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The Fatigue Behavior Study of Intelligent Tower Crane by Finite Element Theory

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Abstract

Intelligent tower crane has large structure deadweight. The service life of the whole machine is dependent on the life of the structure. As a result, the metal structure should be designed by using correct and reasonable methods to obtain excellent fatigue properties. And it can guide the design, manufacturing, use and maintenance process for crane. And it has great significance to prevent the fatigue fracture accident. The theoretical mechanics and material mechanics theory is a semi-theoretical semi-empirical traditional design method, but it is not the suitable design method. Now, the finite element method, fracture mechanics, the boundary element method, the optimization design method, reliability design and fatigue design methods are widely used in the structure design of crane. In this paper, the intelligent tower crane structure is analyzed by finite element modeling. According to the actual situation, crane structure is studied by finite element statics analysis. Then mechanical property of this kind of structure is analyzed in detail. And the weak links of the structure are found out. The residual life can be estimated finally. As a result, designers can comprehensively understand the fatigue life distribution of different parts in the crane. Therefore, they can provide intuitive and comprehensive basis for comparing the advantages and disadvantages of different design schemes and fatigue performances for design improvement.

Keywords: *Tower Structure, Tower Crane, Fatigue Life, S-N Curve, Dynamic Simulatio, Finite Element Analysis*

1. Introduction

Crane is one of the special equipment prescribed by the country. Therefore, its safety has always been paid highly attention. Because cranes are typical welding structure, they have defects such as porosity, slag inclusion, incomplete fusion. These defects will gradually expand under the action of load after many cycles. Then it will lead to structural fatigue fracture failure. Cranes are mostly used in coal industry, power industry, transportation, industrial raw materials and machinery manufacturing industry [1]. The safety life of the cranes depends on their fatigue strength of metal structure.

From the beginning of the 70's, the design of simple structure, easy to calculate and to reduce the cost of development, the relatively simple structure of tower crane trolley jib tower crane -- head instead of the tower crane boom in the construction market, along with the time development calculation, people found, structure belongs to the calculation of tower type crane computational complexity, which urgently requires a simpler structure, more convenient for calculation of tower crane.

The construction of industrial plants, national landmarks (Olympic Stadium), the symbol of the city building, residential building floor, large ships berthing port construction, with world-class large bridge state nuclear power construction, the wind turbine installation, construction of cooling tower thermal power plants and large water construction and hydraulic power unit lifting equipment and so on, these

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construction are used in the jib tower crane jib tower crane, and also play an irreplaceable role, compared to other lifting equipment, because of its rapid installation and low cost and be the most respected tower construction units, after installation can be long-term use, especially long-term projects, such as residential buildings, large chain construction, port construction and the construction of sports venues and so on, can save a large rental expenses, compared with inconvenient installation crawler cranes, truck crane is expensive, more expensive car hanging all terrain crane, tower crane cost to make the most of construction units are satisfied, especially some of the projects, other lifting devices are not appropriate [2].

Crane life is composed of the design life, economic life, technical life, plan (depreciation) life, natural life and reliable life, etc. Among these, natural life refers to the life of gantry crane which can't be used anymore due to physical abrasion such as fatigue, corrosion, deformation and wear, etc. It is the practical life of crane. It is also the main theoretical basis for a crane in service to ensure the safety and service life.

The main failure form of crane is fatigue damage under random loading. According to the report "general principle of metal fatigue test" published by the international standardization organization (ISO) in 1964, fatigue is defined as the performance changes of metal materials under the action of repeated stress or strain [3]. Fatigue failure is composed of three stages: crack formation, crack propagation and instantaneous fracture. As a result, fatigue life includes crack initiation life and crack propagation life. So it is very different to evaluate the fatigue life of crane.

This paper reviewed the four kinds of fatigue cumulative damage theory, the basic principle and data processing on the basis of analysis, and four kinds of theories in the status and role of different stages of development, analysis of the possibility of their use in engineering practice and the accuracy, advantages and disadvantages and compare them in the engineering application, a the most consistent with the theory of fatigue calculation of fatigue cumulative damage theory. Using ANSYS finite element model establishment of tower body, due to the dynamic simulation, load time history curve and the data can only view node, so use beam element BEAM188 modeling, although simple, but can only view chord truss joint, which is the point of load time history curve and data, load cannot view tower string the ventral rod position this region of the node in the cluster a time history curves and data; considering the above reasons, this paper using shell element SHELL63 to create the model of the tower body, completely simulate the actual string truss joint position of dry conditions, then load and calculation.

