Quantitative estimation method for rebar corrosion degree of RC structures

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ABSTRACT: It is well-known that the corrosion of reinforcing steel-bars in RC structures results in the decrease of the effective cross section of reinforcement, the occurrence of cracks in concrete and the bond degradation. As a result, the ultimate load-bearing capacity and the durability of structures could decrease. So, it is very important to estimate the corrosion of rebar quantitatively and, to this end, the development of nondestructive evaluation NDE techniques is in great demand. So far, the conventional NDE methods are marginally successful to identify the corrosion degree and the thickness of the corrosion products, in other word, to estimate the effective cross-section of rebar quantitatively. In this paper, a very promising NDE technique is presented by applying thermography. The corrosion characteristics and behaviors of rebar in RC could be evaluated on the basis of temperature history at concrete surface, which would vary due to heat conduction from reinforcement heated by electromagnetic-induction.

1 INTRODUCTION

In RC structures, the corrosion of reinforcing steel-bar (rebar) is well-known to not only initiate cracks due to the expansion of corrosion products, but also to decrease the ultimate strength with the decrease in the effective cross section of rebar. Moreover, the delamination in cover concrete could lead the remarkable decline of the durability and the ultimate strength as the accelerated degradation with the exposure of rebar to atmosphere. Consequently, it is very important to quantitatively estimate the characteristic of the corrosion of rebar in RC structures. The most accurate technique currently available for the estimation of the corrosion is to remove the rebar and to measure visually. It is, however, realistically difficult to take rebar in existing structures, and thus non-destructive evaluation (NDE) techniques have been applied. NDE techniques, which are currently applied to the estimation of rebar corrosion, is the half-cell potential method constituted by ASTM (2001) and the polarization resistance method constituted by ASTM (2009). It is known that both methods are marginally successful to predict the occurrence or not of rebar corrosion, and that there exists one problem that a damage is inevitably exerted by chipping covered concrete to set the electrode in rebar directly. That is, it seems that any NDE techniques currently available could not predict the rate of corrosion or the thickness of corrosion products in rebar accurately.

Figure 1. General of proposed system.

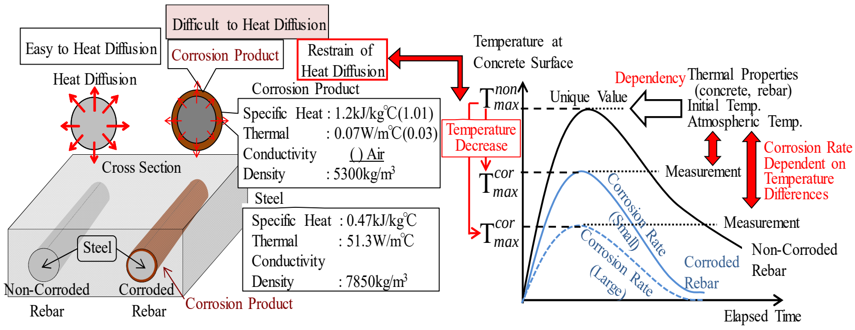


Figure 2. Detailed proposed system.

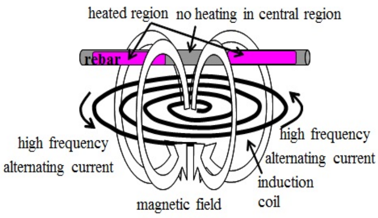


Figure 3. Circle coil.

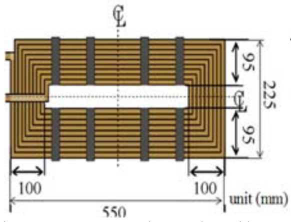


Figure 4. Developed coil.

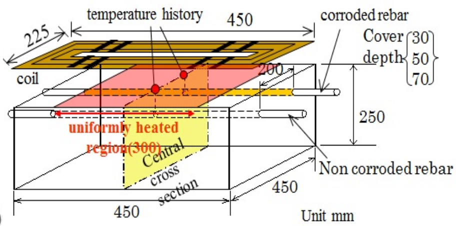


Figure 5. Specimen.

In this paper, one promising NDE technique is presented by applying thermography. The corrosions of rebars are estimated from the temperature history at the concrete surface, which would vary due to heat conduction from reinforcement heated by electromagnetic-induction.

