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科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Long-term structural performance assessment of corroded reinforced concrete structures using an integrated approach of probabilistic and finite element method

研究課題名（英文）Long-term structural performance assessment of corroded reinforced concrete structures using an integrated approach of probabilistic and finite element method

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研究成果の概要（和文）：RC梁の時間依存性鋼腐食とひび割れに対する定電流(GS)腐食法と人工塩化物環境(ACE)腐食法の影響をX線技術を用いて研究した。 50 マイクロアンペア/cm2 未満の電流密度を適用する GS 法は、その結果が ACE 法の結果に近いため、鋼の腐食を研究するために推奨されます。 GS 法では亀裂幅が大幅に小さくなり、構造劣化レベルの予測には使用できませんでした。 構造性能評価では、縦方向と横方向の相関を考慮して、有限要素法で空間的な鋼材の腐食をモデル化することが重要です。 10 マイクロアンペア/cm2 の梁の鋼材重量損失のデータを使用することで、負荷容量を控えめに見積もることができました。

研究成果の学術的意義や社会的意義
X-ray and image processing techniques enable a comprehensive study the time-dependent steel corrosion and crack widths and its associated structural performance. Prediction of the long-term structural performance considering spatial steel corrosion is important for better-informed maintenance plans.

研究成果の概要（英文）：The effects of galvanostatic (GS) and artificial chloride environment (ACE) corrosion methods on the time-dependent steel corrosion and cracks of RC beams were studied using X-ray and image processing techniques. GS method applying current density lower than 50 micro amperes per cm2 is recommended to study steel corrosion since it produces the results close to that of ACE method. However, the GS method generated significantly smaller crack widths due to leakage of corrosion products. A correction factor is needed to modify the crack widths of GS method when predicting deterioration levels of structures. For long-term structural performance assessment, it is important to model spatial steel corrosion in finite element method considering its correlation in longitudinal and transverse directions for desired prediction results. Using statistic data of steel weight loss of corroded beams with 10 micro amperes/cm2 provided conservative estimation of loading capacities.

研究分野：Concrete engineering

キーワード：Maintenance and repair　Spatial steel corrosion　Spatial corrosion cracks　Finite element analysis　Current density　Galvanostatic corrosion　Reliability

１．研究開始当初の背景

Steel corrosion is a major durability problem for RC structures and represents enormous economic loss to the nations worldwide. Establishment of a reliable model for the long-term performance assessment of RC structures is essential to assist the government and asset owners in decision-making on maintenance plans. Since the structural performance of RC structures primarily depends on localized corrosion damages to their reinforcements, it is crucial to model the spatial steel corrosion. Recent studies have focused on modeling spatial steel corrosion using the statistical data of steel corrosion from RC members corroded with galvanostatic (GS) method by applying a current density, and the modeled steel corrosion by Monte Carlo simulation (MCS) was incorporated into a probabilistic method for the reliability analysis of RC structures. However, researchers applied a wide range of current densities neglecting their influences on the spatial steel corrosion, which might not represent the corrosion and associated structural performance in the natural conditions. Moreover, cross-section analysis is usually incorporated with the probabilistic method for structural performance assessment, ignoring rebar-and-concrete bond loss. The FE method can provide more accurate structural performance assessment considering the bond loss; the research using FE method considering spatial steel corrosion and bond loss is still scarce.

２．研究の目的

In this research, the main purpose is to establish a procedure to assess the long-term structural performance of corroding RC structures using the integrated approach of finite element and probabilistic methods. In the experiment, the effect of GS (with different current densities) and artificial chloride environment (ACE) corrosion methods on the spatial steel corrosion, corrosion cracks, and structural behavior of reinforced concrete specimens are investigated. Recommendations on suitable current densities to be used in a laboratory test are provided. Moreover, Monte-Carlo probabilistic-based 2D FE models are applied to estimate the distribution of loading capacity of corroded RC beams at various corrosion levels. 2D and 3D FE models are used to study the effect of correlation of spatial steel corrosion in transverse directions on the structure performance of RC beams.

