MULTI-TECHNOLOGY NDT INSPECTION AND MONITORING OF CORROSION IN STEEL BRIDGE MEMBERS

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ABSTRACT

On-site evaluation of corrosion damage is posing challenges to maintenance engineering as corrosion damage is difficult to be evaluated accurately and it has significant spatial variation. When measures are not taken, corrosion could lead to reduction of load caring capacity, large repair costs and in some extreme cases could lead to collapse of the structure.

The present study proposes a multi-technology approach for effective evaluation of corrosion progress rate and of the damage extent, combining monitoring with periodic inspections. The progress of corrosion is estimated by Atmospheric Corrosion Monitoring (ACM) technology, and by ultrasonic (UT) and electromagnetic (EM) inspection technology.

Continuous monitoring by Atmospheric Corrosion Monitoring (ACM) technology is being used for determining the overall environment corrosivity. Also, ACM helps to pinpoint areas on the structure where more aggressive local corrosion inducing factors exists. Corrosion progress trends obtained from environmental corrosivity monitoring are presented.

In addition to monitoring, on-site periodic inspections are used for measuring corrosion progress. Electromagnetic (EM) inspection is applied to measuring the corrosion scale thickness, even through the paint layer. Inspection by ultrasonic testing (UT) is applied for determining accurately the remaining thickness of the steel plates.

The applicability and limitations of these corrosion assessment technologies are evaluated in three experimental setups, in urban environment, costal environment and in an aggressive environment with salt solution spraying. H-shaped and box shaped steel specimens made of SMA-490 weathering steel are exposed to atmospheric corrosion. The study summarizes the results of the first two years of inspection and monitoring of the corrosion progress. The factors affecting corrosion progress are identified and the corrosion progress trend is determined, while accounting for the local factors such as the effect of the surface orientation.

Keywords: Corrosion, steel bridges, ACM, electromagnetic inspection, UT inspection.

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1. INTRODUCTION

Corrosion is affecting the rapidly aging infrastructure, raising difficult challenges to maintenance engineers due to the large variation of corrosion progress at various locations and the difficulty to correctly asses by visual inspection the extent and risk posed by corrosion. When appropriate maintenance measures are not taken, corrosion could lead to degradation of load carrying capacity (Hung et al. 2002) and in extreme cases to the failure of the structural elements.

Current study is looking to address the difficult task of accurately evaluating the extent of corrosion damage by proposing a multi-technology corrosion assessment approach, which combines monitoring of environmental conditions with periodic NDT inspections. Accurate and more reliable measurements (and prediction) of the corrosion extent and its spatial variation could reduce the need for large scale repair works, making up for the increased cost of inspection.

2. ATMOSPHERIC CORROSION MONITORING TECHNOLOGY

Atmospheric Corrosion Monitoring system technology uses Fe/Ag or Zn/Ag ACM galvanic current sensors for determining the corrosivity of the environment, and for indirectly determining the progress of corrosion at the sensor's location. An empirical relation has been established between galvanic current generated by the ACM sensor and various atmospheric factors contributing to corrosion (Sasaki and al. 2011), thickness loss due to corrosion Y could be estimated by equation (1), where X is the exposure time in years, while A_s and B_s are parameters. ACM current is related to parameter B_s. To account for the seasonal variation, ACM data collected over one year interval are used for the estimation of the corrosion progress.

$$Y=A_sX^{B_s} \tag{1}$$

Experimental Setup

For the evaluation of corrosion monitoring and inspection technologies, steel specimens were exposed to different environmental conditions at three locations, near the coast line in Okinawa (EO), in urban environment (EU) and in an environment simulating accelerated corrosion (EA).

Figure 1: The experimental setup in costal environment (Okinawa).

The steel specimens made of SMA-490 weathering steel were monitored for corrosion over two years. A number of 10 H-type and 10 box type elements were exposed at the three locations. Box-type elements are reproducing the conditions inside of closed type box elements. H-type elements are mounted partially embedded in RC blocks at an angle of 45º, 60º and 90º, reproducing typical steel bridge members passing through concrete deck, see Figure 1.

