Experimental Investigation of the Mechanical Behavior of Corroded Q345 and Q420 Structural Steels

Nan Zhao and Chuntao Zhang

Abstract: This study investigated the residual mechanical behavior of Q345 and Q420 structural steels after corrosion. Firstly, the tensile specimens were corroded in an acid solution until the weight loss rate reached 20%, 30%, and 40%. The corroded specimens were then subjected to axial tensile experiments to observe the tensile fracture behavior and obtain the engineering stress–strain curves. The effects of corrosion on stress–strain curves, failure modes, tensile strength, and ductility were analyzed and discussed. The strength and ductility of Q345 and Q420 structural steel dropped sharply after corrosion. In addition, a constitutive model of Q345 and Q420 structural steels with different mass loss rates was established. Based on the test data, empirical equations were proposed to predict the residual strength and ductility of corroded Q345 and Q420 structural steels.

Keywords: mechanical behavior; corrosion; structural steels; weight loss rate; constitutive model

1. Introduction

Because of its various advantages, steel is an important building material [1,2]. However, the mechanical properties of steel gradually deteriorate under fatigue load [3,4], fire [5,6], corrosion [7,8], etc. Therefore, the residual tensile strength and deformability of corroded steel are crucial indicators for evaluating structural damage and for reinforcing the damaged structures. When steel structures are exposed to a humid environment and the protective coating fails, corrosion occurs [9,10] and inevitably weakens the load-bearing capacity and safety of the steel structure. In addition, when coupled with fatigue load, corrosion further deteriorates the bearing capacity of the steel structure [11], leading to potential economic loss and risk to life. For instance, according to a report from the National Steel Bridge Alliance (NSBA) [12], the Silver Bridge collapsed because of corrosion, causing 46 deaths, with two of the victims never found. Therefore, it is important to clarify how the mechanical properties of steel deteriorate after corrosion damage.

To date there have been several studies that have investigated the corrosion performance of various types of steel. In these studies, the precorrosion mechanisms of steel mainly included pitting corrosion [13–16] and uniform corrosion [17–20]. Although there is a small difference in the ultimate strength of the steel caused by these two precorrosion methods [14], corrosion can reduce the mechanical properties of steel. However, each type of steel has different corrosion resistance because of the differences in chemical composition as well as in the type of corrosion [21]. Therefore, it is necessary to investigate the deterioration of different types of steel under corrosion conditions. In terms of steel corrosion, the residual mechanical properties of thin-walled steels [21], carbon steels [13,16,21,22], ultra-high-strength reinforcing steel [23], steel bars [20,24], and other steels [18,19] have been investigated in previous studies. However, there have been no reports on the corrosion performance of Q345 and Q420 steels, the two most extensively used steels in Chinese engineering structures [25]. Existing research on the residual tensile strength of corroded Q345 structural steel has only been carried out through numerical analysis [13], and there
is a lack of systematic experimental research. In addition, the effective stress area of the tensile specimen gradually decreases with increasing load, which cannot be reflected by the traditional engineering stress–strain curve. Furthermore, in corrosive environments many micropits are formed in the steel, which further reduces the effective cross-sectional area. Therefore, it is necessary to verify the accuracy of the residual mechanical properties of corroded steels via true stress–strain curves. To date, many researchers have proposed various models for the calculation of true stress–strain curves using finite element analysis [26–28] and mechanics deduction [29,30]. The Swift-type equation used to determine the true stress–strain curve has been proven to be excellent up to ultimate strength [31–33]. Based on the Swift-type equation, Kamaya [34] proposed parameter expressions to ensure both accuracy and simplicity, and the results proved that the expressions were precise. However, these expressions were originally proposed for stainless steels, and require validation before use for other steels. In addition, an accurate predictive constitutive model is also very important in numerical analysis. Since Ramberg and Osgood [35] proposed the classic stress–strain model that was originally used for aluminum alloys, this equation has also been proven to be applicable to other steels such as stainless steel [36,37]. Rasmussen [37] proposed a modified model, which has been adopted in EN 1993-1-4 [38] because of the accuracy of its estimation. However, no previous studies have investigated the accuracy of this constitutive model when applied to carbon steel. Therefore, this study comprehensively examined the residual mechanical behavior of corroded Q345 and Q420 steel specimens. An improved constitutive model and empirical equations were proposed, and their accuracy and reliability were discussed.

2. Experimental Details

2.1. Test Specimens

Q345 and Q420 steel tubes were corroded in sulfuric acid solution with different mass loss rates. Tensile specimens were then cut from the corroded Q345 and Q420 steel tubes, as shown in Figure 1, and their chemical compositions are listed in Table 1. The initial nominal thickness and outer diameter of the Q345 and Q420 steel tubes were 4 mm and 102 mm, respectively. As shown in Figures 2 and 3, the tensile specimens were designed and processed in accordance with the guidelines provided in GB/T 228.1-2010 [39]. Before the tensile tests, a total of 24 tensile specimens were prepared according to the predesigned test content. The mechanical behavior of Q345 and Q420 structural steels with four mass loss rates was investigated. Three specimens were tested for each mass loss rate, and the average values of these test data were used for detailed analysis and discussion. In addition, to avoid slippage in the tensile test, both ends of each specimen were flattened from their original curved shape, as shown in Figure 4.
Table 1. Chemical composition of the test specimens (%).