2. Fatigue Analysis Method

2.1. Fatigue Classification

Fatigue can be studied from different directions, according to the different direction can be classified in the following on the fatigue [4]. The fatigue types according to different conditions were shown in Table 1.

Table 1. The Fatigue Types on the Basis of Different Conditions

Classification basis	Fatigue types
Different research object	Structural fatigue
	Material fatigue
Different cycle index	High cycle fatigue
	Low cycle fatigue
Different stress state	Uniaxial fatigue

	Multi-axial fatigue
Different amplitude and frequency of the load	Constant amplitude fatigue
	Variable amplitude fatigue
Different load condition and working environment	Random fatigue
	Conventional fatigue
	High and low temperature fatigue
	Thermal and mechanical fatigue
	Contact and wear fatigue
	Corrosion and impact fatigue

2.2. Fatigue Analysis Flowchart

Based on the domestic and foreign enterprises in the past design strength, in the probability to reduce duplication of work and product design cost, cycle; ensure the product design stage of uniform stress distribution and the stress concentration point is reasonable planning; anti fatigue ability, increase the reliability of the products and market competitiveness; especially in recent years, fatigue failure probability is increasing, causing trouble to the safety and construction unit staff budget, the fatigue design concept to win support among the people, become one of the most important current international advanced design method. The fatigue life analysis flowchart was shown in Figure 1.

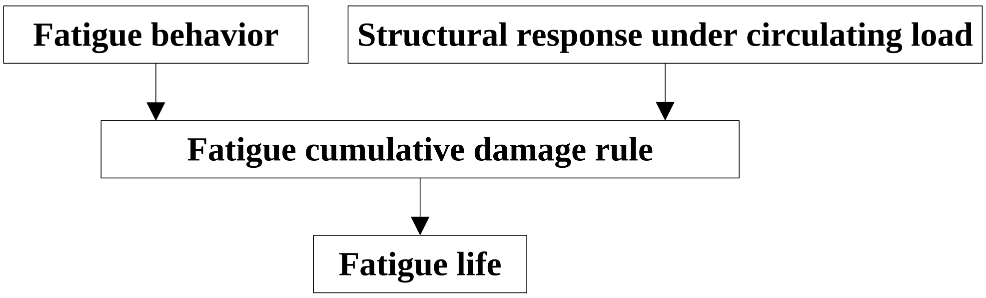

Figure 1. The Life Evaluation of Tower Crane

The finite element software commonly used engineering designer for ANSYS, 3D modeling software for the PRO/E, ADAMS flexible body model of rigid flexible paste machine model of the desired result file can not limit element analysis and 3D results file, so this paper on the dynamic simulation for structure fatigue risk position calculation required and load spectrum [5].

Fatigue analysis process requires three pieces of information: geometric information, load information and material characteristics. The material parameters (such as S-N curve and so on) according to the standards at home and abroad are directly obtained from the experiment, it can be obtained from the material manual or FATIGUE software material database. The fatigue analysis method and general process was shown in Figure 2.

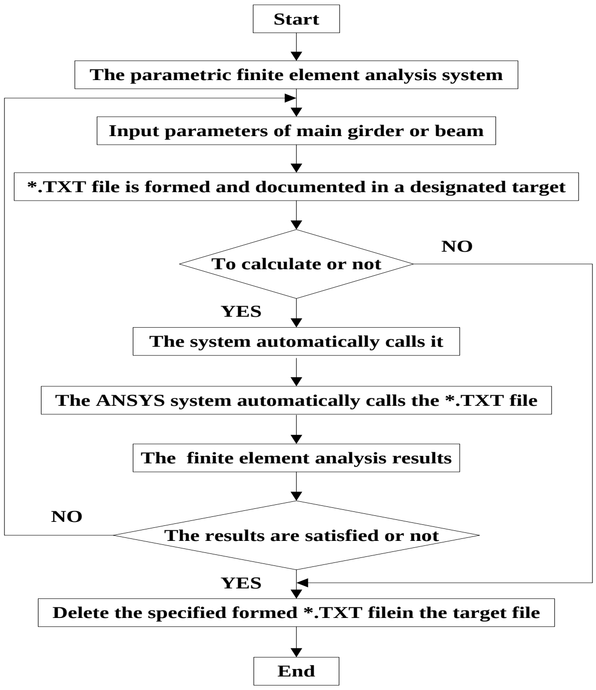

Figure 2. The Flowchart of the Ansys Program

2.3. The Virtual Prototype Model of Tower Crane

The counterweight adjustable 20 balance arm, increase the lifting moment, to play its role; the three is the recently most of the tower crane boom to realize step speed regulation, with 1? Good speed performance, because of the rotary way past, belongs to the multi gear speed, multi gear speed will increase the tower crane rotary inertia braking, is not conducive to the tower crane rotary brake, at the same time, amplitude, if not adopting step speed regulation, easy happening backward, not conducive to the tower crane safety; four is the assembly and disassembly, transportation is convenient and rapid, frequent transfer site requirements [6].