３．研究の方法

Figures 1 and 2 show the front and cross-section views of the single-rebar and multiple-rebar specimens, respectively. Nine single-rebar specimens were used to study the effect of corrosion methods (GS versus ACE methods). Two beams (i.e., WD-1 and WD-2) corroded with ACE method. For GS method, CD-10 and CD-50 were corroded at low current densities (i.e., I_{corr} of 10 and 50 μA/cm^2) while CD-100, CD-200, CD-500 and CD-1000 were corroded at high current densities of 100, 200, 500 and 1000 μA/cm^2, respectively. S0 is the sound beam without corrosion. Four multiple-rebar specimens (B20-1, B20-2, B30-2, and B30-3) were used to study the effect of correlation of spatial corrosion in the transverse direction on the structural performance of RC beams. The four beams were corroded with GS method using I_{corr} of 1000 μA/cm^2 but the corrosion region is concentrated in the center span of beam for only 140 mm.

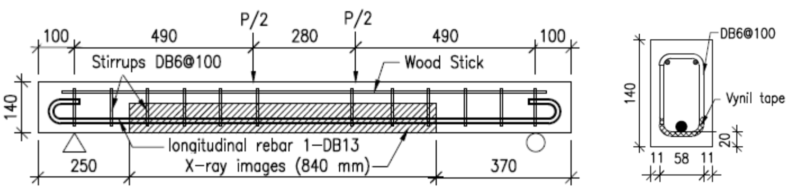

Figure 1. Front and cross-section views of the single-rebar specimens.

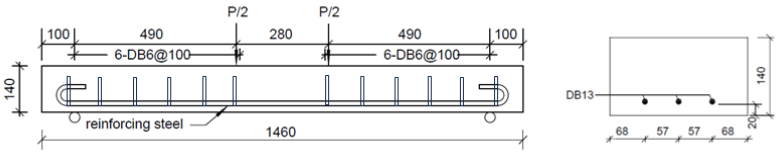

Figure 2. Front and cross-section views of the multiple-rebar specimens.

3.1 Experiment procedure for the single-rebar specimens

Figure 3 summarizes the four steps of experiment procedure to estimate the steel weight loss using X-ray and digital image processing techniques. Firstly, beams were corroded with GS and ACE methods. Before corrosion and at various corrosion levels, X-ray images of rebars inside the specimens were taken. Next, photos of corrosion cracks at the bottom surface of the beams were taken by a digital camera. The X-ray images and photos of crack widths are captured from 250 mm to 1090 mm from the left edge of the beams (i.e. the total length of 840 mm). After that, the crack widths measurement and steel weight loss quantification were conducted using digital image processing technique.

