AN EVALUATION METHOD FOR CORROSION FATIGUE LIFE OF STEEL STRUCTURE CONSIDERING MECHANICAL FACTORS

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ARTICLE INFO

***Article history*:**
Received: 25.05.16.
Received in revised form: 07.09.16.
Accepted: 16.09.16.

Keywords:
Corrosion
Fatigue
Steel structure
Evaluation methods

Abstract:

Steel structures in corrosive environment are often subjected to coupling effect and damage caused by corrosion and fatigue. This paper proposed a new assessment method to study corrosion fatigue life of steel structure, including the effect of cyclic loading and corrosion damage. Based on mechanical factors, the corrosion depth of structure under cyclic loading at different time intervals was defined by a mathematical model for corrosion damage. A finite element model was established to calculate structure damage. Finally, the cumulative damage could be obtained by Miner guidelines to assess the fatigue life. Comparing traditional methods, the coupling effect of corrosion and fatigue were taken into account by this new method. According to this new method, the results showed that the calculated corrosion rate was faster, and the corrosion fatigue life shorter. Corrosion fatigue could cause more damage to structure than was expected. Furthermore, this method was convenient and practical for assessing/estimating the corrosion fatigue life of normal steel structure.

1 Introduction

Corrosion and fatigue are two well-known steel structure failure modes, and easily occurred in the steel structure joint[1]. Scholars had done a long-term and extensive research on it. Corrosion fatigue phenomenon was studied as early as 1917, which referred to a form of steel structure damage under the joint action of corrosive medium and cyclic stress. In essence, it was the product of electrochemical corrosion and mechanical processes, in simple terms, cyclic stress could accelerate steel structure corrosion, and the overall structure strength due to corrosion will continue to decrease, which in turn affects its fatigue life [2-4]. The damage done to the steel structure due to the coupling effect of alternating stress and corrosive medium will be far more than the algebraic sum of the responses caused by each separate factor acting alone. Therefore, corrosion fatigue causes more serious damage to the steel structure [5, 6].

At present, two approaches to fatigue life assessment of the steel structure under corrosive environment are: 1) in order to calculate the hot

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spot stress and analyze the corrosion fatigue damage of the structure, the plate thickness should be the original thickness obtained by subtracting the corrosion thickness. 2) The function of steel corrosion depth and time can be fitted by analyzing the experimental data of coupon test. Thus, the remaining thickness of the steel will be known at any point in time. Time-dependent finite element models are generated to calculate the hot spot stress [7, 8].

The above two methods mainly exhibited shortcomings in two aspects. Firstly, they did not take into account that cyclic stress had accelerating effects on corrosion when calculating the corrosion depth. They also ignored the coupling effect between them so that the steel corrosion depth was small. Secondly, continued development of the corrosion lead to the change of structure shape so that the hot spot stress could not be guaranteed to appear in the same place at different time points. It would produce a conservative result just by hot spot stress analysis of fatigue damage. Therefore, these methods were difficult to accurately assess fatigue damage of the steel structure in corrosive environment.

This paper proposes a new method for corrosion fatigue evaluation. Primarily, this method considers the acceleration of corrosion by mechanical factors so that the remaining thickness of corrosion structure could be obtained at any point in time. The finite-element models are to be performed to assess the fatigue damage directly at each critical location on a structural detail in different time period rather than through hot spot stress analysis. The cumulative damage of structure could be obtained based on the Miner Rule.

2 Steel structure fatigue life evaluation model under corrosive environment

2.1 The mathematical model of steel under atmospheric corrosion

Carbon steel and low alloy steel, commonly used in engineering, have fast corrosion rate in the atmosphere. There is an obvious disparity in the different areas. With a large number of regression analyses, it was proved that the atmospheric corrosion of steel yielded power function law [9]. The average corrosion depth was expressed as the following equation:

$$E = At^{n}, \tag{1}$$

where, E is the average corrosion depth (mm), t is exposure time (year), A, n is constant, obtained by the data of real sea coupon.

