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Corroded reinforced concrete beams under low-speed and low-cycle fatigue loads

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HIGHLIGHTS

- Low-cycle fatigue behavior of corroded RC beams are studied experimentally.
- The fatigue cycles decreased with the increase of mass loss.
- The fatigue design curve of CEB-FIP 2010 is safe for corroded RC beams.

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ABSTRACT

The study performs experimental investigation of the behavior of reinforced concrete (RC) beams with corroded steel reinforcement under low-speed and low-cycle fatigue loads. A total of 14 specimens were tested. The results indicated that the fatigue life cycles decreased by 88.7% when the mass loss increased from 1.56% to 12.56%. The fatigue lives from the present tests were compared with those from other experimental studies and predictions from the CEB-FIP 2010 code and indicated that the fatigue life of concrete estimated by the code is safe for a corroded beam under low-cycle fatigue loading.

1. Introduction

In an aggressive environment, the corrosion of steel reinforcement is a major concern for the durability of reinforced concrete (RC) structures. Corrosion can reduce the capacity of an RC beam through several mechanisms including the loss of the cross-sectional area of a reinforcing bar [1–3], reduction in the concrete section due to cracking and spalling of concrete[4,5], and deterioration of bond between the steel reinforcement and concrete [6–9].

Recently, there is significant interest in the load bearing capacity of corroded RC structures [10–14]. Higgins and Farrow conducted an experimental investigation of corrosion on the shear capacity of conventionally-reinforced concrete beams. Tests indicated that corrosion damaged specimens exhibited reduced shear capacity. Sequentially-damaged stirrups significantly affected the structural performance of test specimens [15]. Gao et al. conducted an experimental study to investigate the effects of sustained loading and pre-existing cracks on corrosion behavior of reinforced concrete slabs. They concluded that pre-cracked initial condition and sustained loading caused a larger reduction in the ultimate load carrying capacity [16]. El-Sayed et al. examined the influence of stirrup corrosion on shear strength of reinforced concrete beams. They indicated that the reduction in shear strength is more pronounced when the corrosion level increased [17]. Ou and Nguyen investigated the effects of location of reinforcement corrosion on the seismic performance of corroded reinforced concrete beams. The results indicated an insignificant effect on the peak load and the ultimate drift when the failure mode was caused by the fracture of tension reinforcement [18]. Wei et al. examined the residual load capacity of a corroded reinforced concrete beam undergoing bond failure. They concluded that the bond in the anchorage significantly affects the corroded beam undergoing bond failure [19]. In conclusions, the consequences of corrosion in RC structures include reduced load bearing capacities and a weakened bond between concrete and reinforcement.

With respect to RC structures under repeated loading, such as RC railroad bridges and crane girders, fatigue may be the most significant factor that controls the design [20–23]. The fatigue failure of an RC structure is a result of the damage to the material components (concrete or steel) and the bond between them [24]. Therefore, fatigue-resistant design of RC structures is generally

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classified as a capacity limit state. The fatigue strength of concrete decreases with increases in the magnitude of repeated loading and the number of cycles [25]. If the cyclic stress of reinforcing steel exceeds its allowable fatigue stress, then the fatigue failure of an RC beam is dominated by the steel reinforcements [26–28]. Conversely, if the compressive stress of concrete exceeds its allowable fatigue stress, the flexural capacity of an RC beam may be controlled by the fatigue strength of concrete [29–31]. A number of studies considered the combined effects of corrosion and fatigue loading. Apostolopoulos and Papadopoulos investigated low-cycle fatigue behavior of corroded reinforcing steel bars S400 and S500. The results indicated that low-cycle fatigue resistance of steel bars was closely related to the level of corrosion [32,33]. Yi et al. examined the fatigue behavior of reinforced concrete beams with corroded steel reinforcement. It was noted that increase in the degree of corrosion of the steel reinforcement decreased the fatigue life of the beams and led to their collapse in a brittle failure mode [34]. Sun et al. tested corroded RC beams and reinforcing bars under repeated loading. They indicated that the flexural stiffness of corroded RC beams reduced under repeated loading [35]. Al-Hammoud et al. examined the fatigue flexural behavior of corroded reinforced concrete beams repaired with CFRP sheets. They indicated that repair with CFRP sheets increased the fatigue capacity of the corroded beams [36]. Ma et al. examined the corrosion fatigue behavior of aging reinforced concrete beam based on crack growth [37–39]. Li et al. examined low-cycle fatigue behavior of corroded and CFRP-wrapped reinforced concrete columns and concluded that steel corrosion reduces low-cycle fatigue life of reinforced concrete columns [40]. Sheng et al. conducted an experimental study on the fatigue behavior of RC beams strengthened with TRC after sustained load corrosion. They indicated that a combination of sustained load and corrosion led to a greater decrease in the fatigue life of the beams than those under either a sustained load or corrosion alone [41].