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Cu</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q345</td>
<td>0.14</td>
<td>0.55</td>
<td>1.40</td>
<td>-</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.01</td>
</tr>
<tr>
<td>Q420</td>
<td>0.17</td>
<td>0.25</td>
<td>1.40</td>
<td>0.007</td>
<td>0.20</td>
<td>0.30</td>
<td>0.20</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Figure 1. The corroded steel tubes.

Figure 2. Dimension of tensile specimens (mm).

Figure 3. Steel tube and tensile specimens after cutting.

Figure 4. Tensile test specimens.
2.2. Test Procedure

The experiment included steel tube corrosion tests and axial tensile tests. Firstly, Q345 and Q420 steel tubes were corroded in dilute sulfuric acid solution. Because the corrosion of steel tubes in a dilute sulfuric acid solution can be classified as uniform corrosion, the degree of corrosion was quantified by the rate of mass loss $\rho$, which can be expressed as:

$$\rho = \frac{m_p - m_0}{m_0} \times 100\%$$

where $m_0$ is the initial weight of the steel tube and $m_p$ is the residual weight of the steel tube with the mass loss rate $\rho$. In general, corrosion is microscopic and abnormal, but Equation (1) is a macroscopic equation that neglects this randomness. However, Hu [23] proved that this deviation is minor, and the expression is therefore appropriate. Based on Equation (1), Q345 and Q420 steel tubes were each corroded by 0%, 20%, 30%, and 40% of their initial mass. In this step, the mass loss was checked every 20 min to ensure that the error of weight loss was within 1%. After corrosion, the tensile specimens were cut from the corroded tubes [39]. Next, axial tensile tests were conducted on the corroded tensile specimens to obtain the failure mode and stress–strain curve (see Figure 5).

![Test equipment and specimen](image_url)

**Figure 5.** Test equipment and specimen: (a) The test equipment; (b) The specimen.

3. Experimental Results

3.1. Stress–Strain Curves

Figure 6 shows the schematic diagrams for the engineering stress–strain curve of corroded Q345 and Q420 steels. Each stress–strain curve was a representative specimen selected from three specimens with the same mass loss rate. Engineering stress–strain curves are composed of three parts, namely: a linear elastic region; a strain hardening region; and a necking region. However, the length of each region exhibited significant differences because of the corrosion. As the corroded mass increased, the lengths of the linear elastic region, strain hardening region, and necking region reduced, which resulted in a sharp drop in maximum strain and stress. It was found that both the bearing capacity and deformability of Q345 and Q420 structural steels decreased as the corroded mass increased. Furthermore, the necking region of most of the corroded specimens was invisible during tensile testing, which resulted in an inconspicuous falling region of the stress–strain curve.
It is widely known that engineering stress is defined as the load divided by the initial cross-sectional area ($\sigma = F/A_0$), and the corresponding stress–strain curve is the engineering stress–strain curve. In practice, the cross-section area of the tensile specimen gradually decreases after the linear elastic region. Because measurement of the instantaneous stress area during the tensile test is difficult, the effective stress area is reduced and the stress calculated by the original method is underestimated [29]. Therefore, the true stress–strain curves for steel are often used to determine the relationship between stress and strain. The Swift-type model, which has been proven to be excellent up to the ultimate strength [31–33], was adopted to determine the true stress–strain curve of Q345 and Q420 structural steels with different mass loss rates. The expression of the Swift-type model is:

$$\sigma = A(\varepsilon_p + \varepsilon_0)^n$$

(2)

where $\sigma$ is the stress, $n$ is the strain hardening constant, $A$ and $\varepsilon_0$ are constants that need to be identified by the test results, and $\varepsilon_p$ is the plastic strain. Based on Equation (1), Kamaya [34] proposed the equation for calculating $A$ and $\varepsilon_0$, which can be written as:

$$\varepsilon_0 = \left(\frac{\sigma_y}{\varepsilon_y}\right)^{\frac{1}{n}}$$

(3)

$$\ln\left(\frac{A}{\varepsilon_y}\right) + \left(\frac{A}{\sigma_y}\right)^{-\frac{1}{n}} + \frac{n}{2} \ln n - n = \ln\left(\frac{\sigma_u}{\sigma_y}\right)$$

(4)

where $\sigma_y$ and $\sigma_u$ are the yield stress and ultimate stress, respectively. Kamaya [34] calculated that the parameter $n$ of stainless steel was 0.5, which is not applicable to Q345 and Q420 structural steels. To obtain the value of $n$, the strain hardening region of an engineering stress–strain curve can be divided into five parts along the strain on average. In each part, the value of $n$ can be determined by the following expression [5]:

$$\ln \sigma = \ln C + n \ln \varepsilon$$

(5)

where $C$ is a material constant. According to the method of least squares, the expression of the optimized constant $n$ can be written as:

$$n = \frac{5 \sum_{i=1}^{5} x_i y_i - \left(\sum_{i=1}^{5} x_i \sum_{i=1}^{5} y_i\right)}{5 \sum_{i=1}^{5} x_i^2 - (\sum_{i=1}^{5} x_i)^2}$$

