Prognosis analysis of strength of H-beams considering corrosion effects

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Abstract. The bearing capacity of components under the influence of corrosion was studied to predict the service life of corroded H-beams. Firstly, based on the experimental data of mechanical properties of corroded steel, the Weibull model was used to fit the test data to obtain corrosion H-beam strength prognosis curve. Then, combined with the target design strength value, the prognosis analysis of the corroded H-beam was carried out. Finally, a numerical example was given to verify the effectiveness of the proposed method. The Weibull model could well fit and predict the bearing capacity of corroded H-beams. According to the bearing capacity attenuation model of H-beams, the service life of the H-beams in our research was well predicted, about 66.5 years. In conclusion, the proposed method can well predict the life of corroded H-beams and it has been verified feasibility and effectively.

1. Introduction

"Damage Prognosis (DP)" is the academic concept proposed by some scholars in recent years for the safety assessment of large-scale civil structures [1-2]. Farrar et al. [2] considered DP to be the future theme of Structural Health Monitoring (SHM). The basic definition of DP is “under the premise of obtaining information and understanding the mechanism of damage evolution of structural health monitoring systems, combined with the history and current status of structural service to evaluate the current damage state of the structure (Level 1), predict the future load environment and structural performance of the structure (Level 2), and predict the remaining life of the structure through numerical simulation techniques and historical experience (Level 3)” [4]. The SHM identify the damage of the current structure based on monitoring data. While DP not only used for the present, but also for the future. DP combined both historical and current information to predict the future damage also the remaining life of the structure.

The steel structure has the characteristics of high strength and light weight. At the same time, steel has unavoidable defects in corrosion. Corrosion is one of the main damage modes that occur in steel structures, which can seriously affect the performance of the structure and even cause it to collapse, greatly reducing the safety, durability and reliability of the structure. At present, there are some researches on corroded steel structures, for example: Chen et al. [5] evaluated the damage of corroded space steel structures in a coastal area; Sarveswarana et al. [6] proposed the reliability of corroded...
steel structural members by interval probability theory Research; Robert et al. [7] considered the reliability analysis of offshore steel structures was affected by corrosion; Chen et al. [8] conducted corrosion damage assessment and monitoring of a large space steel structure, and established a space monitoring system based on the relevant concepts of corrosion. However, these studies mainly analyze the current status of the in-service structure based on the currently measured information, and the resistance of the in-service structure at a certain point in time is not predicted under the influence of environmental corrosion. According to the historical information and the current information to achieve the purpose of structural damage prognosis, the initiative of the whole life of the structure under the influence of corrosion can be fully grasped, so that measures can be taken in advance before the failure of the structure to reduce the risk of structural failure.

In this paper, from the aspect of structural strength, the strength prognosis analysis of corroded H-beams is carried out, which has good practical value for the design of steel structure and maintenance management in the later stage.

2. Study of steel corrosion

According to the relevant research results [9-10], the index of weightlessness can be used to measure the influence of "reduction of average cross-sectional area of steel", "stress concentration formed by uneven corrosion" and "change of internal lattice of steel" on the degree of deterioration of steel performance. For the calculation of the weight loss rate $D_w$, see equation (1):

$$D_w = \frac{W_0 - W_1}{W_0} \times 100\%$$

Where, $W_0$, $W_1$ are the mass of the steel before and after corrosion, g.

The thickness loss of the corroded steel due to corrosion is equal to the weight loss rate $D_w$ multiplied by the original thickness of the plate. See equation (2):

$$d = D_w \times t$$

Where, $d$ is the corrosion thickness of the steel, and $t$ is the original thickness of the steel.

In addition, the corrosion time of the indoor accelerated corrosion test of steel is converted into the relationship of atmospheric corrosion years [5]:

$$T = \frac{d}{K}$$

Where, $T$ is the atmospheric corrosion age converted into, a; $d$ is the corrosion thickness, mm; $K$ is the corrosion rate, mm / a. Refer to the corrosion rate of Shanghai in this paper, the value is 17.8 $\mu$m / a [5]. Table 3 shows the corrosion thickness of 8 mm steel and the converted years of atmospheric corrosion.

