Long-Term Corrosion Monitoring by Titanium Wire Sensor and Vibration-Based Energy Harvester

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***Abstract*—Corrosion mitigation and corrosion control monitoring have been a top concern for reinforced concrete structures. Cathodic protection is known as one of the simple but effective methods in anti-corrosion. This study introduces a detachable galvanic anode system with a characteristic of easy installation and replacement at a low cost. The effectiveness of this model at the early stages was confirmed in the previous researches. In this study, the effectiveness of long-term prospects was assessed through the data recorded continuously for nearly 600 days. In addition, a model allowing automatically monitor the health of the bridge using vibration energy harvester base on magnetostrictive materials was also mentioned with the preliminary experimental results, confirming its feasibility in mass production and wide application into existing structures.**

***Index Terms*—Corrosion monitoring, galvanic anode, titanium wire sensor, vibration energy harvester, magnetostrictive material**

I. Introduction

Corrosion is known as cancer of steel, which reduces the durability and serviceability of reinforced concrete structures. Rodriguez et al. showed that the beam strength decreased by 23% when a corrosion degree of rebar reached 14% [1]. According to Cabrera, the deflection of the corroded beam when the corrosion level reached 9% may increase by 1.5 times compared to the conventional beam [2]. Additionally, the cost of repair and maintenance of corrosive structures is also expensive. In the United State, the estimated total annual cost of corrosion is up to 276 billion USD, and in China is approximately 310 billion, respectively [3], [4]. Furthermore, it is hard to detect corrosion at the early stages. On the other hand, it is almost too late when the corrosion signs can be observed on the surface. Therefore, corrosion mitigation together with corrosion monitoring is indispensable, particularly for the areas situated in strongly aggressive environments.

The Hokuriku region is located in the northwestern part of Honshu, the main island of Japan, where the bridges over the coastal area are greatly affected by the salt from the sea due to seasonal winds. In addition, since the region is also a snowy and cold region, a large amount of deicing salts is sprayed on the main roads in winter. These environmental conditions have accelerated the corrosion process of reinforcement steel, causing the concrete structure deterioration [5], [6].

Cathodic protection is considered as an effective method in corrosion mitigation and suppression [7], [8]. The design of this method is based on the electrochemical principles, in which corrosion current flows between the local action anodes and cathodes due to the existence of a

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potential difference between the two. To reduce the corrosion, the rebar is converted to cathodic sites by either connecting steel with an external anode (sacrificial anode), which is usually a higher active metal than the steel or introducing an impressed current system. The impressed current method can supply a sufficiently large current, but high cost and complexity in the operation and maintenance. In this study, the authors developed a technique to minimize the corrosion of steel in reinforced concrete structures, based on galvanic anode materials. This detachable galvanic anode is characterized by easy installation, replacement, and low cost. The anti-corrosion effectiveness of galvanic anode systems in the early stage has been considered in previous practical experiments, through the measurement of rebar potential and depolarization amount [9], [10]. In this study, the effectiveness and stability of this galvanic anode system in the long-term aspect are reviewed through around 600-days follow-up process. In which, the electric current flow and steel potential are analyzed with the ambient temperature. The results show that temperature has a remarkable influence on the current output. On the tendency of steel potential, in the experiment conducted on the pedestrian bridge, reinforcement in the unprotected concrete shows a potential decrease over time, whereas, in the vicinity of galvanic anodes, even the voltage drop is periodically noticeable but the process of rebar potential recovery is still recognized. Furthermore, in the case of the highway bridge, it is noted that there is a remarkable increment of steel potential in the areas protected by galvanic anodes compared to the rest. These results indicate that the corrosion mitigation effect is still maintained.

In addition, the study also introduces a model of structural health monitoring using vibration energy harvesting aiming to automatically collect data from sensors and then transmit data to the server. A device consists of a U-shaped steel frame with a magnetostrictive bar, made of Fe-Ga alloy, wrapped around by a coil of wire, which allows electricity to be generated when vibrations take place. The device has been developed by Ueno and his colleagues [11], [12]. Compared to the first version [13], the equipment described in this study has been improved with higher durability and is suitable for mass production. This paper describes the operation principle, the structure of the device as well as several test results to preliminarily evaluate its effectiveness and applicability in monitoring the corrosion status of the reinforcing concrete structure.

II. Current Situation of Target Structures

In this study, the corrosion monitoring work was carried out on two concrete bridges built in the 1970s and 1980s, which is the boom period in Japan's economic development. Over the decades under the influence of the salty environment, the durability and serviceability of these structures in the long-term aspect is indeed a matter to be considered.

