# Fatigue life evaluation model for high-strength steel wire considering different levels of corrosion

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## Abstract

Corrosion of steel wires is one of the most severe causes in the deterioration of cables for cable-supported bridges. This paper studies the quantitative influences of corrosion on the fatigue life of high-strength steel wires, considering a wide variation in the degree of corrosion. First, the multi-parameter Weibull model for corrosion-stress-life (C-S-N) proposed by the authors of this paper is introduced briefly, and the Goodman relation is employed to deal with the dependences of stress ranges on positive stress ratios for tension-tension fatigue. Fatigue data for high-strength steel wires are collected from the literature for three groups with different ultimate tensile strengths and the degree of corrosion ranging from 0.18% to 18.67%. This data is then used to estimate the parameters of the Weibull model; subsequently, quantitative influences of corrosion on fatigue life for steel wires with a wide range in the degree of corrosion are illustrate and discussed in detail. The results indicate that the influence of ultimate tensile strengths on fatigue life for corroded high-strength steel wire can be ignored, because corrosion causes crack nucleation more quickly, especially at lower stress ranges. The fatigue life decreases more quickly with the increase in the corrosion, and reduction on fatigue life caused by corrosion is more pronounced under a lower stress range, which indicates that the fatigue life is more sensitive to corrosion at lower stress ranges. Negative correlation of fatigue life and corrosion increases as the stress range decreases, which further confirms that corrosion has a higher influence at lower stress ranges. The proposed Weibull model for C-S-N can provide quantitative evaluation of the survival probability of high-strength steel wires, defined in terms of their fatigue life, considering a wide range in the degree of corrosion; these results can be used by engineering designers to ensure the safety for cable-supported bridges during their lifetime.

**Keywords:** Fatigue life, Corrosion, Weibull model, High-strength steel wire, Probabilistic C-S-N surface

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## 1. Introduction

Cable-supported bridges (e.g., cable-stayed bridges and suspension bridges), distinguished by their ability to span large distances, have been widely used throughout the world to meet growing social and economic demands [1,2]. Stay cables and suspenders (hangers) are some of the most common tension-resisting elements in cable-supported bridges; repetitive loads induced, for example, by traffic and wind loads, can result in fatigue of these elements [2-6]. In addition, corrosion of the main tension elements in cable systems has been identified as a major problem that requires further attention [7]. In practice, the maximum degree of corrosion for high-strength steel wire in stay cables had been found to exceed 10% after 18 years in-service [8]. Regardless of what corrosion protection measures have been employed, corrosion of the high-strength steel wires will eventually occur, resulting in severe deterioration of the cables. This phenomena is a widespread concern for in-situ structures due to the associated reduction in the safety of cable-supported bridges during the in-service period [9-13].

Although some disagreement exists regarding the fracture mechanism for corroded steel wires [14,15], Nakamura et al. [16,17] found that the fracture surface of steel wires was similar to that caused by fatigue, rather than by hydrogen embrittlement, through the investigation of broken wires in old main suspension cables. Greater risk of fracture of corroded wires is caused by fatigue, because the stress fluctuation in stay cables or suspenders is much higher than that in the main suspension cables. Additionally, the fatigue life of stay cables is dominated by the fraction of wires with short fatigue lives caused by corrosion [18]. Therefore, the quantitative influences of corrosion on the fatigue life of steel wires can be viewed as an important step to inform the evaluation on residual fatigue life of stay cables or suspenders.

To evaluate the fatigue life of corroded steel wires, the Paris law and its derivatives from linear elastic fracture mechanics are often used [19,20]. Here, the maximum depth of pitting corrosion is regarded as crack depth, and the propagation life to a critical crack depth is calculated based on crack growth parameters for the specific material. However, the effectiveness of these methods is difficult to verify by experimental data, because much more randomness exists in the corrosion and fatigue processes. To address this problem, probabilistic models based on fatigue testing data provide great promise for characterizing the fatigue life of corroded steel wires. In previous research, the authors proposed a multi-parameter Weibull model to investigate the influence of corrosion on the fatigue life for steel rebars [21]; this model was also used to evaluate the influences of corrosion on the fatigue life of corroded steel wires, where the degree of corrosion was below 3.62% in [18]. Recently, some fatigue data of corroded steel wires has been reported in the literature for a wider range in the degree of corrosion (i.e., from 4.30% to 18.76% [22] and 2.00% to 7.60% [23]). In this paper, a multi-parameter Weibull model for corrosion-stress-life (C-S-N) is developed for this broad range of fatigue data for steel wires and used subsequently to illustrate the corrosion effects on the fatigue life of steel wires considering a wide range in the degree of corrosion.

