Committee Report : JCI- TC234A

Technical Committee on Evaluation of Corrosion Characteristics of Steel Bar in RC and PC Structures Focusing on Structural Performance

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Abstract

Evaluations of the structural performance of reinforced concrete (RC) structures damaged by steel bar corrosion require input parameters including steel bar corrosion characteristics (effective cross-sectional area and corrosion volume), concrete surface cracking features, and other variables. Limitations in obtaining these inputs may produce output values that diverge from actual behavior. Thus, the committee performed preliminary numerical analyses to identify factors critically affecting structural performance, demonstrated the application of nondestructive testing methods to acquire these inputs, and developed techniques to convert discrete data into continuous form. Moreover, the committee evaluated the structural performance of prestressed concrete (PC) structures and consolidated the results from joint experiments on both RC and PC specimens.

Keywords: Structural performance, steel bar corrosion, nondestructive testing, spatial distribution estimation, numerical structural analysis, prestressed concrete

1. Purpose of the Committee

Structural performance evaluations of reinforced concrete (RC) structures affected by steel bar corrosion require input values, including corrosion-property data (effective cross-sectional area and corrosion volume) obtained directly or indirectly through measurements, as well as information on the spatial distribution of surface corrosion cracking. However, no nondestructive method has been established to accurately evaluate corrosion properties from the concrete surface; consequently, investigators must select an appropriate method based on corrosion severity. Furthermore, corrosion-property measurements at discrete locations remain isolated, and no procedure currently extrapolates them into continuous spatial distribution information. Consequently, structural calculations often employ average or maximum corrosion-volume values for the entire steel bar, potentially yielding performance evaluations that diverge from actual structural behavior.

In light of these challenges, the technical committee aimed to develop a method to estimate temporal and spatial corrosion rates of steel bars in existing RC structures in accordance with current periodic inspection guidelines.

The committee composition is listed in Table 1, comprising five working groups (WGs). Initially, the RC Numerical Analysis WG assessed the influence of steel–bar corrosion within RC girder superstructures on structural performance, with emphasis on corrosion location and load application, and separated the analysis into single girders and multiple main girders. Thereafter, the Steel Bar Corrosion Assessment Method Examination WG systematically summarized various testing methods for steel bar corrosion based on these analyses. It also performed experiments using standard specimens with varying inherent chloride contents to elucidate the relationships among measurement results from each investigation method, the degree of rebar corrosion, and the amount of inherent chloride. Additionally, the Steel Bar Corrosion Rate Spatial Distribution Evaluation WG evaluated the use of probabilistic statistical methods to convert discrete corrosion-rate data from standard tests into spatial distributions.

Moreover, the PC Numerical Analysis WG assessed the structural performance of both RC and prestressed concrete (PC) structures. It examined the impact of steel–bar fractures in PC girder superstructures, including fracture location, the number of fractured steel bars, and loading position. Finally, the PC Steel Bar Integrity Survey WG compiled standards for PC-specific deterioration and deformation and performed joint experiments to survey PC grout filling status, steel–bar fractures, and residual prestress. The WG organized survey methodologies, integrating practical technologies with established research techniques.

This paper provides an overview of the committee's findings.

Table 1: Committee Members

Chairman of Committee	Hideki OSHITA	Chuo University
Secretary of Committee	Kentaro OHNO	Tokyo Metropolitan University
Secretary of Committee	Tomoko FUKUYAMA	Ritsumeikan University
Secretary of Committee	Syuichi SUZUKI	Pacific Consultants
Secretary of Committee	Akihisa KAMIHARAKO	Hirosaki University
Secretary of Committee	Yuta YAMADA	Nihon University
Committee members	Mitsuyoshi AKIYAMA	Waseda University
	Takashi OKUBO	Kawada Construction
	Yu OTAKE	Tohoku University
	Hisashi KANADA	Nippon Steel Technology Co., Ltd.
	Toshinori KANEMITSU	Central Research Institute of Electric Power Industry
	Takuya KONDO	National Institute of Technology, Kochi College
	Fumihiko SATO	Central Nippon Highway Engineering Tokyo Co., Ltd.
	Kenta TAKEDA	Nagoya Institute of Technology
	Nobuhiro CHIJIWA	Institute of Science Tokyo
	Kuniharu FUKUSHIMA	Nippon P.S. Co., Ltd.
	Norio FUJIWARA	International Engineering Consultants Association
	Hiroshi MATSUZAKI	Institute of Science Tokyo
	Koichi MATSUZAWA	Meiji University
	Yuki MURAKAMI	National College of Technology, Nagaoka College
	Yasutaka YAMASHITA	Nippon Expressway Research Institute Company Limited

2. RC Numerical Analysis WG

2.1 Overview of Activities

Within the WG, the impact of rebar corrosion on RC superstructures was analytically evaluated based on Sasaki et al.1) Specifically, the analysis assessed how corrosion location influences structural strength and endeavored to replicate the data via finite element analysis.