3. Stress prognosis of simply supported beam of H-beam

3.1 H-beam beam strength calculation

In this paper, considering the influence of environmental corrosion factors, the net section modulus of H-shaped steel beams decreases with the increase of service time, so the net section modulus has time-varying, then the "Code for Design of Steel Structures" (GB50017-2003). The strength formula of the bent member can be expressed as:

$$\frac{M_x}{\gamma_x W_{nx}(t)} + \frac{M_y}{\gamma_y W_{ny}(t)} \leq f$$

Where, $M_x$, $M_y$ are the bending moments of the x-axis and the y-axis at the same section; $W_{nx}(t)$ and $W_{ny}(t)$ are the net-section moduli of the x-axis and the y-axis, respectively, as a function of time; $\gamma_x$, $\gamma_y$ cross-section Plastic development coefficient, I-shaped section $\gamma_x=1.05$, $\gamma_y=1.20$; $f$ is the design value of the bending strength of the steel. Only the strength formula of the x direction is considered here as:
\[ M_s \leq \gamma W_{es}(t) \]  

(5)

3.2 Weibull model
The current forecasting models mainly include gray theory, power function, Weibull model, etc. The gray theory mainly has a good solution effect for the "small sample, poor information" problem of "extended extension and unclear connotation", and the power function is not suitable for the prediction of initial stress, Weibull model is often applied to structural performance degradation caused by structural damage. For this reason, the author uses the Weibull model to fit the stress values of different corrosion years, so as to obtain the stress decay model expression of the corroded H-beam:

\[ \beta(t) = a + be^{ct} \]  

(6)

Where, \( \beta(t) \) is a reliable indicator of time; \( a, b, c, d \) are constants; \( t \) is time.

4. Example

4.1 Overview of H-beams
Based on the corrosion study of the 8mm thick steel with or without coating film in the second section, the cross-sectional dimension of the H-shaped steel beam is selected as \( H \times B \times t_w \times t_f \) (100mm×100mm×8mm×8mm). Figures 1, 2 and 3 illustrated sectional characteristics of the steel beam, corrosion section thickness and loading method. The relevant parameters are listed in Table 1.

![Figure 1](image1.png)  
![Figure 2](image2.png)  
![Figure 3](image3.png)

**Figure 1. Section size of the member.**  
**Figure 2. Thickness of corrosion loss.**  
**Figure 3. Load diagram of H-shaped steel beam(mm).**

| parameter                  | Numerical value |
|----------------------------|-----------------|
| length (mm)                | 1300            |
| Section modulus (mm\(^3\)) | 75700           |
| Bending strength design value (N/mm\(^2\)) | 215 |
| LoadP(KN)                  | 30              |

Table 1. Parameters.

4.2 Calculation of thickness of corroded H-beam
In reference [7], the indoor accelerated corrosion method was adopted. In this paper, the corrosion study of steel with a thickness of 8 mm was selected, and the indoor accelerated corrosion was 3200 hours. Table 2 shows the weight loss rate of the 8 mm material test piece.

| Corrosion time (h) | Weight loss rate (%) |
|-------------------|----------------------|
| 0                 | 0                    |
| 250               | 1.46                 |
| 500               | 2.19                 |
| 800               | 3.13                 |
| 1600              | 5.67                 |
| 2400              | 8.83                 |
| 3200              | 12.03                |

According to the weight loss rate of different corrosion time in Table 2, combined with equation (2) and (3), the indoor corrosion time can be converted into the atmospheric corrosion period and the corresponding corrosion thickness of steel in Table 3.

| Indoor accelerated corrosion time (h) | Atmospheric corrosion years (a) | Steel corrosion thickness (mm) |
|--------------------------------------|---------------------------------|-------------------------------|
| 0                                    | 0                               | 0                            |
| 250                                  | 3.3                             | 0.0584                        |
| 500                                  | 4.9                             | 0.0876                        |
| 800                                  | 7.0                             | 0.125                         |
| 1600                                 | 12.8                            | 0.227                         |
| 2400                                 | 20.8                            | 0.353                         |
| 3200                                 | 27.0                            | 0.481                         |

4.3 Prognosis analysis of the strength of corroded H-beam

Table 4 shows the effect of corrosion on the cross-section geometry of H-beams. The strong axial section modulus after corrosion in Table 5 can be obtained by taking the contents of Table 3 into the relevant formula of Table 4. B0, B1, B2, B3, B4, B5, and B6 represent H-shaped steel beams of different corrosion degrees.

| name | Before corrosion | After corrosion |
|------|------------------|-----------------|
| Sectional area (mm²) | \( A = 2Bt + (H - 2t)f \) + \( t_w \) | \( A(t) = 2(B - 2d(t))(t_f - 2d(t)) + (H - 2d(t) - 2t_f) (t_w - 2d(t)) \) |
| Moment of inertia (mm⁴) | \( I_x = t_w (H - 2t_f)^3 / 12 + 2B tf \) | \( I_x(t) = (t_w - 2d(t))(H + 2d(t) - 2t_f)^3 / 12 + 2(B - 2d(t))(t_f - 2d(t)) \) |
| Section modulus (mm³) | \( W_x = I_x / (H/2) \) | \( W_x(t) = I_x(t) / (H - 2d(t)) \) |

