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Progress in the Research of Fatigue of Weathering Steel after Corrosion

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Abstract: Weathering steel has a good corrosion resistance in the atmosphere, and the application of weathering steel in civil structure also reduces the cost of painting and maintenance. It is also possible for the bare weathering steel to bear the fatigue load with a rust layer. This paper summarizes the fatigue researches after corrosion of weathering steel, including the shape of specimens, failure modes of fatigue and the conclusions obtained through experimental investigations. It is also introduced the fatigue model of weathering steel after corrosion, which can be useful for the engineering application or further researches.

1. Introduction
Corrosion can weaken the cross section and decrease the stiffness of steel structure, which may make it not meet the original design requirements in terms of strength or stability. Replacing the traditional steel by weather resisting steel is a new way to solve the corrosion problem of steel structure [1].

Weather resisting steel, also known as weathering steel, has excellent corrosion resistance in atmospheric environment [2].

A dense rust layer with strong adhesion will form in the surface of weathering steel [3]. This special rust layer can prevent the rust from further spreading and developing to protect the basic under the rust. Weathering steel’s corrosion resistance is usually 2 to 8 times the ordinary steel in the atmosphere [4]. It can reduce the damage caused by corrosion during the use period of the structure, and reduce the maintenance cost or even maintenance-free, and finally reach the decline of the total cost of the structure by using the weathering steel.

When weathering steel is used in the bridge and orbit without coating, it is in a state with rust, but also needs to bear the cyclic load. This paper summarizes the researches of the fatigue behavior of weathering steel after corrosion for engineering applications and further research reference.

2. Fatigue test specimens and main failure mode of weathering steel

2.1. Plate specimen
Local corrosion will form a small hole on the steel surface, that is, pitting pits, which can cause the local stress concentration on the steel surface. So, the local stress level will be increased and the fatigue life will be reduced. To explore the influence of corrosion on the fatigue behavior of weathering steel, plate specimens are commonly used in fatigue test (Figure 1).
Fatigue cracks on the corroded specimens initiate at corrosion dimples. And no cracks starting in the rust layer and continuing into the base material were observed [5]. The surface roughness of the corroded specimen is relatively large and its fatigue life is reduced compared with non-corroded one. The degree of the reduction is related to the type of steel, the environment and the corrosion time [5].

2.2. Weld joint
Stiffener specimen and gusset specimen are commonly used for fatigue test for the welded joints, as shown in Figure 2. The test results showed that, crack initiates at the weld toe, then propagates through the thickness of the main plate. It indicates that the impact of weld on the fatigue life is more serious than corrosion [6-8].

2.3. Beam specimen
Weathering steel I-beam is commonly used in bridges. The fatigue life, the type of crack initiation and the expansion are obtained based on the fatigue test of the corroded weathering steel I-beam, which includes rolled beam, welded beam and cover-plated beam. Cover-plated beam, shown in Figure 3, is used to study the impact of the weld at the flange on the fatigue behavior.

Five types of crack initiation and propagation were observed in the beam specimen test [9,10]:

1) crack initiates at one or more rust pits on the bottom of bottom flange, and propagates first with a semi elliptical front through the flange thickness until the deepest point of the front reaches the top of the bottom flange, then it moves across the flange width and up the web;

2) crack initiates from a defect at the bottom flange edges. It first propagates as a corner crack through the flange thickness and then across the flange width and into the web;

3) crack initiates at rust pits on the top of the bottom flange. Then it propagated as a part-through crack through the flange thickness, then as a through crack across the flange width and into the web;

4) crack initiate from internal weld flaws such as porosities, blow holes, and slag inclusions;

5) crack from external weld flaws such as start-stop positions, tack welds, and irregularities on the surface of the weld bead.
Because water ponded on the top of the bottom flange for some time, the bottom flange corroded more. And the rust pit will lead to stress concentration, then it leads to the initiation of cracks. The most common type of crack found on the hot-rolled beam is Type (1).

Cracks in all boldly exposed, cover-plated beams initiated at the toe of the transverse end weld which is connecting the cover plate to the flange. Cracks in the sheltered beams (covered with metal decking that simulated the sheltering of girders by the bridge deck) initiated in equal numbers at the weld toe or at the rust pits away from the weld toe. In this case, the rust pits produce a stress concentration as severe as the weld toe. If the cover-plated beams had no rust pit. The fatigue life of the beam with the Type 5 crack initiating at the end was always shorter than that with the Type 1 crack initiating at the rust pits away from the end [9,10].

