Corrosion Morphology and Mechanical Behavior of Corroded Prestressing Strands

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Abstract
The corrosion morphology and the mechanical behavior of corroded prestressing strands are investigated in the present study. Nineteen corroded strands are obtained through controlling stress level, corrosion time and chloride ion concentration under artificial climate conditions. A total of 119 corrosion pits are counted to investigate the geometric morphology of corrosion pits. A depth-width ratio parameter is first defined to describe the distribution law of corrosion pits, which obeys the lognormal distribution. A tension test is conducted to investigate the mechanical behavior of corroded strands. The fracture morphology and micro-cracks of corroded steel wires are observed by the scanning electron microscopy. A constitutive model is proposed to predict the stress-strain curve of corroded prestressing strands and verified by the experimental results. Results show that the maximum corrosion loss of strand increases by 4.91% when the stress level changes from 45% to 75% of strand yield strength. The high stress level can promote the propagation of corrosion micro-cracks on strand surface. The propagation of corrosion micro-cracks has a significant effect on ultimate strength of strand, while has a little effect on elastic modulus. The proposed model can give an accurate prediction for the stress-strain of corroded prestressing strand.

1. Introduction
Prestressed concrete (PC) structures in erosion environment are often subjected to the action of aggressive agents, which would cause the strand corrosion issues. The Structural Engineering Institute (SEI) of American Society of Civil Engineers (ASCE) indicates that corrosion has become one of the biggest threats for the structure safety (Biondini and Frangopol 2018). Corrosion will reduce the cross-section area of strand, lead to the concrete cracking, degrade the bond strength, and eventually cause the flexural deterioration (Dai et al. 2020; Zhang et al. 2016; Liu et al. 2017a; Peng et al. 2019; Ma et al. 2020). These would lead to the failure of PC structures without warning in severe situation, causing substantial economic losses (Jin et al. 2016; Lu et al. 2019; Floyd et al. 2018). Some failure accidents of PC structures induced by corrosion have been reported, such as the Ynysy-Gwas Bridge in UK, the Saint Stefano Bridge in Italy and the pedestrian bridge at Lowe’s Motor Speedway in North Carolina (Woodward and Wilson 1991; Proverbio and Ricciardi 2000; Cederquist 2000). The effect of corrosion on the mechanical behavior of strand should be thoroughly investigated to ensure the safety of existing PC structures.

Some studies have been performed to investigate the corrosion morphology of strand, and indicate that the corrosion of strand under the high stress state has a typical characteristic of pitting corrosion (Vélez et al. 2016). González et al. (1995) pointed out that the maximum depth of corrosion pits in strand was about 4-8 times of uniform corrosion. The geometric characteristics of corrosion pits are mainly counted with pit depth, and the corresponding probability models are also proposed (Codaro et al. 2002; Darmawan and Stewart 2007a, 2007b). However, the morphology of corrosion pits both depends on the depth and width. Only using the depth to describe the probability distribution of corrosion pits may be irrational. A more reasonable parameter is needed to reflect the morphology of corrosion pits.

Corrosion can lead to the mechanical deterioration of strands (Li et al. 2011; Liu et al. 2017b). Vu et al. (2009) found that micro-cracks caused by corrosion could lead to a considerable reduction in the ultimate strain of strand. Gardoni et al. (2009) investigated the effects of void and aggressive moisture on mechanical property of strand. Most of the aforementioned studies use the electrochemically accelerated corrosion methods to obtain corroded specimens, which may be different from that of natural corrosion (Yuan et al. 2007; Francois et al. 2013).
The artificial climate box can be employed to corrode strand through alternately controlling the salt fog and humid heat with the computer, which is closer to the natural corrosion situation as compared to the electrochemically accelerated corrosion methods. The mechanical behavior of corroded prestressing strands under artificial climate conditions has not been investigated fully.

Predicting the constitutive relation is another important issue to investigate the mechanical behavior of corroded prestressing strand. Zona et al. (2008) simplified the stress-strain constitutive relation of prestressing strand as an elastic-hardening model. Lu et al. (2016) proposed a stress-strain constitutive model, considering the area damage factor, to predict the mechanical behavior of corroded strand. Lee et al. (2020) established a probabilistic forecasting of the ultimate strength of corroded strand using the Monte Carlo method. Some experimental and analytical investigations are reported in the literatures, yet an overall satisfactory prediction of the constitutive relation of corroded strands has not been achieved and there are large discrepancies among existing constitutive models. A general model for the constitutive model of corroded prestressing strand needs to be further studied.

