Mechanical Degradation of Q345 Weathering Steel and Q345 Carbon Steel under Acid Corrosion

Fan Yang, Miao M. Yuan, Wen J. Qiao, Na N. Li, and Bin Du

1Civil and Architecture Engineering, Xi’an Technological University, Xi’an 710021, China
2School of Civil Engineering, Inner Mongolia University of Science and Technology, Baotou 014010, China
3School of Civil and Traffic Engineering, Shanghai Urban Construction Vocational College, Shanghai 200438, China

Correspondence should be addressed to Fan Yang; yangfan0314@xatu.edu.cn

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1. Introduction

The steel structure bridges had been widely used for their reasonable stress resistance, economic profitability, fast construction speed, and good resistance to wind and earthquake. Due to their poor corrosion resistance, however, a damage to steel structure bridges has been observed to varying degrees in chloride-containing environments. In recent years, with the diversification of road transportation of goods, a tank transport of corrosive liquids has occupied a considerable share of the cargo transportation market and has been used as an important way of industrial supply. The overturning of industrial acid trucks due to traffic accidents may cause a corrosive liquid to leak, resulting in a significant damage to steel structures. There were many examples of such accidents, including a hydrochloric acid truck overturned at the Chongqing high-speed Huadong service area in September 25, 2018 (Figure 1), and more than 20 tons of concentrated hydrochloric acid leaked at the G92 (Hang-yong), less than two kilometres from the Shangyu toll station in August 24, 2018 (Figure 2). In the past 10 years, there had been about 284,000 hydrochloric acid leakage accidents in China [1]. Due to diverse factors including distance and rescue blind spots, it has been difficult to eliminate the effects of the strong acid leakage completely, which makes the corrosion hazard of strong acid leakage to the steel structure bridges even higher. Strong corrosion leads to irregular corrosion pits formation on the steel structure surface, resulting in decreased thickness and strength. The results showed that different corrosion conditions have a great influence on the static performance, dynamic performance, and failure mechanism of steel structure members. Therefore, it is necessary to study the influence of strong acid corrosion on the mechanical properties of steel structure materials.
Many studies on corroded steel in different corrosion conditions have been carried out in China and abroad. The mechanism of the reduction of the capacity and the characteristic changes of the tensile constitutive relation of corroded steel bar were investigated. A simple equation was proposed to predict the residual capacity of corroded reinforcing bars in practice. The trilinear model can give a relatively accurate prediction of the characteristic parameters of corroded steel bars [2]. 3-Dimensional optical, computed tomography scanning, and weight loss measurements were used to evaluate the levels of corrosion [3]. A degradation of mechanical properties of corroded steel plate was studied based on the experimental and numerical simulation method of surface topography [4, 5]. The monotonic tensile tests were carried out on the flat and angular specimens with cross section loss rate in the range of 0–0.384 to determine the stress-strain curve, and the surface topography was measured using ST400 3D noncontact surface morphology scanner. A method for calculating the minimum cross-sectional area of planar and angular specimens based on surface topography data was also established [6]. The corrosion morphology of corroded steel plate was estimated by eddy current method and used to determine the shape of the corroded steel plate. The calculated corrosion morphology was in good agreement with the actual corrosion morphology measured by the laser displacement meter. Corrosion is a stochastic process; therefore, random fields can be reasonably used to characterize the surface topography of corroded steel specimen [7]. Stochastic simulations were used to model the random nature of the pitting corrosion varying pitting shape, depth, and distribution [8, 9]. The corrosion depth of surfaced steel plate in neutral salt spray environment conformed to the normal distribution [10].

The relationship between characterization parameters and mechanical properties was studied through tensile tests on corroded steel plates, and the differences in failure modes and stress-strain relations of steels with different corroded degrees were analyzed. The results showed that corroded steel surface morphology had effects on mechanical properties degradation of the steel plate, and the corrosion rate, local corrosion depth, and the relative size of corrosion pits were the main factors affecting the tensile properties of the corroded steel [11–14]. Pits, having higher aspect ratio, are the most dangerous form as they can cause a significant reduction in the load carrying capacity [15]. A multiscale modelling approach for simulating the tensile behavior of the corroded has been developed, accounting for both the geometrical features of corrosion damage and the effect of corrosion-induced hydrogen embrittlement [16]. The stress concentration effect of corroded steel structure surface was studied through atmospheric exposure test, and its potential fatigue problems and stress concentration level were discussed. An experimental test and numerical analysis showed that the maximum stress appeared in the maximum corrosion depth of corroded surface [17]. The effects of different corrosion conditions (dry air, freshwater, and seawater immersion) and different temperatures (−10°C, 0°C, and 18°C) on the chemical and mechanical properties of structural steels were studied [18]. The strength and deformation capacity of steel plates with different pit size, pit strength, and corrosion degree were also estimated [19]. The failure strain in relation to the finite element mesh size used in the analyses was clarified. A more accurate method of remaining strength estimation of the corroded tensile plates was presented, based on the experimental results of tensile tests conducted on 26 specimens with different corrosion conditions and width of 70–180 mm [20]. The above studies on the mechanical properties of steel are limited to atmospheric corrosion. The researches on strong acid corrosion are less represented. The relationship of the yield strength, ultimate strength, elastic modulus, and elongation and corrosion damage therefore needs to be further experimentally studied due to the various influencing factors including corrosion environment, type of steel, and selection of nominal thickness.