3. Experimental study on fatigue behaviour of corroded weathering steel
Kunz L [5] conducted the fatigue tests on the Atmofix 52 weathering steel which corroded for more than 20 years. Test specimens are shown in Figure 1. The tests used two types of specimens: 1. corrosion layer covered the two frontal sides; 2. corroded layer was milled away. The specimens were machined from an angle iron that had been in service for more than 20 years.

Through the test, the S-N curves of the weathering steels and the fatigue limits defined on $10^7$ cycles were obtained. The fatigue life of the corroded specimen had a significant decrease compared with the non-corrosive specimen at the same stress amplitude (half of the maximum stress and the minimum stress algebra [11]). The results are shown in Table 1.

| Stress ratio | Frequency (Hz) | Fatigue limit for base material (MPa) | Fatigue limit for base material after corrosion (MPa) | Decrease percentage (%) |
|--------------|----------------|--------------------------------------|--------------------------------------------------|------------------------|
| -1           | 40             | 240                                  | 140                                              | 41.7                   |
| 0            | 190            | 190                                  | 120                                              | 36.8                   |

The fatigue notch factor (the ratio of the fatigue limit of the unnotched specimen to the notched specimen) for symmetrical loading is $K_f = 1.5$, which is in reasonable agreement with the experimentally determined value 1.71 for symmetrical loading. The simple fatigue notch theory can reasonable quantitatively predict the decrease of fatigue limit due to presence of corrosion dimples [5].

Albrecht P [6] studied the fatigue behaviour of stiffener specimen to simulate the transverse stiffeners of the web. The specimens were made of A588 weathering steel. The weathered specimens were placed outdoors at a 15° angle from the horizontal. A total of 62 test specimens were divided into non-weathered specimens, 3-year weathered specimens, 8-year weathered specimens and alternating weathered specimens. Alternating weathered refers to first weathered 3 years, then alternately cycled to one-eighth of the mean life of 3-year weathered specimens and weathered for six months. The reason for alternately weathering and cycling the specimens was to simulate the conditions in which bridge girders develop an oxide coating then in a state with rust, but also needs to bear the cyclic load.

According to the experimental data, the double logarithmic S-N curve was obtained:

$$\log N = a - m \log f_r$$

where $N$ is fatigue life, $f_r$ is stress range (the maximum stress and the minimum stress algebra [11]), $m$ is the slope and $a$ is intercept. The double logarithmic S-N curves are shown in Figure 4. The atmospheric corrosion can reduce fatigue life of weathering steel stiffener specimen, and the longer the corrosion time lasts, the more the life decreases.
Albrecht P [6] also calculated the relative loss in stress range $\Delta f_r$, the relative loss in fatigue life $\Delta N$ and fatigue notch factor $K_f$ (Fig 5). The calculation is as follows:

$$\Delta f_r = 1 - \frac{f_{r1}}{f_{r2}}$$  \hspace{1cm} (2)

$$\Delta N = 1 - \left(\frac{f_{r1}}{f_{r2}}\right)^m$$  \hspace{1cm} (3)

$$K_f = \frac{f_{rA}}{f_{r1}}$$  \hspace{1cm} (4)

where $f_{r1}$, $f_{r2}$ and $f_{rA}$ are the weathered, non-weathered specimens and the Category A (like hot-roll beam and base metal [12]) in AASHTO stress range at $5 \times 10^5$ cycles from mean S-N lines, and $m$ is the slope for the curves. As shown in Figure 5. The results are shown in Table 2.

| Weathering time/year | $\Delta f_r$ (%) | $\Delta N$ (%) | $K_f$ |
|----------------------|------------------|----------------|-------|
| 0                    | -                | -              | 1.67  |
| 3                    | 15               | 42             | 1.98  |
| 8                    | 21               | 54             | 2.13  |
| Alternating weathered| 15               | 42             | 1.98  |

The results showed the longer the corrosion time, the greater the fatigue notch factor. Corrosion had a moderate impact on fatigue life. The relative losses in fatigue life were similar between 3-year weathered specimens and alternating weathered specimens [6].