The objective of the present study is to investigate the corrosion morphology and mechanical behavior of corroded prestressing strand under artificial climate simulation. The paper is organized as follows. First, corroded prestressing strands with different corrosion degrees were obtained by controlling the stress level, the corrosion time, and the chloride ion concentration. Then, the number and shape of corrosion pits were measured to investigate its probability distribution. Furthermore, static tensile tests were carried out to study the mechanical property of corroded prestressing strands. Following this, a constitutive model of corroded prestressing strand is proposed. Finally, some conclusions are given.

### 2. Experimental program

In this section, the material properties of strands are introduced at first. Next, the corrosion simulation test under artificial climate test box is presented. Then, the measurement method of corrosion pits is exhibited. Following this, a tension test is conducted to investigate the mechanical property of corroded prestressing strands.

#### 2.1. Details of specimens

Nineteen 15.2 mm diameter seven-wire steel strands were corroded to investigate the mechanical behavior of corroded strands. The length of strand sample was set as 1.5 m. The material performances of strand are given in Table 1. A tensioning device was used to tension strand to simulate the high-stress working state of prestressing strand in the PC beams, as shown in Fig. 1(a). The tensioning device was composed of a steel frame and a special anchorage device, and its size was 1.1 m × 0.6 m × 0.1 m. It could tensile two specimens at the same time. The steel frame was protected by epoxy resin to prevent corrosion. The special anchorage device was designed for applying and releasing the prestressing force of strand, as shown in Fig. 1(b), and its inner cross-section is shown in Fig. 1(c). The principle of the anchorage device is as follow: before applying prestressing force, the high strength fine sand was poured into the device from the reserved hole, and then the hole was sealed with a screw; after the accelerate corrosion test, the prestressing force of strand was released through liberating the fine sand from the reserved hole.

#### 2.2. Accelerated corrosion test

Commonly, the accelerated corrosion methods can be divided into: the electrochemical accelerated corrosion, dry-wet alternating corrosion and artificial climate box corrosion. The artificial climate box can be employed to corrode strand through alternately controlling the salt fog and humid heat with the computer, which is closer to the

### Table 1 Material properties of strand.

| Property                  | Value   |
|---------------------------|---------|
| Maximum tensile force (kN) | 267     |
| Yield strength (MPa)      | 1830    |
| Ultimate strength (MPa)   | 1938    |
| Yield Strain (ε_py)       | 0.012   |
| Ultimate Strain (ε_py)    | 0.03    |
| Elastic modulus (GPa)     | 195     |
| Elongation rate (%)       | 5.5     |
| Weight per meter (g/m)    | 1104    |

![Fig. 1 The tensioning device: (a) steel frame; (b) the special anchorage device; (c) schematic.](image-url)
natural corrosion situation as compared to the other corrosion methods. Therefore, this method is used to corrode strands in the present study. The artificial climate test box consisted of two parts: a computer central control room and external components (cooling tower, condenser, solution storage tank and compressor, etc.), as shown in Fig. 2(a). The salt fog was generated by four spray nozzle that located at each of the upper corners in the climate box, as shown in Fig. 2(b). Intermittent salt fog was applied through a computer control panel with an interval of 240 minutes (a cycle that ran for 120 minutes, and then stopped for 120 minutes). The temperature and the humidity in the climate box were 20 ℃ and 70%, respectively.

Nineteen specimens, one uncorroded strand and eighteen corroded strands, were used to investigate the effect of corrosion on the mechanical property of strand. The different corrosion degrees of specimens were obtained by controlling stress level, corrosion time and chloride ion concentration. The detailed parameters of specimens are given in Table 2. R0 was the control specimen. According to the stress levels of strands, the specimens were divided into two series: R-series and S-series. The initial tension stress of strand was used to reflect the stress level in the present study, which was measured by a load cell. The initial tension stress of series R and S were 45% σs and 75% σs, respectively, where σs is the yield strength of strand. The R-series contained 5 groups, and the S-series contained 4 groups. Each group consisted of two strand samples.