To sum up, although the atmospheric corrosion behavior of the steels had been studied for many years, there were relatively few researches on strong acid steel corrosion. In particular, the relationship between mechanical properties and corrosion time of Q345 steel under strong corrosion is not clear. In this paper, Q345 weathering steel and Q345
carbon steel, both commonly used for steel plate composite bridge, were selected as the research objects. The influence of surface morphology and corrosion rate on the mechanical degradation of corroded steel plate was studied during the short-term exposure to 36% industrial hydrochloric acid. The stress-strain curve models of weathering steel and carbon steel plate under acid corrosion were proposed. The results form a basis for the mechanical study of strong corroded steel plates and provide an application reference to the reinforcement design of steel structure bridges.

2. Experimental Introduction

2.1. Materials. The test specimens, low-carbon steels (the quality variety of Q345 weathering steel and Q345 carbon steel was C), were purchased from Qinhuangdao Steel Co., Ltd., and taken from 1/4 of the width of the plate in a full-thickness manner (8 mm). The chemical composition of weathering steel and carbon steel is shown in Table 1. The materials conformed to the requirements of Steel and Steel Products—Location and Preparation of Test Pieces for Mechanical Testing (GB/T 2975-1998) [21]. The chemical composition and mechanical properties of the steel plate met the standard requirements of High Strength Low Alloy Structural Steels (GB/T 1591-2008) [22].

2.2. Corrosion Method. Firstly, the specimens were numbered, and the weight of each specimen was measured by an electronic balance (accuracy 0.001 g, supplied by Shanghai Electronic Technology Co., Ltd.). Secondly, the holding end was smeared with epoxy resin to prevent it from being damaged during the tensile test. Afterwards, 54 standard specimens were immersed in 36% hydrochloric acid solution at room temperature to simulate the strong acid corrosion of bridge structural steel (shown in Figure 3). The soaking time was 0 h, 1 h, 2 h, 4 h, 8 h, 12 h, 24 h, 48 h, and 72 h, respectively. After the corrosion experiment, the specimens were taken out and neutralized with 3% sodium carbonate solution. The corrosion products on the surface of the specimen were rinsed with clean water and dried in a dryer for 4 h. Finally, the corroded specimens were labelled and weighed by an electronic balance.

2.3. Tensile Test. The specimens for standard tensile test were prepared based on Metallic Materials-Tensile Testing-Part 1: Method of Test at Room Temperature (GB/T 228.1-2010) [23]. The tensile test was conducted with an electronic universal testing machine (DNS200, China Machinery Testing Equipment Co., Ltd.). The measuring range was 200 kN and the accuracy class was 0.5. The specific steps were used, based on those recommended by Metallic Materials-Tensile Testing-Part 1: Method of Test at Room Temperature (GB/T 228.1-2010) [23]. The tensile loading test was carried out by displacement control, the length of the extensometer was 50 mm, and the loading rates at the elastic stage, yield stage, and strengthening stage were 0.75 mm.min$^{-1}$, 0.75 mm.min$^{-1}$, and 5.0 mm.min$^{-1}$, respectively.

3. Experimental Results

3.1. Comparison of Corrosion Dynamic Curves. The quality loss rate was used to express the corrosion rate of the tested steel. The carbon steel and weathering steel were divided into 9 groups according to different corrosion times. After the corrosion time was reached, the specimens were removed from the corrosion solution, cleaned, and weighed.

A nonlinear least squares method was used to fit the relationship between the strong corrosion time and the corrosion rate of the tested steel. The fitting relations and corrosion dynamic curves are shown in Figure 4.

