第18回性能に基づく橋梁等の耐震設計に関する
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Seismic Reliability Assessment of RC Bridge Piers with Chloride-Induced Corrosion of Rebars Based on Inspection Results

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1. INTRODUCTION

Although there are several models for estimating seismic performance of corroded reinforced concrete (RC) bridge structures, few studies have been devoted to seismic reliability assessment of corroded RC structures. It is necessary to consider the effect of steel corrosion on life-cycle seismic reliability of RC structures located in an aggressive environment since steel corrosion is the main factor of decreasing the seismic capacity of RC structures. Seismic demand depends on the result of seismic hazard assessment, while the deterioration of the structural seismic capacity depends on the environmental hazard assessment. RC structures located in marine environments deteriorate over time due to chloride-induced corrosion [1, 2]. Akiyama *et al.* [3] presented a procedure to integrate the hazards associated with airborne chloride into a life-cycle seismic reliability estimation of new RC bridge piers. The capacity for seismic ductility and the energy dissipation of a RC bridge pier strongly depends on the steel corrosion level in the plastic hinge. It is very important to estimate steel weight loss in the plastic hinges.

To estimate reliability of existing RC structures, the observational data from the inspection results play an important role for updating the parameters associated with the prediction of material deterioration. Akiyama *et al.* [2] established a procedure to update the multiple random variables using visual inspection results by Sequential Monte Carlo Simulation (SMCS) for existing RC slabs located in marine environments. However, few studies focus on updating the seismic reliability of existing structures using inspection data. In addition, the effect of the spatial distribution of steel corrosion on the structural performance must be considered, since neglecting localized corrosion may lead to an overestimation of structural reliability [4]. It is necessary to integrate the modeling of spatial variability in steel corrosion into the estimation of the seismic capacity of RC bridges. Based on several inspection locations, possible spatial distributions of steel corrosion in existing RC bridges can be estimated by the statistical estimation error process proposed by Honjo and Otake [5] if parameters to reproduce the spatial distribution of steel corrosion are provided. Akiyama *et al.* [6] have presented the experimental results of the visualization of steel corrosion in RC members by X-ray technology. The parameters to reproduce spatially distributed steel corrosion can be determined based on these X-ray photograms.

A procedure for estimating the updated life-cycle seismic reliability of existing RC bridge piers in a marine environment is established based on the inspection data considering the spatial distribution of steel corrosion. In addition, this study presents a methodology to estimate the average and variance of steel weight loss in the plastic hinge of existing RC bridge piers based on previous experimental results acquired by X-ray technology. Average and variance of the steel weight loss based on inspection data are used to reduce the epistemic uncertainties associated with the prediction of the steel weight loss using SMCS. In an illustrative example, the effect of the inspection results on the updated cumulative time failure probability of RC bridge piers under seismic hazard and hazard associated with airborne chloride is discussed.

2. LIFE-CYCLE SEISMIC RELIABILITY OF CORRODED RC BRIDGE PIERS

Fig. 1 shows the flowchart for estimating life-cycle seismic reliability of corroded existing RC bridge piers based on inspection. As shown in **Fig. 1**, the annual probability of the exceedance of seismic capacity can be obtained in Part A. The steel weight losses at time *t* after construction are calculated in Part B. The combination of the results of Parts A and B yields the cumulative time failure probability for new RC structures [3]. Because inspection results can be obtained for existing structures, model uncertainties associated with the prediction of steel corrosion represented by the multiple