(6)
where $x$ is $\ln x$ and $y$ is equal to $\ln \sigma$. Substituting the value of $n$ into Equation (4), the value of $A$ can be obtained. The value of $A$ can also be determined by the test data, according to which the fit expression of $A$ can be expressed as:

$$A = 0.036\sigma_0 + 1.831\sigma_y$$

(7)

To distinguish the value of parameter $A$ calculated by Equations (4) and (7), the value of parameter $A$ calculated by Equation (4) is marked as $A_c$, and $A_t$ is the value of $A$ determined by Equation (7). Combing the experimental data and the proposed equations, the value of $A_t$, $A_c$, and $n$ are provided in Table 2. It can be seen that the difference between $A_t$ and $A_c$ is in the range of $-1.40\%$ to $5.08\%$, which indicates that both Equations (4) and (7) are able to accurately calculate the value of $A$. Furthermore, the true stress–strain curves plotted with different values of $n$ are shown in Figure 7. Because it is a material constant, it can be clearly seen that the value of $n$ has little effect on the true stress–strain curve.

### Table 2. Values of $n$ and $A$.

<table>
<thead>
<tr>
<th>Mass Loss</th>
<th>Q345</th>
<th>Q420</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$A_t$</td>
</tr>
<tr>
<td>0%</td>
<td>0.094</td>
<td>812.35</td>
</tr>
<tr>
<td>20%</td>
<td>0.111</td>
<td>705.05</td>
</tr>
<tr>
<td>30%</td>
<td>0.095</td>
<td>697.06</td>
</tr>
<tr>
<td>40%</td>
<td>0.115</td>
<td>649.23</td>
</tr>
</tbody>
</table>

Figure 7. True stress–strain curves with different values of $n$.

Substituting the values of $n$, $A_t$, and $A_c$ into Equation (3), the value of $\varepsilon_0$ can be obtained. When the values of $n$ and $\varepsilon_0$ are determined, the true stress–strain curves of the corroded Q345 and Q420 structural steels can be plotted using Equation (2), as shown in Figure 8. It can be seen from the figure that the two types of stress–strain curves of specimens with various mass loss rates coincide before yielding. However, significant differences were observed in these three stress–strain curves because of the shrinkage of the specimen cross-section after yielding. For different mass loss rates, the two types of true stress–strain curves for the corroded steels plotted with $A_t$ and $A_c$ were close to each other, which indicates that the two methods proposed in this study can effectively determine the true stress–strain curves of corroded Q345 and Q420 structural steels. As the effective stress area decreased when the corroded steel specimens yielded, the stress of the engineering stress–strain curves was significantly smaller than that of the two true stress–strain curves. After the ultimate strength, the plastic deformation becomes nonuniform and the specimen undergoes a state of triaxial stress [30]. In engineering design the beginning of necking means that the structural member has failed. Therefore, the relationship between the stress and strain of the specimen after necking was not considered by the true stress–strain model.
Figure 8. Stress–strain curves.
3.2. Key Materials Properties

After corrosion, the key mechanical property parameters of the Q345 and Q420 structural steel specimens with different mass loss rates are listed in Table 3. To quantify the influence of corrosion, Table 4 lists the residual factors for the mechanical property parameters. The residual factor is the ratio of the residual value of the specimen after corrosion to its original value before corrosion. According to the residual factor, the influence of corrosion is analyzed and discussed in the sections below.

Table 3. The key mechanical property parameters of Q345 and Q420 structural steels after corrosion.

<table>
<thead>
<tr>
<th>Mass Loss Rate</th>
<th>Specimen</th>
<th>Yield Strength $f_y$/MPa</th>
<th>Ultimate Strength $f_u$/MPa</th>
<th>Elastic Modulus $E$/GPa</th>
<th>Ductility El/%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
</tr>
<tr>
<td>0%</td>
<td>C0-1</td>
<td>429.13</td>
<td>441.16</td>
<td>589.31</td>
<td>655.81</td>
</tr>
<tr>
<td></td>
<td>C0-2</td>
<td>432.42</td>
<td>444.75</td>
<td>569.93</td>
<td>652.32</td>
</tr>
<tr>
<td></td>
<td>C0-3</td>
<td>416.69</td>
<td>453.4</td>
<td>573.44</td>
<td>644.58</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>426.08</td>
<td>446.43</td>
<td>577.56</td>
<td>650.9</td>
</tr>
<tr>
<td>20%</td>
<td>C20-1</td>
<td>372.79</td>
<td>355.62</td>
<td>499.04</td>
<td>488.83</td>
</tr>
<tr>
<td></td>
<td>C20-2</td>
<td>374.36</td>
<td>348.06</td>
<td>497.58</td>
<td>488.4</td>
</tr>
<tr>
<td></td>
<td>C20-3</td>
<td>385.77</td>
<td>359.32</td>
<td>516.48</td>
<td>488.25</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>377.64</td>
<td>354.33</td>
<td>504.36</td>
<td>488.49</td>
</tr>
<tr>
<td>30%</td>
<td>C30-1</td>
<td>379.66</td>
<td>317.78</td>
<td>521.29</td>
<td>465.33</td>
</tr>
<tr>
<td></td>
<td>C30-2</td>
<td>366.59</td>
<td>321.58</td>
<td>473.07</td>
<td>448.99</td>
</tr>
<tr>
<td></td>
<td>C30-3</td>
<td>373.83</td>
<td>318.85</td>
<td>491.23</td>
<td>449.06</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>373.36</td>
<td>319.40</td>
<td>495.19</td>
<td>454.46</td>
</tr>
<tr>
<td>40%</td>
<td>C40-1</td>
<td>343.54</td>
<td>276.15</td>
<td>451.12</td>
<td>358.68</td>
</tr>
<tr>
<td></td>
<td>C40-2</td>
<td>343.22</td>
<td>278.01</td>
<td>457.58</td>
<td>356.91</td>
</tr>
<tr>
<td></td>
<td>C40-3</td>
<td>356.45</td>
<td>275.02</td>
<td>474.03</td>
<td>359.99</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>347.74</td>
<td>276.4</td>
<td>460.91</td>
<td>358.53</td>
</tr>
</tbody>
</table>