It can be seen from Figure 4 that the corrosion rate of weathering steel and carbon steel increases nonlinearly with the extension of corrosion time, and the parameter $R^2$ in the fitting relation was 0.98, indicating a good nonlinear fitting
relationship between corrosion rate and corrosion time. The corrosion rate of three parallel specimens fluctuated slightly in each corrosion cycle group; however, the fluctuation was within the allowable error range. At the same time, it can also be seen that the corrosion rate of carbon steel was higher than that of weathering steel; that is, the mass loss rate of carbon steel was greater than that of weathering steel at the same corrosion time. The main reason for this observation could be related to the presence of small amount of alloying elements such as Cu and Ti in the weathering steel. Furthermore, a protective layer could have been formed on the steel surface resulting in an improved corrosion resistance. The high concentration of chloride ions in the HCl solution caused a fast reaction with the steel. With the extension of corrosion time, the ferric chloride was produced by strong corrosion and attached to the surface of the steel substrate. Although the corrosion rate continued to increase, the growth rate slowed down with time.

3.2. Comparison of Surface Morphology of Corrosion Specimens. The DSX500 noncontact surface profiler (Shanghai Precision Instrument Co., Ltd.) was used to measure the surface profile of the corroded steel after rust removal. The scanning area of the corroded steel surface was 40 mm × 20 mm. The scanning position was the position of the steel centroid of the bridge. The longitudinal and transversal scanning steps were 50 μm, respectively. By scanning the corroded steel plate, the morphology and pitting corrosion data of the corroded surface were obtained.

Figures 5 and 6 show the three-dimensional surface morphology of carbon steel and weathering steel after strong corrosion by hydrochloric acid in different periods, respectively. It can be seen that different surface pittings form in the hydrochloric acid corroded steel. They can be divided into uniform pinhole shape, cone shape, and ellipsoid shape.

Figures 5 and 6 show the three-dimensional morphology of the pits, and the outline and size of pits on the surface of bridge steel can be clearly seen in these Figures. In addition, the shape change and distribution of pits in the bridge steel can be seen intuitively according to the different color information.

As can be seen from Figures 5 and 6, at early corrosion times, the corrosion pits of weathering steel specimen were relatively shallow and narrow, so the overall surface of steel was still relatively flat. In the early stages of corrosion, the corrosion damage was relatively uniform. At 1 h, the average pit depths of carbon steel and weathering steel were 27.607 μm and 21.918 μm, respectively. The pits had a pin-hole shape. With the increase of corrosion rate, the pits became deeper, and their distribution became uneven. Furthermore, they spread along the entire surface. At 12 h, the average pit depths of carbon steel and weathering steel were 68.037 μm and 45.290 μm, respectively. The pit depth and their concentration gradually increased, and dense pit groups appeared on the surface. The shape of pit groups was mainly saddle and cone. When the corrosion age reached 72 h, the average pit depths of carbon steel and weathering steel were 97.044 μm and 71.521 μm, respectively. The number of pits increased slowly, and the width and depth of pits increased further. The adjacent pits on the steel surface merged to form large local pits, which were mainly ellipsoidal and hemispherical. By comparing the surface morphology of the two specimens, it has been found that the density of pitting corrosion of carbon steel was larger than that of weathering steel, and the number of pitting pits was high. With the increase of corrosion rate, the surface morphology became more uneven.

In the early stages of corrosion, the depth and width of corrosion pits grew rapidly. When the corrosion time reached 12 h, the size of corrosion pits on the surface of the two bridges steel started to grow slowly. This is because with the progress of the reaction between hydrochloric acid and steel matrix, the concentration of chloride ions started to decrease and ferric chloride was formed, which further hindered the pit growth. At the same corrosion time, the size of corrosion pits of carbon steel was significantly larger compared to weathering steel. The main reason is that weathering steel contains a small amount of alloying elements including Mn and Ti (Table 1), which prevents the further expansion of corrosion pits and protects the steel matrix. After 72 h of immersion in hydrochloric acid, the average pit depth of carbon steel increased to 86.3 μm in carbon steel and 53.5 μm in weathering steel.

The relationships between the maximum corrosion pit depth and corrosion time for carbon steel and weathering steel are shown in Figure 7. It can be seen that the maximum corrosion pit depth increases nonlinearly with the increase of corrosion time and follows a parabolic rate law. Furthermore, it is obvious that the corrosion pit depth of carbon steel grows faster. The fitting formulas are included in Figure 7.

