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Effects of simultaneous fatigue loading and corrosion on the behavior of reinforced beams

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HIGHLIGHTS

- Effects of simultaneous fatigue loading and corrosion on RC beams were studied.
- Different fatigue loads, current and loading frequencies were considered.
- The inclusion of corrosion significantly decrease the ductility and fatigue life.
- General and local corrosion simultaneously occurs under corrosion fatigue.
- The flexural stiffness of RC beams exhibits three-stage characteristic.

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ABSTRACT

This paper investigated experimentally the behavior of reinforced concrete (RC) beams under simultaneous fatigue loading and steel corrosion. Fourteen specimens were manufactured and tested under four-point bending fatigue loading, during which reinforcement corrosion was induced by an accelerated method using a 5% NaCl solution combined with a constant impressed current. Four different levels of maximum fatigue loads, namely 50%, 55%, 65% and 75% of ultimate loading capacity with fatigue loading frequencies of 1.5 Hz and 4.5 Hz and corrosion impressed currents of 0.5 A, 1.0 A, 1.5 A and 2.5 A were applied to the beams. Crack patterns, failure modes, fatigue life, reinforcement corrosion, and flexural stiffness were investigated. Test results indicated that the inclusion of corrosion significantly decreased the ductility, fatigue life and flexural stiffness of the RC beams. Greater levels of maximum fatigue loads and impressed current tended to shorten fatigue life. General and local corrosion occurred simultaneously under the joint effects of fatigue loading and corrosion. It was also found that the flexural stiffness of RC beams under coupled fatigue loading and corrosion increased in early loading cycles and then remained approximately stable, followed by a rapid decrease just prior to failure.

1. Introduction

Steel reinforcement corrosion is one of the primary problems causing significant damage to reinforced concrete (RC) structures. The corrosion could significantly decrease load-carrying capacity and durability by causing steel cross-sectional area reduction, cracking, spalling of concrete cover, and bond degradation between reinforcing bars and surrounding concrete [1]. Numerous coastal RC structures, which included RC bridges, offshore plats, and mobile drilling structures, were subjected to cyclic loading combined with chloride-induced steel corrosion [2,3]. This is known as coupled corrosion-fatigue, or the corrosion fatigue phenomenon, in which failure occurs prematurely under conditions of simultaneous fatigue loading and corrosion after a smaller number of cycles or at lower stress levels than would have been observed in the absence of a corrosive environment [4].

Over the past decades, extensive studies have been devoted to the separate effects of corrosion or fatigue loading on RC beams, in which load-carrying capacity, including flexural strength [5–8] and shear capacity [9–11], bending stiffness [12,13], corrosion-induced cracks [14–17], bond strength loss [18–22] of corroded RC beams, and fatigue damage model [23,24], fatigue life prediction [25], and fatigue stiffness [26] of uncorroded RC beams, were investigated. These results indicated that corrosion, specifically local and pitting corrosion, had a significant effect on the mechanical performance and service life of RC beams, while pure fatigue loads within an allowable range had no significant influence.

In addition to concerns regarding the effects of pure corrosion or fatigue loading, fatigue testing of already-corroded beams was

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conducted by a number of researchers. Sun et al. [27] developed a modified calculation formula for fatigue flexural stiffness as well as a constitutive relationship model for reinforcing bars considering the effects of the corrosion mass loss ratio and the number of fatigue loading cycles. Oyado et al. [28] reported that corrosion could change crack patterns, and the decrease in fatigue strength was proportional to the weight loss of the steel reinforcement. Yi et al. [29] reported that an increase in corrosion caused a decrease in fatigue life. Ma et al. [30] proposed a new method for fatigue life prediction of aging RC structures.

With respect to the coupled effects of corrosion and sustained loading, a few experimental studies have been published [31–34]. Test results suggested that steel mass ratios and corrosion-induced crack widths were increased, and the capacity and ductility of beams were significantly under loading [31]. In addition, load levels had a significant effect on the increase in amount of steel corrosion [33].

