Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Structural performance assessment of RC members by incorporating the spatial steel corrosion
鉄筋腐食の空間変動性を考慮したRC部材の構造性能評価

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Steel corrosion is well recognized as a dominant cause of deteriorating RC structures. Through times, it inflicts damages on RC structures, which leads to a decrease in their performance and safety. Corrosion attracts considerable attentions worldwide since it represents tremendous economic loss to all nations. In 2012, the Federal Highway Administration estimated that the U.S. government needed to increase its annual spending from $12.8 to $20.5 billion in order to eliminate the structurally deficient bridge backlog by 2028. Therefore, the establishment of the reliable models to assess the long-term performance of corroding RC structures is an important task for structural engineers and researchers in assisting the government and structure asset owners in decision-making on remedial repair and maintenance action plan to extend their service life and prevent considerable economic loss.

Finite element and probabilistic approaches have been used for the structural performance assessment of corroding RC structures. However, the difficulty in quantifying the spatial steel corrosion along the RC structures has been reported as the primary challenge in conducting the computational methods more objectively and precisely. In addition to improving computation methods, it is more important to adequately assess and incorporate the level and location of reinforcement corrosion into the computational methods in order to obtain more objective prediction results. To estimate the spatial steel corrosion, there is a need to experimentally investigate how the steel corrosion increases or changes at different corrosion times. In this dissertation, novel X-ray and digital image processing techniques are established to quantify the spatial variability of steel weight loss along the corroded rebars embedded in the RC member. The merit of this non-destructive method is of great interest since it enables a continuous monitoring of the spatial growth in steel corrosion in RC members throughout the corrosion process and also provides a high accuracy of steel weight loss estimation.

This dissertation is composed of four main parts. The first part highlights the background and recent problems related to the structural performance assessment of corroding RC structures and significance of the present research on modeling spatial steel corrosion. The second part explains the details of the novel X-ray and digital image processing techniques for quantifying the spatial steel corrosion and discusses the major findings of experimental results. The third part presents how to incorporate the experimental data of spatial steel corrosion into the finite element and probabilistic methods in order to study the effects of uniform and non-uniform steel corrosion on the structural performance assessment of corroding RC structures. The fourth part provides the conclusions of major findings from the experimental and computational results, and the limitations and future works are also discussed. According to the objectives of this dissertation, it is divided into six chapters.

In chapter 1, background and motivation of the research is first described following by the objectives of research. Steel corrosion is a major durability problem of deteriorating RC infrastructures, which represents an enormous economic loss to the nations worldwide. Therefore, constructing engineers and researchers have to focus on solving the corrosion problem. The establishment of computational methods to predict their long-term performance is very important for informing the government and infrastructure asset owners for making in-time repair and maintenance plans to avoid tremendous economic loss. Although there are computational methods that can be used for structural performance assessment of corroding structures, the primary challenge reported in the literature is the important input data associated with spatial steel corrosion which is required to incorporate into the computational models. Therefore, modeling spatial variability associated with steel corrosion is very important. In this dissertation, a novel X-ray and digital image processing technique is established for studying and quantifying the spatial variability of steel weigh loss over the corroded rebars inside the RC beams. The effects of spatial variability associated with steel corrosion on the structural behavior of corroded RC beams are also investigated. The statistical data from the experiment is incorporated with numerical and probabilistic models to predict the performance of corroding RC structures.

In chapter 2, systematic literature review on the fundamental concepts of steel corrosion in RC structure, corrosion effects on the RC materials and structures, and the artificial monitoring method to study the spatial steel corrosion in RC members is conducted. Corrosion can occur on the embedded reinforcements in RC structures when the passivative film is broken down by chloride penetration and carbonation. Several experimental studies have been conducted using corrosion-accelerated RC members to investigate the corrosion effects on RC materials and structural performance of corrode RC structures. Recently, more attentions have been focused on modeling the steel corrosion using statistical data of spatial steel corrosion from experimental studies. The destructive methods by breaking some of corroded RC members to retrieve corroded rebars is commonly used though few non-destructive methods using 3D and 2D X-ray apparatus were reported.