A. *The Highway Bridge*

This highway bridge is located on the elevated line of a highway in the Hokuriku region. The bridge structure consists of a 220 mm thickness reinforced concrete deck, which is supported by four steel girders as described in Fig. 1.

The testing was conducted on the concrete slab with an area of about 20 m^2. Visually observe on the surface, there are many locations with white precipitate (efflorescence) as shown in Fig. 2. The occurrence of efflorescence is clear evidence of the saltwater presence, which caused the deterioration of concrete structures. For analyzing chloride ion concentration, two types of concrete core drilling samples were taken at the sound and efflorescence concrete areas.

Analysis result as per Fig. 3 shows that chloride ion concentration tends to increase with the depth of concrete. This is explained by the process of using deicing salt

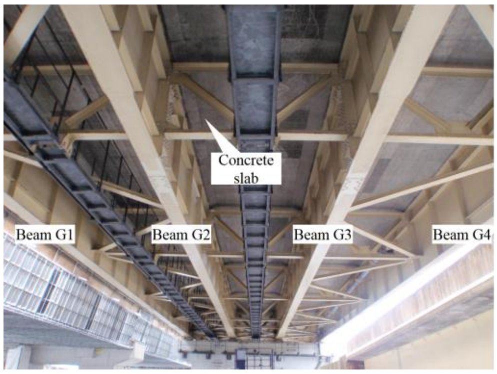

Figure 1. Highway bridge overview

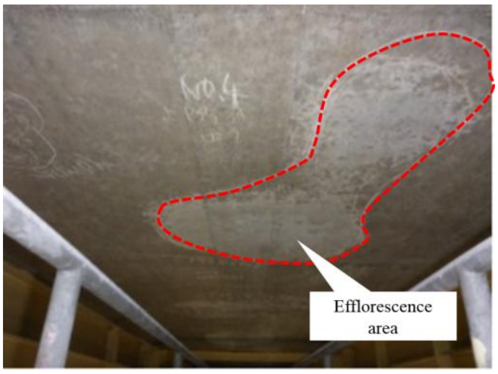

Figure 2. Efflorescence concrete

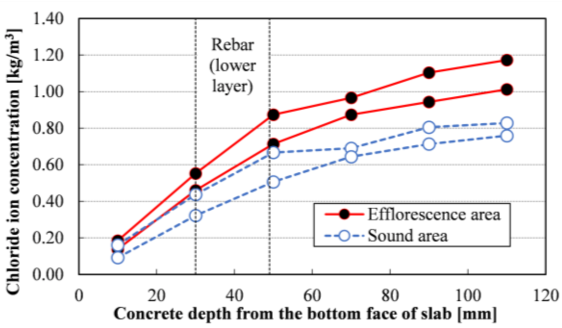

Figure 3. Chloride ion concentration at highway bridge

(sodium chloride) on the expressway surface during the snowy season, causing chloride ions to penetrate the concrete. Therefore, the closer to the road surface, the higher the concentration of chloride ion. In other words, chloride ion concentration will increase as the distance from the lower surface of the deck increases. The result also shows that, in areas where white precipitate appears, chloride ion concentration is always higher than the other area. The graph in Fig.3 does not mention the value of chloride ion concentration for the upper steel layer, where the concrete thickness is greater than 120 mm. However, according to the trend of the graph, it can be predicted that, for the upper layer rebar in the area of white precipitation, the chloride ion concentration may have exceeded 1.2 kg/m^3, which may be set as the marginal chloride ion concentration for causing corrosion according to Standard Specifications for Concrete Structures of Japan [14], and may causing reinforcement corrosion.

B. The Pedestrian Bridge

In addition to the highway bridge, the monitoring of the structure is also carried out on a 10-m-span pedestrian bridge, which composed of pre-stressed concrete girders as shown in Fig.4 and 5. The bridge for pedestrians and bicycles was built along the coast of Japan in 1986. Observing the outer surface of the bridge, it is easy to see the cracks along the pre-tensioned tendons, facilitating rainwater to penetrate the concrete easily. In addition, spalling also appear scattered throughout the soffit of the beam as shown in Fig.6.

Because the pedestrian bridge located near the sea, flying salt is considered to be one of the primary causes of salt damage. The winds from the sea carrying salt penetrate the concrete structure from the underside of the girder. Different from the deicing salt, the chloride ion content of the flying salt decreases with the increase in distance from the beam soffit. Fig.7 shows the relationship between the thickness of the concrete (from the bottom surface of the girder) and the chloride ion concentration measured. The chloride ion concentration reaches approximately 5 kg/m^3 at 10 mm depth and decreases to less than 2 kg/m^3 at 50 mm depth. Comparing the chloride ion concentration with the limit value of 1.2 kg/m^3, it can be confirmed that the reinforcement is in a highly corrosive environment.