The main design parameters are shown as follows. The arm length combination is 35m; the minimum working range is 7m and the maximum working range is 80m. In addition, the lifting mechanism of single rope speed is 100 m/min, and the luffing mechanism of single rope speed is 75 m/min. The rotary mechanism of rotary speed is 0.8 rmp.

2.4. The Finite Element Modeling Of Tower Body Structure

Because the luffing cable wire rope main axial tension, in the shearing direction load is almost negligible; and because its stiffness is very small, with the tensile direction stiffness ratio is almost zero, so only consider the tensile stiffness [7]. The tensile stiffness calculated by Formula 1.

$$K_t = \frac{(n-1)EA}{l} \tag{1}$$

where K_t is cable stiffness; n is is Cable wire rope segments; and E is referred to as a parameter along the direction of pull modulus five one amplitude cable wire rope, and design of the structure of wire rope cable joint department, here $0.8\text{x}10^{11}$ Pa in the formula; A is section cable wire rope (mm^2); l is the cable length of steel wire rope (mm).

3. Analysis of Vibration Characteristics of Tower Crane

3.1. Basic Theory of Modal Analysis

The tower structure is the most common type of structure of the tower crane, tower structure arrangement of web members are generally the way N fonts, K fonts and X fonts and other types, the same layout also have abdominal rod intersect at one point and the ventral rod does not intersect at one point difference. At present, the crane, the basic realization of the stress design, foreign and other life design work has made great progress. The design should have clear load spectrum, imminent to strengthen work in this area [8]. Especially the tower structure of tower crane is a typical fatigue stress structure, the study on the fatigue life of its domestic are limited. In the traditional linear cumulative damage theory and Miner theory, without considering the influence of loading sequence, that the damage value is equal to 1, parts damaged.

The 2D and 3D ANSYS finite element models were shown in Figure 3.

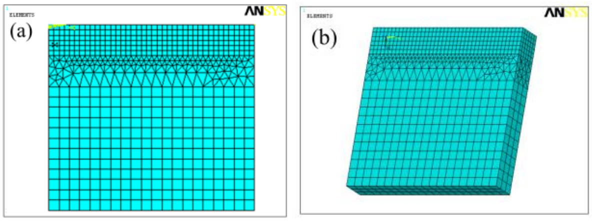

Figure 3. The Ansys Finite Element Model of Steel, (A) 2d Model And (B) 3d Model

3.2. Load Spectrum Analysis

A work cycle including lifting and lifting from the ground, the air speed upgrade, to required position; rotation of 180 degrees to place the lifting position above, and in the original position under heavy loads; hook up to a certain position, turn 180 degrees again to the lifting position. In order to reduce the simulation time of typical working conditions, increase the speed of simulation, the time compression ratio, so that the total time control in the appropriate range, set the simulation step number. In the simulation process, need to use the function in ADAMS software: step (x, x0, h0, Xl, Hl), loading function equation: step (x, x0, h0, Xl, Hl) +step (x, x0, h0, Xl, Hl) + step (x, x0, h0, Xl, Hl).

3.3. The Calculation of S-N Curve

Three stages fatigue damage crack initiation, stable propagation and unstable propagation, to fracture. Basic material S-N curve, the crack initiation life smooth material stress in symmetrical circulation of S-N curve without experimental data, if the fatigue limit of S, and the ultimate strength of materials known, S-N curve can be estimated on the safe side. The mathematical expression of S-N curve is the most commonly used is the double logarithmic linear relationship between the expression of power function type S and N [9]. The test points can be obtained from Table 2.

Table 2. The S-N Test Points

Stress amplitude	Cycle counts
S1	$N_1^{S1}, N_2^{S1}, N_3^{S1}, N_4^{S1}, \cdots N_i^{S1}$
S2	$N_1^{S2}, N_2^{S2}, N_3^{S2}, N_4^{S2}, \cdots N_i^{S2}$

S3	$N_1^{S3}, N_2^{S3}, N_3^{S3}, N_4^{S3}, \cdots N_i^{S3}$
Sn	$N_1^{Sn}, N_2^{Sn}, N_3^{Sn}, N_4^{Sn}, \cdots N_i^{Sn}$

The cycle number less than 103 times the load into consideration, which assumes that the life of N=1, stress equal to the strength limit of.470MPa, the point (470, 1) and (328103) determine a straight line in the double logarithmic coordinates, we can determine the S-N curves of low cycle fatigue region. As shown in Figure 4, the S- S-N curve and modified MATLAB software rendering. Note that the S-N curve of fatigue life prediction, only the stress level in the high cycle fatigue region, predicted to be no higher accuracy. Horizontal stress dangerous tower body parts in this paper were in high cycle fatigue.

