Experimental Investigation of Corrosion Behavior of Zinc–Aluminum Alloy-Coated High-Strength Steel Wires under Stress Condition

Kun Fang 1,2,*, Xiaoyong Liu 1,2, Pei Chen 1,2, Xianfu Luo 1, Zhenliang Liu 3, Xiaoqin Zha 1,2, Xinyao Zhang 1,2 and Jianfei Zhai 1

1 Luoyang Ship Material Research Institute, Luoyang 471023, China; liuxiaoyongsjtu@163.com (X.L.); chenpei_lsmri@outlook.com (P.C.); luoxf_725@126.com (X.L.); xiaoqinzha@sina.com (X.Z.); zhangxinyao98@sohu.com (X.Z.); jianfei_zhai@163.com (J.Z.)
2 State Key Laboratory for Marine Corrosion and Protection, Luoyang 471023, China
3 School of Safety Engineering and Emergency Management, Shijiazhuang Tiedao University, Shijiazhuang 050043, China; liuzhenliang@stdu.edu.cn
* Correspondence: fangkun_cssc@hotmail.com

Abstract: To cope with harsh working conditions, new corrosion-resistant coated steel wires with higher tensile strength have been developed. This study investigates the corrosion characteristics of a new zinc–aluminum alloy-coated steel wire under stress conditions. The particulate corrosion products generated by the oxidation of the coating in the initial stage of corrosion are converted into layer-structured corrosion products at the early stage of corrosion. Moreover, high-stress conditions have a significant influence on the critical conversion time from the coating corrosion stage to the iron matrix corrosion stage. Thus, the uniform corrosion depth (i.e., the mass loss rate) could be fitted with a continuous power function model rather than the previously used two-stage model owing to an ambiguous moment of conversion under stress conditions. The pitting corrosion depth could be fitted with a lognormal distribution in this study. The probability distributions for the aspect ratios of corrosion pits under different stress conditions tended to be consistent. Finally, the block’s maximum pitting factor followed a Gumbel distribution with a scale parameter that changed linearly with the stress level and a location parameter related to the square of the stress level.

Keywords: high-strength steel wire; zinc–aluminum alloy coating; stress condition; uniform corrosion depth; pitting corrosion

1. Introduction

High-strength steel wires are the most widely used materials for the cables of long-span cable-supported bridges owing to their excellent mechanical properties and corrosion protection behavior [1,2]. With recently increasing requirements for longer spans in bridges, particularly for suspension bridges and cable-stayed bridges, high-performance bridge wires have been developed and manufactured to provide cables with better corrosion resistance and higher capacity [3,4]. The improvement in the anti-corrosion performance of high-strength steel wire mainly relies on new type of zinc–aluminum alloy coating because aluminum has a higher activity than zinc, which forms a denser passivation film on the coating surface to slow down the corrosion rate of the base metal [5]. The aluminum content is generally between 5% and 10%, and a small amount of rare earth elements (such as Ce, La, etc.) are added, which is called Galfan material. Its corrosion resistance is better than that of galvanic coating [6]. Technical procedures including cold drawing, zinc–aluminum alloy hot-dip plating, and stabilization treatment for high-strength steel wire have also been developed [7]. In particular, the hot-dip plating technique employs an innovative double plating method, which controls the hot-plating temperature between 430 and 460 °C and ensures the adhesion and uniformity of the coating [8,9].
In addition to the improved performance of the anti-corrosion coating, high-strength steel wires with ultra-high yield and tensile properties have also been developed. Currently, the tensile strength of high-strength steel wires used in newly-built large-span bridges exceeds 2000 MPa [10]. These ultra-high-strength steel wires are used to produce cables for long-span bridges, such as the Nizhou Waterway Bridge, with a main span of 1688 m, and the Hutong Railway Yangtze River Bridge, with a main span of 1092 m [11,12].