2.2 Experimental Overview

A scale bridge superstructure model was fabricated, comprising three connected RC T-girders topped by a deck slab. Rebar corrosion specimens were classified into three types: B0B and BBB with central corrosion, and SBS with non-overlapping corrosion locations (Fig. 1). Measured corrosion rates for individual girders were a maximum of 19.8%, a minimum of 9.8%, and an average of 13.9%. Loading employed a four-point bending test under a simply supported configuration.

2.3 Analysis Method

Finite element analysis was conducted using ATENA (ver. 5.9.1), dividing specimens into individual girders and superstructures. Fig. 2 depicts the element mesh diagrams for both configurations. The analysis compared healthy and deteriorated girders. Steel bar corrosion was modeled as a reduction in the cross-sectional area of the main rebars, with corroded sections located in the center and on the right. The cross-sectional area of the stirrups was similarly reduced in the corroded regions of the main rebars. Bond stress was decreased in accordance with the degree of steel corrosion for the bond stress–slip relationship. A corresponding superstructure analysis was performed under similar conditions.

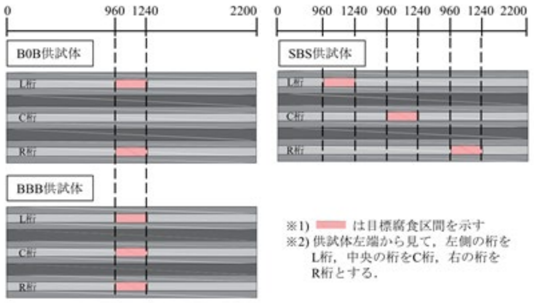

Figure 1. Arrangement of corroded sections in experiment

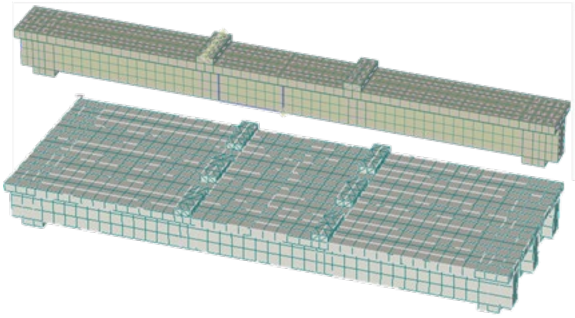

Figure 2. Element division diagram

2.4 Analysis Results

Figure 3 presents the load-displacement relationship for a single girder with centrally located corrosion. The bending load-bearing capacity decreased with increasing corrosion when the main rebars were affected in the center. Conversely, when corrosion occurred on the right, an increase in the corrosion amount resulted in a reduction of load-bearing capacity and ductility. Figure 4 presents the analysis results for the superstructure, where a comparison between experiment and analysis confirmed consistent trends. These findings indicate that load-bearing capacity can be considerably diminished if no sound sections exist adjacent to a deteriorated section.

2.5 Recommendations for Inspection Methods Based on Analysis Results

An analysis of a single girder determined that load-bearing capacity was substantially reduced by a corroded steel bar at the location of maximum bending moment. This outcome suggests that awareness of the load’s location and magnitude is imperative during structural inspections.

The analysis of the superstructure revealed that load-bearing properties varied significantly with the presence or absence of internal deterioration in an adjacent girder. Moreover, the structure’s safety is compromised by internal corrosion, even when the adjacent exterior surface remains intact. Consequently, non-destructive testing to verify the exterior integrity of intact sections adjacent to deteriorated portions is essential.

3. Steel Corrosion Assessment Method Examination WG

3.1 Purpose

As mentioned in Section 1, evaluating the structural performance of RC structures with steel-bar corrosion requires data on the spatial distribution of corrosion properties. Gathering such data and projecting it spatially requires measurements at multiple points.