2 OUTLINE OF PROPOSED TECHNIQUE

2.1 *General of proposed system*

Evaluation technique for the characteristic of rebar corrosion in concrete structures is developed under such conditions as perfectly non-destructive and non-contact at the surface of concrete. Based on the characteristics of rebar with high heat conduction and easy magnetization, heat applied to rebar by an electromagnetic induction heating is diffused to the surface of concrete as shown in Figure 1. When the corrosion product exists on the rebar surface, the temperature on the surface of concrete over rebar could shift from that of non-existence of the corrosion product. Thus, the temperature on the surface is dependent on thickness and distribution of the corrosion products. It is known that thermal characteristics of the corrosion product are similar to that of air, as a specific heat is relatively large and a thermal conductivity is inversely small as shown in Figure 2. The effect of the corrosion product is illustrated in same figure. Since heat conduction is prevented by a layer of the corrosion product, the temperature at the concrete surface over non-corroded rebar is quite different from that of corroded rebar.

2.2 *Electromagnetic induction heating*

As non-contact heating, an electromagnetic induction is applied. By charging a high-frequency electric current on an electromagnetic induction coil, an alternating field is generated around the coil and thus an eddy current is driven in a steel bar located in that field. As a result, rebar is heated. In the case of a circular coil, an electromagnetic induction generates an alternating magnetic field concentrically as shown in Figure 3. At the center and the edge of the coil, the magnetic flux density becomes smaller than that in between. Therefore, for a rebar set in the

Table 1. Specimen's patameters

Specimen's Name	Cover Depth (mm)	Diameter of Rebar	Corrosion Rate(%)	Coil Power (kW)	Heating Time(s)
K30-C0-1	30	16	0.00	2.0	320
K30-C0.66			0.66		
K30-C0-2			0.00	1.8	90
K30-C1.0			1.00		
K30-C5.0			5.00		
K50-C0-1	50	16	0.00	6.0	540
K50-C0.82			0.82		
K50-C0-2			0.00	1.8	420
K50-C1.0			1.00		
K50-C5.0			5.00		
K70-C0	70	16	0.00	6.0	780
K70-C0.70			0.70		

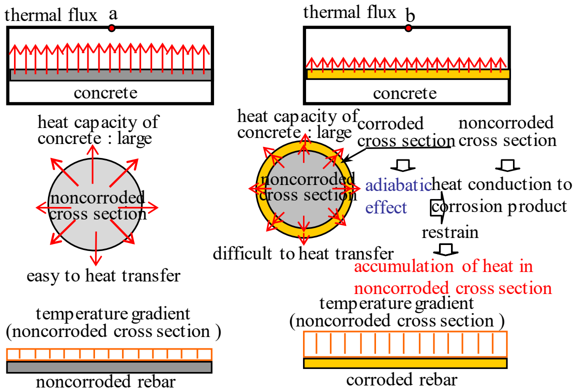


Figure 6. Property of corrosio product.

alternating magnetic field, non-uniform heating areas are generated as the temperature around the center and the edge of the coil becomes lower, while that of the other region becomes higher.

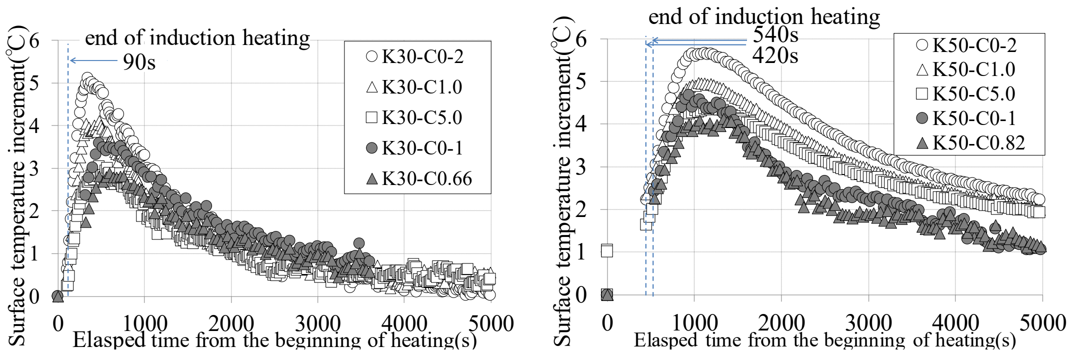
In the proposed procedure, it is very important to heat a rebar uniformly in the longitudinal direction. To this end, various experiments for the characteristics of heating were performed in which the coils were investigated on the shape, the size of steel tube for the coil and the diameter of steel tube. It is found that a rectangular coil shown in Figure 4 is of the most suitable shape to heat the rebar uniformly so that no heating gradients exist in the range of 60 mm x 300 mm. The electromagnetic induction coil developed is equipped with a copper pipe of 10 mm diameter, inside which cooling is performed with water to reduce heat of the coil due to radiofrequency current. The coil temperature becomes about 30 ºC at the time of radio frequency current charge, even if cooling is performed. Therefore, it is necessary to set a styrene foam of about 10 mm of thickness as an insulator at the concrete surface when heating is conducted.

