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Fatigue life assessment of steel structures of gantry crane

Non-destructive testing, finite element analysis and experimental stress analysis were integrated into fatigue life assessment of steel structures of rubber-tire-container gantry crane in this paper. Ultrasonic testing (UT) was adopted to test thickness of steel structures which could evaluate structural corrosion; based on measured dimensions of every components 3D finite element model was built to execute strength and stiffness analysis, where load spectrum of dangerous positions were extracted in a whole working cycle; wireless dynamic resistance strain gauges were applied to test the structural stress, and then the FEA model was improved by comparison with tested results. Finally, based on cumulative damage theory, Miner rules was adopted to calculate total damage, and fatigue life of steel structures was predicted.

Keywords: *Gantry cranes, fatigue life assessment, Ultrasonic test,finite element analysis,experimental stress analysis*

1. INTRODUCTION

Gantry crane was a typical material handling equipment, used in ports, docks and other logistics fields. Rubber-tire-container gantry crane was a primary type of gantry crane. They usually subjected to large external loads and worked in bad environment such as wind, snow, rain and corrosion of seawater which resulted in degradation of material properties. Structural fatigue would appear when this degradation accumulated to a critical level, and it could lead to various accidents which resulted in loss of economics or peoples lives. Therefore, fatigue life assessment played a significant role in application of gantry cranes, and this direction attracted more and more interest in current researches.

Fatigue life assessment could be divided into two fields, one is based on cumulative fatigue damage theory, the other is based on fatigue crack propagation theory[1]. Furthermore, cumulative fatigue damage theory could be divided into stress-based approach[2-3], strain-based approach[4-5], energy-based approach[6-7] and continuum damage mechanics approaches[8-9] according to different formulas of macroscopic quantities. Fatigue crack propagation theory could be divided into three method, long crack growth was based on linear elastic fracture mechanics[10], physically small crack growth was based on elastic plastic fracture mechanics[11], and microstructurally small crack growth was based on microstructural fracture mechanics[12]. However, there were few researches related to fatigue life of gantry cranes. Bing[13] introduced finite element model of steel structures of railroad container gantry crane, and lifetime fatigue analysis of steel structures and welds was adopted to using MSC Fatigue software, so that life distribution of the entire structure and fatigue life of dangerous position were approached. Zhang[14]introduced finite element model of gantry crane, and fatigue life based on crack propagation theory was approached by Paris formulus. Li[15] analyzed the causes, common types and hazards to structural corrosion and wear of gantry crane, and safety assessment system was developed based on fuzzy analytical hierarchy process. Zrnic[16] discussed a combined finite element and analytical method for obtaining transverse and longitudinal vibrations of a gantry crane system subjected to an elastically suspended moving body, and the two-dimensional inertial effects of the moving body are included in derivation of differential equation of motion for the system.

Although there were some great progresses in the literature, practical load spectrum and numerical analysis should be improved deeply. A systematic method was proposed to fatigue life assessment of gantry cranes.

2. Corrosion test

Ultrasonic test applied ultrasonic probes exciting pulse wave of high voltage, and these pulse waves reflected by media surface and received by sensors. These received signals were counted by microcontroller, and the values of thickness would be displayed. The principle was that the thickness was equal to the velocity of ultrasonic wave propagating in the steel structures multiply a half of time of propagation. Since it was dominant in portability and efficiency, ultrasonic test had been used widely in corrosion test of cranes.

Corrosion of steel primarily resulted in reduction of thickness and deterioration of material. The reduction of thickness could influence strength and fatigue life of steel structures. In corrosion test, the positions were located in accordance with stress tests, as shown in figure 1. The results of corrosion tests were listed in table 1.

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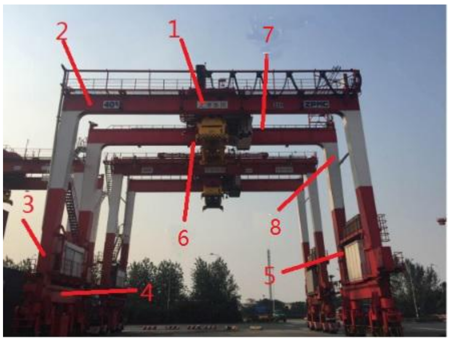

Fig.1 Gantry crane and tested points.