The remainder of this paper is structured as follows: First, the multi-parameter Weibull model for C-S-N proposed by the authors is introduced briefly in Section 2, where the Goodman relation is used to account for the various stress ratios. Subsequently, Section 3 summarizes the recently published fatigue data used in this research. Three groups of steel wires with different ultimate tensile strengths and various degrees of corrosion are considered. Parameters of the Weibull model for C-S-N are estimated, and the quantitative influence of corrosion on the fatigue life of steel wires considering the full range of corrosion in the wires is illustrated. A damage ratio for corrosion is defined to study the effects of corrosion and stress range on the fatigue life of the steel wires. Then, in Section 4, the influence of ultimate tensile strength on the fatigue life of corroded steel wires is discussed. The effect of corrosion on fatigue life is more pronounced at lower stress ranges; this phenomena is explained using the correlation of fatigue life and corrosion. Finally, Section 5 concludes the paper.

## 2. Fatigue life prediction model of corroded high-strength steel wire

The degree of corrosion and stress range are regarded as the independent input variables in the multi-parameter Weibull model for C-S-N proposed by the authors of this paper. This model has been used successfully to evaluate the fatigue life of steel rebars for both natural corrosion and artificially accelerated corrosion [21] and that of steel wires for artificially accelerated corrosion with the degree of corrosion not more than 3.62% [18]. Specifically, the cumulative distribution function (CDF) of fatigue life considering corrosion effects is expressed as

$$F(N;\Delta S,w)=1-\exp\left[-\left(\frac{\Delta S^{B_0+aw}N}{K_0\exp(-rw)}\right)^{\beta}\right] \quad (1)$$

where $N$ is the fatigue life under the stress range $\Delta S$, which is the nominal stress range obtained for the nominal cross-section area of the uncorroded steel wires; $w$ indicates the degree of corrosion, which is quantified here on the basis of weight loss, i.e., $w=\Delta m/m\times100\%$, which is the average loss of cross-section in percent; $\Delta m$ is the mass loss of steel wire, and $m$ is the mass of original steel wire. The unknown parameters of the model (i.e., $B_0,a,K_0,r$, $\beta$) can be estimated by using the maximum likelihood estimation (MLE) based on the test data of all specimens with different degrees of corrosion and different stress ranges; also, $\beta$ is the shape parameter of the Weibull model for C-S-N. Additionally, the expectation-maximization (EM) algorithm can be used to deal with the censored data in statistical analysis based on an iterative process, and the iterative formulas have been provided in [21,[24]]. To evaluate the goodness-of-fit of the proposed model for the estimated parameters, a normalized variable of the Weibull model for C-S-N, denoted as $Z$, can be defined as

$$Z = \frac{\Delta S^{B_0 + aw} N}{\exp(-rw)} \quad (2)$$

The fatigue life, $N$, the corresponding stress range, $\Delta S$, and the degree of corrosion, $w$, of each specimen are normalized into the variable $Z$, which can be regarded as a random variable of a standard two-parameter Weibull distribution, with shape parameter $\beta$ and characteristic parameter $K_0$, as can be seen in Eqs. (1) and (2). Because all the fatigue samples with different degrees of corrosion and different stress ranges are pooled together, the Weibull plot of the normalized variable $Z$ can be used to give intuitive insight into the proposed model for all the available data.

