Effect of Corrosion-Fatigue Coupled Damage on Mechanical Properties of Q345 Angle Steel

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***Abstract*-Atmospheric environmental corrosion and wind-*induced* fatigue achieve a long-term synergistic effect, mutual coupling and promotion with each other. Under this circumstance, the speed of structural performance degradation accelerates and the ability of the structure to resist accidental loading decreases. In this paper, an evolutionary model for evaluating fatigue damage is established based on the characteristics of energy dissipation and fatigue crack propagation. Meanwhile, a corrosion damage model is established based on basic mechanical parameters. Then a coupling factor is deduced to evaluate the correlation between corrosion damage and fatigue damage, and the corrosion-fatigue coupled damage model is established by using this coupling factor. Finally, a quasi-static test of Q345 angle steel is conducted to study the failure modes, the hysteresis curve and the variation of main performance evaluation parameters under three test conditions, and a corresponding coupled damage performance degradation model is established.**

Keywords—corrosion fatigue; Q345 Angle Steel; coupling factor; coupled damage model

I. INTRODUCTION

In a harsh natural environment, high-rise structural system such as derrick and tower withstand continuous and alternating loads of wind and mechanical vibration while bearing atmospheric corrosion. And environmental corrosion leads to a decrease of the fatigue strength of the material, accelerating the expansion of fatigue cracks. Meanwhile, the acceleration of fatigue cracks propagation further promotes the corrosion. The synergistic effect of atmospheric environmental corrosion and wind-induced fatigue facilitates the degeneration of structure, which reduces the possibility to complete predetermined function during the providing time and conditions. At present, although some scholars have studied the corrosion-fatigue damage of steel, the current research is limited to the material category. Whereas the corrosion-fatigue coupling damage problem is relatively lack of research on the component or structural level. Hence, the effect of corrosion fatigue-coupling damage on hysteresis energy dissipation performance of Q345 angle steel members is studied through theoretical modeling and a quasi-static test.

II. COUPLING DAMAGE MODELING

A. Fatigue Damage Modeling

Material damage is actually an irreversible energy dissipation process. Thus, a damage evolutionary equation, which is deduced based on the internal variable orthogonal flow rule, is adopted. That is:

$$D = \partial \psi^* = \frac{1}{m+1} A Y^{m+1} / \partial Y \qquad (1)$$

Where Ψ^* is the dissipative potential of Helmholtz free energy, and Y is the damage energy dissipation rate. The value of Ψ^* determines the damage evolution model, therefore by adopting the power function of Y, the attenuation form of Ψ^* can be determined as :

$$\psi^* = \frac{1}{m+1} A Y^{m+1} \qquad (2)$$

The undetermined parameters A and m are obtained though fatigue tests of material or components. Where A is the characteristic parameter to measure material damage, and m is the shape parameter reflecting the rate of free energy dissipative potential attenuation. By substituting (2) into (1), we obtain:

$$D = \partial \psi / \partial Y = A Y^m \qquad (3)$$

Since the internal cause of structural damage is material property and the external cause is fatigue stress amplitude $\Delta \bar{\sigma}$ [6], the material(or components) damage evolutionary model is established by adopting Paris formula(Equation (4)), and the model is expressed as (5).

$$da / dN = C(\Delta K)^m \qquad (4)$$

$$D = 1 - (1 - N / N_f)^{\frac{1}{m+1}} \qquad (5)$$

Where C and m are material constants, a is the crack length and N is the fatigue life span. Equation(5) can be simplified as Miner fatigue cumulative equation when $m=0$.

B. Damage Evaluation Model Based on Ductility

The ratio of stiffness degradation value ΔK to original stiffness K is adopted to measure the degree of degradation and damage on structural deformation[8], given as:

$$\omega_K = \frac{\Delta K}{K_0} = 1 - \frac{K_R}{K_0} \tag{6}$$

In other words, the damage degree of structure or components can be regarded as a difference between 1 and the ratio of the residual stiffness K_R to the initial stiffness K_0.The yield stiffness K_y, yield displacement Δ_y and the limit displacement Δ_u are obtained though test. The expression of the stiffness degradation value ΔK is determined using Clough two-line degenerate model, which is:

$$\Delta K = K_y \left(\frac{\Delta_y}{\Delta_u} \right)^{\gamma} \tag{7}$$

The unloading stiffness coefficient γ is determined as:

$$\gamma = \lg \left(\frac{\Delta K}{K_y} - \frac{\Delta_y}{\Delta_u} \right) \tag{8}$$