3 THERMAL CHARACTERISTIC AT CONCRETE SURFACE RELATED WITH RATE OF CORROSION

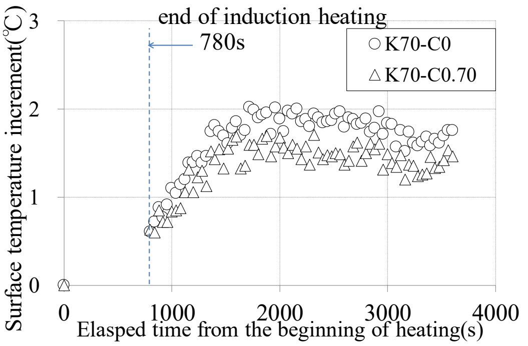
3.1 Experimental outline

Concrete specimens are of a cubic with the height of 250 mm, the width of 450 mm, the length of 450 mm as shown in Figure 5. Two rebars with the diameter of 16 mm are arranged with 200 mm interval of 30, 50, and 70 mm cover-thicknesses. One is non-corroded and another is corroded, where uniform corrosion was confirmed along the axial direction. Charging electric current into a coil for fixed time, the temperature of rebar was controlled by the electromagnetic induction heating and then the coil was removed. Here, the region of rebar uniformly heated is the 300 mm as shown in Figure 5 due to the restrictions of coil size. Both lengths of the coil and the specimen are 450 mm, but extended regions of the rebar outside the concrete specimen were actually heated due to the formation of magnetic field.

In the measurement, the temperature on the surface of concrete was measured by infrared thermography. Initially, the surface temperature was measured before installing the electromagnetic induction coil. Then, the temperature was measured for 90 minutes, during 5 sec. after termination of electromagnetic induction heating. Experimental parameters are the cover depth of concrete and the rate of corrosion. Details of all specimens are listed in Table 1.



(a) Cover depth 30mm (b) Cover depth 50mm



(c) Cover depth 70mm

Figure 7. Temperature increment at Concrete Surface.

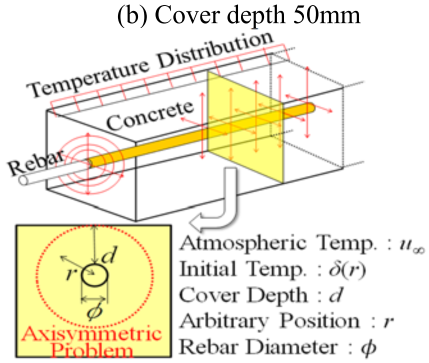


Figure 8. Axisymmetric problem.

Thus, the specimen's name is classified with the cover depth as K30, the rate of corrosion as C0.66. The electric powers applied are also shown in Table 1.

The rate of the corrosion is defined as a mass ratio of the corrosion product to the non-corroded rebar. The corrosion product was removed by soaking the corroded rebar into citric acid di-ammonium solution of 10 % concentration with temperature of 20 ºC for twenty-four hours. The thickness of the corrosion product was calculated from the rate of the corrosion and the density of steel and corrosion product given in Figure 2.

3.2 Thermal characteristics

In case of producing the corrosion product on the surface of rebar shown in Figure 6, the corrosion product restrains the heat diffusion to concrete from non-corroded cross-section of the reinforcing bar. Figure 7 shows the incremental temperature history at the concrete surface over the rebars at the middle point of the rebar shown in Figure 5. It is observed that temperature over the corroded rebar is 0.5-1.0 ºC lower than that of non-corroded.