2.2 A mathematical model for corrosion based on the mechanical factors

Under the loads action, the corrosion current formula of metal after deformation can be derived from corrosion thermodynamics and kinetics process. The expression is as follows [10]:

$$\overline{I_a} = \overline{i_a} \exp(\frac{V\Delta P}{RT}), \tag{2}$$

where, $\overline{I_a}$ is metal electrode dissolution current, $\overline{i_a}$ is electrode of anode current without deformation, R is gas general constant, T is absolute temperature, ΔP is a metal undergoing residual pressure and V is metal's molar volume.

Due to the different corrosion environments, there are large differences in stress sensitivity. Considering the impact of mean stress of cyclic load, stress amplitude, and frequency on the current, the formula (2) is improved as follows:

$$\overline{I_a} = \overline{i_a}\gamma \exp(\frac{\alpha V\Delta P}{RT}), \tag{3}$$

where, γ is the sensitivity factor of corrosion to stress, related to the corrosion system. α is the stress correction factor, related to the cyclic load.

According to Faraday's law, the metal corrosion rate is proportional to the corrosion current. Again, referring to the relationship between the corrosion current and non-deformed current in formula (3), the following formula can be deduced:

$$v = v_a\gamma \exp(\frac{\alpha V\Delta P}{RT}), \tag{4}$$

where, v - corrosion rate, v_a - corrosion rate without deformation caused by external force.

The relationship between corrosion rate without deformation and time can be obtained by the derivative of the formula (1):

$$v_a = Ant^{n-1}. \tag{5}$$

Combined with the formulas (4), (5), the following formula will be deduced:

$$v = Ant^{n-1}\gamma \exp(\frac{\alpha V \Delta P}{RT}) . \qquad (6)$$

The formula (6) is the corrosion model considering the mechanical factors [10], which correlate time and corrosion rate of steel under cyclic load. Thus, the corrosion depth can be obtained at any point in time. To get accurate cumulative damage by using Miner rule, sufficient number of corrosion depth should be gotten by calculating them during infinitesimal time interval and cumulative damage caused by cyclic stress per interval is derived from the model [11, 12]. The smaller the time interval is picked, the more accurate the calculation results will be.

3 Numerical example

3.1 Model and material parameters

Corrosion fatigue occurs frequently in steel joints. To compare different methods for evaluating the corrosion fatigue life of high strength friction grip (HSFG) bolts lap joints, a HSFG bolts butt joint was used in this paper as shown in Figure 1. HSFG bolts and steel plate were assumed to be made of isotropic elastic material. The initial thickness of upper and lower two splice plates was 12 mm, and intermediate connection plate thickness was 24 mm. The plate was made of China Q345 Grade Steel. M20 (10.9 magnitude, 22 mm hole) bolts were used for connecting structure steel member. The joint was subjected to uniform cyclic tensile stress load, which the stress range was from 0 to 47.5 MPa. The characteristics of material parameters listed in Table 1 [13, 14].

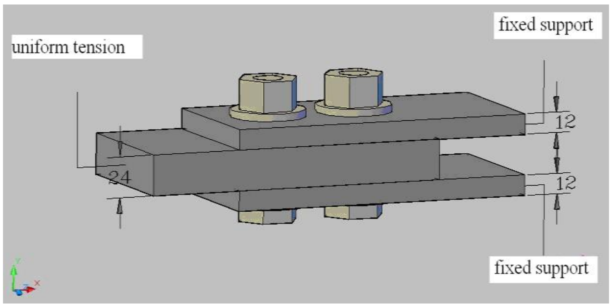

Figure 1. Three-dimensional model of high-strength bolts joint/mm.

Table 1. Material parameter table

Component	$E(GPa)$	ρ (kg/m^3)	μ	$f_y(MPa)$
Splice plate (Q 345)	206	7850	0.4	420
Connecting plate (Q 345)	206	7850	0.4	420
High-strength bolt (M 20)	206	7850	0.4	942
E - Young's modulus, ρ - density, μ - Poisson's ratio, f_y - yield strength				

3.2 Influencing factors of S-N Curve

Stress - Life Cycle (S-N) Curve was a common method to indicate the relationship between load and fatigue failure, which was derived from fatigue tests on samples of the specimen. The S-N curve of plates and bolt was shown in Figure 2. The S-N curve could be influenced by many factors such as ductility of material, surface quality, geometry, as well as load environment, load temperature, average load stress and other factors. The effect of mean stress and stress concentration could be obtained and adjusted by the Gerber method and by introducing the fatigue strength reduction factor Kf [15]. Based on the influence coefficient method [16], the proposed Kf was 0.8 in this paper.