Yamada K [13] conducted the fatigue tests of stiffener specimen and gusset specimen made of JIS SMA50 weathering steel, and compared with SM50 ordinary steel. The specimens were weathered for 2 and 4 years at a 30° angle from the horizontal. Fatigue cracks were initiated at the toes of the transverse fillet welds and then propagated through the thickness of the plate for both types of specimens. No reduction of fatigue life due to the weathering was observed.

Albrecht P [7,8] conducted the fatigue tests of stiffener specimen made of A588 weathering steel after 2, 4 and 8 years corrosion. Transverse stiffeners were manually welded and specimens were placed outdoors at a 15° angle from the horizontal. The results are shown in Table 3. The results show...
that the fatigue life of the stiffener specimen after corrosion was decreased, and the fatigue notch factor increased.

Table 3. The fatigue test results of [7][8] refs

| weathering time/year | Test environment | Δf | ΔN | Kf |
|----------------------|------------------|----|----|----|
| 0                    | Air              | -  | -  | 2.04|
| 2                    | Air              | 7  | 21 | 2.18|
| 4                    | Air              | 8  | 22 | 2.19|
| 8                    | Air              | 11 | 24 | 2.27|
| 8                    | Salt water       | 23 | 57 | 2.63|

Typical tests show that atmospheric corrosion can affect the fatigue life of weathering steel or welded joints. The influence level depends on the factors such as corrosion environment, corrosion time, materials, and processing conditions.

Albrecht P [9,10] studied the fatigue strength of weathered A588 steel beams. There were two types of corrosion: boldly exposed and sheltered corrosion. In addition, to simulate the deicing salt contamination of highway bridges located in snow-belt states, the beams were lightly sprayed during three months of each winter season.

The thickness loss Δt was measured after corrosion and the mean penetration p was calculated:

\[ p = \frac{\Delta t}{2} \]  \hspace{1cm} (5)

Mean corrosion rate is defined as the mean penetration divided by time. The webs on the beam end had different corrosion rate depend on exposed to or sheltered from rain-washing. Corrosion time and mean corrosion rate are shown in Table 4.

Table 4. Corrosion Rate for Beams in the [9][10] refs

| Exposure Environment | Mean weathering time (month) | Mean Corrosion Rate (μm/year) | Top flange | Bottom flange | Web exposed | Web sheltered |
|----------------------|------------------------------|------------------------------|------------|---------------|-------------|---------------|
| a) hot roll beams    |                              |                              |            |               |             |               |
| Boldly-exposed       | 62.5                         | 9.4                          | 12         | 9.9           | -           |               |
| sheltered            | 67.4                         | 56                           | 254        | 58            | 269         |               |
| b) weld beams        |                              |                              |            |               |             |               |
| Boldly-exposed       | 45.1                         | 9.4                          | 10         | 7.4           | -           |               |
| sheltered            | 62.3                         | 48                           | 249        | 74            | 193         |               |
| c) cover-plated beams|                              |                              |            |               |             |               |
| Boldly-exposed       | 74                           | 11                           | 12         | 19            | -           |               |
| sheltered            | 72.1                         | 41                           | 259        | 86            | 249         |               |

The results showed that the corrosion rate of the flanges and web was about 10 μm/year and the section corrosion is uniform for the direct corrosion specimen, and the thickness loss were similar. The corrosion rate of the sheltered beams is larger than that of boldly-exposed beams and the bottom flange had the greatest rate; corrosion situation is more serious, and cross-section corrosion is not uniform.

The reason for the uneven corrosion of the section is related to the corrosion conditions. The protection rust layer requires a period of dry and wet cycle, but the sheltered beams were lack of rain-washing and sunlight, which affecting the formation of the protected layer, so that the corrosion rate increased. At the same time, the deicing salt accelerated corrosion and water ponded on the bottom flange, so making corrosion worse.
Three fatigue test environments were designed for beams [9,10]:
(1) in air; (2) in a moist freshwater environment: the moisture was provided by wet sponges laid in an open-ended trough and in contact with the bottom flange along the center of the beam; (3) in a moist saltwater environment: the sponges were wetted with a solution of sodium chloride instead of fresh water. Fatigue notch factor was calculated according to the data. The results of fatigue tests are shown in Table 5.