### Table 2 Parameters of specimens.

| Series | Symbol | Chloride (%) | Stress level | Corrosion time (days) |
|--------|--------|--------------|--------------|-----------------------|
| Control specimen | R0 | — | — | — |
| R-series | R1 | R11, R12 | 5 | 0.45σs | 30 |
| | R2 | R21, R22 | 5 | 0.45σs | 45 |
| | R3 | R31, R32 | 10 | 0.45σs | 45 |
| | R4 | R41, R42 | 10 | 0.45σs | 60 |
| | R5 | R51, R52 | 15 | 0.45σs | 60 |
| S-series | S1 | S11, S12 | 5 | 0.75σs | 30 |
| | S2 | S21, S22 | 5 | 0.75σs | 45 |
| | S3 | S31, S32 | 10 | 0.75σs | 45 |
| | S4 | S41, S42 | 10 | 0.75σs | 60 |

2.3 Measurement on geometric shape of corrosion pits

The geometric shape of corrosion pits was measured. The outer steel wires of strand were numbered from 1 to 6, and the central steel wire was numbered as 7, as shown in Fig. 3(a). The corrosion pits of all steel wires were observed, and the shape and number of the pits were counted. A micrometer gauge was used to measure the residual diameter of corroded steel wire, as shown in Fig. 3(b). The depth of the corrosion pit was the maximum difference between the original diameters of uncorroded steel wire and the residual diameter of corroded steel wire. The width of corrosion pit was measured by digital caliper.

The mass loss and maximum cross-sectional loss of strand are two main parameters to reflect the corrosion loss. The mass loss presents the average corrosion level of strand, which is more suitable for the uniform corrosion or global corrosion of samples. The maximum cross-sectional loss can better reflect the severity of local corrosion and is suitable for reflecting pitting corrosion of samples. The prestressing strand is made by twisting 7 wires and there are some gaps inside it. After the strand corrodes, a large number of corrosion products exist between the gaps and cannot be cleaned. This will cause the measured mass loss less than the actual value. Besides, the corrosion of prestressing strand has a typical pitting morphology, so the maximum cross-sectional loss was used to reflect the corrosion loss of strands in the present study.

The procedure for determining the corrosion loss (ρ)
of strand was as follows. First, the prestressing strand was taken out from the steel frame. Following this, the corroded strand was cleaned by 12% hydrochloric acid solution, and then neutralized by the alkali. Finally, the most serious corrosion section was selected as the minimum cross-section of strand. The contour shape of corroded strand was transferred to cardboard, and then scanned into the computer. The residual area of corroded strand was calculated by Computer Aided Design (CAD), as shown in Fig. 3(a). The residual cross-sectional area of the corroded strand was the sum of the residual cross-sectional area of seven steel wires. Then, the corrosion loss of strand was calculated as the difference between the initial and residual cross-section of strand and divided by the initial cross-section. The initial cross-section is defined as the cross-section of uncorroded strand in the present study, and the initial cross-sectional area of a 15.2 mm diameter seven-wire steel strand is 140 mm².

2.4. Tension test of corroded strands
After the accelerated corrosion, the corroded strands were tensioned using the LAW-600 electro-hydraulic servo universal testing machine, as shown in Fig. 4. The loading speed was controlled by displacement, and was set at a rate of 1 mm/min. The load data was automatically read by the tension tester, and its elongation was measured by the JZ-73 extensometer. The gauge length of the extensometer was 500 mm. Strand was considered to reach the ultimate tensile force once the steel wire was broken as stipulated in the Chinese Standard (China GB/T 5224-2014 2014). After that, the test was continued at the rate of 2 mm/min until all the wires were broken.

To investigate the fracture morphology and surface appearance of steel wire under different corrosion losses, representative samples (R₀, R₃₂, S₃₂ and R₅₂) were observed by the scanning electron microscopy (SEM), as shown in Fig. 4. The edge fracture section of strand was cut out and its length was about 10 mm. R₃₂ and S₃₂ were used to compare the fracture morphology of strand under various stress levels, while R₅₂ was employed to reflect the fracture morphology of strand with high corrosion degree.