III. Long-Term Monitoring of Galvanic Anode System

The main purpose of this section is to monitor the health of the structures. It means to ensure the safety and reliability of these structures as well as to improve their reliability. To execute this monitoring, a system consisting of galvanic anodes, titanium wire sensors (WR) has been studied and applied to both previously mentioned bridges. While the galvanic anode undertakes the corrosion mitigation process through the consumption of anode material, the titanium wire sensor is responsible for collecting data about steel potential.

A. Galvanic Anode Structure

The galvanic anodes are made of zinc metal and divided into two types. For deck slab (the highway bridge), the galvanic anode is composed of plural pieces of zinc plate with a diameter of 30 mm and 5 mm in the thickness. The anode is located in concrete drill holes of 40 mm in diameter (see Fig.8). Regarding reinforced concrete girders (the pedestrian bridge), the galvanic anode consists of a disk of zinc with a thickness of 5 mm and a diameter of 110 mm attached to the bottom surface of the girders (see Fig.9). Through M6 screw bolt and anchor, the galvanic anodes can be easily replaced when

Figure 4. Pedestrian bridge overview

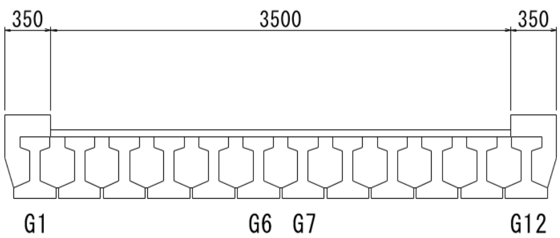

Figure 5. Pedestrian bridge cross section

Figure 6. Spalling at beam soffit of pedestrian bridge

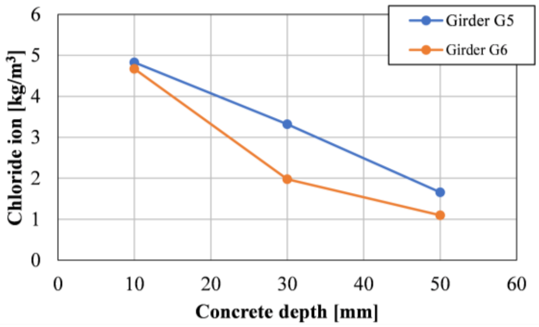

Figure 7. Chloride ion concentration at pedestrian bridge

the zinc metal is consumed. After inserting in the concrete, a backfilling compound will be injected to fix the galvanic anodes and more importantly, to provide an environment that is conducive for anode dissolution. Finally, galvanic anodes are connected to the reinforcement of objective concrete structures by electrical wires. In addition, to evaluate the effect of backfill on the efficiency of the galvanic anode, two types of backfill called bentonite backfill and mortar backfill were applied in the experiment at the highway bridge.

B. Titanium Wire Sensor

Half-cell potential is a commonly used non-destructive method to detect and inspect the corrosion of reinforcing steel in concrete by measuring the natural potential of rebar [15]. In this measurement, the corrosion potential is determined as a potential difference against a reference electrode. Conventionally, rebar potential measurement can be made on the surface of a concrete structure with a portable reference electrode (Fig.10) or an embeddable reference electrode (Fig.11). In particular, the portable reference electrode requires to move from point to point on the surface of the concrete structure, thereby the measurement results are affected by the resistivity of concrete. Moreover, the reference electrode that can be embedded in concrete structures can limit the above disadvantages, but it is reflective only of the steel condition in its immediate vicinity. Furthermore, in case that the measurement is carried out for a wide range, the installation of the embedded reference electrode is expensive and not feasible.