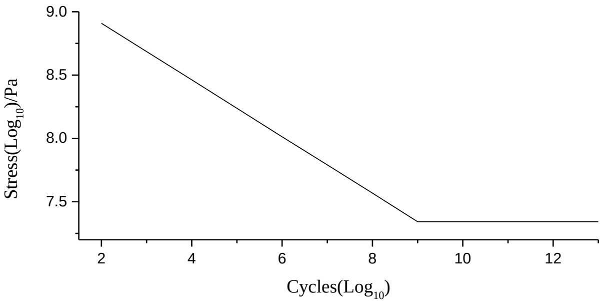

Figure 2. Stress - life cycle (S-N) curve.

The structure was analyzed by ANSYS Workbench software. The model consists of 7 parts where the nut, bolt and washer were made of the same material. For the convenience of analysis and calculation, washer, nut and bolt were created into the same entity. There were 6847 nodes, 1849 higher order 3D 10 or 20 node solid elements and 1548 contact elements. The contact elements were used to represent contact and sliding between two surfaces. These elements were located on the surfaces of splice plate, connecting plate and bolts. To establish a surface contact between bolts and nuts, binding connection was used, while for the other friction connection was used, the coefficient of which was 0.4. The bolt was preload to 155 kN and the intermediate connecting plate was subjected to cyclic tensile stress load, the peak stress of which was 47.5 MPa. Fixed constraints were applied to the free ends of upper and lower splice plate.

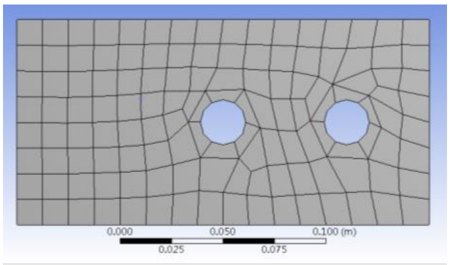

Figure 3. Plate model.

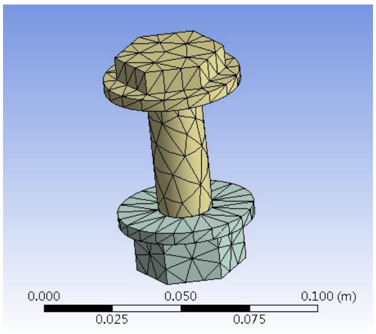

Figure 4. Bolt model.

4 Results

Assuming that the structure was subjected to 10000 cycles of cyclic stress every day, the corrosion fatigue damage value was evaluated by following three methods. A: Fatigue with no corrosion was taken into consideration. The structure subjected only to fatigue damage was not affecting by corrosion. B: Getting the coupon corrosion depth from the reference standard, the finite element model of the propagation of deep corrosion in different years was established respectively to calculate corrosion fatigue damage in ten years. C: the corrosion residual thickness of the structure was calculated during ten years by using formula (6), taking a year as interval, and then by establishing the finite element model. The parameters in the formula (6) were as follows [3, 10]: $A = 0.174, n = 0.859, R = 8.314, T = 295.15$ .In addition, the value of α and γ were gotten through analyzing a large number of experimental data. As limited data was available, α and γ were chosen to be 1.

Error! Reference source not found. showed the relationship among corrosion speed V , corrosion depth E and time t where comparison between method B and C was clear. From **Error! Reference source not found.**, it could be seen that corrosion rate of method C considering the effect of the cyclic stress on the corrosion was higher than that of the method B. Corrosion rate of two methods exhibits downward trends and gradually flatten over time.

showed that the corrosion depth of the method C was greater than that of the method B during the same time.