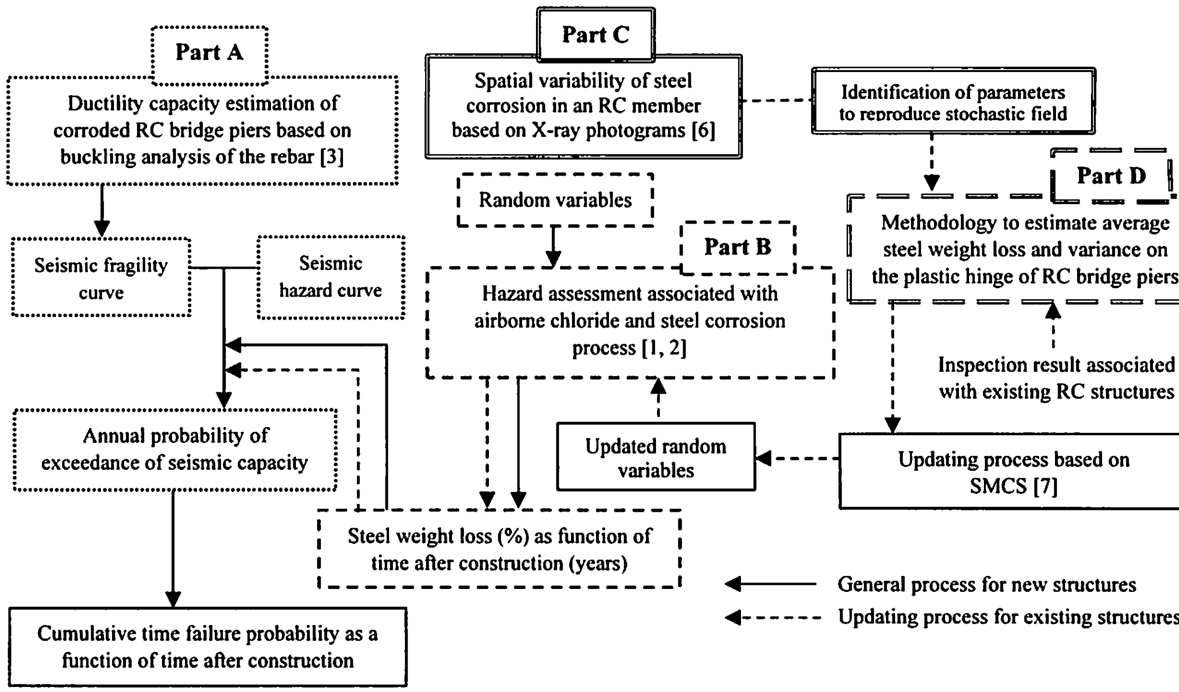

Fig. 1 Framework for estimating the updated life-cycle seismic reliability of a corroded RC bridge structures

random variables can be reduced using SMCS, even if the relationship between these random variables and the inspection results are nonlinear and non-Gaussian variables are involved [2, 7]. Then, the life-cycle seismic reliability of corroded existing RC bridge piers can be estimated based on the updated random variables.

2.1 Average steel weight loss and variance in the plastic hinge (Parts C and D in Fig. 1)

Steel weight loss in the plastic hinge of RC bridge pier can be estimated based on discrete measurements of the steel weight loss over RC bridge piers. The procedure to estimate the possible spatial distributions of steel corrosion in the plastic hinge using the discrete inspection results are explained as follows:

***Step1**: Estimation of steel weight loss (C_w) from the inspection results of plastic hinge.*

From the inspection process, the steel weight loss of existing RC bridge piers can be provided within the plastic hinge length, as shown in **Fig. 2**. The simple average of steel weight loss ($C_{w,avg}$) from all inspection locations can be estimated.

***Step2**: Selection of the steel corrosion trend from the experimental results depending on the magnitude of the measured steel weight loss ($C_{w,avg}$).*

The parameters to reproduce the spatial variability in steel corrosion inside an RC member can be determined using the experimental distribution as shown in **Fig. 3**. These experimental results were obtained from the specimen that was corroded by electrical corrosion. The steel weight loss of the RC component was estimated based on digital pictures using X-rays taken from various angles. When the simple average steel weight loss from Step 1 is provided, a basic steel corrosion trend is selected from the experimental results shown in **Fig. 3**, which has a similar steel weight loss, $C_{w,avg}$, to estimate the spatial variability parameter using the semi-variogram calculation.

