Comparison between theoretical value and measured value of cracking time of rust expansion

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Abstract. The cracks of structures are caused by various reasons. Corrosion cracking of concrete cover caused by steel-bar corrosion is very serious and it is also an important sign of durability limit state of concrete structure. In this paper, by means of acoustic emission, a graph of the cumulative impact change was obtained to determine the cracking time, which was compared with the theoretical formula. In addition, the correction factor *k* will be discussed.

1. Introduction
Due to the corrosion expansion of steel bar and cracking of concrete surface, a series of qualitative changes are produced in concrete, which can threat to the building and human health. Therefore, it is important to monitor the cracking time of concrete. Acoustic emission (AE) technique had an extensive application in the healthy monitor aspect as a kind of dynamic of nondestructive testing. The cracking time of the experiment can be determined by studying the characteristic points in the curve of the change of cumulative impact number of acoustic emission. The feature point existed before the macroscopic fracture, which can be regarded as the feature point of the appearance of cracks. The time of this feature point is extracted to verify the validity of the modified formula. In this paper, the experimental value measured by acoustic emission is compared with the theoretical value obtained by the formula, so as to optimize the correction coefficient *k*.

2. The theoretical formula of the corrosion cracking time of concrete cover

2.1. Not considering the corrosion products into the crack
When the corrosion products entering into the rust expansion crack are not considered, the prediction formula of corrosion time t1 (h) corresponding to complete cracking of concrete protective layer is as follows:

$$t_1 = 234762 \times \frac{d\left\{\left(0.3+0.6\frac{c}{d}\right)\frac{f_{tk}}{E_{cef}}\left[\frac{(r_0+c)^2+r_0^2}{(r_0+c)^2-r_0^2}+v_c\right]+1+\frac{2\delta_0}{d}\right\}^2}{(n-1)i_{corr}} - d \tag{1}$$

where, r_0 =d/2+ δ_0 , d is the original diameter, i_{corr} is the corrosion current density, δ_0 is the thickness of the gap between concrete and steel bar, c is the thickness of concrete cover, E_{cef} is the effective elastic modulus of concrete.

2.2. Considering the corrosion products into the crack

The corrosion time of steel bar is positively proportional to the corrosion rate, so the formula of corrosion time t2 (h) of this stage is as follows:

$$t_2 = k\frac{c}{d}t_1 \tag{2}$$

Where, k is correction factor, k=0.15~0.3; c is the thickness of concrete cover.

2.3. Theoretical formula of cracking time of concrete rust expansion

The theoretical formula of rust-induced corrosion cracking time of concrete protective layer is as follows:

$$\begin{aligned} t_{cr} &= t_1 + t_2 = \left(1 + k\cdot\frac{c}{d}\right)t_1 \\ &= 234762(d+kc)\times\frac{\left\{\left[0.3+0.6\frac{c}{d}\right]\frac{f_{tk}}{E_{cef}}\left[\frac{(r_0+c)^2+r_0^2}{(r_0+c)^2-r_0^2}+v_c\right]+1+\frac{2\delta_0}{d}\right\}^2}{(n-1)i_{corr}} - 1 \end{aligned} \tag{3}$$

3. Comparison between theoretical and measured values

The theoretical value and measured value are compared by using thickness of protective layer which is 30mm, 40mm and 50mm. The concrete with strength grade of 30 was selected, and the test block sizes were 70*70*300, 90*90*300 and 110*110*300 respectively. Steel with 10mm diameter was embedded in each test block. The block was placed in a saline solution (5%) and then the wires were connected to a current with a power density of 170μA/cm^2. Figure.1 shows the schematic diagram of using acoustic emission system for detection.