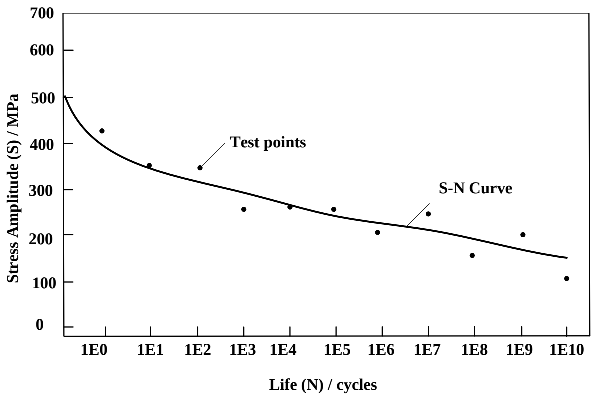

Figure 4. A Typical S-N Curve

4. Experimental Results

4.1. Modal Analysis of Tower Crane

Tower crane (hereinafter referred to as the tower crane) as the key of modern construction lifting equipment, with the increase of high-rise buildings, the load ratio increase, lifting and luffing have dynamic impact on the structure, in the design and analysis of the structure of tower crane, dynamic characteristics has become one of the factors can't be ignored [10]. Therefore, this paper is established based on the finite element model of ANSYS tower crane, from lifting dynamic load and vibration of tower crane structure dynamic analysis on the typical work condition for tower crane structure stress response, vibration modal and transient dynamic structure in different conditions, and the calculation results were load coefficient calculation, dynamic phase should be at the same time, using the ANSYS analysis considering the tower crane has been under static load of structure vibration conditions (prestressed vibration), the natural vibration frequency and vibration frequency under prestressed static loading is compared, the result can offer reference for the design and construction of tower crane. Fatigue analysis process of tower crane was shown in Figure 5.

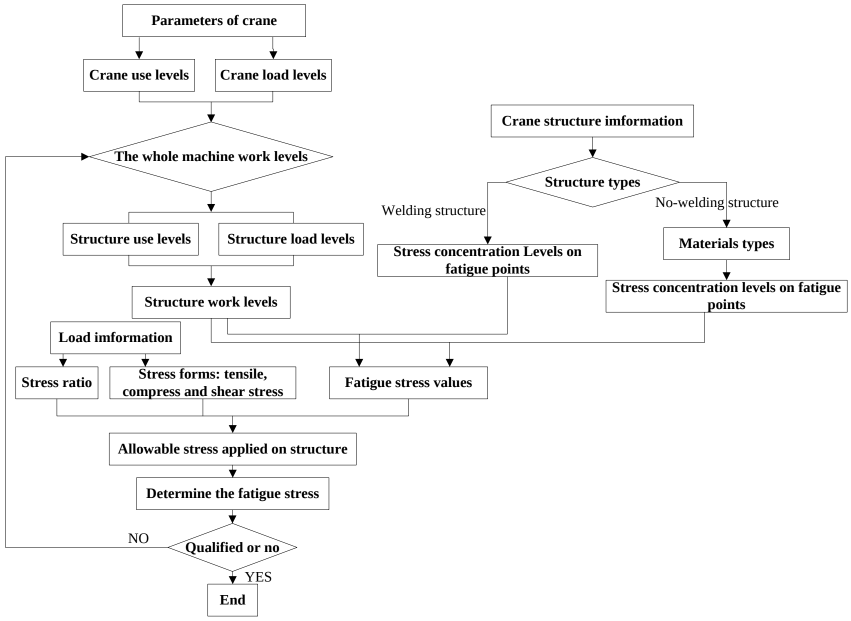

Figure 5. Fatigue Analysis Process of Tower Crane by using Matlab Software

4.2. Dynamic Analysis of Crane Structure

m and C are the parameters and materials, stress ratio, loading related logarithm on both sides, there are

$$lgS=A + BlgM \tag{2}$$

Of particular note is the S-N curve describes the high-cycle fatigue stress, the use of the lower limit of 10^3 - 10^4 not for N <10^3 or less, it is usually assumed that the life of N = 10^3, are:

$$S103=0.89Su \tag{3}$$

☒ Limit defined by the fatigue limit of the metal material, the fatigue limit Sf, the number of cycles corresponding to the general views of N = 107, taking into account the fatigue limit when the error estimate, conservative assumptions made, the fatigue limit is 106.