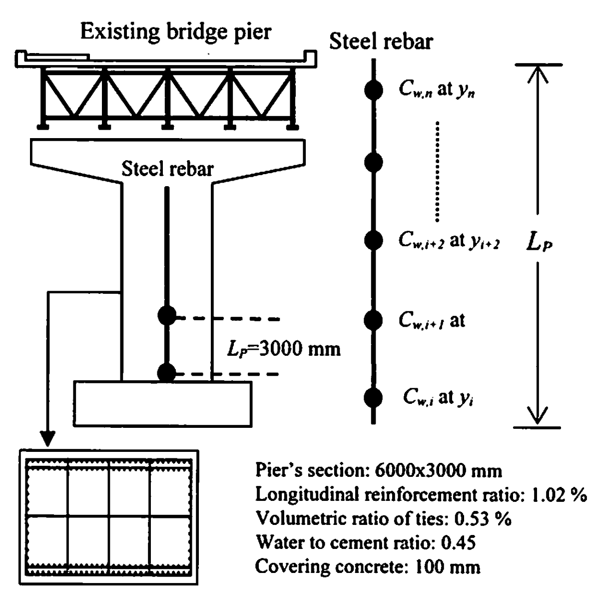

Fig. 2 Analyzed RC bridge pier and positions of inspection

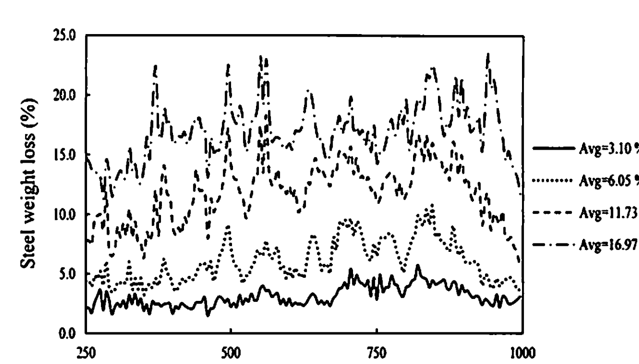

Fig. 3 Relationship between the steel weight losses (%) along the length of the specimen (mm)

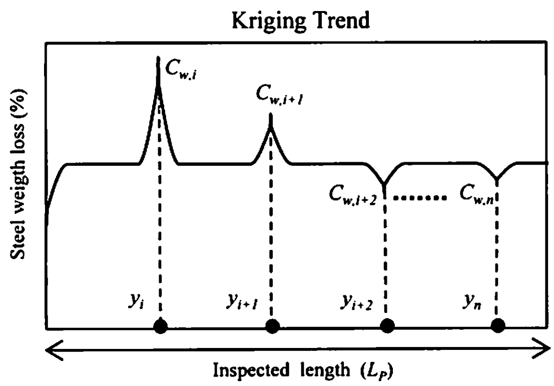

Fig. 4 Relationship between the steel weight loss (%) and the inspected length

***Step3**: Quantifying a correlation of the selected basic steel corrosion trend using the semi-variogram.*
The semi-variogram process is a useful tool for quantifying and characterizing a spatial correlation of any series of data since Kriging interpolation requires parameters (i.e., nugget, sill, and range) representing the characteristics of the trend variation.

***Step4**: Conducting the Kriging interpolation and statistical estimation error process.*
Kriging is a geostatistical interpolation technique that considers the degree of variation between known data points when the values of unknown data points must be estimated. Kriging estimation is a weighted linear combination of the known sample values around the estimated points. The Kriging calculation depends on the semi-variogram parameters used to weight the nearby inspection locations. Average steel weight loss can be calculated from Kriging trend as shown in **Fig. 4**.

Variance is obtained by multiplying the statistical estimation error [5] by the variance of the basic steel corrosion trend. The variance depends on the number of inspections, the interval between inspection locations, and correlation level of basic steel corrosion trend represented by semi-variogram parameters.

3. UPDATING PROCESS BASED ON INSPECTION RESULTS USING SMCS

Since the inspection data are provided by existing structures, the mean and COVs of involved random variables should be updated. Herein, nine random variables are used to calculate the time-variant steel weight loss considering the hazard associated with airborne chloride proposed in [2]. Because the relationship between random variables and estimated steel weight loss are nonlinear, SMCS should be applied to update the random variables. All random variables associated with the inspection results can be updated simultaneously. SMCS procedure to update random variables is applied to the reliability analysis. The details of how to conduct reliability analysis with the updated random variables are shown in [7]. The observational equation based on the inspection data is presented in **Eq. 1** based on the steel weight loss provided by the inspection process.

$$W_{updated} = W_{predicted} + v \tag{1}$$

where $W_{updated}$ is the mean of the steel weight loss from the Kriging trend based on the inspection data. $W_{predicted}$ is the steel weight loss at t years after construction, as estimated from the nine random variables. v is the observation noise with a standard normal distribution. In this study, the observational noise is assumed to be equal to the variance.

