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Deterioration progress and performance reduction of 40-year-old reinforced concrete beams in natural corrosion environments

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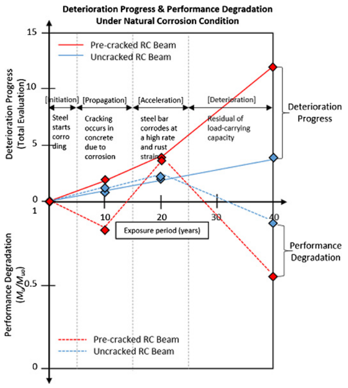
HIGHLIGHTS

- Two 40-year-old RC beams were tested after natural corrosion process.
- Good correlation was observed between crack width and cross-section loss.
- A relationship between cross-section loss and ultimate capacity loss was observed.
- The deterioration period of a naturally corroded RC beam was determined.
- Deterioration progress and performance degradation were observed with exposure.

GRAPHICAL ABSTRACT



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ABSTRACT

Deterioration progress and performance reduction were experimentally evaluated in 40-year-old corroded reinforced concrete (RC) beams. The corrosion process was natural, without acceleration by current application, admixture inclusion, or exposure to an artificial chloride environment. The mechanical performance of the beams was evaluated through a four-point bending test. The corroded steel reinforcing bars were extracted for corrosion evaluation and tensile testing. A good correlation was established between crack width and cross-section loss, as well as between cross-section loss and ultimate capacity loss. Furthermore, the relationship between deterioration progress and performance degradation with the exposure period for each deterioration stage was elucidated.

1. Introduction

The corrosion of reinforced concrete (RC) is the most dominant causal factor for the premature deterioration of concrete structures. The corrosion of steel bars affects the performance of RC beams, causing increases in both the deflections and the crack widths under service loads, and decreases in the strength under ultimate loading [1]. Furthermore, Rodriguez et al. [2] reported that a corrosion degree of approximately 14% caused the beam strength to decrease by 23%, while Misra and Uomoto [3] found that only 2.4% corrosion generated a 17% reduction in beam strength. The ductility of RC is also remarkably affected by reduc-

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tion in the cross-sectional area of the steel reinforcement. Cairns et al. [4] reported that a bar with a maximum reduction in cross-section of 8% lost approximately 20% of its original ductility. Previous studies have evaluated the flexural strength of corroded RC members [1,5–7]. Huang and Yang [5] studied the changes in the flexural behavior of RC beams due to reductions in the reinforcing steel cross-sectional area. Yoon et al. [7] evaluated the residual flexural capacity as a function of the percentage weight loss of the reinforcing steel, one effect of reinforcement corrosion on the residual load capacity. Rodriguez et al. [1] studied the bending and shear strengths of an RC beam affected by reinforcement corrosion. In addition, the relationship between the degree of reinforcement corrosion and the residual strength of flexural members was investigated by Mangat and Elgarf [6].

Studies on the behavior of naturally corroded RC beams are limited at present. In most previous research, corrosion was accelerated by applying an external current [6–10] or by the admixture of $CaCl_2$ or NaCl into the concrete [5,11–13]. However, by such artificial acceleration, corrosion of the surface of the steel bar is homogeneous, whereas under natural corrosion, corroded areas are distributed heterogeneously and concentrated on the lower half of the steel bar surface [9]. The ultimate deflection is not modified by artificial corrosion processes, but is strongly reduced under natural corrosion. This is one of the main differences between the behaviors of artificially and naturally corroded RC beams. Morinaga [14] reported that a bar corroded in service exhibited a larger reduction in strength and elongation than the bar exposed to accelerated corrosion. Otieno et al. [15] and Yuan et al. [9] reported on cyclic wetting–drying, a corrosion acceleration technique that mimics natural corrosion. Therefore, several studies [16–21] have conducted long-term corrosion testing under chloride environments, which were formed by saline fog and wetting–drying cycles in laboratory conditions of confined rooms. The saline fog could be generated by spraying a 35-g/L NaCl solution.