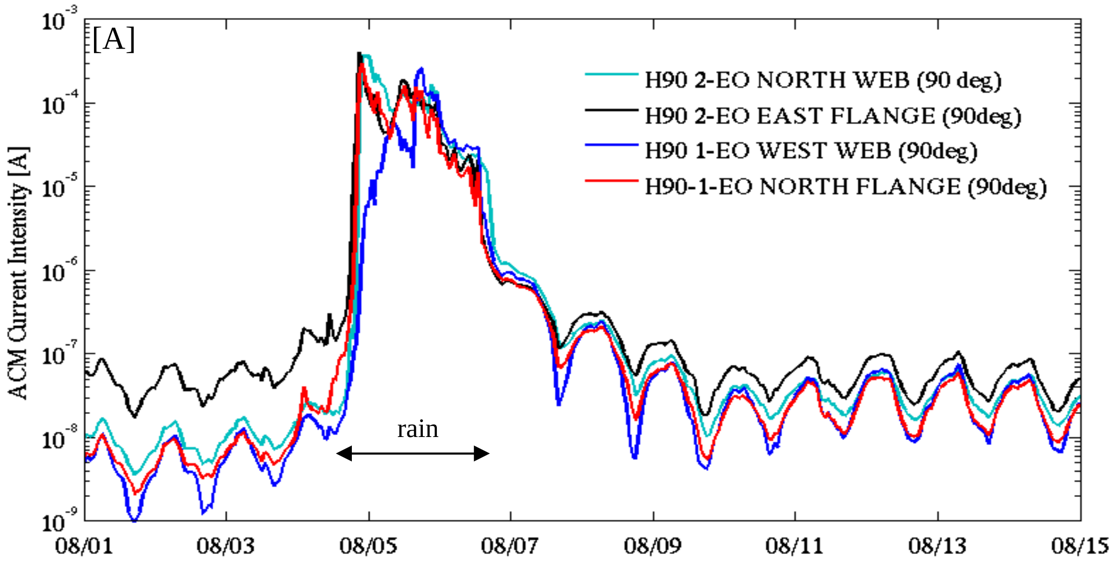

Figure 2: An example of ACM sensor response during rain.

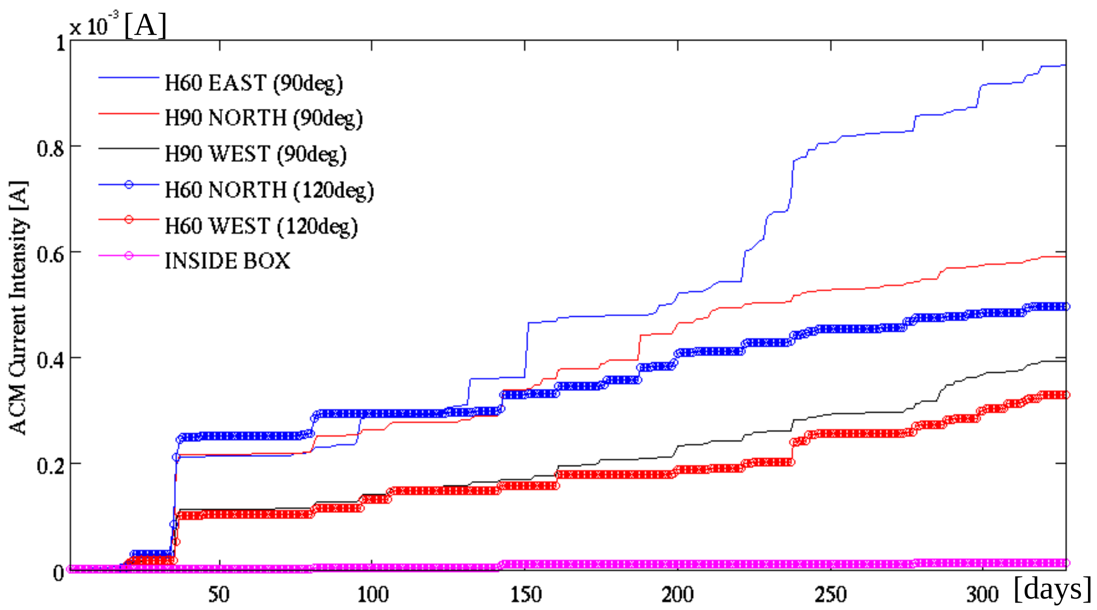

Figure 3: Comparison of integrated electric charge as a function of the surface orientation.