The performance improvement is mainly achieved through the cold drawing of hyper-eutectoid steel, which improves the microstructure of pearlite and increases the number of grain interfaces (ferrite cementite phase interfaces), making it necessary to overcome greater resistance when dislocation motion occurs and reflecting in the improvement in tensile strength at the macro level [13,14]. Alloy elements play a significant role in high-strength impedance. The increased carbon (C) element can contribute to the percentage content of high-strength cementite. The addition of chromium (Cr) element and silicon (Si) can effectively improve the spacing between flakes and solid solution hardening, respectively [15]. Increasing the Si content can reduce the strength loss of high-strength steel wires during cold drawing, and the addition of Cr can further prevent strength loss. The Si element is concentrated at the interface between ferrite and cementite, while the Cr element is concentrated in the cementite. Due to the fact that the spheroidization of cementite requires the diffusion of Si at the interface, an increase in Si content is believed to reduce the spheroidization rate of cementite and suppress strength loss. In the case of high-strength steel wire, the addition of Si and Cr is believed to maintain a layered structure in the microstructure even during the hot-dip coating periods, which means that the steel wire will not experience strength loss [16]. The presence of vanadium (V) element can accelerate precipitation hardening and is beneficial for improving the strength of ferrite [17].

Studies on metal corrosion have been widely conducted for reinforced concrete structures [18,19], pipeline systems [20,21], offshore structures [22], aircraft structures [23,24], and long-span bridges [25]. The corrosion behaviors of various materials such as carbon steel, stainless steel, aluminum and aluminum alloys, and high-strength steel may vary widely for a specific environment [26]. High-strength steel wires are naturally subjected to an environment with high humidity and corrosive solutions containing chloride ions [27]. In addition, steel wires maintain a static working stress under tension, which can easily lead to stress corrosion cracking (SCC), corrosion fatigue, and eventual cable failure [28]. For the purpose of corrosion protection and monitoring, electrochemical methods are used to investigate the factors affecting the pitting corrosion nucleation, corrosion pit evolution, and pit-to-fatigue-crack transformation of high-strength steel wires [29–31]. For practical applications, time-dependent corrosion behavior indicators such as the mass loss rate, uniform corrosion depth, block maximum pitting factor, aspect ratio, and pit volume and density are modeled and statistically analyzed [32–34] to predict the effect of corrosion on the mechanical properties and fatigue failure of high-strength steel wires and cables [35,36]. Several studies [37–39] have investigated the corrosion characteristics of steel bars in prestressed reinforced concrete components and structures. However, a limited number of studies have addressed the corrosion characteristics of bridge wires under stress conditions. Betti et al. [40] studied the effect of corrosion on the mechanical properties of 1700 MPa galvanized and ungalvanized steel wires under different sustained loads using artificial accelerated corrosion experiments. Yang et al. [41] reported the corrosion behavior of 1570 MPa zinc-coated high-strength steel wire under four different tensile stress conditions in simulated acid rain. The relationship between the mechanical properties of the steel and corrosion was investigated and validated with finite element simulations and microscopic observations. At present, research on the corrosion behavior of 1960 MPa high-strength steel wire with a zinc–aluminum alloy coating under stress conditions has rarely been reported.

The contents of this paper are organized as follows. Section 2 presents the artificial accelerated corrosion experiments. In Section 3, the microscopic observation results for the coating of steel wire specimens are presented. The corrosion evolution kinetics of
high-strength steel wires are also explored based on the uniform corrosion depth, and the effect of the preloading stress on the dimensional parameters of corrosion pits is studied using statistical analysis. Finally, some conclusions are drawn in Section 4.

2. Materials and Methods

2.1. Materials

A new type of 1960 MPa high-strength steel wire specimen manufactured by the Jiangyin Walsin Steel Cable Co., Ltd. (Jiangyin, China) with a zinc–aluminum alloy coating with diameter of 5 mm and length of 150 mm is employed for the artificial accelerated corrosion experiments. The mechanical properties of the steel wire specimens are listed in Table 1.

Table 1. Mechanical properties of 1960 MPa high-strength steel wires.

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Elastic Modulus (MPa)</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≥1750</td>
<td>≥1960</td>
<td>(2.0 ± 1.0) × 10^5</td>
<td>≥4.0%</td>
</tr>
</tbody>
</table>

The chemical composition of the 1960 MPa high-strength steel wires is presented in Table 2.