Note: \( t \) is the corrosion time, \( d(t) \), \( A(t) \), \( I_x(t) \), \( W_x(t) \) corrosion thickness after corrosion time \( t \), cross-sectional area, strong axis moment of inertia, strong axis section modulus.
Table 5. The value of corroded section modulus.

| Numbering | Corrosion time (h) | Section modulus (mm³) |
|-----------|--------------------|-----------------------|
| B0        | 0                  | 75700                 |
| B1        | 250                | 74547                 |
| B2        | 500                | 73971                 |
| B3        | 800                | 73233                 |
| B4        | 1600               | 71226                 |
| B5        | 2400               | 69242                 |
| B6        | 3200               | 66892                 |

The stress calculation of the H-shaped steel beam is calculated by the formula (6), and Table 6 is the calculation result. The stress versus time curve of the corroded H-beam is fitted based on the Weibull model, as shown in Fig. 4.

Table 6. Stress calculation.

| Numbering | Equivalent age (a) | Corrosion time (h) | Bearing capacity (N/mm²) |
|-----------|--------------------|--------------------|--------------------------|
| B0        | 0                  | 0                  | 150.97                   |
| B1        | 3.3                | 250                | 153.31                   |
| B2        | 4.9                | 500                | 154.50                   |
| B3        | 7.0                | 800                | 156.06                   |
| B4        | 12.8               | 1600               | 160.46                   |
| B5        | 20.8               | 2400               | 165.05                   |
| B6        | 27.0               | 3200               | 170.85                   |

Figure 4. Weibull model forecast curve and stress value.

It can be seen in Fig. 4 that the actual stress value of the H-shaped steel beam increases with the increase of the corrosion time, indicating that the strength is gradually reduced. When the atmospheric corrosion period is around 66a, the stress value of the H-shaped steel beam will be lower than the strength design value and the component will fail;

\[
\sigma(t) = 131.3595 + 19.5538e^{0.0470t^{0.8318}}
\]  

(7)

Based on the Weibull model, the structural stress caused by corrosion can be well fitted, so that the prognosis of the strength of the structure can be easily analyzed. According to Eq. (7) combined with the strength design value can be obtained:

\[
215 = 131.3595 + 19.5538e^{0.0470t^{0.8318}}
\]  

(8)
Then, when $t=66.5a$, the strength design value is reached, so the structure is considered to be invalid.

5. Conclusion
The author considers the influence of corrosion. Based on the historical data and the stress state of the current structure, the Weibull model is proposed to analyze the strength prognosis of the corroded H-beam, which provides a method for predicting the remaining life of the structure. The strength calculations of the actual structure and the Weibull model curves are compared. The results show that the proposed method can pre-correlate the remaining life of H-beam, verifying the effectiveness and feasibility of the proposed method.

References
[1] Li Z.X. (2013) Current status, research ideas and prospects of multi-scale injury prognosis of large-scale civil structures. Journal of Southeast University, 43(5): 1111-1121.
[2] Farrar, C.R., Worden K. (2007). An introduction to structural health monitoring. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 365(1851): 303-315.
[3] Peng L.X. (2012). Structural Reliability Management: Prediction, Control and Evaluation. China Building Industry Press, Beijing.
[4] Zong Z.H., Zhong R.Z., Zheng P.J., Qin Z.Y., Liu Q.Q. (2014). Research progress and challenges of bridge structure damage prognosis and safety prognosis based on health monitoring. Chinese Journal of Highways, 27(12): 46-57.
[5] Chen, B., Xu, Y.L., Qu, W.L. (2005). Evaluation of atmospheric corrosion damage to steel space structures in coastal areas. International Journal of Solids and Structures, 42(16-17): 4673-4694.
[6] Sarveswaran, V., Smith, J.W., Blockley, D.I. (1998). Reliability of corrosion-damaged steel structures using interval probability theory. Structural Safety, 20(3): 237-255.
[7] Melchers, R.E. (2005). The effect of corrosion on the structural reliability of steel offshore structures. Corrosion science, 47(10): 2391-2410.
[8] Chen, B., Xu, Y.L., Qu, W. (2010). Corrosion damage assessment and monitoring of large steel space structures. Frontiers of Architecture and Civil Engineering in China, 4(3): 354-369.
[9] Shi Y.Z., Tong L.W., Chen Y.Y., Li Z.G., Shen K. (2012). Experimental study on the effect of corrosion on the mechanical properties of steel and steel beams. Journal of Building Structures, 33(7): 53-60.
[10] Liu X., Shi H. (2005). Steel structure anti-corrosion and fireproof coating. Chemical Industry Press, Beijing.