Furthermore, surveys may involve a mixture of corroded and non-corroded steel bars within the same RC component owing to environmental factors such as rain exposure. Therefore, efficient maintenance and management become possible with non-destructive testing to investigate multiple locations and identify high-risk corrosion areas.

However, no established methods currently exist for nondestructively and accurately assessing steel-bar corrosion properties from the concrete surface; thus, an appropriate survey method must be selected based on the corrosion level.

This WG proposes a selection flow for nondestructive steel-bar corrosion testing methods and reports the results of applying various nondestructive techniques to joint test specimens to evaluate their applicability.

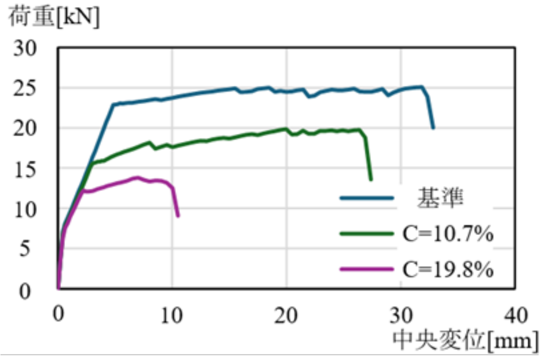

Figure 3. Load-central displacement relationship of single girder

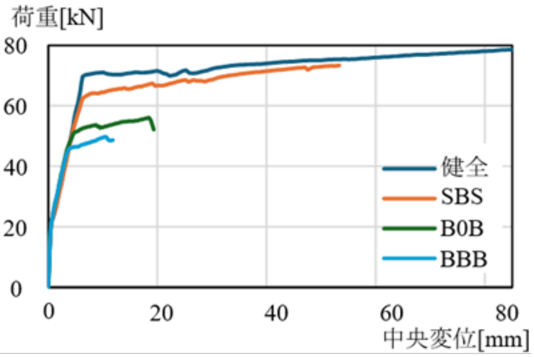

Figure 4. Load-central displacement

3.2 Classification and Selection of Steel Bar Corrosion Survey Methods, and Creation of Measurement Manual

The WG classified methods for estimating steel-bar corrosion (Table 2), referencing research by the Japanese Society for Non-Destructive Inspection Reinforced Concrete Division Rebar Corrosion Diagnostic Methods Technical Committee (September 2014–August 2018; Chairman Ohshita) and the Rebar Corrosion Diagnosis-Related Technical Guidelines Development Committee (September 2018–August 2022; Chairman Ohshita).

As direct corrosion measurement is impractical, a comprehensive evaluation integrating these techniques is essential. The WG provided detailed explanations of the principles and application methods of each measurement technology, systematically organized the investigation process, and proposed a selection approach.

3.3 Joint Experiments to Verify Applicability of Nondestructive Testing Methods

Nondestructive testing techniques are crucial for assessing the durability of existing RC structures. For large-scale specimens, these methods can obtain quantitative information over extensive areas, identify zones of advanced deterioration, and reduce the number of destructive tests.

The WG applied several nondestructive testing techniques to large-scale corroded specimens (Fig. 5), compared estimated concrete quality and steel bar corrosion conditions with the measured steel bar corrosion rate, and verified applicability by checking data consistency between various methods.

3.4 Joint Experiments on the Effect of Chloride Ion Concentration on Imaging of Steel Bars Using Electromagnetic Radar Methods

Research into estimating steel bar corrosion using electromagnetic radar methods has progressed in recent years. Studies have demonstrated that increased chloride content in RC structures induces electromagnetic wave attenuation, leading to reduced amplitude of waves reflected from steel bars. This phenomenon has been exploited to assess changes in electromagnetic wave characteristics and the risk of rebar corrosion caused by variations in chloride content.

The survey conducted with outdoor exposure test specimens in Section 3.3 confirmed that rebar images became unclear in specimens with high chloride content (Fig. 6). However, this effect was attributed to both rebar corrosion and cracking. Consequently, new crack-free test specimens were produced, and factors influencing electromagnetic wave attenuation were investigated in laboratory experiments.