### Table 5. The fatigue test results of [9][10] refs

| Exposure Environment | test environment | AASHTO Detail Category | Type of detail | Number of test data | \(a\) | \(m\) | \(K_f\) |
|----------------------|------------------|------------------------|----------------|---------------------|--------|--------|--------|
| Bold Air             | Air              | A                      | Rolled beam   | 4                   | *      | *      | 0.98   |
| Bold Freshwater      | Freshwater       | A                      | Rolled beam   | 9                   | 10.348 | 1.917  | 1.44   |
| Sheltered Saltwater  | Saltwater        | A                      | Rolled beam   | 15                  | 12.087 | 3.146  | 3.27   |
| Nonweathered Air     | B                | Welded beam            | 10             | 12.403              | 2.766  | 1.38   |
| Bold Air             | B                | Welded beam            | 9              | 14.001              | 3.433  | 1.30   |
| Bold Freshwater      | B                | Welded beam            | 4              | 14.434              | 3.720  | 1.52   |
| Sheltered Air        | B                | Welded beam            | 4              | *                   | *      | 1.82   |
| Sheltered Saltwater  | B                | Welded beam            | 11             | 10.026              | 2.104  | 3.07   |
| Bold Freshwater      | E                | Cover-plate            | 9              | 13.812              | 3.869  | 2.56   |
| Sheltered Saltwater  | E                | Cover-plate            | 11             | 9.765               | 1.849  | 3.01   |
| Sheltered Saltwater  | E                | Cover-plate            | 5              | 8.913               | 1.458  | 3.17   |
| Sheltered Saltwater  | A                | Rolled beam            | 6              | 9.939               | 1.896  | 2.93   |

*: Insufficient number of observations for regression analysis.

The results showed that fatigue life of hot-rolled and welded beams decrease when tested in moist freshwater and saltwater environments compared with air environment. Because of serious corrosion, sheltered beams tested in saltwater environment had the greatest reduction in fatigue life. In the same condition, the fatigue notch factors of hot roll beams and weld beams are 3.27 and 3.07, so they were down to between category D and E from A and B. Whether it is sheltered or boldly exposed, the fatigue notch factor is between category D and E, that means corrosion did not affect the fatigue strength of the cover-plated beams because the stress concentration factor of the shallow pits was smaller than that of the weld toe. The typical tests of beams show that the cross-section structure, corrosion mode and fatigue environment will affect the fatigue behavior after corrosion.

### 4. Experimental study on fatigue behaviour of corroded weathering steel

Albrecht P [14] introduced three factors to calculate the remaining fatigue life of corroded beams after analyzing the data of A7 and A588 steel. Allowable fatigue life \(N_d\) is:

\[
N_d = \frac{10^{5s - 2s}}{(K_eK_pK_{fr}f_{rd})^{m_s}}
\]

(6)

\[
K_e = \frac{f_{fr,c}}{f_{fr}}
\]

(7)

\[
K_e = \left[\left(\frac{da}{dN}\right)_{aq} / \left(\frac{da}{dN}\right)_{air}\right]^{1/2}
\]

(8)

\[
K_p = \frac{K_{fe}}{K_eK_e}
\]

(9)

where \(s\) is standard deviation of mean S-N line for Category A; \(f_{fr}\) and \(f_{fr,c}\) are stress ranges of bottom flange before and after corrosion respectively; \(\left(\frac{da}{dN}\right)_{aq}\) and \(\left(\frac{da}{dN}\right)_{air}\) are crack growth rates in aqueous
environments and in the air respectively; $k$ is the slope constant in plot of crack growth rate versus range of stress intensity factor; $K_{fc}$ is fatigue notch factor after corrosion. 

$N_{used}$ is the number that was applied on the structure. So, the remaining number $N_{rem}$ is:

$$N_{rem} = N_{d} - N_{used}$$  \hspace{1cm} (10)

According to the relationship between the pitting factor and the non-corrosive specimen fatigue notch factor, fatigue notch factor has different calculation methods:

$$\begin{cases} 
K_p < K_{f}, K_{fc} = K_{c}K_{f}\text{ or } K_{f} > K_{f}, K_{fc} = K_{c}K_{p} 
\end{cases}$$  \hspace{1cm} (11)