In the early stages of corrosion, the Fe content of carbon steel was higher
Figure 5: Continued.
compared to that of weathering steel. At 72 h, the Fe content in carbon steel became smaller compared to weathering steel. The main reason is that the conductivity and catalytic activity of rust layer has been changed. The weathering steel has corrosion-resistant alloy element Cr, which may react with Fe ions to form a stable metal oxide. As a result, the penetration of Cl ions from the hydrochloric acid solution into the weathering steel was greatly inhibited, which caused the corrosion rate of steel substrate to decline. This conclusion is consistent with the apparent morphology (Figures 5 and 6).

3.3. Fracture Analysis. The fracture morphology can evidently reflect the failure made of corrosive steels [24–26]. In this study, the fracture morphologies for all corroded specimens were investigated using a high-resolution camera and contrast analysis. It was found that the fracture morphology characteristics of carbon steel and weathering steel were identical. There were three types of typical fracture morphologies of the corroded specimens appearing after the tensile test (seen in Figure 10). The main reason was that with the prolongation of corrosion time, the increase of surface erosion pit concentration leads to stress concentration, which makes the fracture path irregular, and the roughness increases gradually. By contrasting the details of the deformations near the breaking zone, shown in Figure 10, it became apparent that the deformability of the whole tensile region was correlated with the surface information of the localized corrosion.

The behavior leading to the “brittle failure” of the corroded steel could be confirmed by the microstructure observation via scanning electron microscopy (Figure 11). The scanning position was taken close to the center of the fracture.

Figure 11 presents the fracture surfaces of the corroded steel after different corrosion durations. A scanning electron microscope with the magnification 3000 times was used to observe the fracture morphology of steel at different corrosion times. The scanning position was near the central area of fracture. Obviously, there are many dimples in the corrosion fracture. The average sizes of dimple at 0 h, 1 h, 2 h, 4 h, 8 h, 12 h, and 24 h were 14.67 μm, 11.33 μm, 8.67 μm, 7.00 μm, 6.00 μm, 4.00 μm, and 3.00 μm, respectively. As the corrosion time increases, the number of dimples gradually increases, while their sizes gradually decrease. Once the

![Figure 5: Surface morphology of corroded carbon steel (scale bar unit: μm). (a) 0 h. (b) 1 h. (c) 2 h. (d) 4 h. (e) 8 h. (f) 12 h. (g) 24 h. (h) 48 h. (i) 72 h.](image-url)
Figure 6: Continued.
corrosion time reaches 48 hours, the fracture gradually becomes brittle with stepped section. As a result, the state of the fracture model changes from a ductile damage to brittle damage. The fracture mechanism of steel is shown in Figure 12.

### 3.4. Comparison of Stress-Strain Curves

The stress-strain curves of carbon and weathering steels are compared in Figure 13. With the extension of corrosion time, the toughness of the two steels is observed to decrease. Compared with the carbon steel, the ultimate strength of the weathering steel was higher, and the decline rate was slightly smaller. The constitutive curve of steel during tensile process can be divided into four stages: elastic stage, yield stage, strengthening stage, and necking failure stage. With the increase of corrosion degree, the four stages gradually shortened and showed significant differences. The elastic modulus decreased gradually. The surface pits and stress concentration caused by hydrochloric acid corrosion led to an uneven stress distribution on the same section, which made the steel yield at different times. The large local pits led
Figure 8: Continued.
to the increase of uneven stress distribution, and the yield platform became shorter. When the corrosion rate reached about 4%, the yield platform became less obvious and even disappeared, which indicates that hydrochloric acid had a certain influence on the plasticity of the specimen. The main reason was that the stress concentration made the area with the maximum stress yield first, while the other areas that could not reach the yield strength were in the elastic range. Under the effect of stress redistribution, the variation amplitude of the bridge steel stress at this stage was small, so the stress effect was small. With the further increase of tensile force, the steel entered the plastic strengthening section, and the stress concentration caused the strengthening section to move forward. At this time, the steel plates all reached the yield strength. The existence of erosion pit made the partial stress at the section to decrease, and finally the ultimate strength was also decreased. At the late loading stage, the necking point gradually moved forward, and the specimen broke in advance, and the elongation at break decreased significantly, and the steel specimen gradually transitioned to brittle failure.