Table 2: Nondestructive testing methods related to steel bar corrosion surveys

Subject	Method
Concrete quality and condition evaluation	Chloride ion measurement (drilling method and X-ray fluorescence method) ・Sampling and analysis methods
	Self-potential method: Estimation of environmental conditions
	Concrete surface strength
	Neutralization depth
Steel bar shape information	Electromagnetic radar method: Estimation of rebar diameter and cover thickness
	Electromagnetic induction method: Estimation of rebar diameter and cover thickness
Corrosion	Polarization resistance method (including AC impedance and dual-frequency methods): Evaluation

evaluation of steel inside concrete	of corrosion progression (cumulative corrosion amount)
	Indirect estimation of corrosion amount from corrosion crack width
	Actual chiseling ・Comparison of actual corrosion amount measurements and nondestructive estimation results

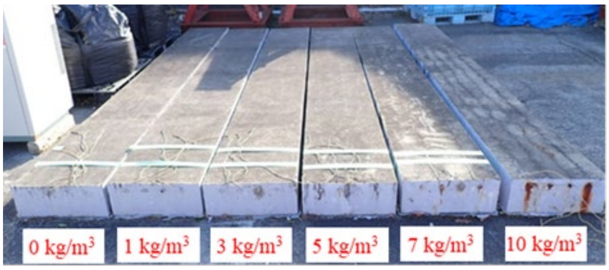

Fig. 5: Outdoor Exposure Test Specimen

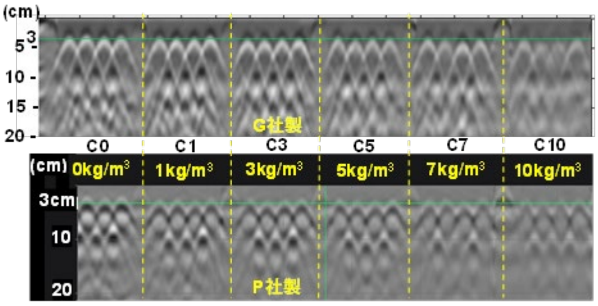

Fig. 6: Electromagnetic Radar Image of Outdoor Exposure Test Specimen

4. Steel Bar Corrosion Rate Spatial Distribution Evaluation WG

4.1 Purpose

Accurate evaluation of structural performance affected by steel bar corrosion requires information on the spatial distribution of corrosion characteristics and corrosion-induced surface cracking. As the extent of steel bar corrosion cannot be measured from the surface, rebar removal from the concrete is required—a process that damages the structure and limits the measurable quantity. Typically, either the average or maximum measured steel bar corrosion is used as input in structural calculations to represent the corrosion level of the entire structure. Accuracy in evaluating the structural performance of corrosion-affected structures increases when measured corrosion levels can be converted into reliable spatial information. Therefore, the WG examined approaches to characterize the spatial variability and uncertainty of steel bar corrosion and to incorporate this information into structural performance evaluations. Nevertheless, direct measurement of steel bar corrosion damages the structure, complicating the acquisition of sufficient data for spatial conversion. Accordingly, the WG investigated a method for estimating the spatial distribution of steel bar corrosion from corrosion crack widths on the concrete surface.

4.2 Study Content

In geotechnical engineering, spatial distribution estimation typically employs techniques such as kriging or Gaussian process regression (GPR). Kriging was originally devised by South African mining scientist D. G. Krige and statistician H. S. Sichel to improve calculation methods for mineral resource reserves and was later formalized by G. Matheron within the framework of probability theory3). Moreover, GPR was established as a statistical machine learning method based on Bayes' theorem4). Both methods share the basic principle of predicting via linear combinations; however, the former targets two- or three-dimensional space, whereas the latter applies to multidimensional space. Furthermore, the two methods exhibit differences in representation attributable to variations in their development. In this WG, we employed the latter, GPR, to examine the spatial distribution estimation and spatial features of steel bar corrosion rates.

This study estimated the spatial distribution and characterized steel bar corrosion using measurements from residual strength tests on specimens subjected to electrolytic corrosion and from exposure test specimens in Section 3.3. The results confirmed that the GPR-based estimation of steel bar corrosion yielded minor errors and proved fully applicable. Analysis of the estimated distribution indicated that the spatial correlation range was greater for corroded rebars in exposure tests than for those corroded by electrolytic corrosion. Nonetheless, even in the exposure test, the correlation range was only about 1 m, confirming the limited range of influence. The study also compared GPR with recent methods in the literature for estimating the spatial distribution of steel bar corrosion from corrosion crack width. In cases where corrosion crack width and steel bar corrosion were highly correlated, GPR enabled quantitative estimation of the corrosion distribution tendency; however, estimating local fluctuations remained challenging. Recent research proposed advanced spatial distribution estimation techniques that integrate image analysis, FEM analysis, and machine learning algorithms5),6).