### *2.1. Limitation conditions of the Weibull model*

To ensure some physical meaning for the fatigue life prediction considering corrosion effects, the Weibull model should satisfy several conditions. First, consider a specified survival probability and rewrite Eq. (1) as follows

$$N = \exp\left( \frac{1}{\beta} \ln\left( -\ln(1 - F(N; \Delta S, w)) \right) + \ln K_0 - B_0 \ln(\Delta S) - aw\ln(\Delta S) - rw \right). \quad (3)$$

Note that both $B_0$ and $K_0$ should be non-negative for the uncorroded steel wire (i.e., $w = 0\%$). As can be seen in Eq. (3), to ensure fatigue life decreases monotonically as the stress range increases for a certain degree of corrosion at an identical survival probability, $B_0 + aw > 0$ is also required. Further, to ensure the fatigue life decreases monotonically as the degree of corrosion increases for a certain stress range at an identical survival probability, $r + a\ln(\Delta S) > 0$ is required.

### *2.2. The effects of stress ratio*

Different stress ratios are used in the literature to study corrosion effects on the fatigue life of steel wires [18,22,23]. However, direct comparison of the data can be difficult, because for different mean stress levels, the stress ratio for tension-tension fatigue will increase, which will result in a fatigue life decrease for the same stress range. To pool all the available fatigue data together and estimate the parameters of the Weibull model considering a wide range in the degree of corrosion, stress ranges with different stress ratios for corresponding fatigue life of corroded steel wire should be converted to the stress ranges with an identical stress ratio. In this way, the effect of the stress ratio on the fatigue life is eliminated. The stress ratio $R$ is defined as

$$R = \frac{S_{min}}{S_{max}} \tag{4}$$

where $S_{min}$ and $S_{max}$ are the minimum and maximum stresses, respectively, in one loading cycle, and the stress range $\Delta S = S_{max} - S_{min}$. In fact, high-strength steel wires within cables undergo tension-tension fatigue due to the effect of dead load and live load; therefore, the stress ratio $R$ is positive and less than 1. Gerber and Goodman proposed different relationships to deal with the dependence of the allowable stress range on the mean stress [25]. For the sake of simplicity, the Goodman relation is used to deal with the dependence of stress range on stress ratio in this study and is given by

$$\Delta S_1 = \frac{\sigma_u \Delta S_2}{\sigma_u + \frac{\Delta S_2}{2}\left(\frac{1+R_1}{1-R_1} - \frac{1+R_2}{1-R_2}\right)} \tag{5}$$

where $\Delta S_1$ and $\Delta S_2$ are the stress ranges corresponding to the stress ratios $R_1$ and $R_2$, respectively, for an identical number of cycles; $\sigma_u$ is the ultimate tensile strength of the steel wire. The ultimate tensile strength of uncorroded steel wires are also used in this study for the corroded steel wires. Thus, all the available fatigue data for the corroded high-strength steel wires with different stress ratios in the literature can be converted to the stress ranges with an identical stress ratio to estimate the parameters of Eq. (1) and study corrosion effects on the fatigue life of steel wires.

## 3. Fatigue life evaluation for steel wires with a wide range in the degree of corrosion

### *3.1. Available fatigue data of high-strength steel wires*

The available fatigue data for high-strength steel wires with different degrees of corrosion, different stress ranges, and different stress ratios in the literature [18,22,23] are collected and presented in this section. This information for the three groups of high-strength steel wires undergoing different accelerated corrosion tests is shown in Table 1, including the original fatigue test conditions.

Note that the main distinction of steel wires in Table 1 are the minimum specified ultimate tensile strengths, which are 1670 MPa in Group I, and 1770 MPa in Groups II and III. Assuming that influences of the degree of corrosion and stress range dominate the fatigue life of these corroded steel wires, the effects of ultimate tensile strength on fatigue life will be discussed in the subsequent paragraphs.