3. Corrosion morphology of prestressing strands

3.1 Effect of chloride concentration, stress level on corrosion loss
The corrosion scenes of R₁₁ in the 0, 7th, 14th and 30th days are shown in Fig. 5. Under the alternating wetting and drying cycles of salt fog, the corrosion scene of strands changes significantly at various corrosion stages. In the initial corrosion phase, corrosion products first occurred in the wire gaps. With corrosion time increased, the accumulation of corrosion products in the wire gaps...
became slow, while corrosion products on the wire surface were gradually intense. As corrosion further progressed, the corrosion products on the strand surface fell off, leading to a large corrosion loss of strand. Table 3 gives the corrosion losses of nineteen specimens.

The effects of chloride ion concentration and stress level on corrosion loss of strand have been investigated, as shown in Fig. 6. It is found that the corrosion losses of S1, S2 and S4 are 1.83%, 1.16% and 4.91% higher than those of R1, R2 and R4, respectively, which illustrates that high stress level can accelerate the strand corrosion loss. When the stress level changes from 45% to 75% of strand yield strength, the maximum corrosion loss of strand increases by 4.91% in the current experimental study. Under the same conditions except for the different chloride concentrations, it is found that the corrosion losses of S3, S5 and S4 are 1.58%, 10.8% and 1.51% higher than those of R2, R4 and S2, respectively. A 5% change of chloride ion concentration can lead to a 10.8% maximum difference in strand corrosion loss. These demonstrate that the high chlorine ion concentration can lead to a large strand corrosion loss.

### Table 3 Corrosion losses of specimens.

| Series | Symbol | Corrosion loss ρ (%) | Average corrosion loss (%) |
|--------|--------|----------------------|---------------------------|
| Control specimen | R0 | 0 | 0 |
| R1 | R11 | 4.34 | 4.45 |
| | R12 | 4.56 |
| R2 | R21 | 8.89 | 8.60 |
| | R22 | 8.30 |
| R3 | R31 | 9.96 | 10.18 |
| | R32 | 10.40 |
| R4 | R41 | 14.82 | 13.60 |
| | R42 | 12.38 |
| R5 | R51 | 21.30 | 24.40 |
| | R52 | 27.50 |
| S1 | S11 | 6.10 | 6.28 |
| | S12 | 6.45 |
| S2 | S21 | 9.95 | 9.76 |
| | S22 | 9.57 |
| S3 | S31 | 11.74 | 11.27 |
| | S32 | 10.80 |
| S4 | S41 | 17.51 | 18.51 |
| | S42 | 19.50 |

#### 3.2 Geometric morphology of corrosion pits

A total of 119 corrosion pits were counted from the seven steel wires of all the corroded strands to investigate the geometric configuration of corrosion pits. The shape of corrosion pits can be divided into three types: spheroidicity, saddle and pyramid, as shown in Fig. 7. Statistics indicate that there were 29 pyramid pits, 38 spheroidicity pits and 52 saddle pits, accounting for 24%, 32% and 44% of total number, respectively.

Strand exists many micro-crystal clusters of pearlitic grain, and the electrochemical property of each pearlite is different (Toribio and Ayaso 2003). This may cause the pits having different shapes and the formation process of corrosion pits may be as follows. In the corrosion initiation, the strand surface is smooth, which can be easy to corrode. Once a single pearlite corrodes, corrosion will spread around the strand surface, forming a spheroidicity pit. With corrosion proceeding, the initial pits gradually occupy the strand surface, the development of new pits

![Corrosion losses](image-url)
will be limited at a certain extent, and corrosion products mainly accumulate on the old pits. In this stage, the adjacent old pits are slowly connected to form a saddle-shaped. If corrosion pits developed by the pearlite are far apart, the single corrosion pit will slowly form a pyramidal shape.

To reflect the effect of corrosion pit types on the mechanical properties of strand, a deformation coefficient $\Omega$ (the ratio of the maximum elongation of the corroded strand to that of the uncorroded strand) is defined in the present study, as shown in Fig. 8. The eighteen corroded strands are divided into three kinds according to the types of pits on the surface. The "strand with saddle pit" in Fig. 8 means that the saddle pits are main pattern on the strand surface, that is, the number of saddle pits on the strand surface is more than the number of spheroidicity pits and pyramidal pits.