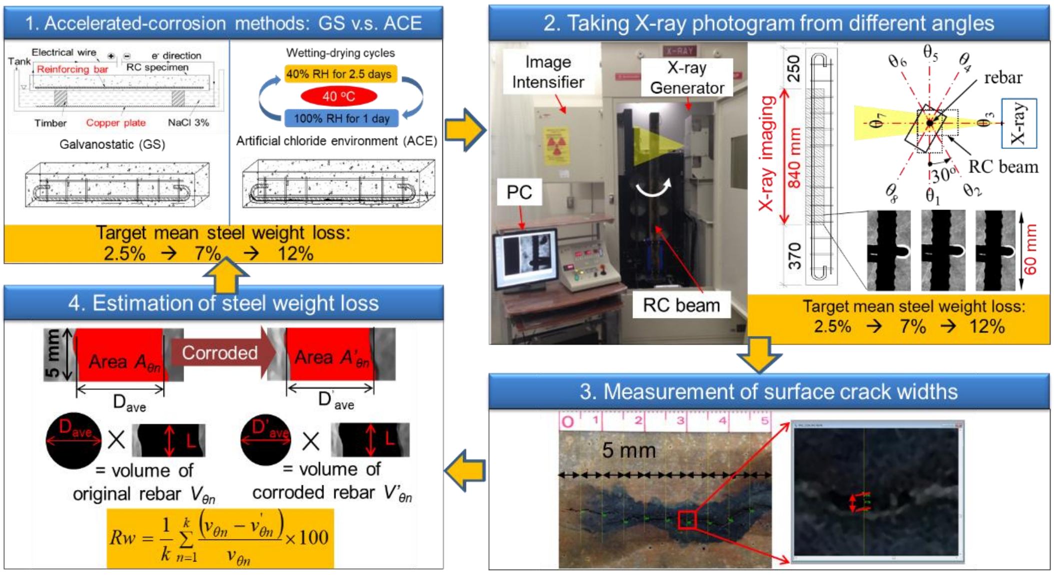

Figure 3. Experimental procedure to estimate the steel weight loss using X-ray and digital image processing techniques.

3.2 Experiment procedure for the multiple-rebar specimens

GS method with I_{corr} of 1000 µA/cm^2 was used for corrosion test. To obtain the localized corrosion in the middle part of the beam, only the mid-span region of the beam (i.e., 140 mm) was corroded. A wet sponge was placed under RC specimens to supply the chloride irons from the bottom side. Next, the four-point bending test of the corroded RC beams (Figure 2) was conducted. After that, specimens were destroyed to retrieve the corroded rebars. After cleaning the corrosion products, the diameters of the corroded rebars were measured by a vernier caliper at several positions spaced at around 10 mm. At each measurement position, the minimum diameter (d_a) was chosen as the first measurement direction in the cross-section of rebar and the direction perpendicular to it was chosen to measure the second diameter (d_b). The steel weight loss ($Rw3$) of a rebar in the multiple-rebar specimen was estimated by:

$$Rw3 = 1 - \frac{(d_a + d_b)^2}{4d_0^2} \tag{1}$$

where d_0 is the diameter of sound rebar.

After the measurement, the mean steel weight loss of the three rebars ($MRw3$) were found to be 25.1%, 22.5%, 27.9%, and 27.1% for B20-1, B20-2, B30-1, and B30-2, respectively.

4. 研究成果

4.1. Results and discussion for single-rebar specimens

4.1.1 Spatial variability in steel corrosion and crack widths

Figure 4(a) shows standard deviation (SD) of steel weight loss of RC beams at different MRw. The corrosion methods have a significant impact on the spatial distribution of steel weight loss. In general, it can be confirmed from SD values suggest that steel corrosion of RC beams corroded under ACE method (i.e., WD-1 and WD-2) and GS method with low current density (I_{corr} < 100 µA/cm^2) are more nonuniform than other beams corroded with high current density (I_{corr} ≥ 100 µA/cm^2).

Figure 4(b) shows the development of mean crack widths at different corrosion levels MRw of GS and ACE specimens. The crack widths of ACE specimens are significantly larger than those of specimens under the GS method. Considering the differences between GS and ACE specimens, a correction factor is needed to modify the crack widths of GS specimens when using data of crack widths of GS specimens to predict the structural deterioration levels.