The ratio of Δ_u to Δ_y is determined as ductility ratio, thus (8) can be rewritten as:

$$\gamma = \lg \left(\frac{\Delta K}{K_y} - \frac{1}{\mu} \right) \tag{9}$$

Obviously, the degradation value ΔK can be calculated by substituting γ into (7), then the stiffness damage degree ω_K is derived by substituting aforementioned ΔK into (6). Thus, the stiffness damage degree ω_i of certain cycle i under reversible loading can be derived through (6), and the stiffness damage degree under n cyclic loading can be expressed as:

$$\omega = \sum_{i=1}^{n} \omega_i = \sum_{i=1}^{n} \frac{\Delta K_i}{K_0} \tag{10}$$

C. Damage Evaluation Model Based on Bearing Capacity

When the bearing capacity of structure or components is undertaken as a measure of damage degree, as the initial bearing capacity and residual bearing capacity are determined as P_0 and P_R respectively, the degradation model is:

$$\omega = 1 - \frac{P}{P_0} \tag{11}$$

D. Coupling Modelling

It is vital to establish the variation law of the damage degree ω with the erosion damage t or the fatigue damage d calculated by (10) and (11), and the influence of the two damage conditions is a crucial issue. If θ is assumed to be the coupling factor which measures the interaction between corrosion and fatigue and promotes each other, then the coupling damage formula of the two kinds of damage is:

$$\begin{aligned} P(t,d) &= P_0\left(1-\omega(t,d)\right) \\ &= P_0\left(1-\omega(t)\right)\left(1-\omega(d)\right) \\ &= P_0\left(1-\omega(t)-\omega(d)-\theta(t,d)\,\omega(t)\,\omega(d)\right) \\ &\Rightarrow \omega(t,d) = \omega(t)+\omega(d)+\theta\omega(t)\,\omega(d) \end{aligned} \tag{12}$$

The coupling factor of two kinds of damage can be calculated through (12) as:

$$\theta = \frac{\omega(t,d) - \omega(t) - \omega(d)}{\omega(t)\,\omega(d)} \tag{13}$$

Therefore, the expression of coupling factors under various damage d_i(i=1,2,…,n), is determined as:

$$\theta = \frac{\omega(d_1,d_2,...,d_n) - \sum_{i=1}^{n} \omega(d_i)}{\prod_{i=1}^{n} \omega(d_i)} \tag{14}$$

The coupling factor θ of (14) can effectively measure the effects of multiple damage interactions and mutual coupling. When $\theta=0$, it indicates that all kinds of damage are mutually independent, and the total damage of the components or structure under the combined effect of multiple damage is equal to the sum of the damage caused by the component or the structure separately; When $\theta<0$, it shows that each kind of damage are mutually restraint with each other, and the total damage of the components or structure under the combined effect of multiple damage is less than the sum of the damage caused by the component or the structure separately; When $\theta>0$, it indicates that mutually promotion and intercoupling are among all kinds of damage, and the total damage of the components or structure under the combined effect of multiple damage is more than the sum of the damage caused by the component or the structure separately.

III. TEST OVERVIEW

In this test, the MTS electro-hydraulic servo loading system is used to conduct a low frequency cyclic test on Q345 angle steel components, as shown in Fig.1 and Fig.2. The specimens are corroded by M corrosion method, then fatigue vibration is conducted after corrosion, and test conditions are shown in Table.1. At last, the quasi-static test is carried out by using the

loading system shown in figure 3.