Galvanized steel wires were employed as specimens in the accelerated corrosion tests in Groups I and II; these tests were conducted using acetic acid salt spray (AASS) according to ISO 9227: 1990 [26]. For Groups I and II, both the temperature and the exposure period were varied, which are 35±2 ºC for 24, 168, 240, 720 and 1440 hours for Group I specimens and 50±2 ºC for 318.5, 678, 997, 1370, 1712 and 1864.5 hours for Group II specimens. The ranges of the degree of corrosion are from 0.18% to 3.62% for Group I specimens, and from 4.30% to 18.67% for Group II specimens. Corroded steel wires in Group III were obtained from concrete specimens immersed in 5% NaCl solution, using the DC galvanostatic method to control the applied current density at approximately 100 μA/cm$^2$. The ranges of corrosion are from 2.00% to 7.60% for Group III specimens. For all the available fatigue data, the degree of corrosion, $w$, for each steel wire was measured by the loss of weight. More detailed information of accelerated corrosion tests for the three groups of steel wires is available in [18,22,23].

**Table 1. Testing parameters for the three groups of high-strength steel wires.**

| Specimen series | Group I [18] | Group II [22] | Group III [23] |
|---|---|---|---|
| Nominal diameter (mm) | 7 | 7 | 7 |
| Minimum specified ultimate tensile strength (MPa) | 1670 | 1770 | 1770 |
| Number of samples | 99 | 26 | 24 |
| Range of the degree of corrosion (%) | 0.18-3.62 | 4.30-18.67 | 2.00-7.60 |
| Accelerated corrosion method | AASS | AASS | Galvanostatic method in concrete |
| Free length in fatigue test (mm) | 150 | 300 | 310 |
| Stress range $\Delta S$ (MPa) | 335, 418, 520, 670 | 270, 300, 360, 450, 520 | 352, 391, 430 |
| Stress ratio $R$ | 0.5 | 0.4 | 0.7353, 0.7143, 0.6944 |

### *3.2. Corrosion effects on fatigue life of steel wires*

Fatigue data of Groups II and III steel wires are listed in Table A1 and A2 of Appendix A. Stress ranges for Groups II and III steel wires with various stress ratios are converted to that with a stress ratio of 0.5, which is the same as that used for Group I steel wires, by using the Goodman relation in Eq. (5). Fatigue data for Group I steel wires can be found in Table A1 of Appendix A in [18].

Based on all the available fatigue data with a stress ratio of 0.5, the Weibull plot of the normalized variable, $Z$, for the corroded steel wires is shown in Fig. 1, where the estimated parameters of the multi-parameter Weibull model for C-S-N based on the EM algorithm are also given. The fatigue data in the three groups are shown in Fig. 1 using different marks, and the estimated expected values of the normalized variable, $Z$, for the censored samples in Group II are marked individually in Fig. 1. Samples of the normalized variable, $Z$, for the three groups of corroded steel wires are nearly linear, based on the estimated parameters, as shown in Fig. 1. Also, the standard Weibull distribution of the normalized variable $Z$ can be accepted by the KS test at the 5% level of significance with characteristic parameter $K_0 = 7.8821 \times 10^{22}$ and shape parameter $\beta = 4.1935$. As can be seen in Fig. 1, the fatigue data of steel wires with a wide range in the degree of corrosion from 0.18% to 18.67% can be fitted quite well by the Weibull model for C-S-N.

Fatigue data in the three groups of corroded steel wires and the corresponding probabilistic C-S-N surfaces are shown in Fig. 2. The upper surface in Fig. 2 is the C-S-N surface with a survival probability of 50% and the lower surface with a survival probability of 97.7%. The fatigue data for the corroded steel wires scatter around the C-S-N surface with a survival probability of 50%, and almost all fatigue data is located on the top of the C-S-N surface with a survival probability of 97.7%. The estimated expected values of the fatigue life for the censored samples in Group II are marked using cubes in Fig. 2, which are close to the C-S-N surfaces with a survival probability of 50%. As can be seen in Fig.2, the C-S-N surfaces are distorted surfaces, and the fatigue life of steel wires decreases monotonically as the stress range increases or as the degree of corrosion increases for the C-S-N surfaces. Moreover, the fatigue life decreases more quickly at a lower degree of corrosion as the stress range increases or under a lower stress range as the degree of corrosion increases.