4. ILLUSTRATIVE EXAMPLE

It is assumed that the existing bridge pier located in Niigata city is inspected 30 years after construction to obtain the steel weight loss at each inspection locations, as shown in **Fig. 5**. The average steel weight loss can be calculated using the Kriging trend shown in **Fig. 6**. The variance is estimated based on the statistical estimation error process. In this example, the magnitude of the variance depends on the number of inspection locations. The limited number of inspection locations increases the variance. As shown in **Table 1**, the statistical estimation error of Case 1 (3 inspections locations), is higher than that of Case 2 (5 inspection locations). The mean and variance of the steel weight loss are used to update the random variables. Finally, the updated life-cycle seismic reliability of the existing RC bridge pier can be obtained

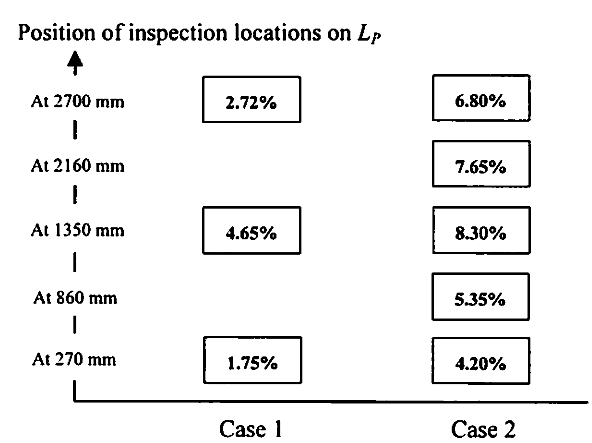

Fig. 5 Locations of inspection and inspection results

Table 1. Lists of the average and variance of steel weight loss

Case	Average corrosion from the inspection results ($C_{w,avg}$) (**Fig. 5**)	Average corrosion from the Kriging trend ($W_{updated}$) (**Fig. 6**)	Variance of the basic corrosion trend (**Fig. 3**)	Statistical estimation error	variance (v)
1	3.04%	3.07%	0.73	0.289	0.21
2	6.46%	6.43%	3.17	0.103	0.33

