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Statics Analysis and Fatigue Analysis on Double Telescopic Column of Hydraulic Support

***Youjin Gao*[1], *Tingsheng Zhao*[2, #]**

1. Zhengzhou Coal Mining Machinery Croup Co., Ltd., Zhengzhou 450016, China.

2. School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China.

#Email: tszhao@hust.edu.cn

Abstract

The statics analysis and fatigue analysis on double telescopic columns are studied in this paper. First, based on the actual mechanical conditions, which the column are subjected, the mechanical calculation model is established. The reasonable assumptions of the load and boundary conditions for the model are proposed. Considering the actual force and deformation state of the column, the revised deformation compatibility conditions for the longitudinal bending beam model are presented. For each column component, the deflection, angle, maximum bending moment and its position are calculated under two load conditions, respectively. Then, according to the fourth strength theory, the combined stress of each part are calculated. The numerical results show that the revised continuity boundary conditions reflect actual force and deformation state of the column better. Second, according to the fatigue test datum of the double telescopic column, the strain history is processed statistically to determine the working cycle by the rain flow counting algorithm. Based on the linear cumulative fatigue damage theory and the assumption of equivalent damage, fatigue life of each column component is estimated.

Keywords: Double Telescopic Column; Statics Analysis; Deformation Compatibility; Fatigue Life

1 INTRODUCTION

Hydraulic support is the key equipment of mechanized mining, which is used for supporting stope roof, maintaining safe working space, and pushing coal mining equipment. The equipment industries are demanded to improve reliability, safety and performance, as well as reduced weight, production cost. The column is the main carrier component of the hydraulic support, which is subjected continuous and variational high pressure during the working period. To satisfy the application of the hydraulic support, the column should both have sufficient caring capacity and reliable working performance. The fatigue life is an important evaluation index of reliability. For structure design and force analysis of the hydraulic support and its columns, ones have been studied based on empirical, analogical and experimental methods. Ferreras et al (2008) investigated the roof pressure on hydraulic support columns based on empirical formulas and experimental investigations, and proposed a new empirical formula to calculate the roof pressure. Nicieza et al (2008) also analyzed the pressure on hydraulic support columns with two load tests. Recently, the double telescopic column is widely used in the hydraulic support as the prop, because it can change with the thickness of coal seam. The mathematic model and calculating method of accounting intensity for double telescopic column have been presented by Cao et al (2011). Wang et al (2013) studied the stress analysis and stability analysis on 360-type double telescopic column with finite element method. Many researches have attracted attention on investigating mechanical properties of hydraulic support columns with the finite element method. Liu and Fang (2012) studied the stress distribution and deformation of hydraulic support columns, and acquired the simulation conditions of the column. Zhang et al (2012) analyzed theoretically the buckling of hydraulic support columns, and obtained the critical buckling load of the column. However, the researches about its reliability and fatigue life are very limited. Therefore, the study on reliability and fatigue life of hydraulic support columns has important theoretical significance and practical value in engineering design.

In this paper, static analysis has been investigated on the basis of the standard and actual mechanical conditions. By means of the linear cumulative fatigue damage theory and the assumption of equivalent damage, strain history is processed statistically by the rainflow counting algorithm. Then, as a function of the relationship between fatigue life, strength and survival rate, the fatigue life of the double telescopic column for three kind of hydraulic steels have been estimated, respectively.

2 MECHANICAL MODEL AND ANALYSIS OF A DOUBLE TELESCOPIC COLUMN

Considering the double telescopic column as a longitudinal bending beam with initial deformation and deflection. The mechanical model is shown in Figure 1.

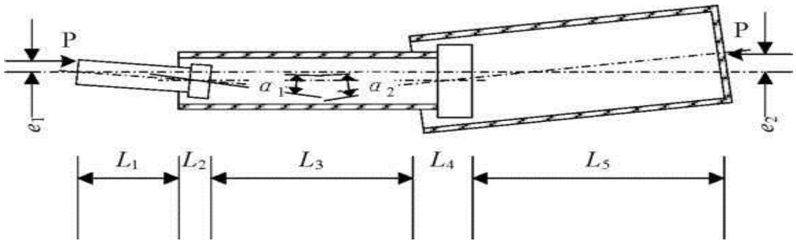

FIGURE 1: MECHANICAL MODEL.