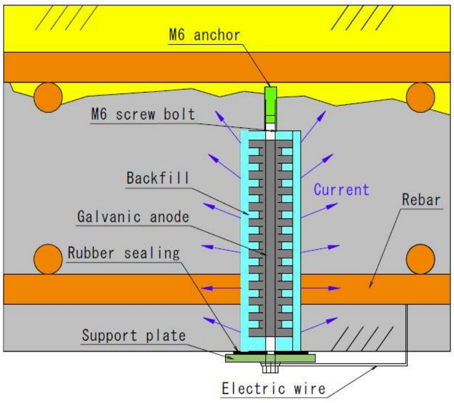

Figure 8. Galvanic anode system for reinforced concrete slab

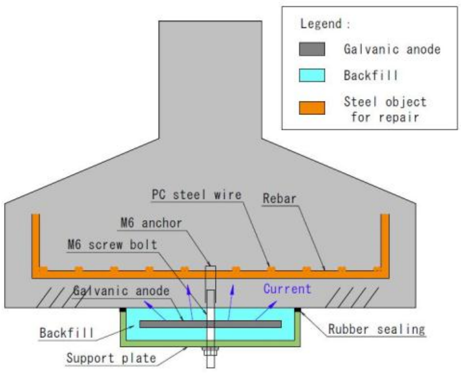

Figure 9. Galvanic anode system for reinforced concrete beam

Compared with the conventional reference electrode, the novel reference electrode with a titanium wire sensor has many advantages. As depicted in Fig.12 and 13, the titanium wire sensor has only 3 mm in diameter, and the length may vary. Therefore, it can be easily inserted in concrete structures by a drill hole with a 10 mm diameter only, allowing to ensure the integrity of the structure. In addition, in terms of price, the new reference electrode with a 50 mm length of sensor costs only 1/20 compared to a conventional one.