To evaluate the applicability of the Weibull model for C-S-N for the fatigue data in different groups in detail, the curves for fatigue life versus the degree of corrosion for steel wires in the three groups under different stress ranges for different survival probabilities are shown in Fig. 3, along with the experimental data in three groups. The censored data and its estimated expected value in Group II are also shown in Fig. 3 (b). As can be seen in Fig. 3, the fatigue data of steel wires in different groups are scattered around their median; most of the fatigue data falls between survival probabilities of 10% and 90%; nearly all of the fatigue data is located over the curves with a survival probability of 97.7% for the corresponding stress range.

The curves for fatigue life versus the degree of corrosion for steel wire with survival probabilities of 97.7% and 50% are shown in Fig. 4. As the stress range increases, the curves for fatigue life versus the degree of corrosion becomes flatter; fatigue life decreases sharply at lower stress ranges, as the degree of corrosion increases from 0% to 20%. When the degree of corrosion approaches to 20%, the fatigue life of steel wire under a stress range of 200MPa is lower than $2 \times 10^5$ cycles with a survival probability of 97.7%. However, the reduction in fatigue life at a lower stress range is more serious as the degree of corrosion increases, which indicates that the fatigue life of steel wire is more sensitive to corrosion at a lower stress range.

The S-N curves of steel wire for different degrees of corrosion with survival probabilities of 97.7% and 50% are shown in Fig. 5. As the degree of corrosion increases, the slope of the S-N curve becomes steeper; the fatigue life decreases more quickly at lower stress ranges for steel wires. As can be seen from Fig. 5, when the degree of corrosion is less than 1%, no obvious effects of corrosion on the fatigue life of steel wires can be found when the stress range exceeds 500 MPa; the effects of corrosion become visible when the stress range is lower than 400 MPa. However, the stress range seems to dominate the fatigue life of steel wires more notable rather than the degree of corrosion under higher stress ranges.

The allowable stress ranges of one million cycles and two million cycles for steel wires with different corrosion degrees are shown in Fig. 6, based on the Weibull model for C-S-N in Eq. (1) and the estimated parameters shown in Fig. 1. As can be seen here, the allowable stress range for steel wires decreases as the degree of corrosion increases with a specified survival probability. The estimated allowable stress range of two million cycles is 321.04 MPa for uncorroded steel wire with a survival probability of 97.7%. For two million cycles and a survival probability of 97.7%, the allowable stress ranges for a degree of corrosion of 2%, 5%, 10%, 15%, and 20% are 301.37 MPa, 270.24 MPa, 214.10 MPa, 153.59 MPa, and 92.02 MPa, respectively. These results indicate that the fatigue resistance of corroded steel wires cannot satisfy the safety requirements as corrosion degree increases, even for lower stress ranges.

### *3.3. Damage ratio for corrosion of fatigue life of steel wire*

To give intuitive insight into the effects of corrosion on the fatigue life of steel wires, the damage ratio for corrosion denoted as $D_w$ is defined as

$$D_w = 1 - \frac{N_{\Delta S,w}}{N_{\Delta S,w=0\%}} = \frac{N_{\Delta S,w=0\%} - N_{\Delta S,w}}{N_{\Delta S,w=0\%}} \tag{6}$$

where $N_{\Delta S,w}$ is the fatigue life of the steel wire with a certain degree of corrosion, $w$, at the specified stress range, $\Delta S$, for a given survival probability; Note that $w = 0\%$ corresponds to the uncorroded steel wire. Further, substituting Eq. (3) into Eq. (6) yields