### 3.5. Performance Degradation Comparison

Figure 14 shows the performance degradation of corroded steels. The fitting equations of nominal elastic modulus, nominal yield strength, nominal ultimate strength, yield ratio, and elongation with corrosion time of carbon steel and weathering
steel are also shown in Figure 14. It can be seen that the yield strength, ultimate strength, and ductility of bridge steel specimens were gradually decreased due to the corrosion. Compared with carbon steel, the ultimate strength of weathering steel was larger, and the decline rate was slightly smaller. When the corrosion time was smaller than 10 h, the mechanical properties and plastic properties of the corroded steel plates decreased significantly. Furthermore, the rate of mechanical properties degradation of carbon steel was higher than that of the weathering steel. After the corrosion time exceeded 10 h, the mechanical properties of the two bridge steel plates continued to decrease. Nevertheless, the decrease at later stages of corrosion was not as fast as in the early corrosion stage. The rate of mechanical properties’ decrease of carbon steel became smaller compared to weathering steel at later stages of corrosion. The corrosion time had no effect on the yield strength ratio of the two steels. The reason could be that at the early stage of corrosion, chloride ion reacts with iron element violently. With the extension of corrosion time, the concentration of hydrochloric acid decreases and the corrosion rate slows down. The main reason for the mechanical properties’ degradation was the surface damage caused by corrosion. The stress concentration increases the local stress level, which made the specimen to yield in advance and enter the plastic zone, resulting in an uneven plastic deformation in the middle of the steel plate. The microcracks first appeared at the edge of erosion pits and continued to expand, and finally a brittle fracture appeared.

Table 2 shows the degree of degradation of mechanical indexes of the two kinds of bridge steels. With the extension of corrosion time, the yield strength, ultimate strength, elastic modulus, and elongation of the steel all degraded to different degrees, but the yield stress and ultimate stress of
Figure 11: Fracture morphology. (a) 0 h. (b) 1 h. (c) 2 h. (d) 4 h. (e) 8 h. (f) 12 h. (g) 24 h. (h) 48 h. (i) 72 h.

Figure 12: Fracture mechanism of steel. (a) The formation of micropores. (b) The deformation of micropores. (c) The cut-through of micropores.
the weathering steel were always larger than that of carbon steel. The average yield strengths of weathering steel at corrosion time of 1 h, 2 h, 4 h, 8 h, 12 h, 24 h, 48 h, and 72 h were of 10.77 MPa, 12.71 MPa, 12.75 MPa, 12.07 MPa, 12.01 MPa, 8.87 MPa, 6.86 MPa, and 8.81 MPa greater than that of carbon steel. The average ultimate strengths of carbon steel and weathering steel at corrosion times 1h, 2h, 4h, 8h, 12h, 24h, 48h, and 72h were 5.84MPa, 8.16MPa, 3.96MPa, 5.72MPa, 5.37MPa, 3.68MPa, 3.21MPa, and 3.87 MPa greater than that of carbon steel.

4. Constitutive Model of Carbon Steel and Weathering Steel Corrosion

Based on the segmented model [27], the constitutive model of carbon steel and weathering steel under the action of strong corrosion was obtained as follows:

\[ \sigma = \begin{cases} E_1 \varepsilon, & \varepsilon < \varepsilon_y, \\ f_y, & \varepsilon_y \leq \varepsilon \leq K_1 \varepsilon_y, \\ K_3 f_y + \frac{E_1 (1 - K_3)}{\varepsilon_y (K_2 - K_1)} (\varepsilon - K_2 \varepsilon_y)^2, & K_1 \varepsilon_y \leq \varepsilon \leq K_2 \varepsilon_y, \\ \end{cases} \]

(1)

In this equation, \( \sigma \) is the stress, \( E_1 \) is the elastic modulus, \( \varepsilon \) is the strain, \( f_y \) is the yield strength, \( \varepsilon_y \) is the yield strain, \( K_1 \) is the ratio of strengthened strain to yield strain, \( K_2 \) is the ratio of peak strain to yield strain, and \( K_3 \) is the ratio of the ultimate strength to yield strength, namely, the strength yield ratio. \( K_1, K_2, \) and \( K_3 \) are used to control the shape of the constitutive curve.

The relationships between \( K_1 \) and corrosion time of carbon steel and weathering steel were fitted, as shown in Figure 15(a). The relationships between \( K_2 \) and corrosion time were also fitted, as shown in Figure 15(b).

From Figure 15, it can be seen that \( K_1 \), \( K_2 \) of both kinds of bridge steels differ significantly. The \( K_1 \) parameter decreases linearly with the increase of corrosion time. The reason for the decrease was that with the increase of the corrosion time, the corrosion pit expanded further, which made the stress accumulation more obvious, resulting in the shortening of the steel yield platform, so the yield strain and the initial strain in the strengthening stage decreased gradually. The model parameter \( K_3 \) fluctuated and had no obvious correlation with the corrosion rate. The safety reserve capacity of steel remains basically unchanged regardless of the corrosion degree. To simplify the model, the \( K_3 \) of carbon steel and weathering steel was set constant. The minimum values of weathering steel and carbon steel were suggested to be 1.30 and 1.28, respectively.