In chapter 3, the details of experimental program and the procedure on how to estimate the spatial steel corrosion using novel X-ray and digital image processing techniques are described. Corrosion of the embedded longitudinal rebar in the RC beams was accelerated via the electrochemical technique. At specific time intervals, the crack widths were recorded by taking photos of surface cracking on the bottom of the beams. X-ray radiography was performed once before the steel corrosion initiated and several times during the corrosion process to capture the non-corroded and corroded rebars embedded in the RC beam from different viewing angles. The X-ray images of steel rebar and photos of cracking were used in the digital image processing to estimate the steel weight loss and crack width per 5 mm along the RC beam for the total length of 840 mm.

In chapter 4, the major findings of experimental studies are given and discussed. The estimated rebar weight loss calculated using the digital image analysis was found to be only 3% higher than that of the actual measured steel weight loss. This demonstrated the good accuracy of the present technique for investigating the spatial growth of steel corrosion. The distributions of the steel weight loss and crack width are spatially non-uniform, and their degree of non-uniformity significantly increases with the global mean steel weight loss (*MRw*) and corrosion cracking (*MCw*). Nevertheless, there also appears a consistent trend of the erratic shapes of spatial steel corrosion as the values of *MRw* exceed 5%. The effect of W/C ratio on the increased steel weight loss is not obvious. Meanwhile, the crack width of the specimens with low W/C ratios increased faster than those with high W/C ratios. The crack width and steel corrosion of the specimen without stirrups increased more quickly than those of specimens with stirrups. Regarding the effects of spatial variability of steel corrosion on structural performance of corroded RC beams, for a small dispersion in the steel weight loss (i.e., a standard deviation below 4.3%), the mean steel weight loss instead of the corrosion pits appear to have a dominant effect on the loading capacity of the corroded beams. However, as the dispersion in the steel corrosion increases, the influence of the pitting corrosion on the loading capacity becomes more significant than the corrosion level.

In chapter 5, the structural performance assessment using finite element and probabilistic methods is presented. For the finite element method, the effects of two different inputs (i.e., uniform and non-uniform cross-sections along the reinforcement) on the computational accuracy were studied. It is found that although the adopted FE method can provide good predicted results for the loading capacity of corroded RC beams, it overestimates the stiffness of the beam throughout all the damaging stages. For the probabilistic methods, the Gumbel statistic of the maximum steel weigh loss ratios per 50-mm-long rebar was established. The relationships between the Gumbel parameters and global mean steel weight loss are then developed; and an example is illustrated for the application of Gumble statistics of the maximum of steel weigh loss ratios to study the effects of the spatial and non-spatial steel corrosion on the failure probability of a corroded RC beam under flexure. Both of the results from FE and probabilistic methods indicate that an assumption of uniform steel cross-section loss over the RC beam provides an overestimation of structural performance of corroding RC structures in comparison to the other assumption with non-uniform cross-section.

