



# Fatigue behavior of naturally corroded plain reinforcing bars



Shibin Li<sup>a,b,\*</sup>, Hongwei Tang<sup>c</sup>, Qiang Gui<sup>b</sup>, Zhongguo John Ma<sup>b,\*</sup>

<sup>a</sup> School of Civil Engineering, Shandong Provincial Key Laboratory of Appraisal and Retrofitting in Building Structures, Shandong Jianzhu University, Jinan 250101, PR China

<sup>b</sup> Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996, United States

<sup>c</sup> School of Civil Engineering, Shandong University, Jinan 250061, PR China

## HIGHLIGHTS

- Naturally corroded plain bars were collected and measured before testing.
- The effect of corrosion on fatigue behavior of the corroded plain bars was studied.
- Fatigue strength loss by pitting corrosion has a significant effect on fatigue life.
- The S-N curves were presented, and the fatigue life and strength were evaluated.
- A linear relation between the relative pit depth and fatigue life was observed.

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## ABSTRACT

Segments of corroded plain reinforcing bars were firstly extracted from an aged reinforced concrete (RC) pole after its breaking. The testing specimens were then taken from these segments. The cause for corrosion of the specimens was analyzed, and the corrosion degree of the specimens was measured before testing. Tensile loading tests were performed with 3 non-corroded specimens to obtain the mechanical properties of the plain reinforcing bars prior to any corrosion. Axial tensile fatigue tests were conducted with 34 corroded specimens to investigate the fatigue behavior of the naturally corroded plain reinforcing bars. Corrosion of the specimens was initiated by the carbonation of concrete. Two corrosion levels and five stress ranges were considered. Fatigue test results showed that the median fatigue life of lightly and medium corroded plain reinforcing bars was reduced by 48 and 75% respectively under the same stress range of 240 MPa by compared with that of non-corroded plain reinforcing bars. Based on the test results, the fatigue  $S_{fc}$ - $N$  curves of the lightly and medium corroded specimens were presented by using least square method. Then, the predicted fatigue lives and fatigue strengths of naturally corroded plain reinforcing bars were suggested and compared with those of other related literature. The fatigue strength with 50% guarantee rate of lightly and medium corroded plain reinforcing bars is reduced by 18 and 28% respectively under a fatigue loading with cycles of 2 million by compared with that of non-corroded plain reinforcing bars. The fatigue fracture mechanism of the corroded specimens was interpreted by using Scanning Electron Microscope (SEM) images. Further, the pit depth was measured, and the relationship between the relative maximum pit depth and fatigue life of the corroded specimens was explored. It was found that one or more crucially localized pits of a specimen leading to the reduction of fatigue strength had an important influence on its fatigue life. A linear relationship between the relative maximum pit depth and the relative fatigue life of the corroded specimens was observed under three given stress ranges. This study provides a necessary basis for the determination of the remaining fatigue life of aged existing RC bridges.

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## 1. Introduction

Corrosion of reinforcing bars induced by concrete carbonation and/or chlorides contamination and/or stray current is one of the major types of deterioration of reinforced concrete (RC) structures. It results in the loss of cross-sectional area of reinforcing bars, the loss of bond between the reinforcement and the concrete, the

\* Corresponding authors at: School of Civil Engineering, Shandong Provincial Key Laboratory of Appraisal and Retrofitting in Building Structures, Shandong Jianzhu University, Jinan 250101, PR China (S. Li).

E-mail addresses: [lsbtj@163.com](mailto:lsbtj@163.com) (S. Li), [tanghongwei@sdu.edu.cn](mailto:tanghongwei@sdu.edu.cn) (H. Tang), [qgui@vols.utk.edu](mailto:qgui@vols.utk.edu) (Q. Gui), [zma2@utk.edu](mailto:zma2@utk.edu) (Z.J. Ma).

cracking and even the spalling of concrete cover leading to the loss of carrying capacity of these structures [1,2]. Furthermore, it may cause the brittle fracture of reinforcing bars and the collapse of RC structures, especially for railway and highway bridges, because they are subjected to not only corrosion damage but also repeated loads. It was reported that millions of dollars had been invested to maintain, rehabilitate, and strengthen the deteriorated RC bridges in the United States [3,4]. Despite the fact that corrosion of reinforcement is not the one and only factor of all structural shortcomings, it has become an important research topic.

In China, approximately 1 million bridges had been built until Dec. 2016. Most of them were made up of RC. Field surveys showed that many RC bridges began to corrode from 5 to 10 years after they were completed [5]. With the potential corrosion of reinforcement and increase of traffic loads, the safety of aged existing RC bridges in their life cycles is much more serious. Several efforts have been placed on the studies referring to the strength capacity and fatigue performances of corroded RC beams by researchers during the past two decades [6–17]. However they still have not specifically identified the fatigue properties of corroded RC beams. They commonly concluded that the fatigue strength of corroded RC beams is governed by the fatigue behavior of corroded reinforcing bars.

The fatigue failure of an RC beam is usually the consequence of the damage of reinforcing bars, concrete, and the bond between reinforcing bars and concrete. It is controlled by the brittle fracture of reinforcement if the stress range of the reinforcing bar is higher than its fatigue strength [18,16]. Also, the fatigue strength of reinforcing bars is influenced by the surface condition and rolling process [19,20].