5. Finite Element Analysis

Finite element analysis was used to establish a specimen model according to the size of the specimen, in which the material properties were determined by the mechanical property parameters of the uncorroded specimen (elastic modulus 2.2 \( \times \) 10^5 MPa, Poisson’s ratio 0.3, and steel density 7900 kg m\(^{-3}\)). The element type was C3D8R, hexahedral mesh, and free division. Grid partitioning and loading pattern diagram are shown in Figure 16. The unit size was approximately 1 mm. The loading mode was displacement loading, with one end constrained and the other end moving during loading. The loading mode and mesh generation are shown in Figure 16. The constitutive model was transformed into real stress and strain by the following:

\[ \begin{align*}
\sigma_1 &= \sigma_0 \times (1 + \varepsilon_0), \\
\varepsilon_1 &= \ln(1 + \varepsilon_0).
\end{align*} \]

(2)

In (2), \( \sigma_1 \) and \( \varepsilon_1 \) are the real stress and strain; \( \sigma_0 \) and \( \varepsilon_0 \) are the engineering stress and strain.

Figure 17 shows the modelled stress-strain curves. It can be seen that the two kinds of stress-strain curves of bridge
steel basically coincide in the elastic stage and the yield stage. When the stress value reached the ultimate strength, the strength in the engineering curve degenerated gradually, while the ultimate strength in the true curve increased continuously. In the true stress-strain curve, the real stress of carbon steel and weathering steel at 72h corrosion time decreased by 9.14% and 8.24%, respectively.

Figure 18 shows the finite element results of carbon steel and weathering steel at 0h, 1h, 2h, 4h, 8h, 12h, 24h, 48h, and 72h in comparison with the test results. It can be seen
Table 2: Degradation of mechanical indexes of steels.

| Steel type       | Corrosion time | Average corrosion rate % | Average $f_y$/MPa | Degenerate $f_y$ % | Average $f_u$/MPa | Degenerate $f_u$ % | Average $E_s$/GPa | Degenerate $E_s$ % | Average $\delta_s$ | Degenerate $\delta_s$ % |
|------------------|----------------|--------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-----------------------|
| Carbon steel     |                |                          |                   |                   |                   |                   |                   |                   |                   |                       |
| 0                | —              | 469.73                   | —                 | 598.13            | —                 | 218.68            | —                 | 36.32             | —                 |                       |
| 1                | 0.53           | 457.28                   | 2.65              | 594.48            | 0.61              | 214.61            | 1.86              | 34.28             | 5.59              |                       |
| 2                | 0.68           | 450.38                   | 4.12              | 586.95            | 1.87              | 209.93            | 4.00              | 32.11             | 11.58             |                       |
| 4                | 1.30           | 443.66                   | 5.55              | 582.16            | 2.67              | 202.96            | 7.19              | 29.86             | 17.80             |                       |
| 8                | 1.82           | 438.45                   | 6.66              | 578.15            | 3.34              | 198.41            | 9.27              | 27.85             | 23.33             |                       |
| 12               | 2.49           | 434.03                   | 7.60              | 572.89            | 4.22              | 194.87            | 10.89             | 26.38             | 27.36             |                       |
| 24               | 3.45           | 431.07                   | 8.23              | 568.76            | 4.91              | 190.30            | 12.98             | 24.76             | 31.83             |                       |
| 48               | 4.36           | 426.94                   | 9.11              | 562.96            | 5.88              | 184.63            | 15.57             | 23.07             | 36.48             |                       |
| 72               | 4.77           | 418.20                   | 10.97             | 556.92            | 6.89              | 175.53            | 19.73             | 21.16             | 41.74             |                       |
| Weathering steel |                |                          |                   |                   |                   |                   |                   |                   |                   |                       |
| 0                | —              | 475.32                   | —                 | 618.19            | —                 | 234.96            | —                 | 43.30             | —                 |                       |
| 1                | 0.47           | 468.05                   | 1.53              | 600.32            | 2.89              | 221.85            | 5.58              | 40.54             | 6.38              |                       |
| 2                | 0.74           | 463.09                   | 2.57              | 595.11            | 3.73              | 214.17            | 8.85              | 37.13             | 14.25             |                       |
| 4                | 1.39           | 456.41                   | 3.98              | 586.12            | 5.18              | 207.70            | 11.60             | 34.41             | 20.54             |                       |
| 8                | 1.80           | 450.52                   | 5.22              | 581.87            | 5.87              | 196.85            | 16.22             | 31.82             | 26.52             |                       |
| 12               | 2.57           | 446.04                   | 6.16              | 578.26            | 6.45              | 189.68            | 19.27             | 28.61             | 33.92             |                       |
| 24               | 3.04           | 439.94                   | 7.44              | 572.44            | 7.39              | 186.70            | 20.54             | 25.91             | 40.17             |                       |
| 48               | 3.90           | 433.80                   | 8.74              | 566.17            | 8.41              | 180.73            | 23.08             | 23.25             | 46.31             |                       |
| 72               | 4.30           | 427.01                   | 10.16             | 560.79            | 9.28              | 174.86            | 25.58             | 20.71             | 52.17             |                       |