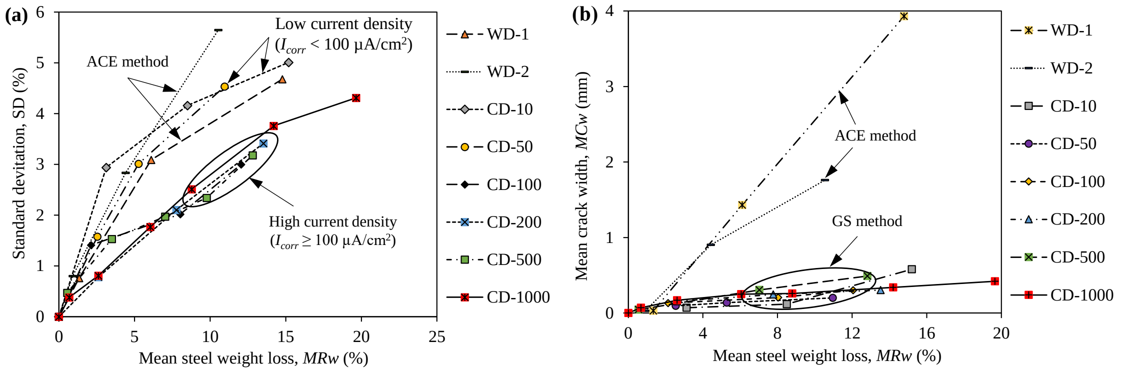

Figure 4. (a) standard deviation (SD) of steel weight loss and mean crack widths of each RC beam at different *MRw*.

4.1.2 Effect of the corrosion method on the yield loads estimated by Monte Carlo-based FE analysis

Figure 5 shows the PDFs of yield load capacity and the associated extreme value fit for the corroded rebar with *MRw* of 5%, 15%, and 25% based on regressions of Gumbel parameters in case of CD10, CD-50, WD-1 and WD-2, and high current density, using 1000 FE analyses. With increasing *MRw*, the mean yield load capacity of the corroded beams in all cases decreases significantly while the dispersion of yield load capacity increases as indicated by the SD values. Moreover, it should be noted that, at *MRw* of 5%, 15%, and 25%, the PDFs of yield load capacity in case of high current density have a larger mean but smaller SD than those in the case of WD-1 and WD-2. This result means that using Gumbel distribution parameters derived from a corroded beam with a high current density can provide overestimated yield load capacity since the more uniform steel corrosion is generated. The PDFs of yield load capacity in the case of CD-10 and CD-50, at *MRw* of 5% and 15%, have an approximately same mean but larger SD of yield load capacity compared to those in the case of WD-1 and WD-2. This result proves that using Gumbel distribution parameters derived from a corroded beam using current densities of 10 μA/cm^2 and 50 μA/cm^2 conservatively estimates yield load capacity for the corroded beam under the natural chloride environment.

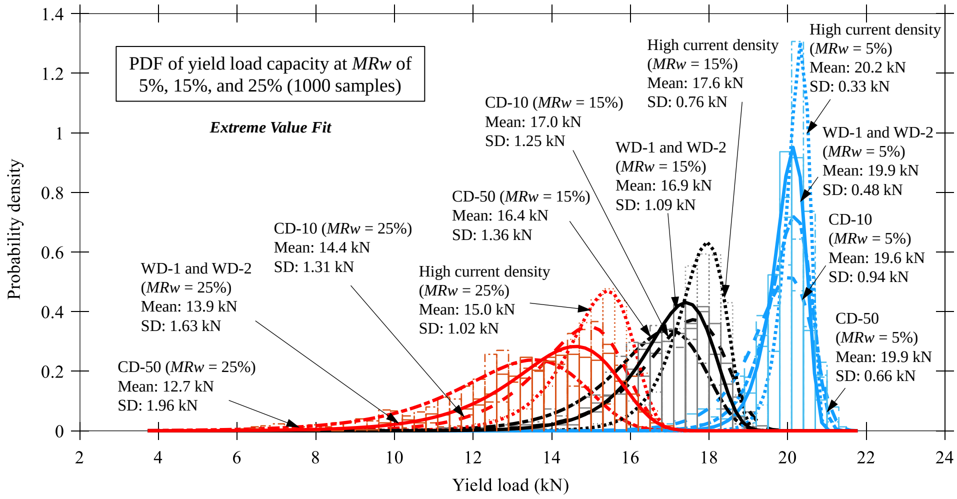

Figure 5. PDF of yield load capacity at *MRw* of 5%, 15%, and 25% based on regressions WD-1 and WD-2, CD-10, CD-50, and high current density.