In this study, two 40-year-old RC beams, exposed to real marine environments (i.e., tidal and splash zones) for up to 20 years, are tested and compared. The beams are categorized into two conditions in terms of pre-cracking, denoted as A and B. Condition A indicates the presence of pre-cracks (henceforth abbreviated as RC-S-A), while condition B indicates no pre-cracking (henceforth called RC-S-B). The corrosion process was natural, without acceleration by applied currents, admixtures, or artificial chloride environments. The aim of the study is to understand the influence of pre-cracks on the performance of the RC-S-A beam under natural corrosion processes. The effects of pre-cracks on the steel bar cross-sectional loss, ultimate capacity loss, and mechanical strength are also presented. Moreover, the study presents the mechanical and corrosion behavior of the RC-S-B beam, without pre-cracks, with the natural corrosion process. The deterioration progress and performance degradation of the RC beam, including the cross-sectional loss of steel bars and the ultimate moment capacity, were analyzed in this work.

Table 1
Summary of aggregates.

Aggregate	Specific gravity	Fineness modulus
Fine river sand	2.25	2.84
Coarse-crushed stone	2.75	6.63

2. Materials and methods

2.1. Composition

Normal Portland cement was used to make the concrete. The properties of the aggregate are presented in Table 1 and the mix proportions of the concrete are presented in Table 2. After casting, the beams were moisture-cured for one day and demolded before being air-cured until exposure began.

2.2. Material properties

After completing the ultimate loading tests, described in Sections 3.2 and 3.4, several cores of 50 mm in diameter and 100 mm in height were taken from each beam in the areas that did not crack during the bending tests. The compressive strength for the concrete was obtained from the average of ~3–4 core specimens. The average compressive strength and the elastic modulus were 30 MPa and 27 GPa, respectively. The compressive strength after 28 days of curing was similar to the compressive strength after corrosion. The average compressive strengths and elastic modulus of ~2–5 cylinder specimens, measuring 100 mm in diameter and 200 mm in height, were 30 MPa and 22 GPa, respectively.

2.3. Beam details

Two RC beams were used for evaluation. Both beams measured 2400 mm in length, with identical cross-sectional areas of 150 × 300 mm, called S-shapes. Longitudinally deformed steel bars with diameters of 13 mm and yield strengths of 363 N/mm^2 were embedded as shown in Fig. 1. Additional round steel bars of 6 mm in diameter were embedded as compressive bars and stirrups with a spacing of 100 mm. A detailed cross-section of the test beam configuration is shown in Fig. 1.

2.4. Exposure conditions

The beams were exposed to a real marine environment for 20 years (1975–1995) at Sakata Port (see Fig. 2), which is located in northwestern Japan (38°56·N, 139°47·E) facing the Sea of Japan. The average annual temperature is ~11.9 °C. The minimum temperature between December and March is below 0 °C almost every day, which may cause freezing and thawing action. Furthermore, during the winter, the daily maximum wind velocity exceeds 25 m/s, which produces significant splashing. The beams were located in the tidal zone, just in front of a caisson-type quay wall, two months after the placement of the concrete. Here, the beams were subjected to alternating wet and dry conditions because of tidal action.

A summary of the exposure conditions is as follows:

- 0 to 20 years: real splash zone and tidal marine environment at the Sakata Port. The exposure site view is shown in Fig. 2 [22–25] (1975–1995).
- 20 to 35 years: stored and sheltered from the rain at the Port and Airport Research Institute (PARI) laboratory in Yokosuka, Japan (1995–2010).
- 35 to 40 years: stored at Kyushu University in Fukuoka, Japan (2010–2015).

2.5. Loading system

As described in Section 1, the beams are categorized based on the existence of pre-cracking. The RC-S-A specimen was pre-cracked through the application of a bending moment of 0.75 M_u, where M_u is the ultimate bending moment. The pre-cracked bending moment exceeded M_{crd}, where M_{crd} is the design cracking bending moment, equal to 0.2 M_u. After cracking, the bending moment was released, and no continuous load was applied during exposure. According to the JSCE Standard Specification [26] with each safety factor set to 1.0, the calculated ultimate flexural moment of the RC beam is 34.8 kN·m, which corresponds to a load of 99.4 kN.

Table 2
Mix proportions of concrete.

Concrete	MSA (mm)	Slump (mm)	Air (%)	w/c %	s/a %	Unit weight (kg/m^3)				
						W	C	S	G	Adm.
RC	20	12 ± 2	4 ± 1	68	47	204	300	793	964	1.2

MSA: maximum size of coarse aggregate; W: water; C: cement; S: sand; G: gravel; Adm.: admixture.