Based on the true stress–strain model, the residual yield strength, ultimate strength, and corresponding residual factor calculated from the measured true stress–strain curves are set out in Table 5. When the corroded mass of the steels increased, the strength calculated from the true stress–strain curves reduced. The difference between the test data and calculated values is discussed in the sections below.

Table 4. Residual factors of Q345 and Q420 structural steels after corrosion.

<table>
<thead>
<tr>
<th>Mass Loss Rate</th>
<th>Specimen</th>
<th>Yield Strength</th>
<th>Ultimate Strength</th>
<th>Elastic Modulus $E$/GPa</th>
<th>Ductility El/%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
</tr>
<tr>
<td>0%</td>
<td>C0-1</td>
<td>1.01</td>
<td>0.99</td>
<td>1.02</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>C0-2</td>
<td>1.01</td>
<td>1.00</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>C0-3</td>
<td>0.98</td>
<td>1.02</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>20%</td>
<td>C20-1</td>
<td>0.87</td>
<td>0.80</td>
<td>0.86</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>C20-2</td>
<td>0.88</td>
<td>0.78</td>
<td>0.86</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>C20-3</td>
<td>0.91</td>
<td>0.80</td>
<td>0.89</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>0.89</td>
<td>0.79</td>
<td>0.87</td>
<td>0.75</td>
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Table 4. Cont.

<table>
<thead>
<tr>
<th>Mass Loss Rate</th>
<th>Specimen</th>
<th>Yield Strength</th>
<th>Ultimate Strength</th>
<th>Elastic Modulus</th>
<th>Ductility</th>
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<td></td>
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<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
<td>Q420</td>
</tr>
<tr>
<td>30%</td>
<td>C30-1</td>
<td>0.89</td>
<td>0.71</td>
<td>0.90</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>C30-2</td>
<td>0.86</td>
<td>0.72</td>
<td>0.82</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>C30-3</td>
<td>0.88</td>
<td>0.71</td>
<td>0.85</td>
<td>0.69</td>
</tr>
<tr>
<td>Mean value</td>
<td></td>
<td>0.88</td>
<td>0.72</td>
<td>0.86</td>
<td>0.70</td>
</tr>
<tr>
<td>40%</td>
<td>C40-1</td>
<td>0.81</td>
<td>0.62</td>
<td>0.78</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>C40-2</td>
<td>0.81</td>
<td>0.62</td>
<td>0.79</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>C40-3</td>
<td>0.84</td>
<td>0.62</td>
<td>0.82</td>
<td>0.55</td>
</tr>
<tr>
<td>Mean value</td>
<td></td>
<td>0.82</td>
<td>0.62</td>
<td>0.80</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 5. Residual yield strength and ultimate strength determined from measured true stress–strain curves.

<table>
<thead>
<tr>
<th>Mass Loss</th>
<th>Yield Strength $f_y$/MPa</th>
<th>Ultimate Strength $f_u$/MPa</th>
<th>Residual Yield Strength Factor</th>
<th>Residual Ultimate Strength Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
<td>Q420</td>
</tr>
<tr>
<td>0%</td>
<td>431.20</td>
<td>479.24</td>
<td>705.60</td>
<td>754.75</td>
</tr>
<tr>
<td>20%</td>
<td>388.20</td>
<td>385.33</td>
<td>604.15</td>
<td>594.21</td>
</tr>
<tr>
<td>30%</td>
<td>372.45</td>
<td>335.45</td>
<td>553.07</td>
<td>541.38</td>
</tr>
<tr>
<td>40%</td>
<td>328.45</td>
<td>287.13</td>
<td>601.80</td>
<td>413.28</td>
</tr>
</tbody>
</table>