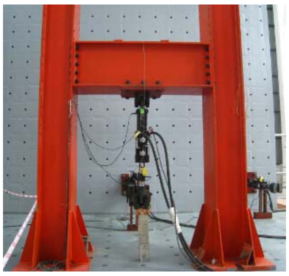


FIGURE I. THE MTS COMPUTER-ACTUATOR ON-LINE SYSTEM

FIGURE II. SPECIMENS OF Q345 ANGLE STEEL

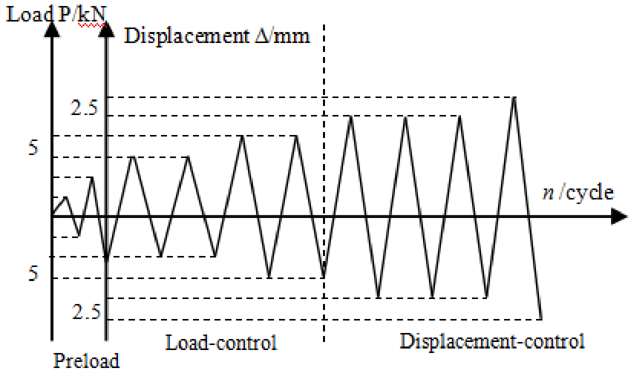


FIGURE III. THE P-Δ DOUBLE CONTROLSYSTEM

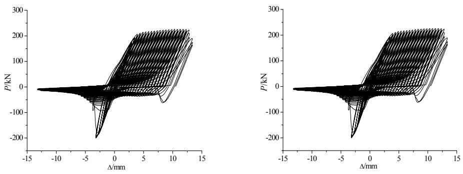
TABLE I. TEST CONDITIONS

Test category	Specimen serial number	Corrosion-fatigue test conditions				Specimen number	Quasi-static test
		Corrosion model		*Fatigue vibration*			
		M	***ti/h***	***Smax/MPa***	***N/ cycle***		
None-damage	L	-	-	-	-	2	√
corrosion	CL-1	M	12	-	-	2	√
	CL-2	M	24	-	-	2	√
	CL-3	M	36	-	-	2	√
fatigue	LF-1	-	-	177.96	4.0×10^4	2	√
	LF-2	-	-	177.96	2.5×10^4	2	√
	LF-3	-	-	177.96	1.0×10^4	2	√
Corrosion-fatigue	CLF-1	M	12	177.96	4.0×10^4	2	√
	CLF-2	M	12	177.96	2.5×10^4	2	√
	CLF-3	M	12	177.96	1.0×10^4	2	√

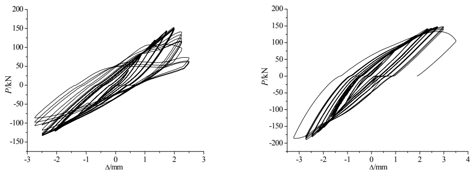
IV. TEST RESULTS

A. Hysteretic Behavior

The hysteretic curves of specimens under different test conditions are shown in Fig.4. From the figures presented, significant differences can be observed in the variation trend of curves in each group. The plasticity of specimens decreased under corrosion-fatigue damage, and the enveloping area of the hysteresis loop, the ultimate tensile and compressive load, ductility and cumulative energy dissipation decreased as the cycle number reduced.



(a) L (a) C L



(a) LF (a) CLF

FIGURE IV. EFFECTS OF TEST CONDITIONS ON HYSTERETIC CURVES

B. Bearing Capacity

The yield load *Py*, forward (tensile) ultimate bearing capacity *Pt*, negative (compressive)ultimate capacity *Pc*, and corresponding ratios and differences of the test are shown in Table.3. Compared with the parameters of non-damaged specimen, the reduction value *ΔP* and the degradation percentage *ω* of the bearing capacity under various working conditions are shown in Table 2.

TABLE II. BEARING CAPACITY OF Q345 EQUAL-ANGLES WITH DIFFERENT DAMAGE

Test conditions	P_y(kN)	P_t(kN)	P_c(kN)	Δ P_y/kN)	Δ P_t/kN	Δ P_c/kN	ω_y	ω_t	ω_c
L	212.746	228.130	201.662	-	-	-	-	-	-
CL1	188.340	199.772	192.457	24.406	28.358	9.205	0.1147	0.1243	0.0456
CL2	184.981	195.273	179.078	27.765	32.857	22.584	01305	0.1440	0.1119
CL3	179.628	190.923	173.088	33.118	37.207	28.574	0.1556	0.1631	0.1417
FL1	135.968	143.333	163.552	76.778	84.797	38.11	0.3609	0.3717	0.1890
FL2	174.428	193.960	191.320	38.318	34.170	10.342	0.1801	0.1498	0.0513
FL3	205.625	213.295	202.795	7.121	14.835	-1.133	0.0335	0.0650	-0.0056
CFL1	111.218	126.722	177.910	101.528	101.408	23.752	0.477	0.445	0.1178
CFL2	151.104	177.002	184.381	61.642	51.128	17.281	0.2897	0.2241	0.0857
CFL3	177.340	197.272	190.708	35.406	30.858	10.954	0.1664	0.1353	0.0543

The bearing capacity degenerated with the decease of the net sectional area of specimens, and the tensile and compressive capacity of the specimens decreased by 16.31% and 13.61% respectively when corrosion time reach to 36h. Meanwhile, the yield load was also reduced by 15.57%. The yield load and the maximum tensile and compressive capacity have changed significantly under fatigue damage condition. When fatigue damage d increased from 0.167 to 0.669, the yield load and the maximum tensile and compression capacity were reduced by 32.74%, 30.67% and 19.46%; The degradation of bearing capacity is more obvious when fatigue damage increased, whereas the degradation speed of P_c decreased when the ratio of P_c to P_y increased.