$$D_w = 1 - \left( \exp(-r)\Delta S^{-a} \right)^w \tag{7}$$

which indicates that the damage ratio for corrosion, $D_w$, is also a function of the degree of corrosion, $w$, and the stress range, $\Delta S$, irrespective of the specified survival probability. The corrosion damage ratio, $D_w$, is equal to 0 for the uncorroded steel wire (i.e., $w = 0\%$), and the fatigue life decreases monotonically as the degree of corrosion increases, indicating that the damage ratio for corrosion, $D_w$, is asymptotic to 1, that is $0 \le D_w < 1$. Therefore, the larger the corrosion damage ratio is, the less the residual fatigue life is for a specified stress range. The damage ratios for corrosion of steel wires are shown in Fig. 7, considering different stress ranges. As shown in Fig. 7, the damage ratio for corrosion increases monotonically as the degree of corrosion increases. The damage ratio for corrosion increases more quickly under lower stress ranges for the small levels of corrosion (i.e., $w \leq 2\%$). The damage ratio for corrosion approaches to 1 more quickly under a lower stress range as the degree of corrosion increases, indicating that fatigue life decreases much more quickly than that under a higher stress range. As shown in Fig. 7, the damage ratio for corrosion is close to 1 under a stress range of 200 MPa when the degree of corrosion approaches to 20%. This result indicates that the residual fatigue life of corroded steel wires can be ignored, compared with that of uncorroded steel wires.

**4. Discussion of results**

In practice, the fatigue limit of the intact high-strength steel wires should be influenced by the ultimate tensile strength. The high-strength steel wire is cold drawn eutectoid steel wire suffering large plastic deformation during the drawing processing process, and its fatigue resistance to crack nucleation increase as the ultimate tensile strength increases. However, the results obtained in this study demonstrate that the proposed Weibull model for C-S-N fits all fatigue data of corroded steel wires well for different ultimate tensile strength, as shown in Fig. 1. This result indicates that the fatigue life of these high-strength steel wires is insensitive to the ultimate tensile strength, once corrosion occurs in steel wires. The resistance to crack nucleation is strong, and the resistance to crack propagation is poor for such high-strength steel wires, while corrosion causes more reduction in fatigue life, mainly in the crack nucleation stage for the high-strength steel wires. Therefore, the fatigue data for corroded high-strength steel wires with the minimum specified ultimate tensile strength of 1670 MPa in Group I and 1770 MPa in Groups II and III can be pooled together to estimate model parameters considering different levels of corrosion in this study.

The fatigue data in Groups II and III is relatively sparse, and the fatigue data in Group III is quite scattered, making this data difficult to employ to evaluate the quantitative influence of corrosion on the fatigue life. However, this fatigue data becomes meaningful as a supplement, which makes the fatigue dataset for corroded high-strength steel wires abundant and comprehensive at large levels of corrosion. As more fatigue data with larger degrees of corrosion has been added, the shape parameter, $\beta$, for the Weibull model reduces to 4.1935, as compared a value of 6.8781 obtained in [18] considering only small levels of corrosion; this result implies that the fatigue life of steel wires becomes more scatter as the degree of corrosion increases. The slope of the S-N curve for uncorroded steel wire (i.e., parameter, $B_0$) shows little change (i.e., from 6.7600 obtained in [18] to 6.4655), while the slope of the S-N curve shows significant deviation (i.e., the parameter, $a$, changes from –37.9225 obtained in [18] to –16.8198. As more fatigue data with different levels of corrosion has been used in parameter estimation, the range of application of the proposed Weibull model for C-S-N has been extended. Once the degree of corrosion is known, the Weibull model for C-S-N can provide a quantitative evaluation on the fatigue life of high-strength steel wires with a specified survival probability, which is essential to estimate the residual fatigue life of parallel-wire cables considering corrosion effects.

The corrosion effect on fatigue life is more pronounced at lower stress ranges, while stress range dominates fatigue life more significantly at higher stress ranges. Similar conclusions are obtained based on the fatigue data for a degree of corrosion below 3.62%; the detailed rationale is discussed in [18]. In this study, the damage ratio for corrosion is further proposed to illustrate corrosion effects on the fatigue life of steel wires for different stress ranges. As the degree of corrosion increases, the damage ratio for corrosion approaches to 1 more quickly at lower stress ranges, and the residual fatigue life reduces much more caused by corrosion. Additionally, fatigue life and the degree of corrosion are negatively correlated, and their correlation has been found to increase as the stress range decreases. For example, for the fatigue data in Group I with enough samples under each stress range, the Pearson's linear correlation coefficients and their 95% confidence intervals of fatigue life and the degree of corrosion at different stress ranges are given in Table 2. The negative correlation of fatigue life and the degree of corrosion becomes larger as the stress range decreases, indicating that the influence of corrosion on fatigue life increases as the stress range decreases.