3.2.1. Yield Strength

The residual factor can be used directly to show the effect of corrosion on the mechanical property parameters. Figure 9 presents the yield strength residual factors corresponding to different mass loss rates for the corroded Q345 and Q420 structural steels and a comparison with other corroded steels. Based on the test results provided in Table 5 and Figure 9a, it can be seen that the yield strength of Q345 and Q420 structural steels dropped sharply when the corroded mass increased. Under the same corrosion test conditions, the yield strength of Q420 structural steel decreased more than that of Q345 structural steel because of differences in their chemical compositions. The difference in the yield strength of the two tested steels became more significant as the mass loss rate increased. For example, when the mass loss rate was 30%, Q345 and Q420 structural steels retained 88% and 72% of their initial yield strength, respectively. When the corrosion mass of both types of tested steels was the same, the reduction in the yield strength of Q420 steel was more than twice that of Q345 steel. Of these two tested steels, it was found that Q345 structural steel had better corrosion resistance under the same corrosive environment. In addition, the yield strength decreased in line with the increase in mass loss rate. Compared with the uncorroded steel specimens, the yield strengths of Q345 and Q420 structural steels with a mass loss rate of 20% decreased by 11% and 21%, respectively. However, when the corroded mass increased to 40%, the yield strengths of Q345 and Q420 structural steels reduced by 18% and 38%, respectively. The yield strength reduction in Q345 and Q420 structural steels increased by 7% and 17%, respectively, when the mass loss rate increased from 20% to 40%. Furthermore, the yield strengths obtained from the engineering stress–strain curves and true stress–strain curves were very close, as shown in Figure 9a. In this experiment, the difference between the two yield strengths of Q345 steel was in the range of $-5.54\%$ to $2.80\%$, whereas the difference between the two yield strengths of Q420 steel was in the range of $3.88\%$ to $8.75\%$. 
In this study, we also compared the yield strength residual factors of the corroded Q345 and Q420 steels with those of corroded A706 [21] and Q235 [22] steels, as shown in Figure 9b. The yield strength of these four structural steels presented similar changes after corrosion. The yield strength of A706, Q235, Q345, and Q420 structural steels sharply decreased with the increase in the mass loss rate.

3.2.2. Ultimate Strength

Q345 and Q420 structural steels were corroded with different masses, and the residual ultimate strength of the specimens is shown in Figure 10. Because of the reduction in the cross-sectional area of the steel, Q345 and Q420 structural steels also exhibited a clear reduction in ultimate strength after corrosion. When the mass loss rate was 20%, Q345 and Q420 structural steels retained 87% and 75% of their initial ultimate strength, respectively. When the corroded mass increased from 20% to 40%, Q345 and Q420 structural steels only retained 80% and 55% of their initial ultimate strength, respectively. The reduction in ultimate strength of Q345 and Q420 structural steels increased by 7% and 20%, respectively. Compared with Q420 structural steel, Q345 structural steel exhibited a smaller reduction in ultimate strength after corrosion. Furthermore, as the corroded mass increased, the ultimate strength obtained from the true stress–strain curves dropped sharply because of the reduction in the cross-sectional area of the specimens. When the mass loss rate was 30%, the ultimate strength of the corroded Q345 and Q420 steels decreased by 22% and 28%, respectively. Because the effective stress areas of the two stress–strain curves were different, significant differences were observed between the ultimate strength obtained from the engineering stress–strain curves and that obtained from the true stress–strain curves. Based on the ultimate strengths shown in Tables 3 and 4, the difference between the two ultimate strength values of Q345 structural steel was in the range of 11.69% to 30.57%, whereas for Q420 structural steel this difference was in the range of 15.27% to 21.64%. Comparing the yield strength from the engineering stress–strain curve and the true stress–strain curve, it was explicitly found that the difference between the two yield strength values was small because of the slight shrinkage of the cross-section of the tensile specimen in the linear elastic stage. In contrast, there was greater cross-sectional shrinkage of the tensile specimen at ultimate strength, which resulted in the significant difference between the ultimate strength values obtained from these two stress–strain curves.
When the mass loss rate did not exceed 30%, the ultimate strength of Q345 and Q420 structural steels was reduced by 5%, whereas Q345 and Q420 structural steels with the same mass loss rate only retained 87% and 75% of their initial ultimate strength. For example, the ultimate strength of A706 and Q420 structural steels reduced more than other steels. It was clear that both the yield strength and ultimate strength of Q345 and Q420 structural steels were sharply reduced because of the reduction in the effective stress areas of specimens in the corrosive environment.

3.2.3. Ductility

In addition to tensile strength, ductility is another important indicator for steel and reflects its plasticity under tension. In this study, the percent elongation (EI) as well as the strain corresponding to the key points on the stress–strain curve were used to evaluate the ductility of the corroded specimens, as shown in Figure 11. The yield strain $\varepsilon_y$, ultimate strain $\varepsilon_u$, and fracture strain $\varepsilon_f$ of the corroded Q345 and Q420 structural steels under tension are listed in Table 6. As shown in Figure 11, both the percent elongation and the strain of Q345 and Q420 structural steels exhibited significant reductions after corrosion. Compared with the strain of noncorrosion specimens, the ultimate strain of Q345 and Q420 structural steels with the mass loss rate of 30% were reduced by 14.81% and 27.50%, respectively. In addition, the fracture strain of Q345 and Q420 structural steels with the mass loss rate of 30% were also reduced by 27.91% and 30.00%, respectively. The reduction in ultimate strain and fracture strain indicates that the deformability of Q345 and Q420 structural steels was significantly reduced after corrosion. Like strain, the percent elongation of Q345 and Q420 structural steels also reduced sharply after corrosion. When the mass of the specimens was corroded by 30%, the percent elongations and Q420 steels were decreased by 15% and 34%, respectively. Notably, the strain and percent elongation reductions in Q420 structural steel were both greater than the corresponding reductions for Q345 structural steel.