According to the bearing capacity variation rule of specimens in corrosion group and fatigue group, the degradation model of damage degree ω with corrosion time t and fatigue damage d is established as:

$$\omega_y(t,d) = 0.19403e^{\frac{t}{49.591}} + 0.21229e^{\frac{d}{0.65275}} - 0.39463 + \theta_y\left(0.04119e^{\frac{t}{49.591}+\frac{d}{0.65275}} - 0.04467e^{\frac{t}{49.591}} - 0.0349e^{\frac{N}{0.65275}} + 0.03785\right) \quad (15a)$$

$$\omega_t(t,d) = 0.35639e^{\frac{t}{72.182}} + 0.09035e^{\frac{d}{0.41773}} - 0.43411 + \theta_t\left(0.036858e^{\frac{t}{72.182}+\frac{d}{0.41773}} - 0.03395e^{\frac{t}{72.182}} - 0.035044e^{\frac{d}{0.41773}} + 0.032279\right) \quad (15b)$$

$$\omega_c(t,d) = 0.13354e^{\frac{t}{54.587}} + 0.00296e^{\frac{d}{0.16168}} - 0.16238 + \frac{\theta_c}{10000}\left(5.21e^{\frac{t}{54.587}+\frac{d}{0.16168}} - 38.55e^{\frac{t}{54.587}} - 5.21e^{\frac{d}{0.16168}} + 38.55\right) \quad (15c)$$

The coupling factor θ is derived by substituting the trial value into (15), as shown in Table.3. And the degradation model of specimens under corrosion-fatigue coupling effect can be determined by substituting θ into (15). The curve of ω varies with d and the surface of ω varies with t and d when t=12h are shown in Fig.5. Each surface proves that the degradation degree of bearing capacity increases with the damage multiplying under coupling effect.

TABLE III. THE COUPLING FACTOR OF BEARING CAPACITY

θ_y	θ_t	θ_c
0.196	1.243	11.978
0.248	3.004	38.138
0.474	7.391	29.705

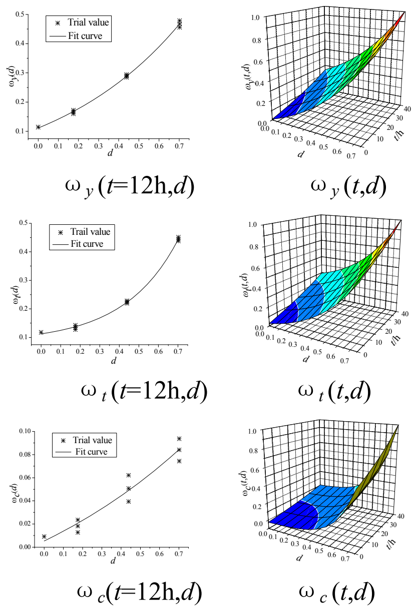


FIGURE V. THE VARIATION OF BEARING CAPACITY WITH THE CORROSION-FATIGUE COUPLING EFFECT

V. CONCLUSION

In this paper, the coupling factor is proposed, which is able to measure the mutual promotion, coupling and accelerating damage of corrosion and fatigue. Meanwhile, a coupling model to measure the degradation of components is established. The effects of three kinds of damage on the failure model of the components are observed through the test, and the variation rule of damages on main evaluating parameters of seismic behavior of components is analyzed. The results show that: 1) The interaction of corrosion and fatigue promotes and

accelerates the damage development of members, whereas this effect is not taken into account in existing formulas. 2) Coupling damage significantly reduces the number of reciprocating loads and the area of hysteresis loop. Likewise, the amplitude of stiffness degradation, ductility and energy dissipation decreases. 3) The degradation rate of cumulative energy dissipation parameters and ductility under coupling is much larger than that under the same corrosion and fatigue alone.

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