Table 2. Chemical composition of 1960 MPa high-strength steel wires (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>Si</th>
<th>Al</th>
<th>V</th>
<th>Ni</th>
<th>Cu</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>0.95~ 0.6~</td>
<td>0.1~</td>
<td>0.10~</td>
<td>0.05~</td>
<td>0.01~</td>
<td>0.01~</td>
<td>0.03</td>
<td>≤0.05</td>
<td>≤0.025</td>
<td>≤0.015</td>
</tr>
</tbody>
</table>

Note: The balance is iron and impurities.

2.2. Artificial Accelerated Corrosion Test Setup

Artificial accelerated corrosion tests were conducted using a salt spray test chamber (Model YWX/Q-016B, Jiangsu AMS Test Instrument Technology Co., Ltd., Changzhou, China) with an internal size of 1600 mm × 850 mm × 600 mm, as shown in Figure 1. The experiments were carried out in accordance with the ISO 9227 standard [43], which is widely used to simulate corrosive marine environments. The specific experimental parameters were as follows: a temperature of 35 °C ± 2 °C, 95% humidity, and pH values of 3.1–3.2 adjusted by glacial acetic acid of analytical grade. The corrosive solution was prepared using a 0.025 wt.% copper chloride and 5.00 wt.% sodium chloride solution. The salt spray settlement was set to 1–2 mL/(80 cm²·h).

Figure 1. Artificial accelerated spray corrosion test and stress-holding device.
Six different exposure days (2, 3, 7, 15, 20, and 40 d) and four tensile stress conditions (0, 500, 750, and 1000 MPa) were used in the experiments, resulting in a total of 24 different exposure time and stress condition combinations. For each case, 4 steel wire specimens with a length of 250 mm were tested for a total of 96 experimental specimens.

2.3. Preloading Procedure for High-Strength Steel Wire Specimens

In order to apply tensile stress to the specimen effectively, pre-processing of the specimen is required. One end of the specimen is machined into a thread that is partnered with high-strength nuts. Thus, the stress can be maintained with the high-strength nuts. The other end of the specimen is squeezed into a pier head. The pier head should satisfy the following requirements: (1) the pier head is drumstick shaped, and the maximum outer diameter is $1.5 \pm 0.1$ times the diameter of the specimen, i.e., $8.25 \pm 0.55$ mm in the experiment; (2) there should be no transverse cracks on the surface or inside of the pier head; and (3) the capacity force of the pier head should be no less than 95% of the ultimate strength of the steel wire specimen.

The preloading stress of the steel wire specimen is maintained with a stress-holding device (SHD) throughout the experiment, as shown in Figure 1. A tensile force is applied by the counterforce frame. The SHD with a steel wire specimen is installed on the counterforce frame and stretched with the lifting jack. The real-time strain is monitored throughout the preloading procedure with electronic extensometers and an acquisition device; the system can measure a strain range of $105 \mu \varepsilon$ with a precision of $20 \mu \varepsilon$. The electronic extensometers are fixed on the specimen.

The preloading procedure is as follows: (1) the steel wire specimens are assembled on the SHD; (2) electronic extensometers are fixed to the specimens; (3) a stress of 1.05 times the target tensile stress is applied to the SHD through the counterforce frame by the lifting jacks; (4) the high-strength nuts of the SHD are tightened, and the lifting jacks are unloaded; and (5) owing to stress loss during the unloading process, steps (3) and (4) are repeated until the target value is achieved.

2.4. Measurement of Pitting Corrosion

Owing to the cylindrical surface of the high-strength steel wire specimens, it is difficult to measure the surface pitting corrosion depth directly. Therefore, a high-precision line-scan mechanical probe contact surface roughness profiler (Model JB-5C, manufactured by Shanghai Tai Ming Optical Instrument, Shanghai, China) was used to measure the surface pitting corrosion on the specimens, as shown in Figure 2.

![Figure 2. Pitting corrosion measurement system.](image-url)
The instrument measures the pitting corrosion depth at intervals of 1 µm along the longitudinal direction of the specimens, and the measurements are accurate to 1 µm. The instrument can only measure a length of 100 mm along a straight line at one time. Therefore, an artificial rotation of the specimens is required to measure all of the pitting corrosion on the specimen surface. In this study, the specimen is rotated at intervals of 6°, and measurements are recorded for every rotation. Thus, the specimen surface is measured 60 times in the circumferential direction, resulting in a total of 6,000,000 measurement points for each specimen.