Figure 15: Relationships between $K_1$ (a) and $K_2$ (b) and corrosion time for carbon and weathering steels.

Figure 16: Grid partitioning and loading pattern diagram.
Figure 17: True stress-strain curves. (a) Carbon steel. (b) Weathering steel.

Figure 18: Continued.
Figure 18: Stress-strain curves of corrosive carbon steel and weathering steel. (a) 0 h. (b) 1 h. (c) 2 h. (d) 4 h. (e) 8 h. (f) 12 h. (g) 24 h. (h) 48 h. (i) 72 h.
from the figure that the proposed model was in good agreement with experimental curve for corroded carbon steel and weathering steel at different corrosion times, which indicates that the model has a sufficient accuracy.

6. Conclusions

This paper presented an experimental study of mechanical degradation of carbon steel and weathering steel under strong acid corrosion. The stress-strain curves, elastic modulus, yield strength, ultimate strength, elongation, and ratio of strength and yield were obtained by tensile test. A degradation of mechanical properties of corroded carbon steel and weathering steel were analyzed. Some conclusions based on testing result are as follows:

(1) The corrosion rate of carbon steel was higher than that of weathering steel; that is, the mass loss rate of carbon steel was greater than that of weathering steel at the same corrosion time. With increasing corrosion time, the difference of mass loss between the steels became larger.

(2) At corrosion time smaller than 12 h, the mechanical properties and plastic properties of the corroded steel plates decreased significantly, and the rate of mechanical properties degradation of carbon steel was higher than that of the weathering steel. When the corrosion time exceeded 12 h, the rate of mechanical properties degradation started to decline.

(3) Most of the corrosion specimens fractured on the surface or root of the pit instead of starting at the center of the section. The size of the pits on the surface of the steel plate was inversely proportional to the size of the dimples, which revealed that the fracture mechanism of the steel plate changed from ductile failure to brittle failure.