**Table 2. Correlation coefficients of fatigue life and the degree of corrosion at different stress ranges.**

| Stress range $\Delta S$ (MPa) | 335 | 418 | 520 | 670 |
|---|---|---|---|---|
| Pearson's linear correlation coefficient $\rho$ | -0.9494 | -0.9442 | -0.8647 | -0.7715 |
| 95% confidence intervals | (-0.9813, -0.8668) | (-0.9769, -0.8683) | (-0.9369, -0.7219) | (-0.8827, -0.5785) |

## 5. Conclusions

Based on the multi-parameter Weibull model for corrosion-stress-life (C-S-N) and the available fatigue data reported in the literature, this paper explores the quantitative influence of a wide range in the degree of corrosion, i.e., the loss of weight from 0.18% to 18.67%, on the fatigue life of high-strength steel wires. The limitation of the Weibull model for representing C-S-N is elaborated, and the dependence of stress ranges on positive stress ratios is considered for the available fatigue data based on the Goodman relation. The damage ratio for corrosion is proposed to illustrate the effects of corrosion and stress range on the fatigue life of high-strength steel wires. From the statistical point of view, all the available fatigue data for corroded steel wires is pooled together to improve the accuracy of parameter estimation and the applicable scope of the Weibull model for C-S-N.

The analysis results show that the Weibull model for C-S-N fits well the available fatigue data reported in the literature for high-strength steel wires with different ultimate tensile strengths and different levels of corrosion. The influence of ultimate tensile strength on fatigue life can be ignored, because corrosion causes more reduction in fatigue life associated with crack nucleation stage for corroded high-strength steel wires. The fatigue life of steel wires decreases monotonically as the degree of corrosion or the stress range increases; and the allowable stress range for a specified number of cycles decreases monotonically as the degree of corrosion increases. As more fatigue data for steel wires with a larger degree of corrosion was added, the variability of the fatigue life of steel wires increased. The fatigue life decreased more quickly as the degree of corrosion increased, and the damage ratio for corrosion is more pronounced under a lower stress range, which indicates that the fatigue life is more sensitive to corrosion at a lower stress range. Moreover, the negative correlation of fatigue life and corrosion increased as the stress range decreased, which further confirms that corrosion has a higher influence at lower stress ranges for high-strength steel wires. The proposed Weibull model for C-S-N was shown to provide a quantitative evaluation of the fatigue life of high-strength steel wires with different survival probabilities considering a wide range in the degree of corrosion. These results can be used by engineering decision makers to evaluate the residual fatigue life once the level of corrosion of steel wires is known. Avoiding corrosion in high-strength steel wires is crucial, because any improvement in the ultimate tensile strength of steel wires is negated, once corrosion occurs.

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## Contributions

H.L. and C.L. conceived the study. N.B. and J.M collected the data and conducted the parameter estimation. C.L. and B.F.S. interpreted the results and wrote the paper.

## Appendix A

**Table A1**

Fatigue data in Group II of corroded high-strength steel wires reported in [22].