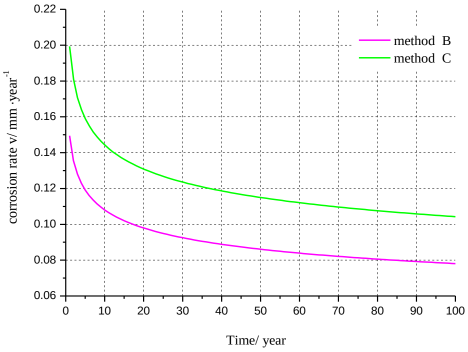

Figure 5.Comparison chart of corrosion rate versus time.

Corrosion fatigue damage is expressed by:

$$D = 1 - \frac{L_A}{L_D} \ , \tag{7}$$

where D - fatigue damage, L_A - available fatigue life, L_D - design fatigue life.

The results of FEM are listed in table 2. The fourth line content was the growth rate which was obtained by comparing the structure damage of method C with that of the method B year by year.

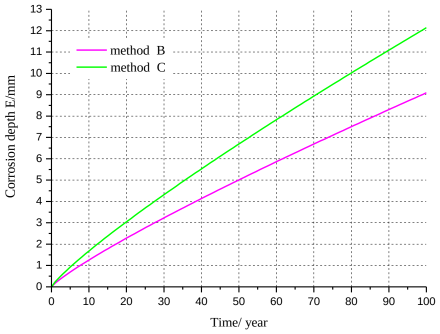

Figure 6. Comparison chart of corrosion depth versus time.

Table 2. Calculated result of D

Years	1	2	3	4	5	6	7	8	9	10
Method A	0.0124	0.0248	0.0373	0.0497	0.0621	0.0745	0.0869	0.0994	0.1118	0.1242
Method B	0.0129	0.0261	0.0398	0.0539	0.0684	0.0833	0.0986	0.1144	0.1305	0.1471
Method C	0.0130	0.0266	0.0408	0.0556	0.0709	0.0869	0.1034	0.1206	0.1384	0.1567

From Table 2 the following conclusions could be drawn:

(1) The structure was withstanding fatigue showing corrosion resistance, and the damage value did not change over time and consequently was found in agreement with its theoretical values.

(2) After considering the effect of corrosive environment, the structure weakened over time so that the fatigue damage was increasing year by year.

(3) During the same time, the fatigue damage of method C was much bigger than that of the conventional method B, because the coupling effect of corrosion fatigue was considered in method C.

(4) The comparison clearly showed that the single year growth rate of the structure damage by method C was increasing year by year, which indicated the structural damage value gap calculated by the two methods would grow larger.

The cumulative damage of three cases could be obtained by the combination of the results in Table 2 and Miner criteria. The comparison of result was shown in Figure 5. From Figure 5, it could be seen that the method C took into account the coupling effect of corrosion fatigue, and the cumulative damage value (the blue curve) was faster than the other two ways.

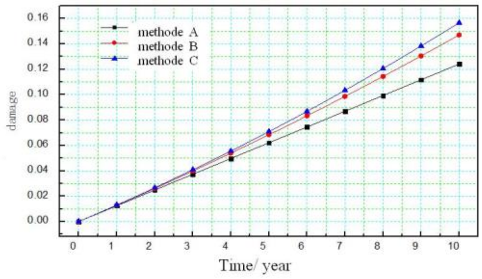

Figure 5. Comparison chart of calculated result.

5 Conclusion

This paper deals with a new and simple assessment model developed for wide application. Considering the coupled action of corrosion and fatigue, it could give conservative predictions of steel structure corrosion fatigue life. Through theoretical analysis and finite element simulation, it could be seen that corrosion fatigue causes more damage to the structure than the traditional one after considering the coupling effect of fatigue and corrosion.

It would be interesting to know if there are many other factors which have a great effect on corrosion fatigue. The proposed values of α and γ in equation 6 are worthy of further research.

Acknowledgements

This work was supported by the Foundation of China Scholarship Council (201506060044, 201508210247); Foundation of Liaoning Provincial Department of Education Funded Projects (L2014027); Foundation of Research Funds for the Central Universities (DUT15QY34); Foundation of State Key Laboratory of Structural Analysis for Industrial Equipment, the Dalian University of Technology (S13209). The authors would also like to thank the reviewers for their critical comments and valuable feedback, which have been very useful in improving the work presented in this paper

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