$$S_{10}{}^{6}==Sf=kS_u \tag{4}$$

Where different forms of factor loadings k reflect, that when the tension and compression. For the ultimate strength of the material Q345 Su = 470Mpa, can be obtained from the above equation parameters are as follows:

$$M=3/lg(0.89/k)=3/lg(0.89/0.35)=7.3 \tag{5}$$

$$C=(0.89Su)^m{}_*10^3 \tag{6}$$

4.3. Struture Dynamic Analysis

Many scholars at home and abroad are trying to seek a practical and convenient estimation model for crane in engineering application to analyze fatigue life [11]. Then structure analysis can be divided into the following processes as listed in Table 3.

Table 3. The Structure Analysis

Structure analysis	Contents
Static analysis	Used for static load, linear and nonlinear behavior of structures can be considered.
Modal analysis	To calculate the natural frequency and mode shapes of linear structure.
Spectrum analysis	To calculate the the stress and strain of structure under the random load.
Spectral response analysis	To determine the linear structure according to the load response of the sine curve changes over time.
Transient dynamics analysis	To determine the structure change over time with the load response, and static analysis can be considered.
Characteristic buckling analysis	To calculate the linear buckling critical load and determine the buckling shape.
Special analysis	Including fracture analysis, composite analysis and fatigue analysis.

In general stress field, the displacement of the crack surface is divided into three modes: open mode, sliding mode and tearing mode, as shown in Figure 6.

The corresponding stress intensity factors are K_I, K_{II} and K_{III}. In the practical application for low stress brittle fracture, many cracks are in mixed modes [12]. However, most of cracks are in I type mode. And Type I crack is also one of the most dangerous cracks.

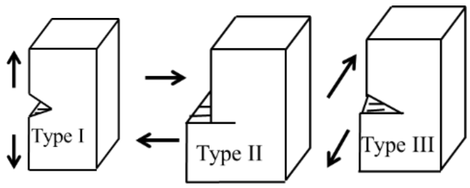

Figure 6. Three Fatigue Crack Modes

$K_I = \sigma\sqrt{\pi a}$

K_I-----Stress intensity factor of type crack

σ-----Tensile stress (MPa)

a-----Half length of the crack (mm)

4.4. Finte Element Modeling

The tower crane tower crane attachment due to the relatively small size of the overall structure in terms of geometry, mass concentration, while the overall analysis of the structure, the physical parts accessories using the equivalent treatment, uniform distribution, which can be added by changed the mass density of the corresponding lever. Change the car, hook and hanging by resynchronization, from the weight of its quality and processed together as lifting load;

The basic steps of ANSYS finite element method is structure discretization based on the material properties, shapes, sizes, number of nodes and location of the unit.

Large tower at the bottom of the structural rigidity, but also connected with the foundation with anchor bolts, constraint handling is a fixed support; from heavy arms connected by a pin and the roots of the tower crane slewing section, boom has set up in the plane can be considered fixed hinge bracket; boom hanged two rods at a fixed point hinged bearing; lifting points on the balance arm rod handle methods and boom similar to the fixed hinge bracket [13].

In this paper, the establishment of a tower crane using ANSYS finite element model for modal analysis and transient dynamic analysis, calculated from three typical conditions of dynamic load factor up and do the analysis, modal analysis of obtained vibration frequency and free vibration frequencies were analyzed, the results for the tower crane dynamic impact analysis and vibration analysis to provide a reference.

5. Conclusions

On the basis of the ANSYS finite element method and fracture mechanics theory, the mechanical property of the tower crane structure is analyzed and the service life in practical environment is evaluated by means of advanced computer software. It is very different to evaluate the fatigue life of crane. Because the crane structure is complex and the applied load is random. The basic idea of the finite element analysis is that simpler problem is solved instead of the complicated problem. Finite element method has distinctive advantages compared with other numerical methods. Physical concept of the finite element method is very clear. It can simplify mechanics calculation, and the users are also able to master and apply it easily. The essence of the finite element method is to make the elastic continuum cell with unlimited freedom degrees into the ideal aggregation with only several finite freedom degrees. Many practical researches show that fracture mechanics method and ANSYS techniques can be well used to study the fatigue crack growth mechanism for welded crane structure, and estimate the residual fatigue life of the crane in service. It has great significance to prevent the fatigue fracture accident, and it is helpful in the crane design, fabrication, inspection and management.

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