C. Setup the Experiment

1) The highway bridge

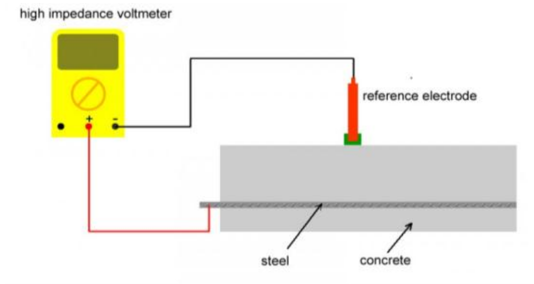

Figure 10. Conventional reference electrode – Surface mounting technique

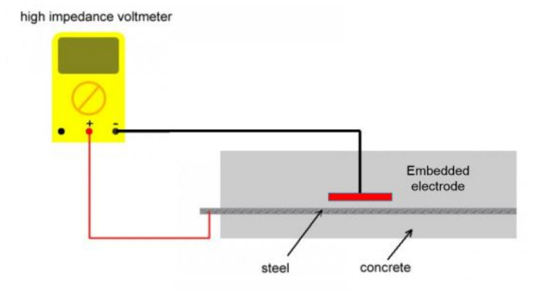

Figure 11. Conventional reference electrode – Embeddable technique

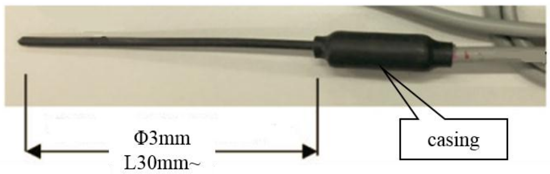

Figure 12. Titanium wire sensor structure

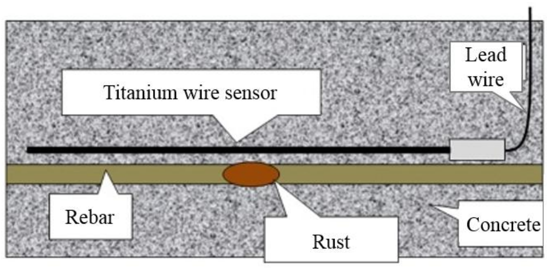

Figure 13. Titanium wire sensor in concrete

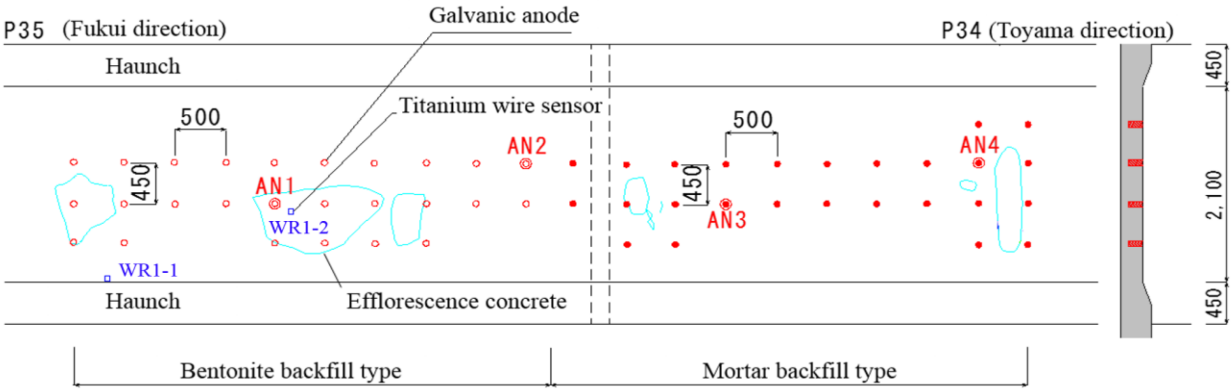

Figure 14. Highway bridge deck slab layout

A layout of galvanic anodes for the slab deck is described as Fig.14. In the longitudinal direction of the bridge, the galvanic anodes were arranged at an interval of 500 mm, while in the transversal direction, this interval was 450 mm. These distances are determined based on the corrosion status of steel, the resistance of concrete, reinforcement and so on. Among them, measurements of generated current flow were carried out at four galvanic anodes denoted as AN1, AN2, AN3, and AN4. Additionally, there were 2 wire sensors named WR1-1 and WR1-2 that were designated to measure the potential of steel in the natural state and in the activating anode condition, respectively.

2) The Pedestrian Bridge

The experiment took place on beam G6 (see Fig.15), where spalling occurred quite commonly on the soffit of the beam. Before the installation of galvanic anodes and titanium wire sensors, patch repair had been performed for these damaged concrete locations. After that, the experiment was set up by conducting nine sets of galvanic anodes named from A1 to A9 and two sets of titanium wire sensors as the description in Fig.15. To evaluate the anti-corrosive effectiveness of the galvanic anode system, wire sensor 2-2 (WR2-2) was arranged close to the galvanic anode, while wire sensor 2-1 (WR2-1) was located in an area where galvanic anodes are not surrounded.

D. Results and Discussion

The anti-corrosion performance of these two structures, which is evaluated through the steel potential measured following ASTM C 876 (with the Silver/Silver reference electrode) and depolarization amount, has been confirmed in previous studies [9], [10]. In this research, the change over time of current output, steel potential when activating galvanic anode in the relationship with temperature are introduced. Thus, the anti-corrosion performance in the long-term period of this galvanic anode system can be assessed.

1) Current flow

About the current output in the highway bridge and pedestrian bridge, as shown in Fig.16 and 17, except for the disturbance in the initial stage, the graphs show that the current intensity seasonally increases and decreases following the sinusoidal shape. In addition, there is a difference between the currents generated from galvanic anode using the mortar backfill and the bentonite backfill in the case of the highway bridge. While the current flow generated from mortar type (AN1 and AN2) only fluctuates around the value of 5 mA, galvanic anode using bentonite backfill (AN3 and AN4) can maintain a higher average current of 10 mA to 15 mA. In regard to the effect of concrete quality on current flow, the outcomes in Fig. 16 indicates that, within 600 days of follow-up, the difference does not seem to be noticeable when observing the current in sound concrete (AN1, AN4) and efflorescence concrete (AN2, AN3).

In term of the relationship between current intensity and ambient temperature, many previous studies have noted that the current flow is a function of temperature [16], [17]. In this case, the measurement results at the highway bridge (Fig.16) and the pedestrian bridge (Fig.17) also show that the rhythm in the fluctuation of the current is directly proportional to the ambient temperature. This means, the current flow generated by this galvanic anode system tends to intensify in the summer and decrease in the winter.

2) Steel potential

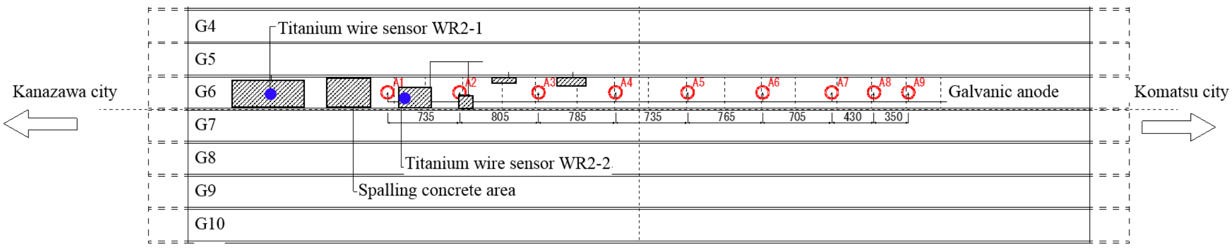

Figure 15. Pedestrian bridge beam layout

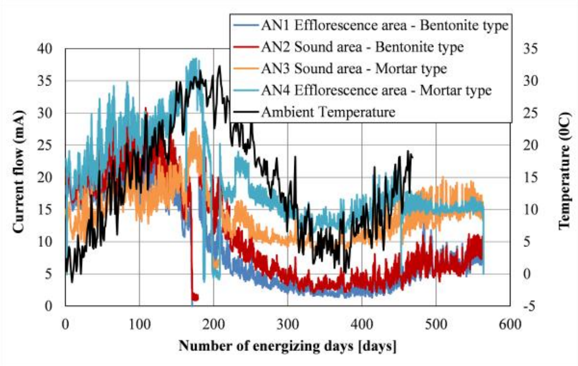

Figure 16. Relationship between Current flow and Ambient temperature – Highway bridge