The dramatic loss in the fatigue life of corroded RC beams is generally attributed to the obvious reduction of the fatigue strength of corroded reinforcing bars. So, it is urgently needed to study the fatigue of corroded reinforcing bars. The high strain low cycle fatigue of corroded reinforcing bars has been studied for the seismic assessment of RC structures in earthquake prone regions [21–25]. It was found that the life, ductility, dissipated energy, hysteresis response as well as bearing capacity of corroded reinforcing bars were significantly reduced due to the existence of localized pits. The low strain high cycle fatigue properties of corroded wires and cables have also been identified for the safety assessment of large cable stayed bridges [26–28]. The fatigue life and fatigue strength of the corroded wires and cables were reduced dramatically.

The residual fatigue life of corroded members is usually controlled by the fatigue of corroded reinforcement. So, the high cycle fatigue properties of corroded reinforcing bars have been studied to evaluate the safety of existing aged RC bridges [29–36]. Most of reinforcing bars used in previous publications were quickly corroded under simulated environment. The test results indicated that the fatigue life and fatigue strength of corroded specimens were reduced greatly with the occurrence and development of corrosion; and the effect of the natural corrosion on fatigue life is greater than that of the accelerated corrosion.

Some studies were performed on the high-cycle fatigue of naturally corroded reinforcing bars. Cao and Wen [29] investigated the specimens of plain reinforcing bars taken from a RC girder of an old RC railway bridge in China. The bridge had been on service for about 32 years to 1997. Zhang et al. [31] used the plain reinforcing bars extracted from the RC beams of a 30 years old building as the specimens. Li et al. [34] conducted the testing with the deformed reinforcing bars cut from a 3 years halted RC project. Li et al. [35] used the specimens of plain reinforcing bars from a 35 years old RC pole. The test results of the four studies indicated that natural corrosion of reinforcing bars gives rise to an obvious decrease in their fatigue properties, such as fatigue life and fatigue strength. Even though the reinforcing bar corrodes slightly, its fatigue life

is dropped significantly; and this dropping rate tends to weaken with the corrosion development. Also, the  $S_{fc}$ - $N$  curves of corroded reinforcing bars were linear on a logarithmic scale just like those of non-corroded reinforcing bars. The experienced vehicle loads have disadvantage effects on the fatigue strength of reinforcing bars [29]. The four studies were focused on the influence of natural corrosion on fatigue behavior of plain reinforcing bars under the same stress range. But, the previously testing data are very limited. The corrosion degrees are exorbitant [31], and the stress ranges are relatively high [35]. As a result, the effect of natural corrosion on fatigue properties of plain reinforcing bars is not explicit.

Other studies were performed on the high cycle fatigue of accelerated corroded reinforcing bars. Apostolopoulos and Michalopoulos [30], Li et al. [32], Luo et al. [36] and Fernandez et al. [37] are worth mentioning. These four studies used three methodologies to accelerate the corrosion of reinforcing bars. As regards the first study, the deformed reinforcing bars were accelerated corroded in a salt spray chamber by directly exposing them to salt spray for 15 and 30 days. As for the second and the third studies, the deformed reinforcing bars were quickly corroded in RC slabs by using impress current. As for the fourth study, the deformed reinforcing bars were extracted with caution from non-crucial section of the artificially corroded RC beams after they were statically loaded. A distinct decrease in fatigue strength and a great reduction in fatigue life of deformed reinforcing bars were observed due to corrosion. For example, Apostolopoulos and Michalopoulos [30] found that the fatigue strength of the corroded deformed reinforcing bars with mass loss of 1.6 and 2.9% was reduced by 20 and 40% respectively under the fatigue life of 8.1 million cycles compared with that of sound deformed reinforcing bars. Li et al. [32] and Luo et al. [36] concluded that the fatigue life of the corroded deformed reinforcing bars attenuated approximately by following an exponential law with the development of corrosion. Fernandez et al. [37] investigated the effect of the pit dimension and stress range on the fatigue life, and found that the fatigue life of the corroded deformed reinforcing bars except very little corroded bars was seriously reduced compared with that of intact deformed reinforcing bars. They uniquely studied the effect of accelerate corrosion on fatigue of deformed reinforcing bars considering the same fatigue loads rather than the same stress ranges [37]. So, a much more reduction in fatigue life was observed due to the increase of the stress range with corrosion. All of these four studies were emphasized the chloride-induced corrosion of deformed reinforcing bars, and more than two hundred corroded specimens were tested under fatigue loads. However, the fatigue testing data of corroded deformed reinforcing bars with mass loss below 10% were scanty.

In a word, the investigations on fatigue properties of corroded reinforcing bars are insufficient, especially on the high cycle fatigue of lightly and moderately corroded reinforcing bars. Therefore, fatigue test results on plain reinforcing bars with lightly and medium natural corrosion are presented in this paper. The  $S_{fc}$ - $N$  curves of the lightly and medium corroded specimens were established on the basis of the fatigue test results, and the relationship between the relative maximum pit depth and fatigue life was explored. Further, the fracture mechanism of corroded reinforcing bars was explained by using SEM images. It was found that one or more crucially localized pits were the primary factors in determining the fatigue life of corroded plain reinforcing bars.

## 2. Experimental study

Tensile loading tests were conducted with three non-corroded specimens to obtain the mechanical properties of the plain reinforcing bars prior to any corrosion. Axial fatigue tests were performed on 34 naturally corroded specimens to investigate the effect of corrosion on the fatigue of plain reinforcing bars. Two corrosion levels and five constant stress levels were considered in this paper.

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