Table 1 results of corrosion tests

number	Tested point	thickness（mm）
1	1#	14.3
2	2#	14.8
3	3#	10.4
4	4#	8.6
5	5#	10.7
6	6#	14.5
7	7#	8.7
8	8#	10.2

3. finite element analysis

Steel structures of rubber-tire-container gantry crane were composed of many box beams, such as bottom crossbeams, legs, girders etc. This crane was designed into symmetric structures for its stability.The rated load of this crane was 40t. According to Timoshenko theory of elastic mechanics, it was the most dangerous working case when the truck was located at the middle of girders, i.e. it was the case of maximum stress.

Based on drawings and results of corrosion tests, 3D model of this crane was built by Pro/engineer, and then imported into commercial finite element software ANSYS. After rational boundary conditions were imposed, static analysis was performed. Since gravity of the steel structure was an important load, it should be referred. In this paper gravity was considered by imposing acceleration. The 3D finite element model was shown in figure 2.

For the symmetry of steel structure, two cases were executed in finite element analysis. The first case was that the rated loads were imposed on the left end of girders, and the analysis result was illustrated in figure 3, The second case was that the rated loads were imposed at the middle of girders, and the analysis result was illustrated in figure 4.

As shown in figure 3, the maximum stress of steel structure under the first case was 72.4MPa, and the maximum deflection was 4.19mm. As shown in figure 4, the maximum stress of steel structure under the second case was 102MPa, and the maximum deflection was 14.24mm.

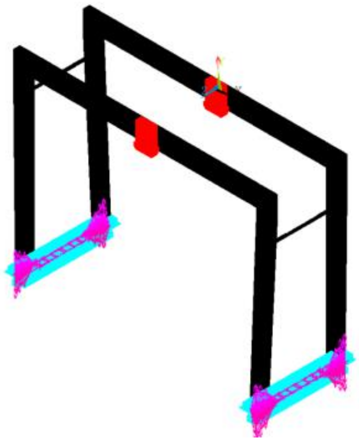

Fig.2 Three-dimensional FEA model.

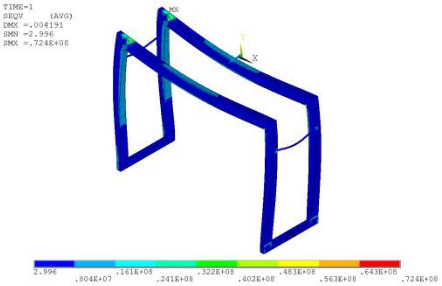

Fig.3 Stress contour of case 1

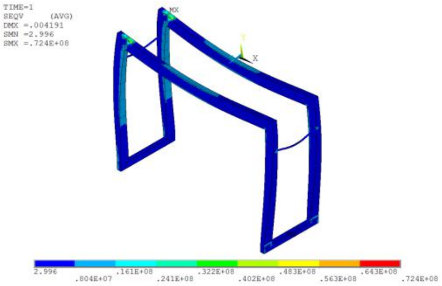

Fig.4 Stress contour of case 2

4. experimental stress analysis

Wireless dynamic resistance strain gauges were adopted to test the stress of dangerous positions, which could not only achieve the peak value of stress under a certain case, but approach the load spectrum in a whole working cycle. Since resistance strain gauges could not approach the stress resulted from gravity of steel structures, analytic calculation was applied and these two parts were superpositioned together to achieve the total stress.

Two of the tested points were illustrated in figure 5 and figure 6. As an example, the tested results of point 1 were listed in table 2.

In order to verify the precision of finite element analysis, the results of finite element analysis were compared with the results of stress tests, as listed in table 3.

