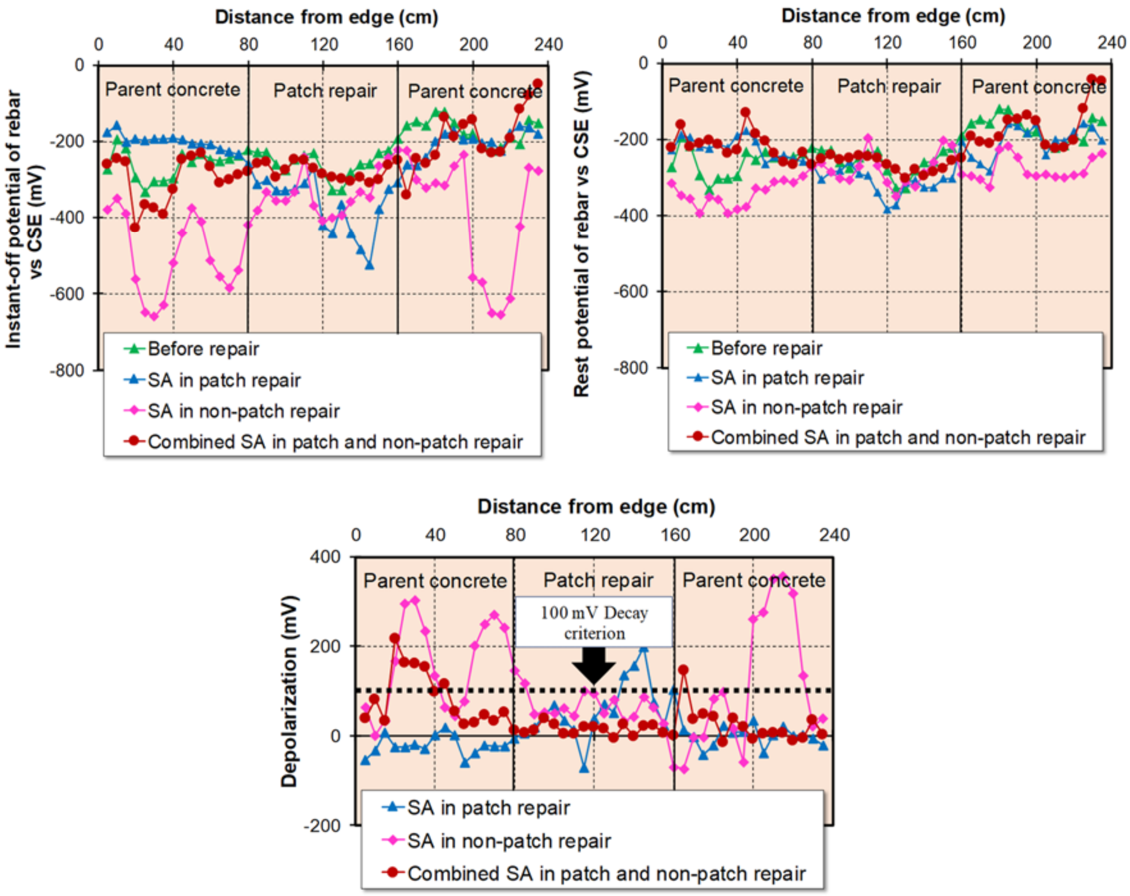


Figure 8. Potential development of tensile steel bar, (a) instant-off potential, (b) rest potential and (c) depolarization test value

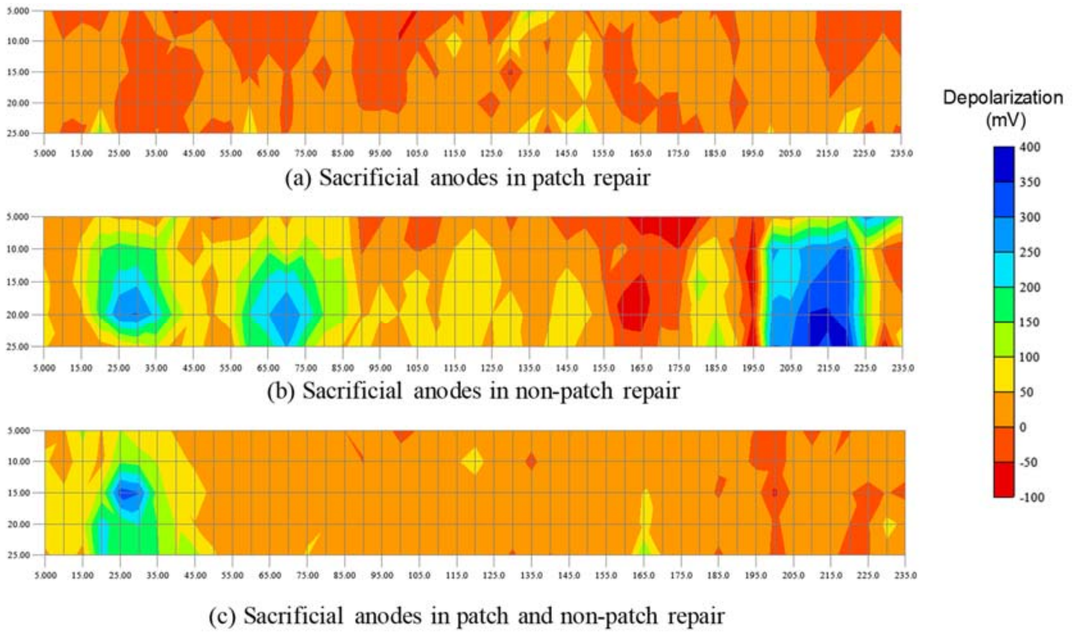


Figure 9. Depolarization map

4. CONCLUSIONS

The repair method by combining a different kind of sacrificial anodes in the patch and non-patch repair presented no significant polarization of rebar nor current flow. Therefore, the combination sacrificial anodes in the patch and non-patch repair method at the same time with closed distance could not be suitable repairing system.

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