4 PREDICTION MODEL FOR RATE OF COTTOSION OF REBAR

4.1 General

The rate of corrosion of a reinforcing bar is greatly dependent on such characteristics of the temperature at the concrete surface, as the maximum temperature and the rate of the temperature rise. As mentioned above, the presence of the corrosion product causes the decrease in the maximum temperature at the concrete surface and then the decreasing value is corresponding to the rate of the corrosion. Hence, the rate of the corrosion will be predicted by the comparison between the value measured in corroded RC structure and the prescribed value, which is in case of the non-corroded bar.

4.2 Prediction model

4.2.1 Temperature at concrete surface

To predict the rate of the corrosion of rebar, the information of the temperature at the concrete surface $T_{\max}$, where the non-corroded rebar is arranged, is essential. One empirical estimation is known as the solved value by the non-steady heat conduction problem.

Now, the non-steady heat conduction as an axisymmetric problem shown in Figure 8, in which the center of rebar is origin and the radius is the length from the center of the rebar to the surface of the concrete, can be expressed as a following equation.

$$\frac{1}{\kappa}\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \quad , \ \kappa = \frac{\lambda}{\rho c} \tag{1}$$

where, u is a temperature, t is a time, γ is a coordinate from an origin, ρ is a density and λ is a heat conductivity.

The initial temperature of concrete and rebar can be expressed as Equation (2) and the boundary condition on the surface of concrete is heat transfer as Equation (3).

$$u(r,0) = \delta(r) \tag{2}$$

$$\frac{\partial u}{\partial r}_{r=d} = h(u - u_\infty) \tag{3}$$

where, u_∞ is an atmospheric temperature, h is a coefficient of heat transfer and d is cover depth.

Solving Equation (1) under the condition of Equation (2) and (3) and discretizing the exact solution to the rebar and concrete region, the temperature at arbitrary position and time can be derived as follows.

$$u(r,t) = u_\infty - \left\{ \frac{2(u_{con}-u_\infty)h^2}{d} \sum_{i=1}^{\infty} \frac{J_0(k_i r)e^{-\kappa k_i^2 t}}{(k_i^2+h^2)k_i J_1\ (k_i d)} + \frac{(u_\phi - u_\infty)\phi}{d^2} \sum_{i=1}^{\infty} \frac{k_i J_1\left(\frac{k_i \phi}{2}\right) J_0(k_i r) e^{-\kappa k_i^2 t}}{(k_i^2+h^2) J_0^2(k_i d)} \right\} \tag{4}$$

where, u_{con} and u_ϕ are an initial temperature of concrete and rebar, respectively and ϕ is a diameter of rebar. J_0 and J_1 are 0 order and 1order Bessel function and k_i is a solution of the Bessel's equation.

$$hJ_0(k_i d) - k_i J_1(k_i d) = 0 \tag{5}$$

Finally, the temperature on the surface of concrete just above where the rebar is arranged can be derived substituting the position of concrete surface *d* into *r*. Regarding to the initial temperature of rebar, its value was defined as the adiabatic temperature rise of only rebar by the magnetic induction heating dependent on the diameter and cover depth of rebar.

4.2.2 Rate of corrosion of rebar

The corrosion product at the surface of rebar restrains the heat conduction from the non-corroded section inside steel to concrete and thus the heat restrained is dependent on the rate of the corrosion, as shown in Figure 9. In conclusion, the rate of the corrosion is able to be estimated, if the heat restrained is obtained from the difference between the temperature at the surface over corroded rebar and that of non-corroded.

The temperature rise at the concrete surface is dependent on the heat flux conducted which is predominated by the thermal characteristics of constitutive material, i.e. the thermal conductivity, specific heat, density, thickness and the thermal gradient. One empirical estimation is known as the coefficient of overall heat transmission (K value) which is defined the heat flux passing unit area under the differences of unit temperature.

Namely, it is an index expressing the heat transfer and is similar to the heat conductivity. However, the heat conductivity is an index as the material characteristic, but the coefficient of overall heat transmission is heat flux transferring per unit area taking the thickness of the material into account.

$$\bar{K} = \frac{1}{\sum_{i=1}^{n} \frac{\ell_i}{\lambda_i}} \tag{6}$$

where, $\bar{K}$ is the coefficient of overall heat transmission, ℓ_i and λ_i are the thickness and the heat conductivity of each material, respectively.