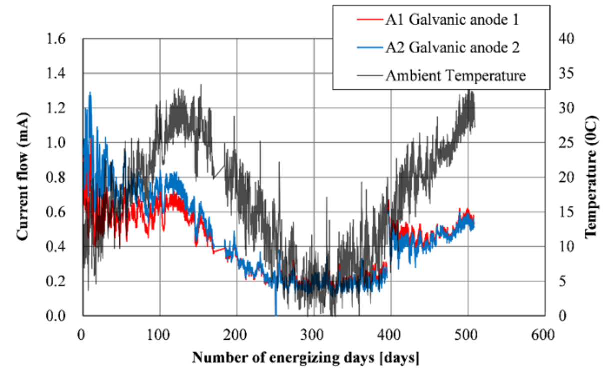

Figure 17. Relationship between Current flow and Ambient temperature – Pedestrian bridge

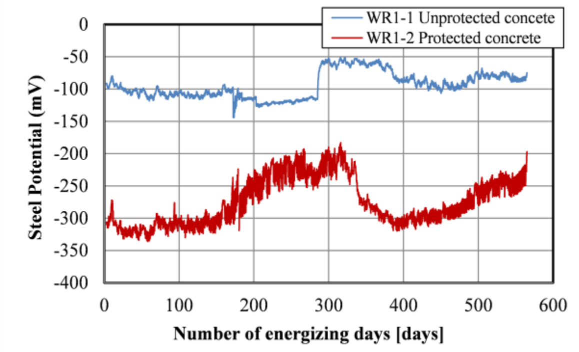

Figure 18. Rebar potential response in long-term - Highway bridge

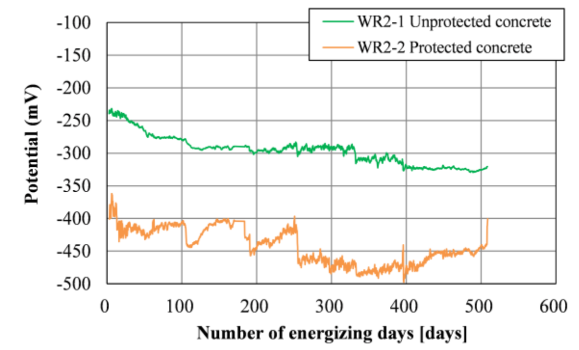

Figure 19. Rebar potential response in long-term – Pedestrian bridge

The steel potential measured at the positions of the sensors of these two bridges is described as in Fig.18 and 19. With respect to the highway bridge (Fig.18), at the WR1-1 location, where the galvanic anode is not applied, the natural potential of the steel fluctuates up and down around the value of -100 mV. Conversely, at the WR1-2, surrounded by the galvanic anode system, the steel potential increases markedly. Compared to the unprotected area, there has been a signal improvement in the voltage value of steel.

On the other hand, the potential of the steel at the pedestrian bridge decreases over time, taking place both for the protected and non-protected concrete (Fig.19). However, for locations where the galvanic anode is not available (WR2-1), attenuation in potential happens rapidly (from -240 mV to -320 in 500 days) and there is no recovery ability (green line). On the contrary, for the WR2-2, which is covered by the galvanic anode system, after the initial stage of maintaining the potential at -400 mV, the voltage suddenly drops sharply in 250-500 days. However, the recovery can be seen obviously in the period after 500 days (orange line).

The improvement in the potential of steel is reflected by the increase of voltage in the case of the highway bridge and the voltage restoration in the pedestrian bridge proves that the efficiency of the galvanic anode system in corrosion mitigation is still being promoted.

IV. Corrosion Condition Monitoring by Power Generating Device

Recently, most research has focused on the development of sensor technology as well as high-precision corrosion monitoring methods. Since most sensors are battery-powered, while the health monitoring of the structure takes place over a long period, therefore the requirement for long life or seldom battery replacing/recharging is difficult to respond. To solve this problem, one of the currently expected directions is energy harvesting. That is the process by which energy is derived from external sources (ambient energy), captured and can be converted to electrical energy. Although energy harvesters provide a very small amount of power, it still can strongly maintain sensor operation, as well as sampling, calculating and data communication. In the following section, a low-cost high-performance power generating device using magnetostrictive materials for corrosion condition monitoring is introduced.