As Fig. 8 shows, the deformation coefficient of corroded strand with saddle pit decreases significantly, as compared with that of spheroidicity pit and pyramidal pit. Saddle pits with wide width and deep depth makes the steel wire easy to break under the small tensile force, which will reduce the tensile capacity of strand. The depth-width ratio of pyramidal pits is larger than that of spheroidicity pits. A more significant stress concentration effect will appear on strand with pyramidal pits, as compared with spheroidicity pits. Therefore, the tensile capacity of strand with pyramidal pits is lower than that of strand with spheroidicity pits.

### 3.3. Probability distribution of corrosion pits

The dimensions of all corrosion pits were measured, and the relationship between size parameters and corrosion losses is shown in Fig. 9. The size parameters of corrosion pits in the present study contain: depth, width and depth-width ratio. The depth-width ratio is defined as the ratio of the maximum depth of corrosion pit to the maximum width. When the corrosion loss of the steel wires changes from 0.78% to 33.4%, the maximum depth of pits is from 0.12 mm to 2.79 mm, the maximum width is from 0.33 mm to 4.45 mm, and the depth-width ratio is from 0.10 to 1.27. As shown in Fig. 9, the curve fitting was performed on the size parameters of corrosion pits. It is found that the maximum depth and depth-width ratio roughly follow the distribution law of the curve, and the correlation coefficient $R^2$ of their fitting with the curves are both 0.49, while the maximum width has a great discrete, and its correlation coefficient $R^2$ is only 0.06.

To investigate the probability distribution of the size parameters of corrosion pits, the statistical analysis is conducted on it. The frequency histograms of maximum depth, maximum width and depth-width ratio of all corrosion pits are shown in Fig. 10.

The regression analysis is employed to describe the frequency histograms of corrosion pit sizes. As Fig. 10(a) shows, the maximum pit-depth of corroded prestressing strand obeys the Gumbel extreme value distribution. Some existing studies also use the Gumbel extreme value distribution model to describe the depth of corrosion pits (Darmawan and Stewart 2007b; Jeon et al. 2019). As Fig. 10(b) shows, the frequency distribution of
pit width is relatively discrete. The commonly used data analysis curves, such as the normal distribution, exponential distribution and gamma distribution, are poorly fitted with the maximum width distribution of corrosion pits.

Only using the depth to describe the probability distribution of corrosion pits may be unreasonable. As Fig. 7 shows, the depth of the pyramid pit is large and its width is small, while the spheroidicity pit has a small depth and a large width. Additionally, the saddle pit has a deep depth and a wide width. The corrosion morphology of strand both depends on the depth and width of pits. To reflect the corrosion morphology of steel wires more comprehensively, a depth-width ratio is employed to describe the corrosion pits in the present study. As Fig. 10(c) shows, the probability distribution of depth-width ratio has a good agreement with the lognormal distribution.

The goodness-of-fit of the depth-width ratio probability distribution given by frequency distribution histogram is verified by the Kolmogorov-Smirnov (K-S). Results demonstrate that the distribution pass the K-S at the 0.05 significance level, that is, the depth-width ratio distribution of corroded steel wire follows the lognormal distribution. The mean and standard deviation of samples estimated by the moment method of estimation are 8.0 and 7.2, respectively. Substituting the mean and standard deviation into the lognormal function, the probability distribution function of the depth-width ratio can be expressed as

\[ f(x) = \frac{1}{\sqrt{2\pi} \times 8.0x} \exp\left[-\left(\ln x - 7.2\right)^2 / 126.6\right] \] (1)

Similarly, the probability distribution of corrosion pit depth follows the Gumbel extreme value distribution, which can be expressed as

\[ f(x) = \exp\left[-\exp\left(x - 9.3 / 4.5\right)\right] \] (2)

4. Failure model and mechanical behavior of corroded strands

4.1 Failure model of corroded strand

The fracture surfaces of corroded steel wires under different corrosion degrees are shown in Fig. 11. The fracture surface of uncorroded steel wire R0 exhibits a necking phenomenon, which can be considered as a ductile fracture. This is because the maximum tensile stress of uncorroded wires is similar, the wire breaks almost at the same time after failure. After corrosion, the maximum tensile stress of steel wires under different corrosion degrees is different. The failure mode of corroded strand gradually changes from ductile fracture to brittle fracture, and the wire fracture has no obvious necking phenomenon. The tensile test results indicated that the corroded strands usually failed at the location with minimum cross-sectional area. Thus, it is reasonable to use the minimum cross section area to calculate the mechanical behaviors of corroded strand.