Applying Equation (6) into the non-corroded state and corroded state of the rebar, the coefficient of overall heat transmission can be obtained as follows.

$$\bar{K}_{sc} = \frac{1}{\frac{\frac{\phi}{2}}{\lambda_{stl}} + \frac{d}{\lambda_{con}}} \text{ non-corroded state,} \qquad \bar{K}_{src} = \frac{1}{\frac{\frac{\phi}{2}o}{\lambda_{stl}} + \frac{\frac{\phi}{2}m}{\lambda_{cor}} + \frac{d}{\lambda_{con}}} \text{ corroded state} \tag{7}$$

where, ϕ is a diameter of rebar, d is a cover depth. λ_{con}, λ_{stl} and λ_{cor} are coefficient of heat conductivity of concrete, steel and corroded product, respectively. o and m are the rate of the thickness of non-corroded region and corroded region to the radius of the rebar before occurring of corrosion and then o and m are called as “non-corroded ratio” and “corroded ratio”.

The heat flux transferring the covered concrete can be expressed as follows.

$$\bar{Q}_{sc} = \frac{\bar{K}_{sc}}{\bar{\rho}_{sc}\bar{c}_{sc}} \text{ non-corroded state,} \qquad \bar{Q}_{src} = \frac{\bar{K}_{src}}{\bar{\rho}_{src}\bar{c}_{src}} \text{ corroded state} \tag{8}$$

where, $\bar{\rho}_{sc}$ and $\bar{c}_{sc}$ are an average density and specific heat of the rebar and covered concrete for RC member before occurring the corrosion. After occurring the corrosion, $\bar{\rho}_{sc}$ and $\bar{c}_{sc}$ are expressed as $\bar{\rho}_{src}$ and $\bar{c}_{src}$ which are an average value of the non-corroded rebar, corroded rebar and covered concrete. These are expressed as follows.

$$\bar{\rho}_{sc} = \frac{\frac{\phi}{2}\rho_{stl} + d\rho_{con}}{d + \frac{\phi}{2}}, \bar{\rho}_{src} = \frac{\frac{\phi}{2}o\rho_{stl} + \frac{\phi}{2}m\rho_{cor} + d\rho_{con}}{d + \frac{\phi}{2}(m+o)}, \bar{c}_{sc} = \frac{\frac{\phi}{2}\rho_{stl}c_{stl} + d\rho_{con}c_{con}}{\frac{\phi}{2}\rho_{stl} + d\rho_{con}}$$

$$\bar{c}_{src} = \frac{\frac{\phi}{2}oc_{stl}\rho_{stl} + \frac{\phi}{2}mc_{cor}\rho_{cor} + dc_{con}\rho_{con}}{\frac{\phi}{2}o\rho_{stl} + \frac{\phi}{2}m\rho_{cor} + d\rho_{con}} \tag{9}$$

where, ρ_{stl}, ρ_{cor} and ρ_{con} are a density of rebar, corrosion product and concrete, respectively. c_{stl}, c_{cor} and c_{con} are a specific heat of rebar, corrosion and concrete, respectively.

Therefore, according to the accumulate heat in the rebar by the magnetic induction heating to be almost similar between rebar with non-corroded state and corroded state, the ratio ΔQ of Equation (8) as follows is dependent on the degree of corrosion of rebar.

$$\Delta Q = \bar{Q}_{src}/\bar{Q}_{sc} \tag{10}$$

In other words, ΔQ can be defined as the ratio of the temperature increment from the initial value to the maximum value at the concrete surface of the state with non-corroded and corroded rebar as follows.

$$\Delta Q = \Delta T_{src}/\Delta T_{sc} \tag{11}$$

where, ΔT_{sc} and ΔT_{src} are corresponding to the state of non-corroded and corroded rebar, respectively.

According to Equation (8), (10) and (11) and assuming the average heat capacity $\bar{\rho}_{src}\bar{c}_{src}$ with the corroded rebar to be almost similar to that of $\bar{\rho}_{sc}\bar{c}_{sc}$ with the non-corroded rebar in case of the relatively small rate of corrosion of rebar, the following equation can be obtained.

$$\Delta T_{src}/\Delta T_{sc} = \bar{Q}_{src}/\bar{Q}_{sc} = \bar{K}_{src}/\bar{K}_{sc} \tag{12}$$

Substituting Equation (7) into Equation (12), the corroded ratio m can be obtained as a following equation.