Aghoury I M E [15] introduced fatigue strength exponent and fatigue ductility exponent after corrosion and provided the corrosion fatigue strain-life model based on Smith-Waston-Topper (SWT) strain-life method:

$$\frac{\Delta \varepsilon}{2} \sigma_{max} = \left(\frac{\sigma'_{f}}{E}\right)^{2b'} + \sigma'_{f} \varepsilon'_{f} \left(\frac{2N}{2N+\alpha_{b}' \varepsilon'}\right)^{b'+c'}$$  \hspace{1cm} (12)

$$b' = b(1 + \gamma_{cor}\gamma_{a}\alpha_{b})$$  \hspace{1cm} (13)

$$c' = c(1 + \gamma_{cor}\gamma_{a}\alpha_{c})$$  \hspace{1cm} (14)

where $\Delta \varepsilon$ is strain range; $\sigma_{max}$ is maximum stress; $\sigma'_{f}$ and $\varepsilon'_{f}$ are fatigue strength coefficient and fatigue ductility coefficient respectively; $E$ is elasticity modulus in tension; $N$ is number of cycles to failure; $b$ and $c$ are fatigue strength exponent and fatigue ductility exponent respectively before corrosion; $\gamma_{cor}$ is environment corrosivity intensity factor; $\gamma_{a}$ is correction factor depending on the maximum applied stress. Factor $\alpha_{b}$ and $\alpha_{c}$ are:

$$\alpha_{b} = \left(b_{fit}' / b\right) - 1.0$$  \hspace{1cm} (15)

$$\alpha_{c} = \left(c_{fit}' / c\right) - 1.0$$  \hspace{1cm} (16)

where $b_{fit}'$ and $c_{fit}'$ are the modified fatigue strength component and modified fatigue ductility coefficient corrosive environment (e.g., NaCl 3.5% testing environment or equivalent).

To obtain the long-term experimental corrosion fatigue data, Aghoury I M E [15] convert available S-N data points for a corrosive environment to strain-life data points:

$$\frac{\Delta \varepsilon}{2} = \frac{f'_{s} / 2}{E} + \left(\frac{f'_{s} / K'_{c}}{n'}\right)^{n'}$$  \hspace{1cm} (17)

where $f'_{s}$ is stress range; $K'$ is the cyclic strain hardening coefficient; $n'$ is the cyclic strain hardening exponent. The lower and upper bounds of the fatigue life of the calculated by the model (12) are compared with the fatigue life test values of the boldly exposed hot-rolled beams in [10].

| Beam | Stress range (MPa) | Fatigue life | Estimated number of cycles (Modified SWT) | Estimated number of cycles (SWT) |
|------|-------------------|-------------|------------------------------------------|---------------------------------|
|      |                   |             | lower bound                              | upper bound                     | lower bound                              | upper bound |
| B11  | 165               | 15.95x10^5 | 17.00x10^5                              | 33.00x10^5                     | 820x10^5                                 |             |
| B12  | 165               | 15.77x10^5 | 17.00x10^5                              | 33.00x10^5                     | 820x10^5                                 |             |
| B8   | 214               | 10.36x10^5 | 6.50x10^5                               | 10.00x10^5                    | 580x10^5                                 |             |
| B10  | 214               | 9.40x10^5  | 6.50x10^5                               | 10.00x10^5                    | 580x10^5                                 |             |
B1 276 3.86×10^5 2.50×10^5 3.70×10^5 63×10^5 
B2 276 4.57×10^5 2.50×10^5 3.70×10^5 63×10^5 
B9 276 4.36×10^5 2.50×10^5 3.70×10^5 63×10^5 

The results are shown in Table 6. The estimated number of cycles (SWT) is calculated by (12) when \( b' \) and \( c' \) are replaced by \( b \) and \( c \) [15]. The result shows that when considering the corrosion, the estimated number of cycles (Modified SWT) are close to the test results. But the accuracy is poor. Only the individual test results are in the upper and lower bounds or near the upper and lower bounds.

5. Conclusion
Scholars from different countries have studied the corrosion fatigue of plate specimen, welded joint and beams made of weathering steel. However, due to the different corrosion environments, materials and structures of the specimen, the impact of corrosion on the fatigue life is also varied, so the test results can hardly reflect the practical engineering. The further study on fatigue life of weathering steel should consider at least three factors mentioned above.

As the surface pitting and other corrosion factors can’t be ignored, when calculating the fatigue life of corroded weathering steel, corrosion must be considered. The environment corrosivity intensity factor \( \gamma_{cor} \) is only related to the average thickness loss of the steel, so the influence of corrosion can’t be considered comprehensively and the life prediction is not accurate.

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