(4) According to the fitting relationship between the morphology characteristic parameters and mechanical properties, a secondary yield degradation model was established. The model curve was in good agreement with the test curve, and the degradation relationships between the control parameters of the two steel models and the corrosion time were established.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1] W. J. Qiao, H. Y. Zhu, G. Zhang et al., “Mechanical properties and failure mechanism of steel plate composite beams under strong corrosion,” Journal of Chang’an University (Natural Science Edition), vol. 41, no. 2, pp. 46–54, 2021, (in Chinese).
[2] C. Xiong, C. Zeng, Y. Li, and L. P. D. Li, “The constitutive relationship for corroded steel bars: model and analysis,” Materials, vol. 12, no. 24, p. 4058, 2019.
[3] I. Fernandez, K. Lundgren, and K. Zandi, “Evaluation of corrosion level of naturally corroded bars using different cleaning methods, computed tomography, and 3D optical scanning,” Materials and Structures, vol. 51, no. 3, 2018.
[4] M. M. Kashani, A. J. Crewe, and N. A. Alexander, “Use of a 3D optical measurement technique for stochastic corrosion pattern analysis of reinforcing bars subjected to accelerated corrosion,” Corrosion Science, vol. 73, pp. 208–221, 2013.
[5] G.-c. Qin, S.-h. Xu, D.-q. Yao, and Z.-x. Zhang, “Study on the degradation of mechanical properties of corroded steel plates based on surface topography,” Journal of Constructional Steel Research, vol. 125, pp. 205–217, 2016.
[6] B. Nie, S. Xu, J. Yu, and H. Zhang, “Experimental investigation of mechanical properties of corroded cold-formed steels,” Journal of Constructional Steel Research, vol. 162, Article ID 105706, 2019.
[7] S. Bajracharya, E. Sasaki, and H. Tamura, “Numerical study on corrosion profile estimation of a corroded steel plate using eddy current,” Structure and Infrastructure Engineering, vol. 15, no. 9, pp. 1151–1164, 2019.
[8] J. E. Silva, Y. Garbatov, and C. Guedes Soares, “Ultimate strength assessment of rectangular steel plates subjected to a random localised corrosion degradation,” Engineering Structures, vol. 52, pp. 295–305, 2013.
[9] R. Wang, R. Ajit Shenoi, and A. Sobey, “Ultimate strength assessment of plated steel structures with random pitting corrosion damage,” Journal of Constructional Steel Research, vol. 143, pp. 331–342, 2018.
[10] K. Deliang, N. Biao, and X. Shanhua, “Random field model of corroded steel plate surface in neutral salt spray environment,” KSCE Journal of Civil Engineering, vol. 25, no. 7, pp. 2651–2661, 2021.
[11] Y. Garbatov, C. Guedes Soares, J. Parunov, and J. Kodvanj, “Tensile strength assessment of corroded small scale specimens,” Corrosion Science, vol. 85, pp. 296–303, 2014.
[12] B. Nie, S. Xu, Y. Wang, and A. Z. Li, “Local buckling of corroded cold-formed steel stub columns,” Structures, vol. 29, pp. 1837–1846, 2021.
[13] Y.-C. Ou, Y. T. T. Susanto, and H. Roh, “Tensile behavior of naturally and artificially corroded steel bars,” Construction and Building Materials, vol. 103, pp. 93–104, 2016.
[14] S.-h. Xu and Y.-d. Wang, “Estimating the effects of corrosion pits on the fatigue life of steel plate based on the 3D profile,” International Journal of Fatigue, vol. 72, pp. 27–41, 2015.
[15] M. Cerit, “Numerical investigation on torsional stress concentration factor at the semi elliptical corrosion pit,” Corrosion Science, vol. 67, pp. 225–232, 2013.
[16] M. Vasco, K. Tserpes, and S. Pantelakis, “Numerical simulation of tensile behavior of corroded aluminum alloy 2024 T3 considering the hydrogen embrittlement,” Metals, vol. 8, no. 1, p. 56, 2018.
[17] S. Kainuma, Y.-S. Jeong, and J.-H. Ahn, "Investigation on the stress concentration effect at the corroded surface achieved by atmospheric exposure test," *Materials Science and Engineering*, vol. 602, pp. 89–97, 2014.

[18] A. Rajput and J. K. Paik, "Effects of naturally-progressed corrosion on the chemical and mechanical properties of structural steels," *Structures*, vol. 29, pp. 2120–2138, 2021.

[19] M. M. Ahmmad and Y. Sumi, "Strength and deformability of corroded steel plates under quasi-static tensile load," *Journal of Marine Science and Technology*, vol. 15, no. 1, pp. 1-15, 2009.

[20] T. Kaita, J. M. R. S. Appuhamy, K. Itohara, and M. K. Ohga, "Experimental study on remaining strength estimation of corroded wide steel plates under tensile force," *Procedia Engineering*, vol. 14, pp. 2707–2713, 2011.

[21] GB/T2975, "Steel and Steel Products-Location and Preparation of Test Pieces for Mechanical Testing," 1998, http://std.samr.gov.cn/search/std?q=GB%2FT%202975-1998, (in Chinese).

[22] GB/T1591, "High Strength Low Alloy Structural Steels," 2008, http://std.samr.gov.cn/search/std?tid=&q=GB%2FT%201591, (in Chinese).

[23] GB/T 228.1, "Metallic Materials-Tensile Testing-Part 1: Method of Test at Room Temperature," 2010, http://std.samr.gov.cn/search/std?tid=&q=GB%2FT%20228.1, (in Chinese).

[24] S. B. Ren, Y. Gu, C. Kong et al., "Effects of the corrosion pitting parameters on the mechanical properties of corroded steel," *Construction and Building Materials*, vol. 272, 2021.

[25] H. Zhang, S. Xu, Z. Zhang, and B. L. Nie, "Fracture analysis of corroded cold-formed thin steel plates based on actual morphology using micromechanical models," *Construction and Building Materials*, vol. 267, Article ID 120899, 2021.

[26] H. Zhang, S. Xu, B. Nie, and Y. Wen, "Effect of corrosion on the fracture properties of steel plates," *Construction and Building Materials*, vol. 225, pp. 1202–1213, 2019.

[27] Y. J. Shi, M. Wang, and Y. Q. Wang, "Experimental study on constitutive relationship of structural steel under cyclic loading," *Journal of Building Materials*, vol. 15, no. 3, pp. 293–300, 2012.