Figure 10. Ultimate strength of Q345 and Q420 structural steels after corrosion: (a) Ultimate strength residual factors; (b) Comparison of ultimate strength of different steels.
It can be clearly seen that the ductility of Q195 steel presented random changes because of the uneven corrosion in the service environment. In contrast, because of the uniform corrosion in the test environment, the ductility of Q235, Q345, and Q460 structural steels showed uniform changes with the increasing mass loss rate. Therefore, there is a significant difference between naturally corroded steel specimens and those subjected to accelerated corrosion.

### Table 6. Strain of Q345 and Q420 structural steels after corrosion.

<table>
<thead>
<tr>
<th>Mass Loss</th>
<th>ε_y (%)</th>
<th>ε_u (%)</th>
<th>ε_f (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q345</td>
<td>0.004</td>
<td>0.27</td>
<td>0.43</td>
</tr>
<tr>
<td>Q420</td>
<td>0.005</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>Q345</td>
<td>0.005</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td>Q420</td>
<td>0.005</td>
<td>0.18</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The residual percent elongation of A706, Q235, Q345, and Q420 structural steels after corrosion are compared in this section, as shown in Figure 11b. Because of the uneven corrosion of the specimen, the ductility of A706 structural steel exhibited complex changes. As the corroded mass increased, A706 structural steel showed a sharp reduction in ductility. When the mass of the specimens was corroded by 6.24%, Q195 structural steel only retained 17.5% of its initial ductility. However, the ductility of A706 structural steel with its initial mass corroded by 15.06% was only reduced by 10%. When the mass of the specimens was corroded by 36.14%, A706 structural steel only retained 30% of its initial ductility. It can be clearly seen that the ductility of Q195 steel presented random changes because of the uneven corrosion in the service environment. In contrast, because of the uniform corrosion in the test environment, the ductility of Q235, Q345, and Q460 structural steels showed uniform changes with the increasing mass loss rate. Therefore, there is a significant difference between naturally corroded steel specimens and those subjected to accelerated corrosion.

### 3.3. Failure Modes

Figure 12 presents the surfaces and tensile failure modes of Q345 and Q420 structural steels after corrosion. As shown in Figure 12a, these steel tubes with various mass loss rates exhibited different corrosion characteristics. The surface of the noncorrosive steel tube was silver-gray, whereas the surface of the corroded steel tube was covered with reddish-orange rust. However, the color of the corroded steel tube also changed according to the difference in the corroded mass of the specimens. As the corroded mass increased, the thickness of the rust on the surfaces of the corroded steel tube also increased, which caused the surface of the steel tube to become rougher. Figure 12b shows that many pits are evenly distributed on the surface of the corroded steel tube. When the corroded mass increased, these adjacent etch pits formed larger ones, which led to a reduction in the cross-sectional area of these tensile steel specimens. Consequently, the effective stress area of the steel specimen was reduced. The failure modes of corroded Q345 and Q420 structural steels under tension are provided in Figure 13.
reduced. The failure modes of corroded Q345 and Q420 structural steels under tension are provided in Figure 13.

![Figure 12](image_url)

Figure 12. Surface characteristics of corroded Q345 and Q420 structural steels: (a) Steel tubes with different mass-loss rates; (b) Etch pits.

![Figure 13](image_url)

Figure 13. Failure modes of corroded Q345 and Q420 structural steels under tension.

4. Constitutive Model

Our test results clearly indicate that the influence of corrosion on the tensile behavior of Q345 and Q420 steels was significant. Therefore, a constitutive model was developed. Compared with the true stress–strain curve, the engineering stress–strain curve has a larger safety margin and meets actual engineering design requirements. Based on the test result provided in Section 3, two types of constitutive models were established to predict the stress–strain relationship. The first constitutive model is the bilinear constitutive model [40–42], which can be expressed as:

$$
\sigma = \begin{cases} 
E \varepsilon & \sigma < \sigma_y \\
K \varepsilon & \sigma_y < \sigma < \sigma_u 
\end{cases}
$$

(8)

$$
K = \frac{\sigma_u - \sigma_y}{\varepsilon_u - \varepsilon_y}
$$

(9)

where $\sigma$ and $\varepsilon$ represent stress and strain, respectively; $\sigma_y$ and $\varepsilon_y$ represent the yield stress and yield strain, respectively, $E$ represents the elastic modulus, and $\sigma_u$ and $\varepsilon_u$ are the ultimate stress and ultimate strain, respectively. Another constitutive model, Rasmussen’s
model [37], is often used to predict the stress–strain relationship, and this has been adopted in EN 1993-1-4 [38]. The expression of Rasmussen’s model can be written as:

\[
\varepsilon = \begin{cases} 
\frac{\sigma}{E} + 0.02\left(\frac{\sigma}{E}\right)^n & \sigma < \sigma_y \\
0.02 + \frac{\sigma - \sigma_y}{E_y} + \varepsilon_u \left(\frac{\sigma - \sigma_y}{\sigma_u - \sigma_y}\right)^m & \sigma_y < \sigma < \sigma_u 
\end{cases}
\]

(10)

\[m = 3.5 \frac{\sigma_y}{\sigma_u} + 1\]