Based on the ACM measured values, the corrosivity of the environment is classified as mild corrosion for galvanic corrosive current below 10^{-8}A threshold level, rusty when values are between

10^{-8} and 10^{-7}A and as aggressive (very rusty) environment when the values of galvanic current exceed 10^{-7}A (Sasaki et al. 2011). ACM average daily charge in costal environment on vertical elements is 1.2 to 2.9μA due to the presence of airborne salt and harsher environmental conditions; compared to 0.18 to 0.28μA in the urban environment. The sensor response increases during time of rain and higher humidity, typical response measured in costal environment is plotted in Figure 2, showing a significant increase in measured values on Aug. 5th-6th due to the effect of the rain.

The integrated daily values of ACM sensors response in costal environment are shown in Figure 3. In costal environment, higher corrosivity is recorded on the vertical surfaces orientated toward the sea (located North-East from the site) and toward the dominant wind direction, than on the surfaces orientated in opposite direction from the sea (West). This trend has been confirmed by the EM inspection of corrosion scale thickness, see Table 1. In urban environment the corrosion progress is uniform on all vertical surfaces. Low corrosivity was determined on the inside surfaces of the box specimens. As shown, ACM technology provides a measure of the overall corrosivity, allowing to characterize actual site exposure conditions and to identify the locations with higher corrosivity.

Table 1: Comparison of the effect of surface orientation in costal environment

Case	*NORTH*	*EAST*	*WEST*	*SOUTH*	*ALL DIRECTIONS*
ACM day mean [μA]	1.7	2.7	1.2		1.9
ACM day mean [%]	89.2	139.8	63.6		100.0
EM corr. thickness [μm]	313.8	268.1	206.5	303.3	272.9
EM corr. thickness [%]	115.0	98.2	75.7	111.1	100.0

3. CORROSION INSPECTION

Corrosion inspection technology could evaluate corrosion progress on the surface of steel members. In our study Ultrasonic Technology (UT) and Electromagnetic (EM) inspection technologies were applied to determine the remaining plate thickness and the thickness of corrosion scale respectively.

3.1. Electromagnetic (EM) corrosion inspection

EM inspection is applied to measuring the corrosion scale thickness, even though the paint layer. EM does not require the preparation of the surface, and is relatively fast, its principle of operation

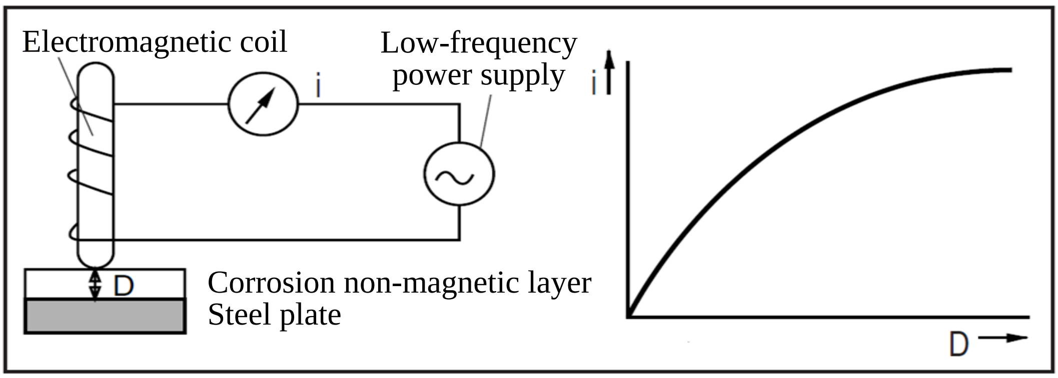

Figure 4: Electromagnetic corrosion scale thickness sensor operation principle.

is shown in the Figure 4. The EM inspection results for weathering steel specimens are shown in Figure 5 and 6. The values are plotted based on the orientation of the element's surfaces. The maximum thickness of corrosion scale is typically recorded on the underside of the elements. This could be explained by formation of deposits of corrosive substances and dust on the under surface, deposits which are not washed away by rain. Such behavior was confirmed by other researchers (Sasaki et al. 2011; Kihira et al. 2005) using corrosion coupons exposed under shed conditions. As summarized in Table 2, higher corrosion is measured on the underside and the inclined surfaces.

