Construction and Building Materials 187 (2018) 681–690

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on fatigue performance of corroded high-strength steel wires used in bridges

Chao Jiang, Chong Wu, Xu Jiang *

Department of Bridge Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

HIGHLIGHTS

- 3D profile measurements and fatigue tests were conducted on corroded bridge wires.
- Investigated the pitting characterizations and fatigue behavior of corroded wires.
- Established an empirical predictive equation for fatigue life evaluation.
- Proposed a method to predict remaining fatigue life of corroded bridge wires.

ARTICLE INFO

Article history:
Received 31 December 2017
Received in revised form 26 July 2018
Accepted 31 July 2018

Keywords:
Corrosion
Bridge wire
Fatigue life
Accelerated corrosion tests
AFGROW

ABSTRACT

This paper presents an experimental research on the fatigue performance of corroded high-strength steel wires used in bridges. Three dimensional (3D) profile measurements and fatigue tests were conducted on the steel wires on six corrosion levels. It is found that the experimental pitting depth followed a normal distribution and both the location and scale parameters increased with the corrosion degree. The fatigue test results indicated that corrosion could cause a significant decrease in the fatigue life of corroded steel wires. The *S-N* curves were bilinear in the log-log scale and the logarithmized fatigue life decreased linearly with the corrosion degree. An empirical formula for fatigue life calculation was established considering the corrosion effect. A method based on 3D measurements and AFGROW software was proposed to predict the remaining fatigue life of corroded steel wires. The predicted fatigue lives agreed well with the test results.

1. Introduction

High-strength steel wires are widely used in the cables and hanger ropes in the modern long-span bridges. To prevent the steel wires from the environmental corrosion, protection systems are employed such as galvanizing, epoxy coating and high-density polyethylene (HDPE) sheathing. However, the cable systems broke down for many bridges within 10 years' service life [1], causing the environment highly humid and corrosive inside the cables and hanger ropes [2]. The steel wires are heavily corroded and their cross-sectional areas are significantly reduced [3]. In order to determine the appropriate time for replacement of the corroded cables and hanger ropes, as well as guarantee the long-term behavior of the bridge structures, accurate evaluation of the mechanical degradation in high-strength bridge wires should be performed, especially for the mechanical properties and the fatigue performance.

The corrosion effects on performance of reinforcing steel bars have been extensively studied, including the effects on stress-strain [4,5] and fatigue behavior [6–9]. However, high-strength bridge wires are quite different from rebars because of the shape, corrosive environment and manufacturing process [10]. The wires with no ribs have smooth surfaces and are produced by a cold drawn process.

Various researchers have investigated the tensile properties of corroded steel wires [11–16]. Tension tests have been carried out for corroded wires which were taken from in-service bridges or made by artificially corrosion processes. Test results indicated a notable reduction in the ultimate tensile strength, ultimate strain, and elongation of the corroded steel wires [13]. The elastic modulus remained nearly unchanged [14] and the actual tensile strength considering the reduction of cross-sectional areas did not decrease. Empirical formulas were proposed to determine the tensile properties of the corroded wires [13,14]. The prediction model of the

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* Corresponding author.
E-mail address: jiangxu@tongji.edu.cn (X. Jiang).

https://doi.org/10.1016/j.conbuildmat.2018.07.249
0950-0618/

remaining strength of the corroded steel wires was also established based on the fracture mechanics [16].

Since the cables and hanger ropes are subject to high-cycle tensile stress induced by traffic and wind loads, fatigue performance of corroded steel wires should be better understood in order to maintain the safety and serviceability of the bridges. However, few works have been conducted related to this issue [17–21]. Most researches conclude that corrosion would significantly reduce fatigue strength and fatigue life of the steel wires. The research of Nakamura and Suzumura [19] indicated that corrosion pits which were deep and sharp decreased the fatigue resistance of corroded wires. The cables and hanger ropes should be inspected regularly when the corrosion pits are shallow. Similar conclusions were obtained by Li et al. [18] that the fatigue initiation zone caused by pitting corrosion was the major factor in decreasing the fatigue life of corroded steel wires.

Even fewer researches have been focused on the quantitative evaluation of corrosion effects on fatigue performance of corroded steel wires. Many studies have been conducted to investigate the remaining fatigue life of corroded aluminum alloy [22–25] and steel [26,27] which are widely used in aerospace and building structures respectively. However, it is not convincing to directly extend the results to high-strength steel wires since the steel wires used in bridges have essential differences in materials and geometric shapes comparing with the aluminum alloy in aerospace industry and steel plates or steel bars in building structures.