Assuming that the axial load p is applied on two ends of the column, eccentricities are e_1 and e_2. Owing to the fit clearance between the plunger, middle cylinder and small guide sleeve, the middle cylinder, outer cylinder and big guide sleeve, two adjacent hydraulic cylinders have axis angles of α_1 and α_2, respectively. For geometrical and mechanical properties of the hydraulic cylinder, form left to right, the overlapping parts of the length are L_2 and L_4, and the non-overlapping parts are L_1, L_3 and L_5. Each part corresponding to the moments of inertia of $J_i (i=1\sim5)$, section moduli of bending of $W_i (i=1\sim5)$ are all constants, where $J_2 = J_1 + J_3$, $J_4 = J_3 + J_5$, $W_2 = W_1 + W_3$, $W_4 = W_3 + W_5$, while, deflections of $\omega_i (i=1\sim5)$ are uncertain.

According to the mechanical model of the double telescopic column, there are mainly four mechanical characteristics:

A. The column is subjected to the axial pressure or off-center pressure,

B. The oil pressure is applied on the inner wall of the cylinder tubes,

C. The lateral deflection of this beam model would bring about the additional bending moment with it,

D. The higher the slenderness ratio, the more possibility the column would get to the critical condition and lose its stability.

The bending moment of each column part is

$$M_i(x_i) = -p(\omega_i + e), \tag{1}$$

Establishing the differential equilibrium equation

$$E_i J_i \frac{d^2\omega_i}{dx_i^2} = p\omega_i, \tag{2}$$

Where, E_i is the i th elasticity modulus, and subscript $i=1\sim5$ always. The general solution can be obtained by solving Eq.2, then, the deflection equation is

$$\omega_i = y_{2i-1}\cos(k_i x_i) + y_{2i}\sin(k_i x_i). \tag{3}$$

Taking the derivative of Eq.3, then, the rotation equation is

$$\frac{d\omega_i}{dx_i} = k_i(y_{2i}\cos(k_i x_i) - y_{2i-1}\sin(k_i x_i)), \tag{4}$$

Where, $k_i = \sqrt{\frac{\mathrm{P}}{E_i J_i}}$. A system of linear equations is given by the deformation compatibility conditions

$$\mathbf{A}\mathbf{y} = \mathbf{B}, \tag{5}$$

Where

$$\mathbf{y}^T = \begin{bmatrix} y_1 & y_2 & y_3 & y_4 & y_5 & y_6 & y_7 & y_8 & y_9 & y_{10} \end{bmatrix}, \tag{6}$$

$$\mathbf{B}^T = \begin{bmatrix} e_1 & \delta_1/2 & \delta_1 & \alpha_1 & 0 & \delta_2 & \delta_2/2 & -\alpha_2 & 0 & e_2 \end{bmatrix}, \tag{7}$$

And $\delta_i (i = 1, 2)$ represents the rotation at each overlapping part.

Assuming that $\sin(k_i x_i) = S_i$, $\cos(k_i x_i) = C_i$, then matrix A is

$$\mathbf{A} = \begin{bmatrix} 1 &&&&&&&&& \\ C_1 & S_1 & -1 &&&&&&& \\ -k_1 S_1 & k_1 C_1 & 0 & -k_2 &&&&&& \\ && C_2 & S_2 & -1 &&&&& \\ && -k_2 S_2 & k_2 C_2 & 0 & -k_3 &&&& \\ &&&& C_3 & S_3 & -1 &&& \\ &&&& -k_3 S_3 & k_3 C_3 & 0 & -k_4 && \\ &&&&&& C_4 & S_4 & -1 & \\ &&&&&& -k_4 S_4 & k_4 C_4 & 0 & -k_5 \\ &&&&&&&& C_5 & S_5 \end{bmatrix}, \tag{8}$$

The rotation, deflection and bending moment of each part can be obtained by solving Eq.5. Further, the location of the maximum bending moment of each part is obtained by seeking the extreme value of Eq.1. Making $\frac{dM_i(x_i)}{dx_i} = 0$, then,

$$x_i = \frac{1}{k_i} \arctan \frac{y_{2i}}{y_{2i-1}}, . \tag{9}$$

For $x_i \le 0$ or $x_i \ge L_i$, the bending moment presents to the two ends, i.e., $M_i(0)$, $M_i(L_i)$.