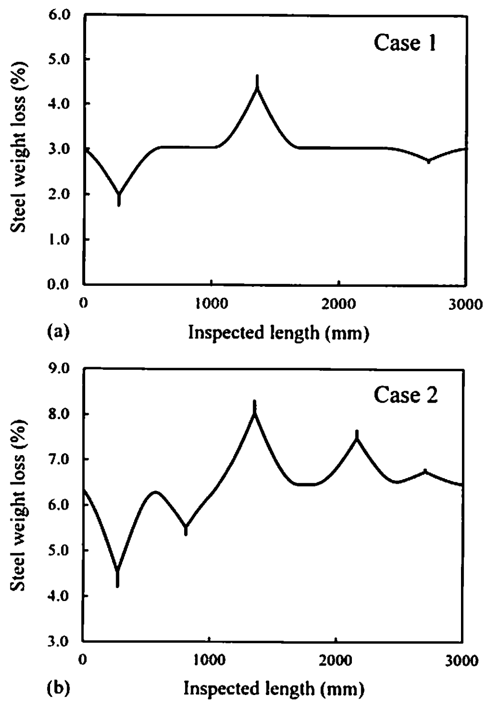

Fig. 6 Kriging steel corrosion trend

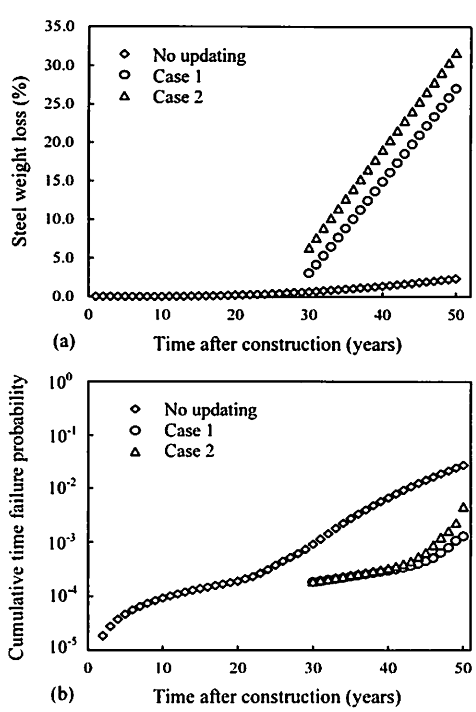

Fig. 7 Relationship between (a) the steel weight loss and (b) the cumulative time failure probability and time after construction (years)

as shown in **Fig. 7**

When the steel weight loss is provided by the inspection, the nine random variables relating to the prediction of steel weight loss can be updated for consistency with the given inspection results. As shown in **Fig. 7(a)**, the estimated steel weight loss increases with time. At 30 years after inspection, estimated steel weight loss in the plastic hinge depends on the assumed inspection results. In this cases study, since the steel weight loss assumed in Cases 1 and 2 is higher than the steel weight loss estimated by the original random variables, the steel weight loss in Cases 1 and 2 estimated by the updated random variables is higher. However, the cumulative time failure probabilities of Cases 1 and 2 are lower than that without updating as shown in **Fig. 7(b)**, since the coefficient of variation after updating is smaller than that without updating. It is important to estimate the seismic reliability of corroded existing RC bridge piers based on the inspection results.

6. CONCLUSIONS

1) A novel procedure to estimate updated life-cycle seismic reliability of corroded existing RC bridge piers based on inspection data by incorporating the spatial variability in steel corrosion is established.
2) The methodology to estimate the mean and variance of the steel weight loss in the plastic hinge of existing RC bridge piers is presented based on the previous experimental results from corroded RC specimens acquired by X-ray technology. The number of inspection locations on the analyzed RC bridge pier is considered in the statistical estimation error process.
3) A more accurate life-cycle reliability assessment could be performed since the random variables associated with the prediction of steel corrosion are updated to be consistent with inspection results. The updated failure probabilities of RC bridge pier assuming the different inspection results are presented in the illustrative example.

REFERENCES

1) Akiyama, M., Frangopol, DM., Suzuki, M.: Integration of the effects of airborne chlorides into reliability-based durability design of RC structures in a marine environment, *Structure and Infrastructure Engineering*, 8(2), pp. 125-134, 2012.
2) Akiyama, M., Frangopol, DM., Yoshida, I.: Time-dependent reliability analysis of existing RC structures in a marine environment using hazard associated with airborne chlorides, *Engineering Structures*, 32(11), pp. 3768-3779, 2010.
3) Akiyama, M., Frangopol, DM., Matsuzaki, H.: Life-cycle reliability of RC bridge piers under seismic and airborne chloride hazard, *Earthquake Engineering and Structural Dynamics*, 40(15), pp. 1671-1687, 2011.
4) Stewart MG.: Spatial variability of pitting corrosion and its influence on the structural fragility and reliability of RC beams in flexure. *Structural Safety*, 26, pp. 453-470, 2004.
5) Honjo, Y., Otake, Y.: Statistical estimation error evaluation theory of local averages of a geotechnical parameter, *Proceeding of Safety Reliability Risk and Life-cycle Performance of Structure and Infrastructure*, pp. 1987-1994, 2013.
6) Akiyama M, Nakajima K, Komoriya T.: Visualization of corrosion process in RC component using X-Ray. *Concrete Research and Technology*, 22(3), pp. 35-45, 2011 (In Japanese).
7) Yoshida, I.: Data assimilation and reliability estimation of existing RC structure, *Proceeding of COMPDYN 2009*, CD281, Rhodes, Greece, 2009.