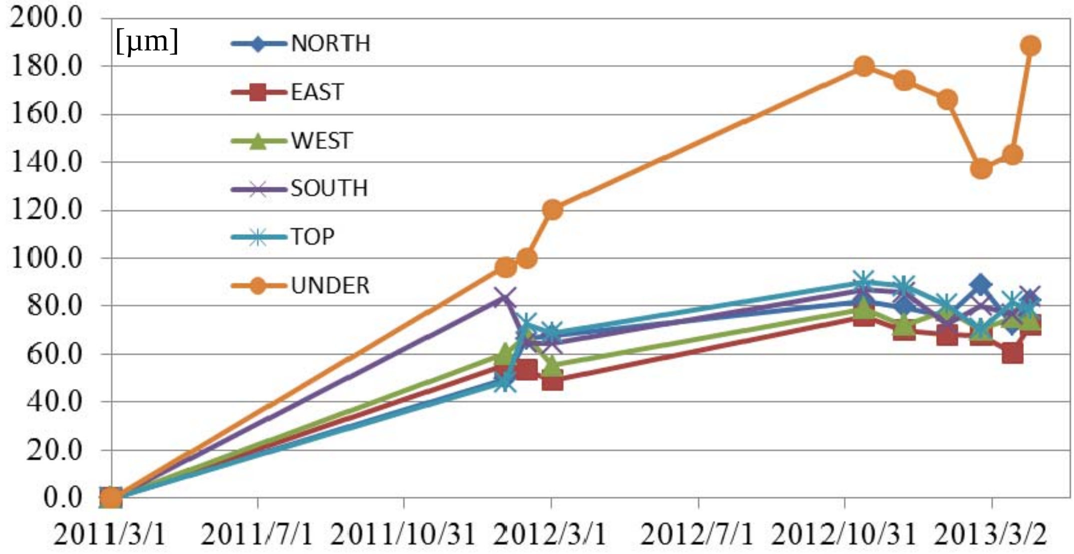

Figure 5: EM mean corrosion scale thickness measurements in urban environment.