A. Outline of Power Generating Device Using Magnetostrictive

The construction of the device is described in Figs. 20 and 21. A steel magnetic plate is bent into a U-shaped frame, after that the upper part is bonded to a bar which is made from Fe-Ga alloy. A coil wire is wrapped around the magnetostrictive bar, and a permanent magnet is arranged within the frame so that the entire part containing the magnetostrictive element becomes magnetically saturated by magnetic bias. At the end of the upper part, there is an adjustable weight (proof mass), which allows the modification of the oscillation frequency of the device to be accomplished.

In the case of operation, the bottom of the steel frame is attached tightly to the oscillating object. Generally, the proof mass is adjusted so that the device's oscillation frequency coincides with the frequency of the oscillating object to create the resonance. Base on it, maximizing the power generation can be achieved. When the object oscillates, because of inertia, the proof mass will move up and down, leading to the magnetostrictive bar to be bent. As a result, the tensile strength and compressive strength occur alternatively along the longitudinal direction of the alloy bar. Thus, a stress change has occurred in the magnetostrictive material. Due to the inverse magnetostrictive effect (see Fig.22), the magnetic flux through the coil will vary, then generating AC voltage according to the Faraday's law.

The highlight of the device's characteristic is its simplicity, which is suitable for mass production with low cost and very durability. The durability of the device depends largely on the fatigue property of the U-shaped metal plate in conjunction with the adhesion strength between it and the magnetostrictive material. If this bond is guaranteed and the amplitude of the proof mass vibration is within the permissible limits, this device may be considered to be eternal.

Regarding the performance of this device in the power generation aspect, a series of experiments with different models have been carried out and the results were very satisfactory. Ueno and colleagues conducted practice on the electrodynamic vibration system with a prototype device [12]. In which Fe-Ga alloy bar with dimensions of 4x0.5x16 mm was attached to a 0.5 mm plate of cold-rolled Fe by epoxy type structural adhesive. The coil wire of 0.05 mm diameter was wrapped 3500 turns (520 ohms) around the magnetostrictive bar. An alloy Nd-B-Fe was used to create the magnetic field. The system first was tested on a proof mass of 1.7 g, oscillated following sinusoidal wave at a frequency of 88.7 Hz, and accelerations of 3.0, 6.0, and 9.0 m/s^2. The maximum voltage measured is 5.4 V at an acceleration of 9.0 m/s^2. On the other side, a practical experiment on a highway bridge conducted in 2019 also showed that the device with proof mass of 312.8 g which was mounted on lateral bracing owning a frequency of 19 Hz can create maximum voltage up to 7.8 V [18]. In this experiment, a remarkable point was that by adjusting the mass of the proof mass to 312.8 g, the natural vibration frequency of the device has coincided with the target object's oscillation frequency. In other words, the resonance phenomenon has great influence in order to generate high electrical energy efficiently.

B. Application of Power Generating Device in Monitoring Corrosion of Concrete Structures

In the future, a model using this power generating device to monitor the corrosion condition of structure can be set up as Fig.23. Accordingly, after embedding galvanic anode and titanium wire sensor systems into the concrete, the operation of this wire sensor system will be maintained by vibration power generators. The energy harvesters are affixed in the desired structural elements, which are usually the components owning significant amplitude or frequency of oscillation. In general, the free-oscillation frequency of the power generator devices is also fabricated with the same frequency of the vibrated object in the aim to occur resonance. The base station then captures data from sensors and delivers them to a computer or mobile phone via a wireless network. This computer or mobile phone can serve as the sink to collect the corrosion data, then loads up data to some internet servers. Through which, users can remotely access the database and have acknowledged the corrosion status of the structure. For large-sized structures, the transmission of data to the base station may be difficult due to long communication distance. In this case, it is necessary to build additional base stations. For components with low frequency and amplitude, the voltage generated by the device is limited, in that condition adjustments of data transmission time interval may be considered·