(11)

where \(E_y\) is the tangent modulus at the point of yield stress, and \(n\) is the strain hardening constant which has been determined in Section 2 (see Table 2). From our test data, the values of \(m\), \(E_y\), and \(K\) are provided in Table 7. Substituting the values of these parameters into Equations (8) to (11), the constitutive models of Q345 and Q420 structural steels after corrosion can be obtained. For a corroded mass loss in the range of 0 to 40%, Figure 14 provides a comparison between the calculated stress–strain curves of the two constitutive models and the tested engineering stress–strain curves of the specimens. Both the bilinear constitutive model and Rasmussen’s model can precisely predict the stress–strain relationship of corroded Q345 and Q420 steels before yielding. Once the stress exceeds the yield strength, significant differences are observed between the stress–strain curves of the bilinear constitutive model and the tested engineering stress–strain curve. By contrast, Rasmussen’s model is more accurate in the strain hardening region close to the ultimate strength. However, Rasmussen’s model overestimates at the yielding stage and the initial part of the strain hardening region because this model was originally evaluated for stainless steel that lacks a yield plateau in a tensile test [36]. In summary, both the bilinear constitutive model and Rasmussen’s model can be used to predict the stress–strain relationship of corroded Q345 and Q420 structural steels. The predicted value of the bilinear constitutive model has a larger safety margin, whereas the predicted value of Rasmussen’s model is more accurate [37].

**Table 7. Parameter values of the constitutive model.**

<table>
<thead>
<tr>
<th>Mass Loss Rate</th>
<th>(m)</th>
<th>(E_y)</th>
<th>(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q345</td>
<td>Q420</td>
<td>Q345</td>
</tr>
<tr>
<td>0%</td>
<td>3.57</td>
<td>3.40</td>
<td>14.851</td>
</tr>
<tr>
<td>20%</td>
<td>3.63</td>
<td>3.54</td>
<td>15.953</td>
</tr>
<tr>
<td>30%</td>
<td>3.63</td>
<td>3.46</td>
<td>13.871</td>
</tr>
<tr>
<td>40%</td>
<td>3.63</td>
<td>3.70</td>
<td>8.065</td>
</tr>
</tbody>
</table>

**Figure 14. Cont.**

- (a) Q345-0
- (b) Q420-0
Figure 14. Constitutive model of Q345 and Q420 steels.

5. Prediction Equation

In previous studies [2,5,6], the prediction equation has been proposed to determine the residual tensile strength of steels after various types of predamage. In terms of steel corrosion, many previous studies have evaluated the relationship between the residual mechanical properties and the mass loss rate [18–20,24], thickness [17], and pitting depth [22]. Table 8 provides the prediction equations for various steels after corrosion. As described above, there are significant differences in the residual bearing capacity and deformability of Q345 and Q420 structural steel specimens with the same mass loss rate. In addition, the existing prediction equations for other structural steels are not suitable for evaluating the residual mechanical properties of corroded Q345 and Q420 structural steels. Therefore, in this section we propose an equation to predict the residual tensile strength and ductility of
Q345 and Q420 structural steels after corrosion. The reliability of these prediction equations was also evaluated using the adjusted R-squared ($R^2_{\text{adj}}$) and error value. Furthermore, this study also used the area between the curve of the prediction equation and the test data line to validate the error of these prediction equations. Because the test data line was composed of discontinuous line segments, the area between the fitted curve of the prediction equation and the test data line needed to be integrated using the following expression:

$$e = \sum_{i=1}^{n} \int_{x_{i}}^{x_{i+1}} \left| f(x_i) - f^T(x_i) \right|$$

(12)

where $n$ is the number of test data, $e$ is the error of the prediction equation, $x_i$ represents the $i$-th mass loss rate, $f(x_i)$ represents the calculative value of the prediction equation, and $f^T(x_i)$ represents the value on the test data line.

### Table 8. Predictive models of various steels after corrosion.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Steel Type</th>
<th>Predictive Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garbatov 2014 [18]</td>
<td>S235: $f_y = 235$ MPa, $f_u = 400$ MPa</td>
<td>$f_{y,c} = \frac{-0.0229\rho^2 + 0.5551\rho + 235}{f_y}$, $f_{u,c} = \frac{-0.0064\rho^2 + 2.3599\rho + 400}{400}$, $E_{T,c} = \frac{-0.0015\rho^2 - 0.5505\rho + 22%}{f_y}$</td>
</tr>
<tr>
<td>Garbatov 2016 [19]</td>
<td>S235: $f_y = 235$ MPa, $f_u = 400$ MPa</td>
<td>$f_{y,c} = \frac{-0.0112\rho^2 + 0.3539\rho + 235}{f_y}$, $f_{u,c} = \frac{-0.0064\rho^2 - 2.568\rho + 400}{400}$, $E_{T,c} = \frac{0.0023\rho^2 - 0.3607\rho + 22%}{f_y}$</td>
</tr>
<tr>
<td>Ou 2016 [20]</td>
<td>A706: $f_y = 420$ MPa, $f_u = 630$ MPa</td>
<td>$f_{y,c} = \frac{1 - 0.0127\rho}{f_y}$, $f_{u,c} = \frac{1 - 0.0116\rho}{f_u}$</td>
</tr>
<tr>
<td>Vanama 2020 [24]</td>
<td>MS250: $f_y = 250$ MPa, $f_u = 410$ MPa</td>
<td>$f_{y,c} = \frac{1 - 0.0136\rho}{f_y}$, $f_{u,c} = \frac{1 - 0.0128\rho}{f_u}$</td>
</tr>
</tbody>
</table>