The above mentioned studies all dealt with either the separate effects of corrosion and fatigue loading, in which corrosion and fatigue loading did not coexist simultaneously in the tests, or the coupled effects of corrosion and sustained loading where loading remained constant during the tests. Only limited studies have been conducted on the coupled effects of corrosion and fatigue loading. Bastidas-Arteaga et al. [35] proposed a new theoretical model based on the coupled corrosion-fatigue phenomena in analytical methods and concluded that coupled corrosion-fatigue had a significant effect on the performance of RC structures and significantly decreased their expected lifespans. Zhang et al. [36] developed a theoretical reliability-based approach for evaluating the damage of the combined effects of pitting corrosion and fatigue loading. W. Ahn at al. [37] conducted a galvanostatic test of full- and half-sized RC beams under static and fatigue loading with different water-cement ratios, and reported that more significant damage of RC beams was induced with fatigue loading and increasing water-cement ratio. However, the studies in [35,36], which were primarily theoretical and based on certain specific hypotheses, including that single pitting corrosion is considered during corrosion fatigue and concrete is a homogenous and isotropic material when using Fick's second law, might not be consistent with the situations in practice. The study in [37] conducted tests focused on the cracking patterns and ultimate strength bearing capacity of beams. Limited studies have investigated the coupled effects of corrosion and fatigue on the performance of RC beams, specifically for the study of fatigue life, steel corrosion, and flexural stiffness of beams under simultaneous corrosion and fatigue loading.

The primary objectives of this study were to experimentally investigate the effects of fatigue loads, corrosion current, and fatigue loading frequency on fatigue life of RC beams; characterize reinforcement corrosion in terms of mass loss and average corrosion rate; and examine the joint effects of fatigue loading and corrosion on the flexural stiffness of RC beams. The results of the study could provide insights on the joint effects of corrosion and cyclic loading on the behavior of corroded RC beams.

2. Experimental program

2.1. Specimens

In this study, fourteen RC beam specimens were prepared and divided into three groups: two specimens subjected to monotonic static loading (Group A), one specimen subjected to cyclic fatigue loading (Group B), and the remaining eleven specimens subjected to simultaneous fatigue loading and corrosion (Group C). The test parameters included:

- maximum fatigue load: 50%, 55%, 65% and 75% of ultimate loading capacity;
- impressed corrosion current: 0.5A,1.0A,1.5A and 2.5A;
- fatigue loading frequency: 1.5 Hz and 4.5 Hz.

The 0.5–2.5 A current, which corresponded to a current density of 1327–6635 $\mu A/cm^2$ was greater than that of the bulk of previous studies, which typically ranged from 200 to 3000 $\mu A/cm^2$ [38]. The load level of 55–75% was marginally greater than the specified value according to GB50010-2010 [39]. The values selected were aimed at appropriately shortening the time of corrosion fatigue test as the test was both labor-intensive and time-consuming. The inclusion of frequencies from 1.5 to 4.5 Hz was because frequencies in typical engineering structures ranged from 1 to 5 Hz.

A summary of the specimens is presented in Table 1. The designations of the specimens were defined as follows: C-4.5-50-1.5, where 'C' was the group, '4.5' was the fatigue loading frequency, '50' was the percentage of maximum fatigue load to the ultimate loading capacity, and '1.5' was the level (A) of the impressed corrosion current.

All beams were cast as follows: 200 mm deep, 120 mm wide, and 1700 mm long. In addition, a calculated length of 1500 mm and a constant-moment section length of 500 mm were designed for four-point bending loading. Each beam was reinforced with two 12-mm deformed bars in tension, and two 8-mm plain bars in compression. Smooth stirrups with a diameter of 6.5 mm were spaced at 80 mm intervals within the shear span. The dimensions and steel reinforcement arrangement of the beams is shown in Fig. 1. The tensile reinforcement in the constant-moment section was designed to corrode. All other steel including the tensile rein-

Table 1
Details of the specimens.

Groups	Specimens	Frequency (Hz)	Fatigue loads	I (A)	Loading scheme
A	A-1	–	–	–	Monotonic loading
	A-2	–	–	–	
B	B-1	4.5	0.1 P_u-0.55 P_u	–	Fatigue loading
C	C-4.5-50-1.5	4.5	0.1 P_u-0.5 P_u	1.5	Fatigue loading
	C-4.5-55-1.5	4.5	0.1 P_u-0.55 P_u	1.5	
	C-4.5-65-1.5	4.5	0.1 P_u-0.65 P_u	1.5	
	C-4.5-75-1.5	4.5	0.1 P_u-0.75 P_u	1.5	
	C-4.5-55-0.5	4.5	0.1 P_u-0.55 P_u	0.5	
	C-4.5-55-1.0	4.5	0.1 P_u-0.55 P_u	1.0	
	C-4.5-55-2.5	4.5	0.1 P_u-0.55 P_u	2.5	
	C-1.5-55-0.5	1.5	0.1 P_u-0.55 P_u	1.5	
	C-1.5-55-1.0	1.5	0.1 P_u-0.55 P_u	1.5	
	C-1.5-55-1.5	1.5	0.1 P_u-0.55 P_u	1.5	
	C-1.5-55-2.5	1.5	0.1 P_u-0.55 P_u	1.5	

Note: *P*u is the ultimate loading capacity of the uncorroded beam.