The fracture morphology of the representative samples (R0, R32, S32 and R52) in the cross-section was observed by SEM. The fracture morphology of corroded steel wire mainly contained the cup type, the cup-cone type, the wedge type and its combination form. The fracture morphologies of the representative samples are shown in

Fig. 10 Frequency distribution histogram: (a) depth; (b) width; (c) depth-width ratio.

Fig. 11 Fracture surfaces of corroded steel wires: (a) R0; (b) R32; (c) R52.
The fracture surface of the uncorroded sample R_0 was the cup type, showing a necking phenomenon. The fracture surface of the lightly corroded sample R_32 was the cup-cone type. With corrosion increased, the sample S_32 exhibited the combination form (cup-cone-wedge type), the necking phenomenon at the fracture surface weakened. For the sample R_52 with serious corrosion, the fracture surface of wire was the wedge type, which had no obvious necking phenomenon.

To investigate the micro-cracks of corroded steel wires, the surface appearances of representative samples (R_0, R_32, S_32 and R_52) were also observed, as shown in Fig. 13. The surface of the uncorroded sample R_0 was relatively smooth, and no micro-cracks were found. With corrosion propagation, some micro-cracks were observed on the surface of R_32. Compared with R_32, the crack width of S_32 became large and the number of cracks increased. For severely corroded R_52, more micro-cracks were found, and the crack width was more obvious. This indicates that the micro-cracks on the wire surface increase significantly in width and depth with increasing corrosion loss. Comparing with R_32 and S_32, it can be found that even the corrosion losses are similar, the higher stress level can lead to a larger corrosion micro-crack. This means that the high stress level can promote the propagation of corrosion micro-cracks.

![Fracture morphology of corroded wire](image1)

![Micro-cracks of corroded steel wires](image2)
4.2. Mechanical behavior of corroded strands
The load-deformation curves of the samples are shown in Fig. 14. For the uncorroded strand $R_0$, the load-deformation curve can be divided into three stages: elastic stage, yielding stage and hardening stage. $R_0$ fractures at the hardening stage with a significant plastic deformation. Slightly corroded strand specimens ($\rho \leq 10.4\%$) fail at the yielding stage or the hardening stage, while the severely corroded specimens ($\rho > 10.4\%$) all fail at the elastic stage, exhibiting the brittle failure. As Fig. 14 shows, the maximum tensile load of prestressing strands decreases gradually with the increase of corrosion degree. Moreover, the yield stage of corroded strand is gradually shorter and the seriously corroded strand does not have a yield plateau. This indicates that corrosion can cause the ductility degradation of strand.

The relation between ultimate strength and corrosion loss ($\rho$) of strand can be expressed as

$$f_{pu,c} = \frac{F_{pu,c}}{A_c} = \frac{F_{pu,c}}{F_{pu}} \cdot \frac{A_0}{A_c} = \mu \cdot \frac{f_{pu}}{1 - \rho}$$

where $f_{pu,c}$ and $f_{pu}$ are the ultimate strengths of corroded and uncorroded strands, respectively; $A_0$ is the cross-sectional area of uncorroded strand, $A_0 = 140 \text{ mm}^2$; $A_c$ is the minimum cross-sectional area of corroded strand; $F_{pu,c}$ and $F_{pu}$ are the maximum tensile loads of corroded and uncorroded strands, respectively; and $\mu$ is the ultimate load ratio, $\mu = F_{pu,c} / F_{pu}$.