3. Results and Discussion

Corrosion products attached to the surface of the high-strength steel wire specimens have different colors owing to the different corrosion behaviors of the zinc–aluminum alloy coating and the iron matrix, as shown in Figure 3; the oxidation products of the zinc–aluminum coating and the iron matrix appear as a white powder and as dark red, respectively. In addition, the color of the corrosion products deepens with increasing exposure time. After the steel wire specimens are removed from the chamber, a cleaning procedure can be performed on the surface corrosion products in accordance with the ASTM G1-03 standard [44]. A comparison of steel wire specimens with different stress conditions before and after the removal of corrosion products is shown in Figure 3. It can be clearly seen in Figure 3 that pitting corrosion is much more severe under high-stress conditions.

Figure 3. Comparison of steel wire specimens before and after corrosion product removal.
3.1. Microscopic Observation

It can be seen from Figure 4 that the thickness of the coating is approximately 75 µm. According to the region scanning results using an energy-dispersive spectrometer (EDS), shown in Figure 4, the proportion of zinc and aluminum in the zinc–aluminum alloy coating is approximately 95% and 5%, respectively.

![Figure 4. SEM photos of zinc–aluminum alloy coating of a steel wire specimen.](image)

3.2. Corrosion Evolution Kinetics

The uniform corrosion depth is widely used to describe corrosion evolution kinetics [45,46], as it describes the overall average corrosion condition of the specimen, rather than focusing on localized corrosion phenomena such as pitting. In calculating the uniform corrosion depth of the steel wire specimens, the error caused by the corrosion product removal process should be considered. The corrosion products on the surface of the steel wire specimens are removed immediately at the end of the experiment. In addition, new specimens are prepared and tested under the same conditions as the control group to eliminate the aforementioned error. The uniform corrosion depth can be calculated as follows:

\[
d_u(t) = \frac{m_0 - m - \Delta m_R}{\rho \pi LD} = \frac{D}{4} w
\]

where the subscript “u” represents the uniform corrosion; \(m_0\) is the original mass of the specimen; \(m\) is the mass of the specimen after removal of the corrosion products; \(\Delta m_R\) is the mass loss due to pickling, where \(\Delta m_R = \frac{1}{n} \sum_{i=1}^{n} (m_{R_0}^{(i)} - m_{R}^{(i)})\), in which \(n\) is the number of new specimens, \(m_{R_0}^{(i)}\) denotes the original mass of the \(i\)-th specimen in the control group, and \(m_{R}^{(i)}\) represents the mass after pickling of the \(i\)-th specimen in the control group; \(\rho\) is the mass density of the specimen; \(L\) is the length of specimen; \(D\) is the diameter of the specimen; and \(w\) means the mass loss rate.

3.2.1. Non-Stressed Condition

The corrosion behavior of high-strength steel wire specimens is a complex electrochemical process. Moreover, there is a significant difference between the coating corrosion and the corrosion of the iron matrix due to the differences in their material properties. Thus, a two-stage model [47] is suitable to describe the corrosion process, as described by the following equation and shown in Figure 5.

\[
d_u(t) = \begin{cases} 
  d_{u,coat}(t) & 0 \leq t \leq t_c \\
  d_{u,coat}(t_c) + d_{u,Fe}(t-t_c) & t > t_c
\end{cases}
\]

where \(d_{u,coat}(t) = \psi_1 t_1^\gamma_1\) and \(d_{u,Fe}(t-t_c) = \psi_2(t-t_c)^\gamma_2\).

![Figure 5.](image)
where $d_u(t)$ is the uniform corrosion depth of the specimen at exposure time $t$, $t_c$ is the critical time at which the coating is completely consumed, $d_{u,coat}(t)$ refers to the time-dependent uniform corrosion depth of the coating, $d_{u,Fe}(t)$ is the time-dependent uniform corrosion depth of the iron matrix, $\gamma_1$ and $\gamma_2$ are model parameters for the coating corrosion, and $\gamma_1$ and $\gamma_2$ are model parameters for the iron matrix corrosion.

Figure 5. Two-stage model of time-varying uniform corrosion depth.