| No. | $w$ (%) | Number of cycles | Original stress range $\Delta S$ (MPa) | Original stress ratio $R$ | Stress range $\Delta S$ with $R$ = 0.5 (MPa) |
|---|---|---|---|---|---|
| 1 | 4.51 | 162,711 | 520 | 0.4 | 473.62 |
| 2 | 4.93 | 220,664 | 450 | 0.4 | 414.84 |
| 3 | 4.78 | 464,954 | 360 | 0.4 | 337.14 |
| 4 | 4.30 | 2,000,000[a] | 270 | 0.4 | 256.94 |
| 5 | 5.57 | 2,000,000[a] | 300 | 0.4 | 283.96 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | 8.30 | 132,464 | 520 | 0.4 | 473.62 |
| 7 | 8.50 | 185,447 | 450 | 0.4 | 414.84 |
| 8 | 7.73 | 366,536 | 360 | 0.4 | 337.14 |
| 9 | 8.02 | 2,000,000[a] | 270 | 0.4 | 256.94 |
| 10 | 8.48 | 2,000,000[a] | 300 | 0.4 | 283.96 |
| 11 | 11.09 | 73,560 | 520 | 0.4 | 473.62 |
| 12 | 11.73 | 123,274 | 450 | 0.4 | 414.84 |
| 13 | 11.87 | 230,367 | 360 | 0.4 | 337.14 |
| 14 | 11.26 | 1,072,495 | 270 | 0.4 | 256.94 |
| 15 | 14.56 | 59,111 | 520 | 0.4 | 473.62 |
| 16 | 14.89 | 103,675 | 450 | 0.4 | 414.84 |
| 17 | 15.51 | 163,443 | 360 | 0.4 | 337.14 |
| 18 | 14.64 | 586,464 | 270 | 0.4 | 256.94 |
| 19 | 17.76 | 57,457 | 520 | 0.4 | 473.62 |
| 20 | 17.31 | 83,697 | 450 | 0.4 | 414.84 |
| 21 | 17.03 | 159,810 | 360 | 0.4 | 337.14 |
| 22 | 16.56 | 510,750 | 270 | 0.4 | 256.94 |
| 23 | 18.67 | 47,727 | 520 | 0.4 | 473.62 |
| 24 | 18.51 | 67,622 | 450 | 0.4 | 414.84 |
| 25 | 17.82 | 127,807 | 360 | 0.4 | 337.14 |
| 26 | 18.26 | 306,577 | 270 | 0.4 | 256.94 |

[a] The limit number of cycles of two million has been reached without failure.

**Table A2**

Fatigue data in Group III of corroded high-strength steel wires reported in [23].

| No. | $w$ (%) | Number of cycles | Original stress range $\Delta S$ (MPa) | Original stress ratio $R$ | Stress range $\Delta S$ with $R = 0.5$ (MPa) |
|---|---|---|---|---|---|
| 1 | 2.00 | 57,355 | 352 | 0.7353 | 544.51 |
| 2 | 2.50 | 93,780 | 352 | 0.7353 | 544.51 |
| 3 | 2.40 | 73,070 | 352 | 0.7353 | 544.51 |
| 4 | 2.60 | 78,625 | 391 | 0.7143 | 584.77 |
| 5 | 2.50 | 38,602 | 391 | 0.7143 | 584.77 |
| 6 | 2.50 | 58,430 | 391 | 0.7143 | 584.77 |
| 7 | 2.40 | 38,671 | 430 | 0.6944 | 622.46 |
| 8 | 2.60 | 48,404 | 430 | 0.6944 | 622.46 |
| 9 | 5.10 | 92,209 | 352 | 0.7353 | 544.51 |
| 10 | 5.30 | 28,846 | 352 | 0.7353 | 544.51 |
| 11 | 5.50 | 92,474 | 352 | 0.7353 | 544.51 |
| 12 | 5.10 | 41,520 | 391 | 0.7143 | 584.77 |
| 13 | 5.10 | 43,378 | 391 | 0.7143 | 584.77 |
| 14 | 4.80 | 68,947 | 391 | 0.7143 | 584.77 |
| 15 | 5.30 | 63,693 | 430 | 0.6944 | 622.46 |
| 16 | 5.10 | 28,927 | 430 | 0.6944 | 622.46 |

| | | | | | |
|---|---|---|---|---|---|
| 17 | 5.30 | 21,049 | 430 | 0.6944 | 622.46 |
| 18 | 7.60 | 70,403 | 352 | 0.7353 | 544.51 |
| 19 | 7.40 | 36,662 | 352 | 0.7353 | 544.51 |
| 20 | 7.50 | 44,222 | 391 | 0.7143 | 584.77 |
| 21 | 7.50 | 40,570 | 391 | 0.7143 | 584.77 |
| 22 | 7.60 | 38,932 | 430 | 0.6944 | 622.46 |
| 23 | 7.50 | 35,127 | 430 | 0.6944 | 622.46 |
| 24 | 7.50 | 30,954 | 430 | 0.6944 | 622.46 |

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