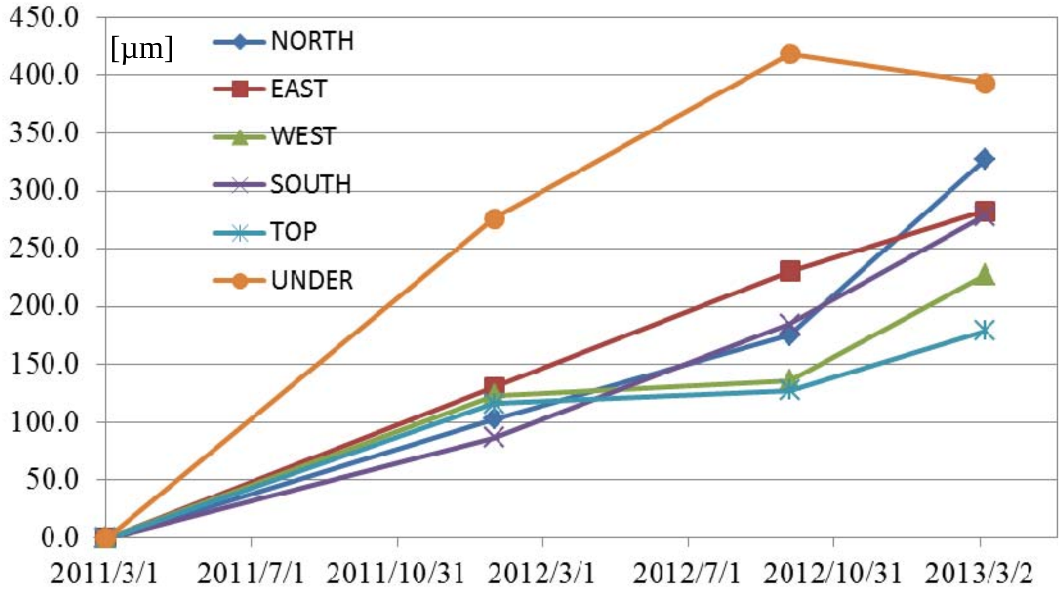

Figure 6: EM mean corrosion scale thickness measurements in costal environment.

Table 2: Electromagnetic corrosion scale measurements summary after 2 years of exposure

	NORTH	*EAST*	*WEST*	*SOUTH*	*TOP*	*UNDER*
URBAN [μm]	81.1	66.9	73.3	80.1	76.8	156.5
COSTAL [μm]	327.1	282.5	227.3	278.4	179.0	393.4
	90º	*45º*	*60º*	*135º*	*120º*	*AVERAGE*
URBAN [μm]	78.1	71.7	67.0	100.1	83.8	85.0
COSTAL [μm]	247.1	431.4	300.2	348.1	205.2	292.7

3.2. Ultrasonic technology corrosion inspection

The UT is applied for determining accurately the remaining thickness of steel plates (Minesawa et. al. 2011). The ultrasonic pulse from the transducer is reflected by the opposite face of the steel plate, and the thickness of the plate is computed from the travel time of the UT waves. The limitations of the UT method are: the difficulty of receiving the reflected signal on corroded surfaces and the necessity to assure adequate coupling of probe to the surface.

On very rough corroded surfaces, the UT wave is dispersed or reflected away from the probe resulting in poor readings. This phenomenon has been addressed in our study (Minesawa et. al. 2011) by using phased array (PA) probes which have a large receiving area while also being able to focus the incident wave at a given point by adjusting the timing of each individual waves, see Figure 7. In addition, in our research the scanning was applied for the same location under various incident angles, resulting in improved probability of receiving the reflected waves and an increased of the number of points from which the reflected wave is received from. Multiple–angle scanning reduces the inspection speed therefore the spacing between two consecutive readings and the number of scanning angle should be adjusted accordingly, based on desired accuracy and surface condition. For improving accuracy, several sets of reflections corresponding to each inspected point are combined using the SAFT algorithm into one reading obtained from the superposition of the individual readings.

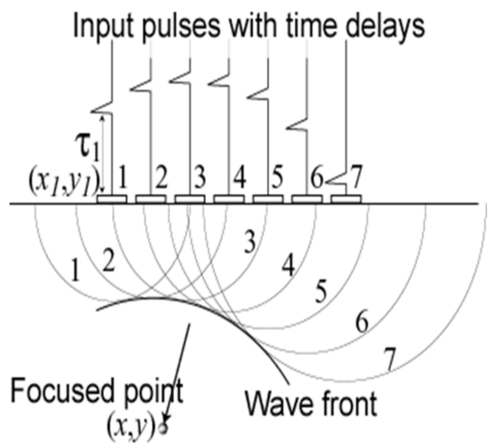

Figure 7: PA UT multi-angle focused beam scanning of corroded surface.

Figure 8: Corrosion inspection specimen from Benoki Bridge (Okinawa) web plate.