3 Statics Analysis On Each Part Of A Double Telescopic Column

First, the plunger is in the uniaxial stress state, which is subjected to pressure and bending stress, i.e.,

$$\sigma_z = \frac{p}{F_1} + \frac{M_{1\max}}{W_1}, \tag{10}$$

Where, F_1 (mm2) represents the area of the transverse section of the plunger. Second, the middle cylinder is in the triaxial stress state, which consists of the axial stress, the radial stress and the circumferential stress. The axial stress is

$$\sigma_{z3} = \pm \frac{M_{3\max}}{J_3} \gamma_3 \quad (d_3 \le 2\gamma_3 \le D_3). \tag{11}$$

According to the Meira's formula, the radial stress and the circumferential stress are

$$\begin{cases} \sigma_{\theta 3} = \dfrac{d_3^2 q_3}{D_3^2 - d_3^2} \left(1 + \dfrac{D_3^2}{4\gamma_3^2}\right) \\ \sigma_{r3} = \dfrac{d_3^2 q_3}{D_3^2 - d_3^2} \left(1 - \dfrac{D_3^2}{4\gamma_3^2}\right) \end{cases} \quad (d_3 \le 2\gamma_3 \le D_3), \tag{12}$$

Where, D_3 (mm), d_3 (mm) are external diameter, inner diameter of the middle cylinder, q_3 (Mpa) represents the oil pressure. As a function of the fourth strength theory, the combined stress is

$$\sigma_{\text{mid}} = \sqrt{\frac{1}{2}\left[\left(\sigma_{\gamma 3} - \sigma_{\theta 3}\right)^2 + \left(\sigma_{\gamma 3} - \sigma_{z3}\right)^2 + \left(\sigma_{\theta 3} - \sigma_{z3}\right)^2\right]}. \tag{13}$$

(15)

Finally, the stress state of the outer cylinder is the same as that of the middle cylinder, i.e., The axial stress is

$$\sigma_{z5} = \pm \frac{M_{5\max}}{J_5} \gamma_5 (d_5 \le 2\gamma_5 \le D_5). \tag{14}$$

The radial stress and the circumferential stress are

$$\begin{cases} \sigma_{\theta 5} = \dfrac{d_5^2 q_5}{D_5^2 - d_5^2}\left(1 + \dfrac{D_5^2}{4\gamma_5^2}\right) \\ \sigma_{r5} = \dfrac{d_5^2 q_5}{D_5^2 - d_5^2}\left(1 - \dfrac{D_5^2}{4\gamma_5^2}\right) \end{cases} (d_5 \le 2\gamma_5 \le D_5), \tag{15}$$

Where, D_5 (mm), d_5 (mm) are external diameter, inner diameter of the middle cylinder, q_5 (Mpa) represents the oil pressure. The combined stress is

$$\sigma_{\text{out}} = \sqrt{\frac{1}{2}\left[\left(\sigma_{\gamma 5} - \sigma_{\theta 5}\right)^2 + \left(\sigma_{\gamma 5} - \sigma_{z5}\right)^2 + \left(\sigma_{\theta 5} - \sigma_{z5}\right)^2\right]}. \tag{16}$$

4 4 STRAIN TEST FOR A DOUBLE TELESCOPIC COLUMN

In this section, according to European standard PrEN1804-1:2000 and Chinese powered support for coal mine-Part 1:General specification GB25974.1-2010, strain test for a ZY18000/32/70D type double telescopic column is implemented. This telescopic column is manufactured using high strength 27SiMn steel and composed of plunger, middle cylinder and outer cylinder. A 30000kN synthetic test platform is customized for this superhigh hydraulic support(see figure 2). During the measurements, static YJ-33 strain gage is used to measure the stain. The mechanical properties of 27SiMn steel is shown as Table 1.