$$m = \frac{\beta}{\gamma}(\Delta T - 1) - \alpha\gamma \tag{13}$$

$$\alpha = \frac{\lambda_{con}}{\lambda_{stl}}\ , \beta = \frac{\lambda_{cor}}{\lambda_{con}}\ , \gamma = \frac{\phi}{2d}, \Delta T = \frac{\Delta T_{sc}}{\Delta T_{src}}, \nu = \frac{\rho_{cor}}{\rho_{stl}}$$

Now, applying the mass conservation law to the non-corroded rebar and corroded rebar, the following equation can be obtained.

$$o^2 + (m^2 + 2om)\nu = 1 \tag{14}$$

The rate of corrosion of rebar defined as the ratio of the mass decreasing can be expressed as follows.

$$n = \left\{\pi\left(\frac{\phi}{2}\right)^2 \rho_{stl} - \pi\left(\frac{\phi}{2}o\right)^2 \rho_{stl}\right\} / \left\{\pi\left(\frac{\phi}{2}\right)^2 \rho_{stl}\right\} = 1 - o^2 \tag{15}$$

Finally, substituting the non-corroded ratio o solved in Equation (14) into Equation (15), the rate of corrosion of rebar n can be obtained as follows.

$$n = 1 - \left\{\sqrt{1 - m^2\nu(1-\nu)} - m\nu\right\}^2 \tag{16}$$

5 APPLICABITILY OF PROPOSED MODEL

5.1 Laboratory measurement

The applicability of the proposed model is examined in comparison with experimental results. Values estimated of the rate of corrosion, which are predicted by the temperature increment at the concrete surface shown in Figure 7 and Equation (16), are shown in Table 2. For specimens with the relatively shallow the cover depth, it can be seen that the proposed model shows a good agreement with the values measured. On the other hand, for relatively deeper the cover depth i.e. the specimen K70-C0.70, the estimated value is fairly large compared with the values measured. Due to the small differences between the temperature increment at the concrete surface for specimens with the non-corroded and corroded rebar.

Table 2. Corrosion Rate

Specimen	Corrosion Rate (%)	
	Measurement	Prediction
K30-C0.66	0.66	0.67
K30-C1.0	1.00	1.13
K30-C5.0	5.00	3.23
K50-C0.82	0.82	0.81
K50-C1.0	1.00	0.81
K50-C5.0	5.00	5.23
K70-C0.70	0.70	1.61

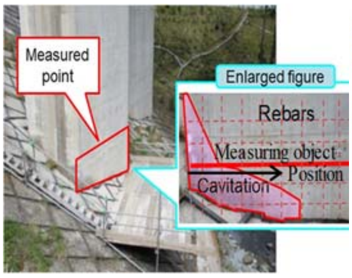


Figure 9. Bridge Pier

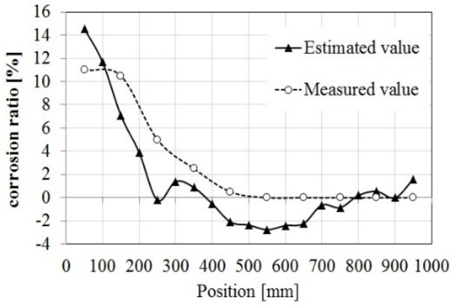


Figure 10. On-site measurement

5.2 *On-site measurement*

An example of on-site measurement is shown in Figure 9. A bridge pier of RC structure has been deteriorated by salt attack and then the corrosion of rebars occur in wide ranges. The values estimated of the rate of corrosion in the direction of the axis of rebars, which are predicted by the temperature increment at the concrete surface and Equation (16), are compared with the measured values in Figure 10. The distribution of the rate of corrosion estimated by the proposed model is in reasonable agreement with that of measured.

6 CONCLUSIONS

One promising NDE technique, which can estimate quantitatively the rate of corrosion of rebar in RC structures, is presented. The technique is based on the temperature history at the concrete surface, which could change due to the heat conduction from the rebar stored by electromagnetic induction heating.

The temperature at the concrete surface over the rebar increases uniformly due to the heat conduction from the rebar, in the case where the heat is applied and stored by electromagnetic heating. If the corrosion product exists on the rebar, the temperature at the concrete surface just over the corroded region of rebar becomes lower than that of the non-corroded region by the effect of the thermal property of the corrosion product.

7 REFERENCES

ASTM C876, 2001. *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete*, Annual Book of ASTM Standards, 452-457.

ASTM G59, 2009. *Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements*, Annual Book of ASTM Standards