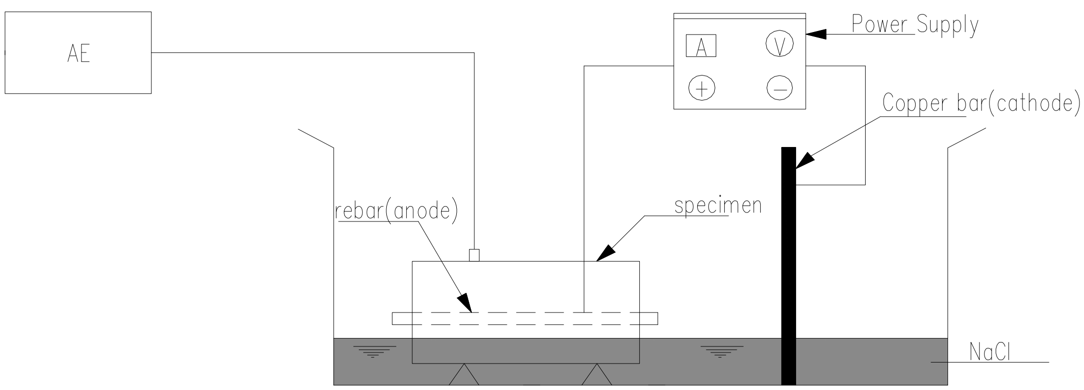

Figure 1. A schematic diagram of acoustic emission monitoring system

IOP Conf. Series: Materials Science and Engineering **452** (2018) 022023 doi:10.1088/1757-899X/452/2/022023

The relevant parameters are follows: Ecef=30GPa, ftk=1.43MPa, d=20mm, n=2, vc=0.2, δ0 =0.2um. Then k=0.15, 0.2, 0.25 and 0.3 were respectively added into formula 3) to calculate the cracking time of reinforced concrete. Using a feature point in the curve of the cumulative impact number of acoustic emission before the occurrence of macroscopic cracks can verify the validity of the formula. Fig 2 shows the graph of cumulative impact number of acoustic emission with different thickness of protective layer. And fig 3 shows the theoretical and experimental corrosion cracking time.