The purpose of this paper is to investigate the fatigue performance of corroded high-strength steel wires which are used in bridges cables and hanger ropes. Steel wires on six corrosion levels were obtained using accelerated corrosion experiments. Three-dimensional (3D) non-destruction scanning was carried out to obtain the surface morphology of the corrosion pits and subsequently the pitting characterizations were analyzed. Fatigue tests were then conducted with the corroded wire specimens. The effects of the stress range and corrosion degree on the fatigue performance of corroded steel wires were investigated. An empirical formula for the fatigue life calculation was also proposed considering both the corrosion degree and the stress range. The remaining fatigue life of corroded wires was finally predicted using AFGROW software [28] and the predictions based on 3D profiles were compared against the test results.

2. Experiments

2.1. Specimen preparation

The high-strength steel wires were supplied by Jiangsu Fasten Cable Co. (Jiangsu, China). The wires were cold-drawn and galvanized with a nominal diameter of 7 mm. The attached zinc mass was 360 g/m^2 and the depth of zinc coating was about 50 μm. The surface of the bridge wire is smooth when they are not corroded. The chemical composition is listed in Table 1. The length of all the wire specimens is 500 mm, which were cut from the cold-drawn steel wires. Material testing was carried out with Electric-Fluid Servo Universal Testing Machine (FM04-06) and mechanical properties of the wire specimens are presented in Table 2.

Table 2
Mechanical properties of high-strength bridge wires at room temperature.

Specimen	E (GPa)	σ_y (MPa)	σ_u (MPa)	δ (%)
1	201.1	1655	1842	6.0
2	200.6	1653	1839	5.5
3	199.8	1638	1825	5.0
Mean	200.5	1649	1835	5.5

E = the elastic modulus; σ_y = the yield stress; σ_u = the ultimate stress; δ = the elongation after fracture.

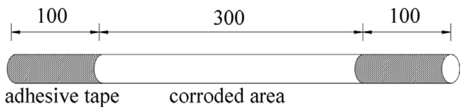

Fig. 1. Size of the wire specimen (unit: mm).

Fig. 1 shows the size of the wire specimen for fatigue tests based on GBT17101-2008 "Hot-dip galvanized steel wires for bridge cables" [29]. The specimen was wrapped with adhesive tape at two ends with a length of 100 mm. In the way, ends were protected from corrosion for the grips of the fatigue loading machine. Therefore, the actual corroded wire specimen was 300 mm in length. The steel wire specimens were divided into six corrosion levels (Corrosion Level A, B,. . .F) and each level included 5 replicated specimens (A-1,2. . .5). Prior to the corrosion experiment, each wire specimen was weighted and the diameter of the wire was also measured for the calculation of the corrosion degree.

2.2. Accelerated corrosion experiment

The acetic acid salt spray test based on the ISO standard 9227:1990 "Corrosion tests in artificial atmospheres-Salt spray tests" [30] was modified to obtain the proposed corroded steel wires for the following fatigue tests. The fog solution consisted of 50 ± 5 g/L NaCl and was adjusted to pH 3.0 by acetic acid. It was then insufflated into the salt spray test chamber by compressed atmosphere. The inner chamber humidity was controlled at 95% and the temperature was set to 50 ± 2 °C in order to provide a more severe corrosion environment. All the specimens were placed in the test chamber and uniform spray exposure was realized by rotating the specimens every 6 h. Corroded wires on six corrosion levels were obtained and the following exposure time in the salt spray test chamber was 318.5, 678, 997, 1370, 1712, and 1864.5 h, respectively. The typical surface view of the wire specimens on Corrosion Level B, D and F is shown in Fig. 2.

After the corrosion test, the corrosion products of the wire specimens were removed at room temperature based on the ASTM standard G1-03 "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens" [31]. Light brushing was employed to remove the loose products in reagent water and the chemical cleaning was then executed on the specimens. The solution involved in the chemical procedures consisted of a 50% HCl and 3.5 g/L hexamethylene tetramine.

The corrosion degree of the steel wires, η, was measured by the weight loss, and can be calculated by the following equation:

$$\eta = \frac{\Delta m}{m} = \frac{m_1 - m_2 - \frac{1}{3}\sum_{i=1}^{3}[m_{c1}(i) - m_{c2}(i)]}{m_1 \times \frac{l_e}{l}} \times 100\% \qquad (1)$$

Table 1
Chemical composition of high-strength bridge wires (wt%).

C	Si	Mn	S	Cu	Cr
0.85–0.90	0.12–0.32	0.60–0.90	≤0.0025	≤0.10	0.10–0.25