FIGURE 2: THE SYNTHETIC TEST PLATFORM.

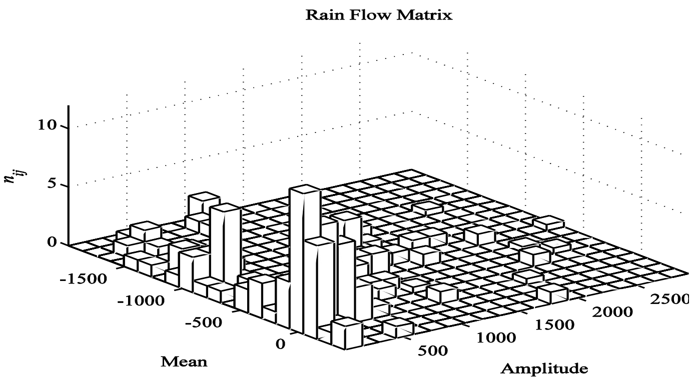

FIGURE 3: TOTAL SIGNAL PROCESSING FOR STRAIN DATA.

TABLE 1 THE MECHANICAL PROPERTIES.

material	Young' s modulus(MPa)	Poisson' s ratio(MPa)	Tensile strength(MPa)	Yield strength(MPa)
27SiMn	207	0.3	980	835

5 FATIGUE ANALYSIS OF A DOUBLE TELESCOPIC COLUMN

In order to determine the working cycle of each component under different mean and amplitude of the load, strain history is processed statistically by the rainflow counting algorithm, the total signal processing is shown in Figure 3.

Based on the linear cumulative fatigue damage theory and the assumption of equivalent damage, fatigue life of each column component is estimated, respectively.

The relationship between fatigue life N, strength S and survival rate P is

$$P = 1 - \int_{N_{\min}}^{N} f(N/S)\mathrm{d}N, \tag{17}$$

Where, $f(N/S)$ is the probability density function of N. The distribution of the fatigue life, which is complied with the lognormal distribution is

$$u_P = \frac{\lg N - \mu(S)}{\sigma(S)}, \tag{18}$$

where, u_P is the standard normal deviator, $\mu(S)$ and $\sigma(S)$ are the mean and standard diviation of the lognormal distribution under stress level of S, which can be determined by life samples of the superhigh hydraulic support prescribed by the experiment agency which is responsible for the strain test under different stress level. The density function is presented as

$$f(x) = \frac{1}{x\sigma(S)\sqrt{2\pi}} e^{-(\ln x - \mu(S))^2 / 2\sigma^2(S)}. \tag{19}$$

Substituting $S_i(1,2,...,n)$ into Eq.19, then, $\mu(S_i)$ and $\sigma(S_i)$ can be obtained.

Assuming that both $\mu(S)$ and $\sigma(S)$ satisfy a certain linear relation, i.e., $\mu(S) = aS + b$, $\sigma(S) = cS + d$. Then, the functional expressions of $\mu(S)$ and $\sigma(S)$ are given by the least square method. Substituting $\mu(S)$ and $\sigma(S)$ into Eq.18, the profile equation of $P - S - N$ can be written as

Where, S_{ai} is the i th stress amplitude, S_{mj} is the j th stress mean, σ_b is the ultimate strength of material of the double telescopic column. Since current experimental data describes the local strain, it is necessary to introduce the Hooke's law to calculate the stress, i.e.,

$$S_k = E\varepsilon_k, \tag{22}$$

Where, E represnets the Young's modulus. Substituting Eq.22 into Eq.21, then, S_{ij} can be wirrten as

$$S_{ij} = \frac{\sigma_\mathrm{b} E\varepsilon_{ai}}{\sigma_\mathrm{b} - E\left|\varepsilon_{mj}\right|}, \tag{23}$$