The relationship between ultimate strength and corrosion loss of strand can be described by a double broken line, as shown in Fig. 15(a). When the corrosion degree of strand is less than the critical value ($\rho_c = 10.4\%$), the ultimate strength of corroded strands decreases steeply. After exceeding the critical value, the decrement rate of ultimate strength slows down. Meanwhile, the propagation of corrosion microcracks also greatly reduces the ultimate strength of the strand.

The relationship between elastic modulus and corrosion loss is further presented to clarify the effect of corrosion on elastic modulus, as shown in Fig. 15(b). The elastic modulus ratio is defined as the ratio of the elastic modulus of corroded strand to that of uncorroded strand. The elastic modulus of uncorroded strand $E_p$ is given in Table 1. Liu et al. (2017b) proposed an effective method to calculate the elastic modulus of corroded strand, which is also used in the present study: the corroded strand is divided into $n$ elements at first; and then the elongation of corroded strand $\Delta l$ is expressed as the sum of the elongation of $n$ elements; following this, the elastic modulus of corroded strand $E_c$, defined as the ratio of the stress $\sigma$ and strain $\varepsilon$ of corroded strand, is given as

$$E_c = \frac{\sigma}{\varepsilon} = \frac{F / A_c}{\Delta l / A_c} = \frac{F \cdot l_0}{\Delta l \cdot A_c}$$

Fig. 14 Load-deformation curves of corroded strands: (a) R-series; (b) S-series.

Fig. 15 Mechanical property parameters: (a) ultimate load ratio; (b) elastic modulus ratio; (c) ultimate strain ratio.
\[ \Delta l = \sum_{i=1}^{n} \Delta l_i = \frac{F l_p}{nE_p} \sum_{i=1}^{n} \frac{1}{A_p} \]  

where \( E_p \) is the elastic modulus of uncorroded strand; \( E_c \) is the elastic modulus of corroded strand; \( \Delta l \) is the elongation of corroded strand; \( l_p \) is the gauge length of the extensometer; \( F \) is the applied load; \( \Delta l_i \) and \( A_p \) are the elongation and minimum cross-sectional area of the \( i \)th element of corroded strand, respectively.

As shown in Fig. 15(b), comparing \( R_0 \) with \( R_{52} \), it is found that although their corrosion losses are different, their elastic modulus is similar, and the difference between them is only 6.67%. Among all specimens, \( R_{52} \) is the most seriously corroded, and the crack length and width on its surface are large. Francois et al. (2013) and Liu et al. (2017b) also investigated that the effect of corrosion on elastic modulus of strand, and indicated that the elastic modulus of strand after corrosion only had a slight change. Therefore, it can be considered that corrosion has a little effect on elastic modulus of strand.

The effect of corrosion on the ultimate strain of strand is shown in Fig. 15(c). The ultimate strain ratio (\( \epsilon_\beta \)) is defined as the ratio of the ultimate strains of corroded strand to that of uncorroded strand. When the strain corrosion loss is less than the critical value, the ultimate strain decreases with the increase of corrosion loss. The ultimate strain ratio in this stage is linearly fitted. After exceeding the critical value, a little change has been found in the ultimate strain of corroded strands with the increase of corrosion loss. This is because when the corrosion degree is larger than the critical value, the strand suffers the brittle failure in the elastic stage, without the yield stage and the hardening stage. The corresponding strain of severely corroded strands can be obtained by the ratio of ultimate strength to elastic modulus.

### 4.3 A constitutive model of corroded prestressing strands

A simplified and universal constitutive model is established in the present study. The stress-strain curve of prestressing strands can be described by elastic-hardening model (Zona et al. 2008). The stress-strain curves of corroded strand have similar variation trend in the elastic stage, while will have different variation trend after yield stage. For slightly corroded strands, the stress-strain curve can be expressed as a bilinear model, and the ultimate strength of strand will decrease with increasing corrosion loss. When the corrosion degree exceeds the critical value, the stress-strain curve of strand will degenerate into a single-linear model.