In chapter 6, the concluding remarks are summarized, and future works for improvements are also discussed. The high accuracy of X-ray and digital image processing techniques in quantifying the steel weight loss proves its validation to study the spatial steel corrosion at multiple corrosion times. Such experimental data of spatial steel corrosion is very valuable and important since it provides the statistical data for facilitating the life-cycle assessment and management of deteriorated RC structures. In this dissertation, the experimental data of steel weight loss was used in the FE method to study the effects of two different inputs (i.e., uniform and non-uniform cross-sections) on its accuracy. Moreover, the Gumbel statistic of maximum steel weight loss ratio has been developed using the experimental data of steel weight loss. In an illustrative example, the relationships between Gumbel parameters and global mean steel weight loss has been incorporated into a probabilistic model to study the effects of non-spatial and spatial steel corrosion on the reliability assessment of corroding RC structures. Both the FE and probabilistic methods suggest an assumption of the uniform steel corrosion is not conservative; it is necessary to consider the spatial steel corrosion when evaluating the structural performance of corrosion-affected RC structures. The limitations and future works are also given herein for further improvements. The RC specimens shall be reinforced with multiple rebars to study the effects of the potentials of neighboring bars on other rebars. The accelerated corrosion test shall be conducted using smaller current densities than the present value of 1000 $\mu A/cm^2$ to study the effects of different current densities on spatial variability of steel weight loss. Constitutive model associated with the bond behavior in the FE method needs to be improved to simulate bond deterioration effect more precisely. Moreover, the method of integrated approach using the FE and probabilistic method might be a better option for considering the effect of change of material properties due to the steel corrosion on the long-term structural performance assessment of corroding RC structures.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む） (theme, journal name, date & year of publication, name of authors inc. yourself)
Academic paper	
O　1.	Sopokhem Lim, Mitsuyoshi Akiyama, and Dan M. Frangopol. Assessment of the structural performance of corrosion-affected RC members based on experimental study and probabilistic modeling. Engineering Structures, 2016; 127:189–205.
O　2.	Sopokhem Lim, Mitsuyoshi Akiyama, Dan M. Frangopol, and Haitao Jiang. Experimental investigation of the spatial variability of the steel weight loss and corrosion cracking of RC members: Novel X-ray and digital image processing techniques. Structure and Infrastructure Engineering, 2017;13(1):118–134.
3.	Sopokhem Lim, Mitsuhiro Matsuda, Ramiz Ahmed Raju, and Mitsuyoshi Akiyama. Flexural behavior prediction of SFRC beams using finite element method and X-ray image. Proceedings of the Japan Concrete Institute, 2017; 39(2):1099–1104.
4.	Sopokhem Lim, Takehiro Okamoto, Mitsuhiro Matsuda, and Mitsuyoshi Akiyama. Flexural behavior prediction of SFRC beams: a novel X-ray technique. Proceedings of the Japan Concrete Institute, 2016; 38(2):1351–1356.
O　5.	Sopokhem Lim, Haitao Jiang, Takehiro Okamoto, and Mitsuyoshi Akiyama. Visualization of corroded steel bars in RC beams using digital image processing of X-ray photograms. Proceedings of the Japan Concrete Institute, 2015; 37(2):1327–1332.
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Conference Paper (peer review)	
O　7.	Sopokhem Lim, Huijuan Song, Lei Nie, and Mitsuyoshi Akiyama. Structural performance assessment of aging RC beams considering the spatial variability of steel corrosion: experimental study and probabilistic model. The Fifteenth East Asia-Pacific on Structural Engineering and Construction Conference (EASEC-15); Oct. 2017, Xi'an, China.
O　8.	Sopokhem Lim, Huijuan Song, Lei Nie, and Mitsuyoshi Akiyama. Effect of spatial variability associated with steel corrosion on the reliability of corroded RC beams. The 8th Asia and Pacific Young Researchers and Graduates Symposium (YRGS2017); Sept. 2017, Tokyo, Japan.
O　9.	Sopokhem Lim, Mitsuyoshi Akiyama, and Dan M. Frangopol. Assessment of the structural behavior of corrosion-affected RC beams: Experimental study and modeling. Proceedings of the Fifth International Symposium on the Life-Cycle Engineering (IALCCE2016); 379–384, Sept. 2016, Delft, the Netherlands.

早稲田大学　博士（工学）　学位申請　研究業績書

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O　10.	Sopokhem Lim, Haitao Jiang, and Mitsuyoshi Akiyama. Investigation of the spatial variability of steel weight loss and corrosion cracking: A novel X-ray technique. Proceedings of the Fifth International Conference on Durability of Concrete Structures (ICDCS2016); 265–269, June 2016, Shenzhen, China.
11.	Sopokhem Lim, Takehiro Okamoto, and Mitsuyoshi Akiyama. Flexural behavior prediction of SFRC beams using X-ray photograms. The Fourteenth East Asia-Pacific on Structural Engineering and Construction Conference (EASEC-14); 1254–1257, Jan. 2016, Ho Chi Min, Vietnam.
O　12.	Sopokhem Lim, Haitao Jiang, Mitsuyoshi Akiyama, and Dan M. Frangopol. Experimental investigation on the relationship between the spatial variation of steel weight loss and the cracking width of RC members using X-ray photograms. Proceedings of the Fourth International Symposium on Life-Cycle Civil Engineering (IALLCCE2014); 429–436, Nov. 2014, Tokyo, Japan.
Conference Paper (non-peer review)	
13.	Sopokhem Lim, Ramiz Ahmed Raju, Mitsuhiro Matsuda, and Mitsuyoshi Akiyama. Prediction method of SFRC beams in bending using FE analysis and X-ray images. 72nd Japan Society of Civil Engineers 2017 Annual Meeting; Sept. 2017; Fukuoka, Japan.
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