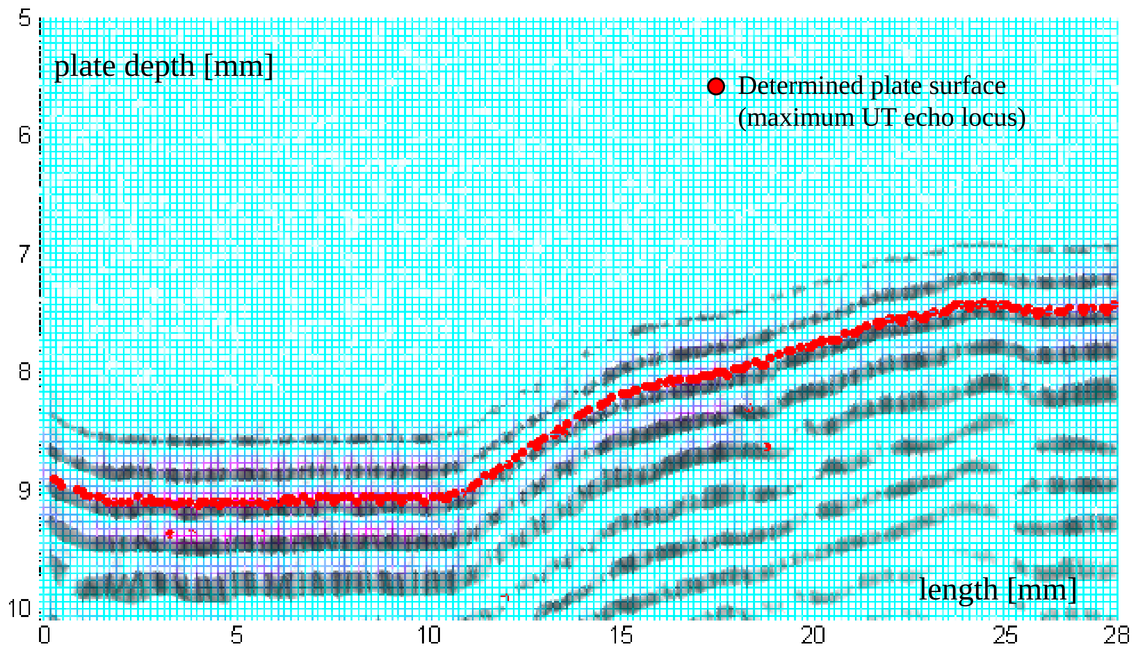

Figure 9: Corroded surface reconstruction obtained by PA UT inspection of plate thickness.

Verification of the procedure was performed using a web plate with corrosion on one surface extracted from Benoki Bridge (Okinawa Prefecture), a section through the plate is shown in Figure 8. The detail of the corroded surface reconstruction from the multi-angle scanning of the steel plate is shown in Figure 9. The volume of material loss and locations of minimum plate thickness are determined automatically by the software. Ultrasonic technology determines accurately remaining plate thickness whenever ultrasonic wave could be received and adequate coupling to the inspected surface could be achieved. Proposed PA UT inspection method enhances applicability to rough surfaces and achieves better reconstruction of corroded surfaces, compared to standard UT.

4. CORROSION PROGRESS EVALUATION BY MULTI-TECHNOLOGY INSPECTION AND MONITORING

Each NDT has its own advantages and disadvantages, as summarized in Table 3. ACM provides the overall corrosivity at a given location and by continuous monitoring could clarify the effect of seasonal factors in corrosion progress. UT PA provides precise measurements of remaining plate thickness whenever the reflected wave could be received. EM inspection is effective on determining corrosion scale thickness and measuring corrosion distribution regardless of the surface condition.

Table 3: Comparison of corrosion evaluation technologies

NDE technology	*measured parameter*	*access required for applicability*	*condition of inspected surface*	*productivity*	*cost*
ACM	environmental corrosivity	any location	any surface	highest	high
EM	corrosion scale thickness	any surface	any surface	high	low
UT	remaining plate thickness	access required to opposite surface	poor response on certain corroded rough surface	low	low
PA UT	remaining plate thickness	access required to opposite surface	improved response from non-uniform surface	lowest	high

5. CONCLUSIONS

1. The study proposes a comprehensive multi-technology approach for the evaluation of corrosion damage using ACM monitoring technology and regular inspection by EM and UT. A practical methodology is tested for on-site evaluation of corrosion in steel members, looking to identify and address limitations of each individual technology. A comparison is made between the corrosion inspection methods in terms of applicability, productivity, and accuracy.

2. Progress of corrosion for weathering steel elements is determined in three different environmental settings and the results for the first 24 months of exposure are summarized. Proposed corrosion evaluation techniques have been applied to the investigation of local factors such as the orientation of the surface and the spatial distribution of the corrosion progress on various surfaces.

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