Figure 6 shows the uniform corrosion depth of zinc-coated [47,48] and zinc–aluminum alloy-coated steel wires under non-stressed conditions. It can be seen from Figure 6 that the thickness of the zinc–aluminum alloy coating (~50 µm) is greater than that of the zinc coating (~33 µm). However, the corrosion rate exhibits the opposite situation, i.e., 2.55 µm/d, with 4.90 µm/d$^{1.024}$ and 3.32 µm/d$^{0.996}$ for the zinc coating and zinc–aluminum alloy coating, respectively, owing to the excellent corrosion-resistance performance of the zinc–aluminum alloy coating. Once the coatings are completely consumed, the corrosion rates for the iron matrices of the two types of specimens are ~0.5 µm/d, which is far smaller than that of the coating.

Figure 6. Corrosion rates and fitting results under non-stressed conditions [47,48].

3.2.2. Stress Condition

The uniform corrosion depth (i.e., the mass loss rate) is used to describe the average corrosion rate in the steel wire specimens, as shown in Figure 7 for bridge steel wires and mild steel with different exposure times. The corrosion rate of mild steel is relatively low in low-concentration hydrochloric acid (HCl) solutions (i.e., 0.00001 M and 0.003 M), while the
corrosion rate under 1 M HCl solution conditions [49] is comparable to that under stressed conditions in this paper. Furthermore, Hong et al. [50] lists the time-varying corrosion rate of high-strength steel wires for suspension bridge cables under four pre-strain conditions in a 3.5% NaCl solution and 1A current. The corrosion rate obtained under corrosive solutions and current conditions is much higher than that under artificial salt spray conditions. And the corrosion rates under stress conditions are always higher than those under non-stressed conditions, which is consistent with the experimental results in this paper.

![Figure 7. Corrosion rates and fitted results under different stress conditions.](image)

For stress conditions in this paper. Furthermore, Hong et al. [50] lists the time-varying corrosion rate of high-strength steel wires for suspension bridge cables under four pre-strain conditions in a 3.5% NaCl solution and 1A current. The corrosion rate obtained under corrosive solutions and current conditions is much higher than that under artificial salt spray conditions. And the corrosion rates under stress conditions are always higher than those under non-stressed conditions, which is consistent with the experimental results in this paper.

![Figure 7. Corrosion rates and fitted results under different stress conditions.](image)

It can also be observed from Figure 7 that the critical time indicating the conversion from coating corrosion to corrosion of the iron matrix is invisible. In this case, the two-stage model has difficulty accurately describing the pitting corrosion behavior of specimens under stress conditions. Thus, a continuous power model is introduced to describe the time-dependent uniform corrosion depth, which can be expressed as follows:

$$d_u(t) = \psi t^{\gamma} \quad (t > 0, \sigma_s > 0)$$  \hspace{1cm} (3)$$

where $\psi$ and $\gamma$ are power model parameters, and $\sigma_s$ is the preloading stress of the steel wires, defined as 500 MPa, 750 MPa, and 1000 MPa in this study.

Figure 8 shows the change in uniform corrosion depth with different stress conditions.
In corrosion time, the effect of the preloading stress on the uniform corrosion depth linearly. Because the stress imposed on the specimens is smaller than the yield strength, the material properties of the high-strength steel wire are in the linear elastic stage. For a certain corrosion time, the effect of the preloading stress on the uniform corrosion depth is in accordance with the linear model. Thus, the uniform corrosion depth considering the corrosion time and stress condition can be generated from the experimental results as follows:

\[ d_u(t, \eta) = \psi \eta^\gamma \quad (t > 0, \eta > 0) \]  

where \( d_u \) is the uniform corrosion depth; \( \eta \) is the normalized stress, where \( \eta = \sigma_s/\sigma_y \); \( \sigma_y \) is the yield strength, which is \( \sigma_y = 1750 \text{ MPa} \) in this study; and \( \psi \) and \( \gamma \) are parameters, where \( \psi = 38.55 \) and \( \gamma = 0.498 \) for the 1960 MPa zinc-aluminum alloy-coated high-strength steel wire in this study.

The measured data and fitting results for the uniform corrosion depth are shown in Figure 8.

![Figure 8. Uniform corrosion depth changes with preloading stress at different exposure time periods.](image)

3.3. Statistical Characteristics of Pitting Corrosion

For a specimen with an exposure time of 40 d and stress condition of 750 MPa at 0°, the measurement data and contour plot are shown in Figure 9.