Where, ε_{ai} is the i th strain amplitude, ε_{mj} is the j th strain mean. Assuming that $P = 0.5$, i.e., $u_P = 0$. Then, substituting Eq.23 into Eq.20 N_{ij} can be calculated. Based on the linear cumulative fatigue damage theory,

$$\mathrm{D_{ij}} = \mathrm{n_{ij}} / \mathrm{N_{ij}}, \tag{24}$$

Where, n_{ij} is the working cycle index under i th stress amplitude and j th stress mean. Further, the total damage degree can be written as

$$D = \sum_{i=1}^{m}\sum_{j=1}^{n} D_{ij}. \tag{25}$$

Finally, fatigue life of each column component can be obtained as

$$\mathrm{T} = 1/\mathrm{D}. \tag{26}$$

6 NUMERICAL EXAMPLES

In this section, it is aimed to calculate the combined stress and fatigue life of each component of the double telescopic column for three kinds of steels. According to Chinese coal industry standard MT313-1992- “The Technical Condition of Hydraulic Support Prop” and European standard EN 1804-2-2001-“Machines for underground mines-Safety requirements for hydraulic powered roof supports_Part 2: Power set legs and rams”, off-center 30mm, 1.1 times loading and 1.5 times axial loading have been applied on a double telescopic column, respectively.

Representative constants in practical double telescopic column of 6.3m superhigh hydraulic support are given as benchmark, i.e., P = 8.82×106N, length of each part L_1 = 1790mm, L_2 = 469mm, L_3 = 1410mm, L_4 = 580mm, L_5 = 1958mm, external diameter D_1 = 355mm, D_3 = 470mm,

D_5 = 580mm, inner diameter d_1 = 260mm, d_3 = 380mm, d_5 = 500mm, and the fit clearance $\alpha_1 = \alpha_2$ = 2.0mm. The results are listed in Table 2 and Table 3.

TABLE 2 STRENGTH

Load condition	Plunger	Middle cylinder	Outer cylinder
off-center,1.1 times(MPa)	344.1	480.0	377.7
1.5 times(MPa)	337.4	631.2	496.9

TABLE 3 FATIGUE LIFE

Plunger	Middle cylinder	Outer cylinder
Fatigue life(x 105) 1.04957	0.34123	0.79195

The numerical results show that middle cylinder is always the part which is subjected to the highest combined force under two different force conditions. In addition, when the column is subjected to 1.5 times axial pressure, the combined stress of middle cylinder is out of the ultimate tensile strength for normal steels such as Q460, Q550 in Chinese standard. Judging from the real state of the column in practical failure reported by the company, it can also reveal that the revised continuity boundary conditions reflect reasonable force and deformation state of the actual column better.

As for the 27SiMn steel column selected in the test, apparently, the middle cylinder has the shortest fatigue life, while the plunger has the longest fatigue life. Both plunger and outer cylinder have higher fatigue life which would satisfy the demand of large mining height, intensity, and reliability.

7 CONCLUSIONS

The Statics analysis and fatigue analysis on double telescopic columns are studied in this paper. Analytical solution is obtained based on the established bending beam model and the prescribed load and boundary conditions. The revised deformation compatibility conditions for the beam model are presented for calculating the deflection, maximum bending moment and its position. Then, according to the fourth strength theory, the combined stress of each part are calculated. The numerical results show that middle cylinder is always the part which is subjected to the highest combined force under two different force conditions. Judging from the real state of the column in practical failure reported by the company, it can also reveal that the revised continuity boundary conditions reflect reasonable force and deformation state of the actual column better.

The fatigue analysis results show that under the design criteria and working conditions, each component of the double telescopic column would not lose working reliability within the appropriate time range. As for the 27SiMn steel column selected in the test, apparently, the middle cylinder has the shortest fatigue life, which is consistent with the fatigue test data indirectly. While, the remaining two components of higher fatigue life would satisfy the demand of large mining height, intensity, and reliability.

8 ACKNOWLEDGEMENT

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AUTHORS

Dr.Youjin Gao, Prof. Zhenzhou Coal Machninery Group Co. LTD. Major: Production Management and Design of Coal Machninery. Email: zzmjj1166@163.com