4.2. Results and discussion for multiple-rebar specimens

4.2.1 Effect of spatial steel corrosion in transverse direction on the structural performance

Spatial steel weight loss of B30-1, and B30-2 are shown in Figures 6(a)-6(b), respectively. Corrosion of rebars intensified at the central parts of the RC beams corresponding to the wet sponge region as indicated by the two vertical dash lines, except for B30-1. Figures 6(a) and 6(b) show that the spatial steel corrosion of B30-1 and B30-2 is very different although the *MRw3* of B30-1 (27.9%) is slightly larger than that of B30-2 (27.1%). The distribution of the localized corrosion of rebars in this beam B30-1 occurred at different locations. Whereas, B30-2 shows localized steel corrosion over rebars concentrates at very similar locations which means maximum steel weight loss located approximately at the same places. As a result, the load-deflection relationship in Figure 7 shows the ultimate load (Pu) and deflection (δu) of corroded RC beam B30-1 are higher than those of B30-2.

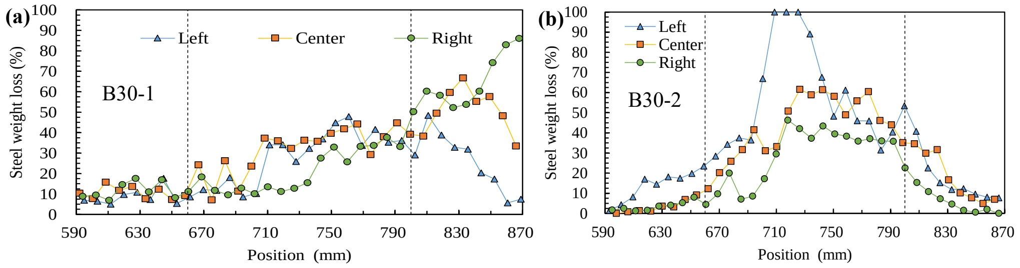

Figure 6. Spatial variability of steel corrosion of rebars in (a) B20-1, (b) B20-2, (c) B30-1 and (d) B30-2.

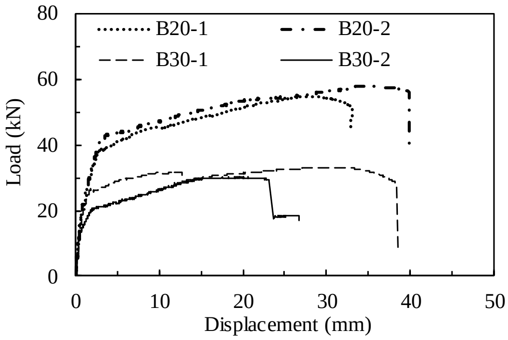

Figure 7. Load-deflection relationship of corroded RC beams.

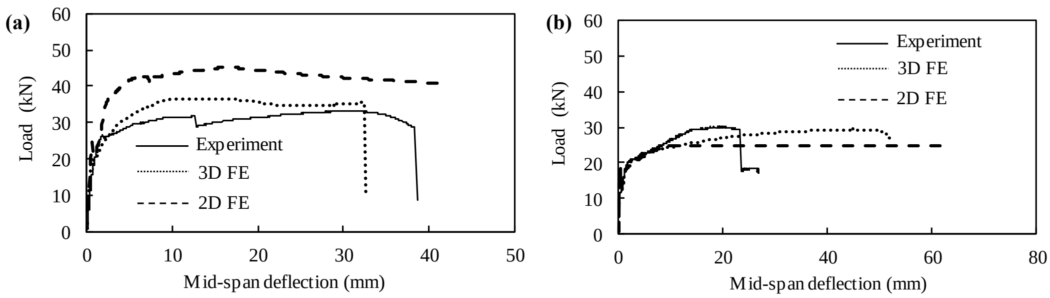

Figure 8. Experimental versus FE simulated P-δ responses of B30-1 and B30-2.