![Figure 9. Uniform corrosion depth and fitted bivariate model.](image)
The corrosion pits are modeled as semi-ellipsoids in this study, as shown in Figure 11, based on their actual geometric characteristics. In Figure 11, parameters $a$ and $b$ refer to the axis lengths of the ellipse projected on the surface of the steel wire specimen. The corrosion pit depth, $h_{\text{max}}$, is defined as the maximum value within the corrosion pit region.

![Geometrical model of individual corrosion pit.](image)

**Figure 11.** Geometrical model of individual corrosion pit.

The contour plot and fitted ellipse results for pitting corrosion are shown in Figure 12.

![Contour line of the corrosion pits and fitted ellipses.](image)

**Figure 12.** Contour line of the corrosion pits and fitted ellipses.

### 3.3.1. Corrosion Pit Depth

The pitting corrosion depth can significantly affect the stress distribution along the steel wires, resulting in stress concentration and SCC. Thus, the corrosion pit depth has been statistically investigated in pipeline systems, reinforced concrete structures, and stayed
cables in numerous studies, which have employed totally different probabilistic models for fitting \cite{22,33}. A lognormal distribution is usually employed to fit the corrosion pit depth for specimens produced in artificial accelerated spray corrosion experiments, which can be formulated as follows:

$$f(x|\mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\ln x - \mu^2}{2\sigma^2}\right) \quad (x > 0)$$  \hspace{1cm} (5)

where $\mu$ is the time-dependent location parameter, and $\sigma$ is the scale parameter.

The Anderson–Darling test does not reject the lognormal distribution for the corrosion pit depth based on the statistical results, which are plotted in Figure 13.

![Figure 13. Fitted lognormal distribution of pitting corrosion depth of corrosion pits under different stress conditions: (A) 0 MPa; (B) 500 MPa; (C) 750 MPa; (D) 1000 MPa.](image)

Figure 13. Fitted lognormal distribution of pitting corrosion depth of corrosion pits under different stress conditions: (A) 0 MPa; (B) 500 MPa; (C) 750 MPa; (D) 1000 MPa.

It can be seen from Figure 13 that the corrosion pits in specimens with longer exposure times are much deeper than those in specimens that experienced a shorter corrosion time under the same stress condition. In addition, the variability in the corrosion pit depth increases with corrosion time. The corrosion pit depth also increases at the same corrosion time with increasing preloading stress, which has a smaller effect on the variability in the pitting corrosion depth than the corrosion time.

### 3.3.2. Corrosion Morphology

The aspect ratio $a/b$ can be used to intuitively characterize the planar shape of corrosion pits. The major axis of the ellipse is along the circumferential direction for $a/b < 1$, whereas the corrosion pit develops along the longitudinal direction for $a/b > 1$, which becomes very large with increasing exposure time under the stress condition. The planar shape of the corrosion pit is circular when $a = b$, and this case will not be discussed separately herein. The time-dependent statistical results for the aspect ratio of the corrosion pits on steel wire specimens under different stress conditions are fitted with lognormal distributions, as shown in Figure 14.
The shape of the corrosion pit is circular when $a = b$, and this case will not be discussed separately herein. The time-dependent statistical results for the aspect ratio of the corrosion pits on steel wire specimens under different stress conditions are fitted with lognormal distributions, as shown in Figure 14.

As can be seen from Figure 14, both the exposure time and the stress condition affect the corrosion pit aspect ratio. Under the non-stressed condition, the corrosion pit morphology is metastable in the early corrosion stage, and the corrosion pit morphology has little variability with the exposure time, as shown in Figure 14A. The corrosion pit morphology becomes stable at exposure times greater than 7 d. As the exposure time increases, the aspect ratio of the corrosion pits grows, which means that parameter $a$ along the longitudinal direction of the specimen surface increases. This is mainly caused by the convergence of small corrosion pits. Under the stress condition, as shown in Figure 14B–D, the corrosion pits become stable at exposure times greater than 3 d, indicating that the preloading stress contributes to the stability of the corrosion pit state. Thus, the aspect ratio of the corrosion pits exhibits greater variability under the stress condition. The statistical distribution results for the aspect ratio reach unity with increasing preloading stress, mainly because corrosion pits are more likely to occur on the specimen surface under the stress condition.