According to the above principles, the constitutive model of corroded prestressing strands can be proposed, as shown in Fig. 16. The relevant parameters in the model are selected as follows. The prestressing strand, as the high-strength steel wire, has no obvious yield point. According to the Chinese standard (China GB/T 50010-2010), the nominal yield strength of prestressing strand is taken as 85% of strand tensile strength. The elastic modulus of uncorroded strand is used to evaluate the elastic modulus of corroded strand. The critical corrosion loss of strand (\( \rho_c \)) obtained from the present experimental study is 10.4%. The constitutive model of corroded prestressing strand can be expressed as

\[
\sigma = \begin{cases} 
\rho \leq \rho_c & f_{p,y} + E_p (\epsilon - \epsilon_{p,y}) \quad \epsilon \leq \epsilon_{p,y} \\
\rho > \rho_c & E_p \epsilon \quad \epsilon \leq \epsilon_{p,y}
\end{cases}
\]

\[
f_{p,y} = 0.85 f_{p,yc} = 0.85 \frac{\mu}{1-\rho} f_{pu} \quad (\rho \leq \rho_c)
\]

\[
E_p = \frac{f_{p,yc} - f_{p,yc}}{\epsilon_{p,yc} - \epsilon_{p,yc}} \quad (1-\rho)E_p \beta \epsilon_{pu} = 0.85 \mu f_{pu}
\]

where \( \sigma \) and \( \epsilon \) are the stress and strain of strand, respectively; \( \epsilon_{p,yc} \) and \( \epsilon_{pu} \) are the ultimate strains of corroded and uncorroded strand, respectively, and \( \epsilon_{p,yc} \) is the yield strain and yield strain of corroded strands, respectively, and \( \epsilon_{pu} = f_{pu} / E_p \); \( E_p \) is the hardening modulus of strand after yielding.

To verify the applicability of the proposed model, a comparison of the predicted and experimental stress-strain curves for specimens \( R_{12}, R_{32}, R_{52}, S_{11}, S_{21} \) and \( S_{41} \) is shown in Fig. 17. Slight deviations between the predicted and experimental curves have been found. Those errors can be attributed to the uncertainty of experimental data. Additionally, the simplification of the model can also cause the errors. Considering the complexity of corrosion process, the proposed model has a good prediction accuracy, which can be employed to predict the stress-strain curve of corroded prestressing strand.

As mentioned above, the minimum cross-sectional area of the corroded strand is used to convert the stress into the force, and then the tensile force of the corroded

Fig. 16 Constitutive model of corroded prestressing strands.
strand can be evaluated with the proposed model. Furthermore, in practical engineering applications, the corrosion loss of strand can be measured by the non-destructive testing techniques, such as the acoustic emission method, half-cell potential and linear polarization resistance (Mangual et al. 2013; Jiang et al. 2019). There are also some models that have been proposed to predict corrosion loss with crack width (Li and Yang 2011; Khan et al. 2014; Wang et al. 2019).

5. Conclusions

The corrosion morphology and mechanical behavior of corroded prestressing strands are investigated in the present study. A constitutive model is proposed to predict the stress-strain curve of corroded prestressing strands. The following conclusions can be drawn.

1. The stress level and chloride ion concentration can aggravate the strand corrosion loss. When the stress level changes from 45% to 75% of strand yield strength, the maximum corrosion loss of strand increases by 4.91% in the current experimental study. A 5% change of chloride ion concentration can lead to a 10.8% maximum difference in strand corrosion loss.

2. A total of 119 corrosion pits are counted to investigate the geometric configuration of corrosion pits, which is divided into spheroidicity pit, saddle pit and pyramid pit. A depth-width ratio is employed to reflect the corrosion morphology of steel wires, and it obeys the lognormal distribution.

3. The high stress level can promote the propagation of corrosion micro-cracks on strand surface, and the propagation of corrosion micro-cracks has a significant effect on ultimate strength of strand, while has a little effect on elastic modulus.

4. The constitutive model of corroded prestressing strand depends on corrosion degrees. For slightly corroded strand, the constitutive model can be modeled as a bilinear model. Exceeding the critical corrosion loss (10.4% in the current experimental study), its constitutive relationship will degenerate into a single-linear model.

This study proposes a constitutive model to predict the mechanical behavior of corroded prestressing strand. In the natural environment, many factors can lead to the mechanical deterioration of strand, and the stress-strain of corroded strand will be more complicated. How to propose a constitutive model of corroded prestressing strand, considering the multi-factor coupled effects, needs to be further studied.

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