4.3 Summary of this WG

The WG aimed to compile knowledge on these methods. It applied spatial distribution estimation approaches from geotechnical engineering to assess steel bar corrosion distribution and characteristics. The results confirmed these approaches' applicability to estimating steel bar corrosion distribution while revealing a limited spatial correlation range. Further findings demonstrated that estimation based on corrosion crack width enabled identification of distribution trends, although detailed estimation remained challenging. The WG also reviewed the latest research to consolidate its knowledge.

5 PC Numerical Analysis WG

5.1 Significance and Purpose of Numerical Analysis of PCT Girder Bridges

Evaluating PC structure integrity requires collecting data on PC steel bar deterioration, which critically impacts load-bearing performance, and on the deterioration locations within the structure to pinpoint key inspection points. The deterioration state varies widely with the structure's operating environment and materials, making the determination of a unified impact on load-bearing performance based on observed phenomena and experimental results difficult. Accordingly, the WG employed numerical analysis to assess the impact of PC steel bar deterioration on the structure's load-bearing performance by conducting a three-dimensional finite-element analysis of a PCT girder bridge with deteriorated PC steel bars. A sample based on an actual simple PCT composite girder[7),8)], which had been in service for 44 years, was selected for analysis. Initially, the WG analyzed a single girder with deteriorated PC steel bars to ascertain the overall effect on load-bearing capacity. Subsequently, an analysis of a multi-girder bridge with these components was performed to assess the system-wide impact and compile data for identifying critical inspection points.

5.2 Impact of PC Steel Bar Deterioration on Load-Bearing Performance of Single PCT Girder

(1) Impact of PC Steel Bar Deterioration at the Center of Span

The WG modeled prestress relaxation from the fracture point, assuming that a PC steel bar at the center of the span—where bending moments become pronounced—fractured owing to corrosion. The analysis results were then employed to delineate the impact of the fracture on reducing load-bearing capacity, increasing crack occurrence, and generating side effects on durability.

(2) Effect of PC Steel Bar Deterioration in Sag Section

The WG aimed to evaluate the impact of PC steel bar deterioration on load-bearing capacity through analyzing an extreme case of PC steel bar fracture at the beginning of the sag section—a region susceptible to deterioration owing to incomplete grout filling—using the fracture location as an analytical variable. The analysis indicated that bending theory may overestimate strength when fracture locations align in the cross-sectional direction, despite a constant number of fractures; the WG further examined the underlying causes.

(3) Effect of Considering Bond Loss and Other Factors

Residual bending strength following a PC steel bar fracture was approximately estimated from the residual steel bar cross-sectional area at the point of maximum applied bending moment, whereas shear strength was predicted by accounting for the complex influence of prestressing on shear load-bearing capacity. Consequently, the WG analyzed PC steel bar fractures at the anchorage end of the sag section, using both the bond recovery section from the fracture and the loading position as analytical variables. This analysis summarized the effects on failure mode and load-bearing performance.

5.3 Load-bearing Performance of PCT Girder Bridges with Deteriorated Girders

The WG analyzed a PCT girder bridge with one girder containing a deteriorated PC steel bar, as described previously. The analysis accounted for both the girder's position and the location of the PC steel bar fracture. The WG then summarized how fractures at midspan versus quarter-span influenced overall load-bearing performance.

6. PC Steel Bar Integrity Survey WG

6.1 Survey Contributing to PC Steel Bar Integrity Evaluation

(1) Current Status and Issues of PC Structures and PC Steel Bar Integrity Evaluation

Deterioration in PC structures encompasses damage to PC steel bars, grout, and anchorages. A comprehensive evaluation of PC structure integrity requires understanding the concrete condition, which dictates durability, and the prestressing state, which determines load capacity. Accordingly, inspections address both concrete and PC steel bar integrity. Notably, PC steel bars represent essential components, with assessments based on their deterioration status. However, because internal bar deterioration does not invariably correlate with external decay, predicting deterioration remains challenging. Observing the condition of PC steel bars in PC structures is challenging owing to their encasement in concrete. Additionally, the application of prestressing force increases prestressing strength compared to RC structures, thereby complicating evaluations of PC steel bar integrity.