3.3.3. Block’s Maximum Pitting Factor

The statistical analysis of the maximum pitting corrosion depth is often the focus of studies, while the maximum pitting factor has been introduced to describe the pitting corrosion characteristics in the literature [51,52]. The maximum pitting factor can be expressed as follows:

$$\lambda = \frac{d_p}{d_u}$$

where $\lambda$ is the maximum pitting factor, $d_p$ is the maximum pitting corrosion depth on the steel wire specimen surface with length $L$, and $d_u$ is the uniform corrosion depth of the steel wire specimen.

It has been confirmed that the maximum pitting factor has a spatial scale effect with increasing length of the high-strength steel wire. Thus, the block’s maximum pitting factor is introduced to consider the spatial scale effect, which obeys a Gumbel extreme value
distribution. The probability density function for the block’s maximum pitting factor with a block length of \( L_0 \) is as follows [51]:

\[
F_0(x) = \exp \left[ - \exp \left( \frac{x - \beta_0}{\alpha_0} \right) \right]
\]

(7)

where \( \alpha_0 \) and \( \beta_0 \) are the scale parameter and location parameter of the Gumbel distribution, respectively.

When the block length becomes \( L_n (= n \times L_0) \), the maximum pitting factor is subject to the following distribution:

\[
F_n(x) = [F_0(x)]^n = \exp \left[ - \exp \left( \frac{x - \beta_n}{\alpha_n} \right) \right]
\]

(8)

where \( \alpha_n \) is the scale parameter, \( \alpha_n = \alpha_0 \), and \( \beta_n \) is the location parameter, \( \beta_n = \beta_0 + 1/\alpha_0 \ln n \).

The area of the block, \( A_\kappa \), which is used to evaluate the variation in the maximum pitting factor, can be expressed as follows [51,52]:

\[
A_\kappa = C \times L_\kappa = \pi D \times \kappa D
\]

(9)

where \( C \) is the perimeter of the specimen, \( L \) is the length of the specimen, \( D \) is the diameter of the specimen, and \( \kappa \) is the spatial effect scale factor.

To avoid statistical differences caused by the parameter \( \kappa \), a proper initial value should be determined, i.e., \( \kappa = 3 \) in this study. The subsequent values of \( \kappa \) can be determined according to the principle of proportionality; \( \kappa = 3, 6, 9, \) and 12 are used in this study, and the fitted results are shown in Figure 15.

Figure 15. Fitted Gumbel distribution of block’s maximum pitting factor.

Figure 15 depicts the fitted Gumbel distribution results for different blocks and stress conditions. Figure 15 shows that the Gumbel distribution functions present a group of parallel lines under the same stress conditions, indicating that the scale parameters are only related to the stress conditions. The scale parameter increases with increasing preloading stress, which indicates that the presence of stress causes the variability in the maximum pitting factor to increase.

The location parameters are generally considered to have a linear relationship with \( \ln \kappa \). Therefore, the scale parameter and location parameter considering the spatial effect scale factor and stress condition can be defined as follows:

\[
\begin{align*}
\alpha_\kappa(\kappa, \eta) &= c_1 \kappa + c_2 \eta + c_0 \\
\beta_\kappa(\kappa, \eta) &= p_{10} \ln \kappa + p_{11} \eta \ln \kappa + p_{02} \eta^2 + p_{01} \eta + p_{00}
\end{align*}
\]

(10)
where $c_0$, $c_1$, and $c_2$ are coefficients for modeling the scale parameter, and $\beta_{00}$, $\beta_{01}$, $\beta_{02}$, $\beta_{11}$, and $\beta_{12}$ are coefficients for modeling the location parameter.

Figure 16 compares the proposed theoretical model with the observed data, which are in good agreement.