### 5.1. Yield Strength

Based on the research results provided in Table 8, the residual yield strength prediction equations for Q345 and Q420 structural steels with different mass loss rates are shown below:

- **Q345**

  $$f_{y,c} = 1 - 0.0046\rho \quad \left(0 \leq \rho \leq 40\%, \ R^2_{\text{adj}} = 0.944\right)$$

  (13)

- **Q420**

  $$f_{y,c} = 1 - 0.0097\rho \quad \left(0 \leq \rho \leq 40\%, \ R^2_{\text{adj}} = 0.993\right)$$

  (14)

Figure 15a shows the experimental data and the corresponding calculated values for Equations (13) and (14). When the value of $R^2_{\text{adj}}$ is in the range of 0.85 to 1, it indicates that the prediction equation follows the test data well [3]. The $R^2_{\text{adj}}$ of Equations (13) and (14) was much greater than 0.85, indicating that the proposed linear expression of the mass loss rate $\rho$ can accurately predict the residual yield strength of the two steels. Based on the research results [18–20,24], the error between the test data and the proposed equation can be calculated using Equation (12). Figure 15b provided the error comparison between test data and the different predictive equations presented in these studies. In general, results with higher value of error indicate that the predicted values deviate to the test value.
more obviously. As observed in Figure 15b, the existing predictive models cannot predict the residual yield stresses of Q345 and Q420 specimens. The proposed models can give accurate predictive yield stresses of the four types of steels.

**Figure 15.** The prediction equation and error analysis.

### 5.2. Ultimate Strength

According to the test data, the predictive expression for the ultimate strength of the two steels can be written as:

\[
\rho_{u,c} = 0.0048 + 0.0025 \times \rho - 0.0003 \times \rho^2, \quad \text{for Q345}
\]

\[
\rho_{u,c} = 0.0104 + 0.0002 \times \rho - 0.0175 \times \rho^2, \quad \text{for Q420}
\]
- Q345

\[
f_{u,c} = 1 - 0.0048\rho \quad (0 \leq \rho \leq 40\%, R_{adj}^2 = 0.938)
\]  

- Q420

\[
f_{u,c} = 1 - 0.0104\rho \quad (0 \leq \rho \leq 40\%, R_{adj}^2 = 0.960)
\]

Figure 15c shows the experimental data and the corresponding calculated values for Equations (14) and (15). Like the yield strength, the value of \( R_{adj}^2 \) was close to 1, and the error shown in Figure 15d was small, while the model proposed by Garbatov [19] gave an inaccurate result in predicting the residual ultimate strength of the Q345 specimens. Hence, the change in ultimate strength of the two steels can also be accurately described by the prediction equations.

5.3. Ductility

According to the experimental data concerning ultimate elongation, the following equations can evaluate the residual ductility of the two steels after corrosion:

Q345 structural steel

\[
\frac{E_l}{E_l} = 1 + 0.0025\rho - 0.0003\rho^2 \quad (0 \leq \rho \leq 40\%, R_{adj}^2 = 1)
\]

Q420 structural steel

\[
\frac{E_l}{E_l} = 1 - 0.0175\rho + 0.0002\rho^2 \quad (0 \leq \rho \leq 40\%, R_{adj}^2 = 0.942)
\]

Because of the obvious randomness, the ductility of the two steels exhibited complex changes. Therefore, the predictive equations of the residual ductility were expressed using a quadratic equation. Figure 15e,f shows that the calculation values of the proposed equations were in good agreement with the experimental data. In summary, the influence of corrosion on the residual loading-bearing and deformation capacity of Q345 and Q420 structural steels is significant, and the prediction equations developed in this paper are able to predict the residual tensile strength and ductility of the two steels. However, it is impossible to develop a comprehensive predictive model to determine the residual tensile strength of all types of steel because of their significant differences in corrosion behavior, chemical composition, processing technology, etc.

6. Conclusions and Future Work

The residual tensile behavior of corroded Q345 and Q420 steel specimens was investigated in this paper. The corrosion characteristics and tensile fracture modes of the two corroded steels were observed and analyzed. According to the bearing capacity and deformability, an improved constitutive model and empirical equations for the corroded Q345 and Q420 steels were proposed. The key conclusions were as follows:

1. An improved Swift-type model was proposed, to effectively determine the true stress–strain curves of Q345 and Q420 structural steels with different mass loss rates;

2. The yield strength, ultimate strength and ductility of Q345 and Q420 steels reduced sharply with increasing corrosion mass, which indicated that the bearing capacity and deformability of the two steels decreased after corrosion. After being corroded with the same mass loss, the tensile strength of Q420 structural steel was reduced more than that of Q345 structural steel because of their different chemical compositions;

3. Both the bilinear constitutive model and Rasmussen’s model were proposed to determine the stress–strain relationship of corroded Q345 and Q420 structural steels. The two constitutive models can accurately predict the stress–strain relationship of the two
steels before yielding. Once the stress exceeded the yield strength, Rasmussen’s model was more accurate in the strain hardening region near the ultimate strength.

4. Empirical equations were proposed to predict the residual tensile strength and ductility of the corroded Q345 and Q420 steels, and the reliability of these empirical equations was also evaluated using the adjusted R-squared ($R^2_{adj}$) and error value.

Future work will use SEM (scanning electron microscopy) to investigate the micro-morphology of Q345 and Q420 structural steels after corrosion.

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