(2) Significance and Purpose of PC steel bar Integrity Survey

A primary concern in PC structures is load-bearing capacity. Thus, verifying prestress maintenance is imperative. A PC steel bar fracture yields a notable decline in load-bearing capacity. Currently, accurately assessing residual prestress in existing PC structures remains challenging. Moreover, no established nondestructive method exists for inspecting PC steel bar corrosion. Therefore, evaluations of PC steel bar integrity require surveys for fractures and assessments of PC grout filling. The inspection of PC grout-filling status and the corrosion and fractures of PC steel bars in post-tensioned PC structures serves to confirm these abnormalities.

(3) PC Steel Bar Integrity Survey Methods

Assessing the load-bearing capacity and durability of PC structures necessitates accurate evaluations of prestress magnitude and PC steel bar integrity. Survey methods vary and are generally classified as minimally destructive or nondestructive. Minimally destructive surveys are limited to specific areas owing to inherent damage and limited repeat measurements. Although ultrasonic methods have been explored for non-destructive prestress determination, they remain impractical. Analysis suggests magnetic flux leakage can determine the presence and location of fractures in PC steel bars. Surveys evaluating PC grout filling extent are limited in scope and often supplemented with drilling to improve accuracy, and no methods currently exist to assess potential corrosion in PC steel bars non-destructively.

6.2 Joint Experiments Contributing to PC Steel Bar Integrity Evaluations

(1) Purpose of Joint Experiments

The WG conducted joint experiments on post-tensioned PC specimens to evaluate nondestructive testing methods for PC steel bar integrity. These experiments aimed to detect fractures, assess the extent of PC grout filling, and measure prestress levels using both practical and research-stage methods. Thus, the WG clarified the measurement principles and application conditions of each method and summarized the associated challenges.

(2) List of Survey Methods

The survey methods employed in the joint experiments are summarized in Table 3, and an overview of the specimens utilized is provided in Table 4.

(3) Summary of Results of Joint Experiments

The WG assessed the current status of each method during experimentation. The survey of PC–grout filling status clarified the applicability scope of each method and enumerated salient precautions. The survey of PC–steel bar fracture illustrated the influence of cover thickness and rebar presence. In the prestressing amount assessment, stress levels were evaluated under various conditions, including a simulation of PC–steel bar fracture.

Table 3: List of survey methods used in PC member

Survey content	Survey method	
PC grout filling status	Ultrasonic method	Wide-range ultrasonic testing (WUT)
		Longitudinal wave multiple reflection method
		Image scanner method
	Impact elastic wave method	iTECS method
		Amplitude differential method
		PRA-TICA (combined multiple reflection and transmission method)
	Electromagnetic pulse method	
PC steel bar fracture survey	Magnetic flux leakage method	
Prestressing level	Ultrasonic method	

Table 4: Overview of PC member

Survey content	Specimen overview
PC grout filling status	PCT girder specimen PC steel strand Sheath diameter φ65mm Cover depth approx. 130–140 mm
	Vertical steel bar specimen PC steel bar Sheath diameter 38 mm Cover depth approx. 200, 275mm

PC steel bar fracture survey	PC steel strand / PC steel bar Sheath inner diameter：70，45，40mm Cover depth：100，105，110mm
Prestressing level	Plate size：2500×1500×200mm Tension control using four PC steel bars

7. Conclusion

The authors investigated the effect of steel bar corrosion on PC structural performance via numerical analysis, identified regions with the greatest structural vulnerability, assessed nondestructive testing applicability for those regions, and evaluated methods for converting discrete data into continuous form. In RC joint experiments, specimens exhibited varying inherent chloride content, whereas PC experiments incorporated steel bar fracture, grout filling level, and residual prestress parameters. Collectively, these studies systematically summarized methods for diagnosing steel bar corrosion with an emphasis on structural performance. The authors examined the impact of steel bar corrosion on the structural performance of PC and PC structures through numerical analysis, identified areas with the greatest structural impact, examined the applicability of various nondestructive testing methods to the selected areas, and examined estimation methods for converting acquired discrete data into continuous data. In addition, for RC, the authors conducted joint experiments using specimens with varying levels of inherent chloride content. For PC, the authors conducted joint experiments using specimens with steel bar fracture, grout filling level, and residual prestress as parameters. Through these studies, the authors systematically summarized methods for understanding and diagnosing steel bar corrosion with a focus on structural performance.

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