Table 2 stress of point 1 in two cases

Point 1	First case	Second case
Maximum stress without gravity (MPa)	11.2	45.5
Stress only with gravity（MPa）	49.4	49.4
The total stress（MPa）	60.6	94.9

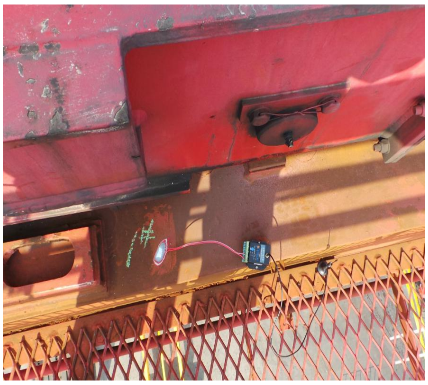

Fig. 5. Stress tested point 1 and sensor

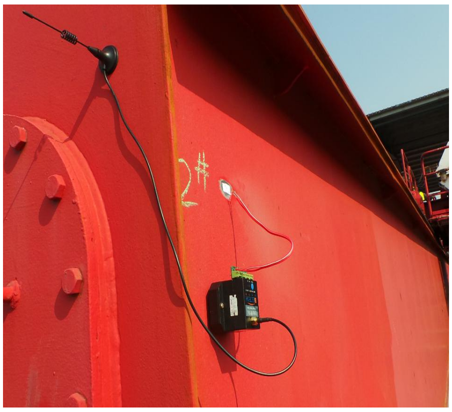

Fig. 6. Stress tested point 2 and sensor

As shown in table 3, the tolerance between FEA and tests was very small. Considering the systematic tolerance of equipment, and stochastic errors resulted from some factors out of control, this tolerance was in allowed range. Consequently, this finite element model was precise,and the results were reliable, which showed a great potential used in safety assessment of gantry cranes.

Table 3 tolerance analysis between FEA and tests

term	FEA(MPa)	Stress test(MPa)	Tolerance (%)
Maximum equivalent stress	102	94.9	6.9

5. fatigue life analysis

Stress-time history of tested points should be preprocessed before fatigue life prediction. The process included compression of equivalent point, extraction of peak and valley values, and elimination of invalid values which threshold was 5% of the substraction between peak value and valley value. Then rainflow counting method was adopted to count the amplitude, mean stress and number of cycles. Finally, Goodman rules were adopted to execute zero mean modification so that the statistics of stress data was accomplished.

The elastic modulus of material of this crane was 210GPa, and its tensile strength was 490MPa, and yield strength was 345MPa. Statistical results indicated the p-S-N curve of this material complied with empirical formula (1) in the log-log coordinate.

$$\lg N_p = a_p + b_p \lg S_{p\max} \tag{1}$$

Where N_p was the fatigue life when survival rate was equal to p， a_p、 b_p was respectively material constant; $S_{p\max}$ was the maximum stress related to N_p and p. From crane handbook, it stated that a_p=31.9285, b_p = -10.51, when the stress ratio was -1 and survival rate was 95%. Consequently, the empirical formula was transformed to (2).

$$\lg N_p = 31.9285 - 10.5100 \lg S_{p\max} \tag{2}$$

According to load spectrum of tested points, the maximum amplitude occured at the first point, which was the most dangerous point and would appear fatigue firstly. Therefore, the first point was taken as the calculated point for fatigue life. Based on formula (2),cycles of fatigue could be approached, as listed in table 4.

Table 4 statistical data of fatigue life of first point

stress（MPa）	Cycles of a year/ni	Cycles of fatigue/Ni	Damage degree/Di
15.04	1.85E+07	1.60E+15	1.16E-08
25.17	1.21E+07	7.11E+12	1.69E-06
35.31	5.05E+06	2.03E+11	2.49E-05
45.44	6.10E+06	1.43E+10	4.26E-04
55.58	3.85E+06	1.72E+09	2.23E-03
64.02	3.10E+06	3.90E+08	7.95E-03
70.78	1.90E+06	1.36E+08	1.80E-02
74.16	1.17E+06	5.2E+07	2.35E-02

Based on Miner rules, the total damage could be computed as following:

$$D = \sum_{i=1}^{i=n} D_i = 4.16E - 02 \tag{3}$$

Therefore, the fatigue life of this crane could be calculated as:

N=1/D=24.04。

According to the usage records, this crane had been serviced for about 17.6 years. So the residual life was 6.44 years based on the above deduction.

6. conclusion

A new fatigue life analysis method was proposed in this paper, and it was applied in the safety assessment of steel structures of rubber-tire-container gantry crane. The analysis results indicated that this method could precisely inspect corrosion, verify strength and stiffness, extract load spectrum, and then predict the residual life of steel structures. This investigation established a good theoretical basis for virtual simulation of large engineering machines.

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