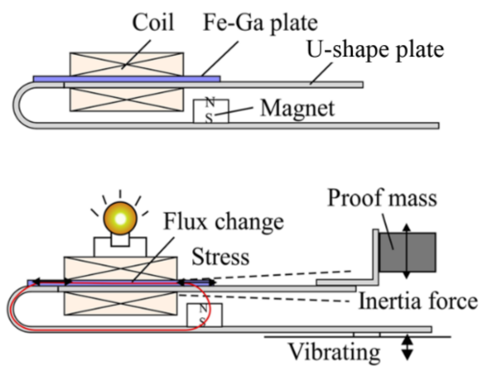

Figure 20. Vibration generator device configuration

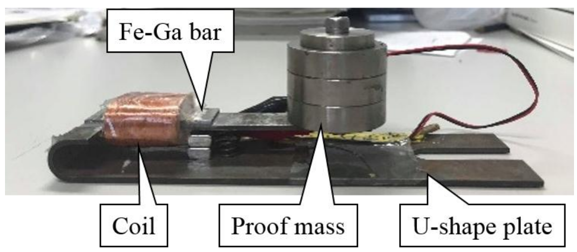

Figure 21. Vibration generator prototype device

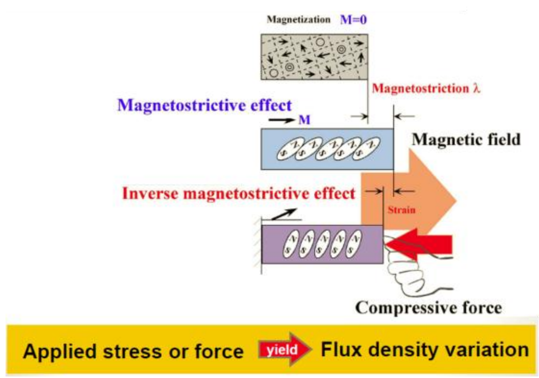

Figure 22. Inverse magnetostrictive effect

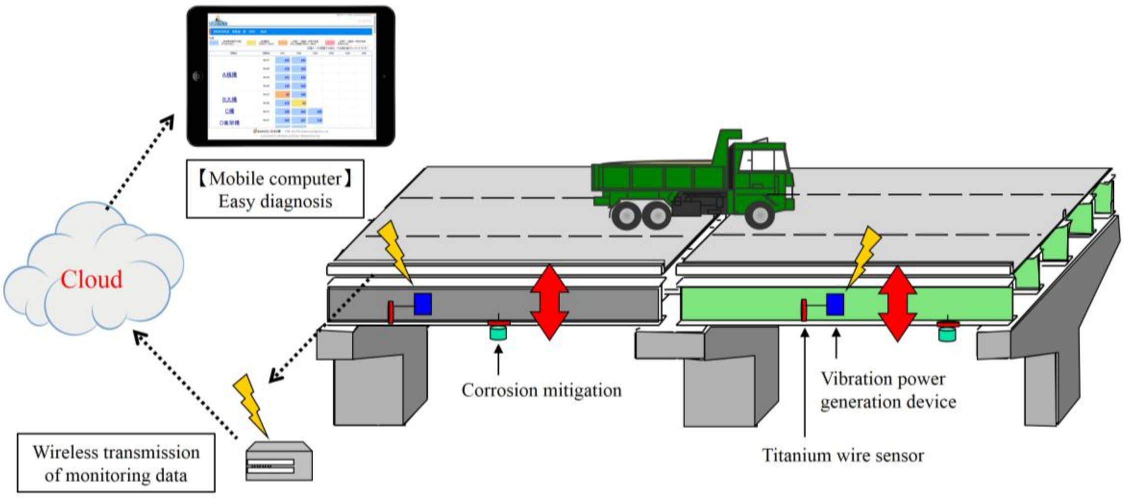

Figure 23. Scheme of corrosion monitoring sensor network

V. CONCLUSION

In this study, a practice on corrosion mitigation by detachable galvanic anode system together with novel reference electrode-titanium wire sensors was conducted on two bridges. The anti-corrosion effectiveness was assessed through the long-term monitoring process, based on measuring the values of current flow and steel potential. At the same time, the impact of temperature on these parameters was considered. The results obtained from this experiment can be summarized as follows:

- On the correlation between ambient temperature and current flow, the increase or decrease in temperature leads to a corresponding increase or decrease in current flow.
- For reinforcing bar locating far away from galvanic anodes, the steel potential tends to decrease over time. On the contrary, for reinforcement in the vicinity of galvanic anodes, the steel potential is maintained and raised up. Through which, it can be concluded that anti-corrosion of this galvanic anode system is still effective.

In addition, the study also confirms that the use of energy harvester base on magnetostrictive material in monitoring corrosion for the reinforcement structure is feasible. The vibration power generation device can substitute for batteries and afford the maintenance-free operation. This opens up a great opportunity to apply the energy harvesters in structural health monitoring in the long-term aspect. Related to this issue, finding out the optimal location to arrange this device is necessary. In this regard, numerical methods are appreciated in allowing us to fully understand the behavior of structures with low costs. In the future, further studies need to be conducted to improve the device's design and performance, aiming for mass production and applicability in real structures.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The research was conducted by Saiji Fukada and Toshiyuki Aoyama. Ueno Toshiyuki developed the power generating device. Tuan Minh Ha and Thanh Tung Tran analyzed the data. Thanh Tung Tran wrote the paper. All authors had approved the final version.

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