4. Conclusions

In this study, the corrosion behavior of a new type of zinc–aluminum alloy-coated 1960 MPa high-strength steel wire for long-span bridge cables under stress conditions is studied. Steel wire specimens with different corrosion conditions are produced in artificial accelerated corrosion experiments. The results show that the stress conditions led to the conversion of the corrosion characteristic. By exploring corrosion indicators, including the uniform corrosion depth, pitting corrosion depth, aspect ratio of corrosion pits, and block’s maximum pitting factor, the following conclusions can be drawn:

1) The corrosion processes of steel wire specimens can be divided into two stages under the non-stressed condition according to the time-dependent uniform corrosion depth. A two-stage model can effectively describe the conversion from coating corrosion to iron matrix corrosion, which is represented by a critical time, \( t_c \). The corrosion rate of the coating (3.32 µm/d for the zinc–aluminum alloy coating) is much higher than that of the iron matrix (~0.5 µm/d). When the exposure time reaches the critical time \( t_c = 15 \text{ d} \) for the zinc–aluminum alloy-coated steel wire, the corrosion rate undergoes a sudden transition to a certain value of ~0.5 µm/d and remains stable.

2) When considering the stress condition, the critical time is almost indistinguishable. The corrosion rates under stress conditions are always higher than those under non-stressed conditions. It can be concluded that the corrosion behavior changes from uniform corrosion to pitting corrosion under stress conditions. Thus, a continuous power model can be used to describe the corrosion phenomena. In addition, the uniform corrosion depth considering the exposure time and stress condition is formulated using an improved power model.

3) A semi-ellipsoid model is used to simulate individual corrosion pits, which obeys a lognormal distribution. It is clear that the preloading stress has little effect on corrosion pit growth compared to the exposure time. The variability in the aspect ratio of the corrosion pit depth increases under the stress condition. Statistical results for different block lengths, \( L_n \), show that the block’s maximum pitting factor under the stress condition still has a spatial scale effect. However, the preloading stress can lead to variation in the location parameter and reduce the variability of the block’s maximum pitting factor, which differs from the behavior of the non-stressed specimens.
Author Contributions: Conceptualization, K.F. and X.L. (Xiaoyong Liu); methodology, K.F.; software, X.L. (Xianfu Luo) and J.Z.; validation, P.C.; resources, X.Z. (Xinyao Zhang); data curation, X.Z. (Xiaqin Zha); writing—original draft preparation, K.F.; writing—review and editing, K.F. and X.L. (Xiaoyong Liu); visualization, X.L. (Xianfu Luo); project administration, X.Z. (Xiaqin Zha); funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key R&D Program of China (No. 2023YFB3709904), National Natural Science Foundation of China (NSFC) (No. 52308512).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

5. Wang, X.; Wang, Y.; Zhu, P.; Zhang, X.; Wang, H.; He, Y. Experimental and numerical investigations of UHSS wire main cables for suspension bridges. Structures 2022, 38, 1582–1594. [CrossRef]
17. Emamian, Y.; Kolahi, A.; Palizdar, Y. Evaluation of microstructures and mechanical properties of delta trip steel with different vanadium contents. Results Mater. 2020, 21, 100530. [CrossRef]
37. Karuppanasamy, J.; Pillai, R. Statistical distributions for the corrosion rates of conventional and prestressing steel reinforcement embedded in chloride contaminated mortar. Corrosion 2017, 73, 1119–1131. [CrossRef] [PubMed]
40. Betti, R.; West, A.C.; Vermaas, G.; Cao, Y. Corrosion and Embrittlement in High-Strength Wires of Suspension Bridge Cables. J. Bridge Eng. 2005, 10, 151–162. [CrossRef]
42. Chen, C.; Ma, H.; Wang, F.; Yang, Z.; Zhang, F.; Yan, Z. Influence of Carbon Content on Tensile Properties of Pure High Manganese Austenitic Steel. Coatings 2022, 12, 1622. [CrossRef]
44. ASTM G1-03 (2011); Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. ASTM: West Conshohocken, PA, USA, 2011.
47. Deng, L.; Deng, Y. Temporal and Spatial Variation Study on Corrosion of High-Strength Steel Wires in the Suspender of CPST Arch Bridge. Coatings 2024, 14, 628. [CrossRef]
50. Hong, H.; Cao, S.; Fu, J.; Tian, H. Experimental Study on Apparent Corrosion Rule of Main Cable Steel Wires of Suspension Bridge in Holding Force State. J. Highw. Transport. Res. Dev. 2022, 39, 97–102. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.