4.2.1 Structural performance assessment using 2D and 3D FE analysis

Figures 8(a) and 8(b) show the experimental versus 2D and 3D FE simulated P-δ responses of B30-1, and B30-2. In general, the 3D FE model can provide better estimation of flexural response of corroded RC beams with multiple rebars than the 2D FE model. However, Figures 8(a) shows that the 2D FE model substantially overestimated the load-deflection of B30-1. This result suggests that 2D FE model cannot well simulate the flexural response of the corroded beams with localized corrosion at different locations in the transverse direction (see Figure 6(a)). Since the performance of corroded beams strongly depends on the most corroded rebar in the transverse direction, the 3D FE model is needed to consider the dominant correlation effect of localized corrosion in the transverse direction for the multiple-rebar specimens. On the other hand, for B30-2 (Figure 6(b)) having the distribution of localized steel corrosion at a very similar locations, the 2D FE model can be used instead of the 3D model to estimate the structural performance of multiple-rebars since both models provided slightly different prediction results.

For more details, please refer to relevant references below for the publications during the research projects:

Sopokhem Lim, Jiyu Xin, Mitsuyoshi Akiyama, Zhejun Xu, Ao Li, Frangopol, D. M. and Miyazato, S. Effects of two corrosion acceleration methods on spatial steel corrosion and structural performance of RC beams. *Proceeding of the 11th International Conference on Bridge Maintenance, Safety and Management* (IABMAS 2022), July 2022, Barcelona, Spain (online conference).

Jiyu Xin, Mitsuyoshi Akiyama, Shinichi Miyazato, Dan M. Frangopol, Sopokhem Lim, Zhejun Xu, Ao Li. Effects of galvanostatic and artificial chloride environment methods on the steel corrosion spatial variability and probabilistic flexural capacity of RC beams. *Structure and Infrastructure Engineering*, 2022; 18(10-11): 1506-1525.

Sopokhem Lim, Zhang Mingyang, & Mitsuyoshi Akiyama. (2020). Effects of non-uniform steel corrosion on the structural behavior of RC beams. *Proceedings of the Tenth International Conference on Bridge Maintenance, Safety, and Management* (IABMAS2020), April 2021, Sapporo, Japan.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Jiyu Xin, Mitsuyoshi Akiyama, Shinichi Miyazato, Dan M. Frangopol, Sopokhem lim, Zhejun Xu, and Ao Li	４．巻 18
２．論文標題 Effects of galvanostatic and artificial chloride environment methods on the steel corrosion spatial variability and probabilistic flexural capacity of RC beams	５．発行年 2022年
３．雑誌名 Structure and Infrastructure Engineering	６．最初と最後の頁 1506-1525
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/15732479.2022.2061016	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Ramiz Ahmed Raju, Sopokhem Lim, Mitsuyoshi Akiyama, Takumi Kageyama	４．巻 262
２．論文標題 Effects of concrete flow on the distribution and orientation of fibers and flexural behavior of steel fiber-reinforced self-compacting concrete beams	５．発行年 2020年
３．雑誌名 Construction and Building Materials	６．最初と最後の頁 1-24
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conbuildmat.2020.119963	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　3件）

１．発表者名 Sopokhem Lim, Jiyu Xin, Mitsuyoshi Akiyama, Dan M. Frangopol, Zhejun Xu, Ao Li, and Shinichi Miyazato
２．発表標題 Effects of two corrosion acceleration methods on spatial steel corrosion and structural performance of RC beams
３．学会等名 International Association for Bridge Maintenance and Safety（国際学会）
４．発表年 2021年～2022年

１．発表者名 LIM Sopokhem
２．発表標題 Effects of non-uniform steel corrosion on the structural behavior of RC beams
３．学会等名 International Association for Bridge Maintenance and Safety（国際学会）
４．発表年 2019年～2021年

1．発表者名 LIM Sopokhem
2．発表標題 Reliability-based approach to determine the distances from coastline for stainless steel application in RC bridges under airborne chloride hazard
3．学会等名 International Association for Life-Cycle and Engineering（国際学会）
4．発表年 2019年～2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関