Despite several studies on the fatigue behavior of corroded beams, there is a paucity of tests on low-cycle fatigue behavior of corroded beams, and extant tests primarily focus on high-speed fatigue load applied by a fatigue machine. Additionally, the actual speed of loading in most practical cases may be significantly lower than those applied by the fatigue loading machine [42]. The present study focuses on experimental studies to investigate the low-cycle fatigue behavior of RC beams with corroded longitudinal reinforcement under a low-speed loading. A total of 14 specimens (150 × 300 × 3300 mm) were tested. Two specimens corresponded to controlling specimens with uncorroded rebars and 12 specimens corresponded to RC beams with corroded longitudinal reinforcement. A specimen was tested under monotonic loading, and 13 specimens were tested in low-cycle fatigue. Subsequently, the fatigue lives from the tests were compared with predictions from CEB-FIP 2010 [42].

2. Test specimens

Fourteen beams including two controlling beams with uncorroded reinforcement and twelve corroded RC beams were cast. The main parameter examined corresponded to the percentage of mass loss of the steel reinforcement. All specimens exhibited identical dimensions with width b = 150 mm, height h = 300 mm, effective depth d = 265 mm, and length L = 3600 mm. The specimens were designed to fail in a flexural mode under a two-point concentrated load by providing ample stirrups to prevent premature shear failure. Concrete mixtures for casting these beams consisted of cement, coarse aggregate, fine aggregate, and water with a corresponding proportion of 1:2.23:3.08:0.54 by weight. The mixture was designed to achieve a cubic compressive strength of approximately 30 MPa. Two deformed steel bars (Grade HRB335) with a diameter of 20 mm were used as the tension reinforcement. The tensile reinforcement ratio was 1.58%. Two deformed steel bars (Grade HPB335) with a diameter of 10 mm were used as the compression reinforcement. Double-legged 8 mm plain steel bars (Grade HPB300) were used as stirrups with a spacing of 150 mm throughout the length of each beam. The dimensions and reinforcement details for the specimens are shown in Fig. 1.

The average 28-d cubic compressive strength of the concrete used was 30.6 MPa. The nominal yield stress of the longitudinal steel bars was 335 MPa. The mechanical properties of the concrete and reinforcing bars are listed in Tables 1 and 2, respectively.

3. Accelerated corrosion of steel reinforcement

A potentiostatic approach was used to accelerate the corrosion of the tension steel bars. The method involves connecting the positive terminal of a DC power supply to the tension reinforcement,

Table 2
Material properties of the reinforcing bars.

Diameter/ mm	Yield stress/ MPa	Ultimate stress/ MPa	Modulus/ MPa	Elongation*
10	375.1	610.5	2.1×10^5	27%
20	370.2	562.4	2.0×10^5	26%

* Elongation was measured in a gage length of 200 mm.

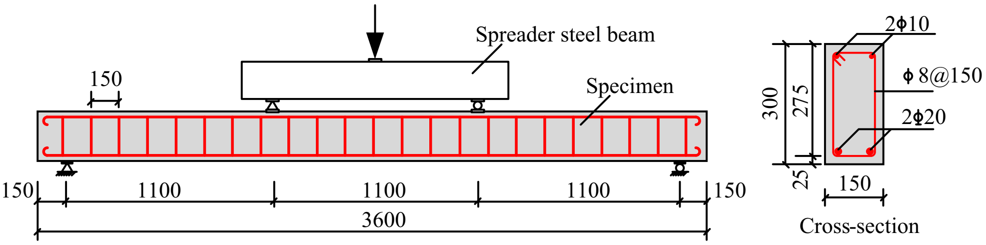

Fig. 1. Dimensions of test specimen (all dimensions are in mm).

Table 1
Material properties of the concrete.

Specimen	DBL1	DBL2	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
f_{cu}*, MPa	31.2	31.5	31.8	31.6	31.5	31.4	31.2	32.1	31.9	31.7	31.5	31.7	31.8	31.6

* f_{cu} is the compressive strength at fatigue testing for a concrete cube of 150 × 150 × 150 mm.