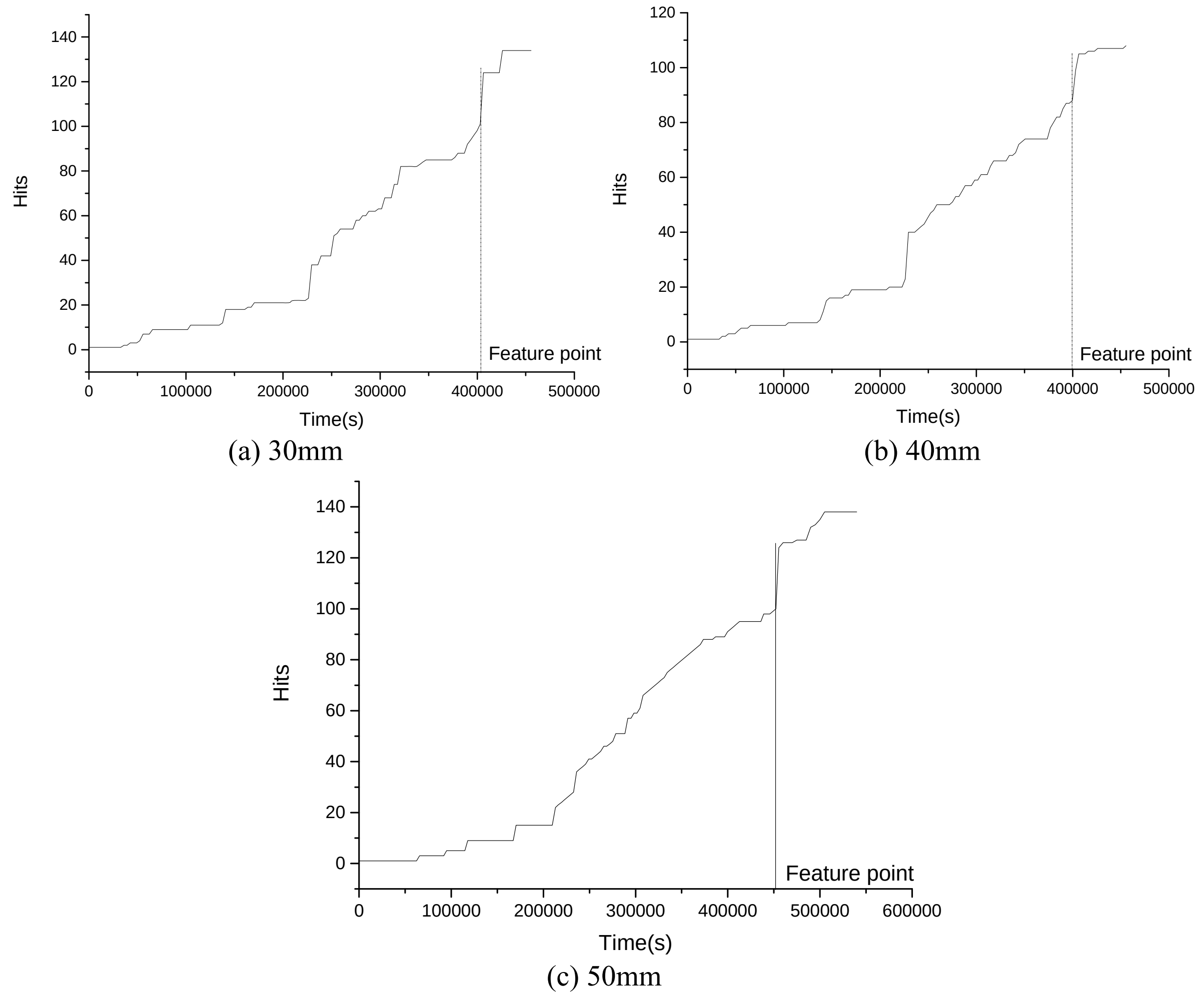

Figure 2. Corrosion cracking time of concrete protective layer

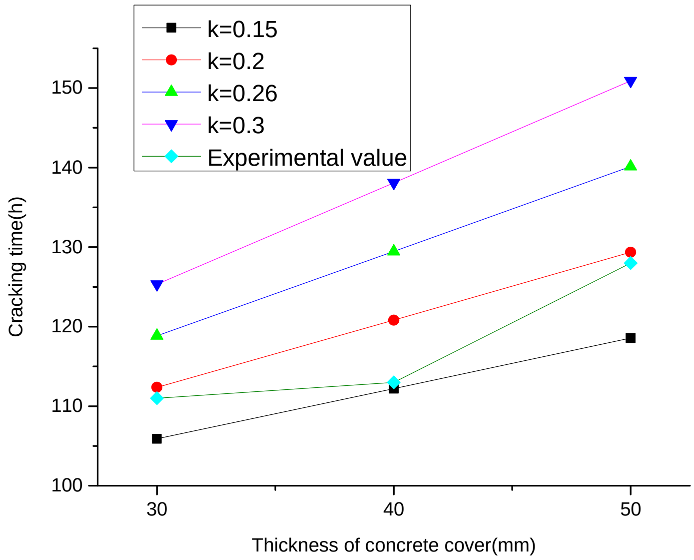

Figure 3. Theoretical and experimental corrosion cracking time

Table 1. Comparison of theoretical and experimental corrosion cracking time

Thickness of concrete cover (mm)	Feature points (h)	Theoretical values (h)							
		k=0.15	error	k=0.2	error	k=0.25	error	k=0.3	error
30	111	106	4.6%	112	1.2%	119	7.1%	125	12.9%
40	113	112	0.7%	121	6.9%	129	14.5%	138	22.2%
50	128	119	7.3%	129	1.0%	140	9.5%	151	17.9%

Both theoretical and measured values show that when the thickness of concrete cover increases from 30mm to 50mm, the cracking time of concrete 'tcr' increases rapidly. The main reason is that the increase of the thickness of the concrete cover will lead to the increase of t1, and the filling time of the corrosion products into the rust expansion crack will be prolonged by t2. The correction factor k in the theoretical formula has certain influence on the simulated cracking time. As can be seen from figure 3.3, when the thickness of the protective layer is the same, the simulated cracking time is also different due to the difference in k value. The experimental results show that when k is between 0.15 and 0.2, the experimental cracking time is in good agreement with the simulated cracking time. Table 3.1 shows that when k=0.2, the error between the two is within 10%. Although the error of k = 0.15 is the lowest when the thickness of concrete cover is 40mm, but the error of k = 0.2 is 6.9%, within the tolerance range of error. Therefore k should be between 0.15 and 0.2, so as to minimize the error.

4. Conclusion

The corrosion depth of steel bar can be divided into two parts when the concrete cracks completely. The calculation formula of the corrosion cracking time of concrete cover is based on the uniform corrosion of steel bar, and it is obtained by using Faraday's corrosion law and elastic theory. In this paper, the modified coefficient k is introduced and the formula is optimized. By studying the different thickness of protective layer of the cumulative impact of change curve and the corresponding relation between the corrosive cracking times of formula, when k is between 0.15 to 0.2, between errors within 10%, it can be seen that both have good corresponding relation.

Acknowledgments

The investigation presented in this paper was supported by National Natural Science Foundation of China (5167082451) and Key R & D project of Shangdong Province (2017GGX90107).

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