

Torque waveform analysis and fastening method on invalid thread of track bolt

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Abstract. Aiming at the problem of bolt fastening failure identification during bolt maintenance, the qualitative analysis of the mechanical mechanism of the track bolts was carried out, torque sensor was used to collect the data of the torque in different failure modes, three kinds of mathematic models, such as curve Euclidean distance, cluster analysis and regression statistical analysis, were established for the collected data. The failure forms of thread were analyzed one by one, and the analysis data was compared with the actual construction results. The experimental results show that the discriminant analysis results of the mathematical model are consistent with the actual construction results, which proves the accuracy and feasibility of the model to judge the failure form of the sample data.

1. Introduction

Maintain and detection of bolt axial pre-tightening force is the comprehensive embodiment of the railway maintenance work ability[1]. Now commonly used torque control method, but often due to the damage caused by the screw bolt axial preload can not be maintained in the ideal range, there is a “virtual twist” phenomenon. Tighten the bolts with the torque method, taking into account the torque control precision friction performance difference and bolt strength fluctuations and other factors, the maximum axial preload can only reach the yield strength of 70%, the actual axial force is only 70%~0% bolt yield intensity, even lower[2]. The axial pre-tightening force is small and dispersive, which leads to poor reliability. Due to track irregularity caused by random train wheel before and after stimulation, thereby affecting the train vertical vibration[3]. In this paper, the torque sensor is used to record the torque of the bolt in different failure forms, and the related analysis is carried out, and puts forward the remedial fastening strategy for each kind of situation. This paper can lay a theoretical foundation for the fastening method and the calculation of the failure form of the bolt.

2. Failure Bolt Tightening Torque Waveform

2.1. Detection of Torque Curve in Rail Bolt Fastening Process

A torque sensor is installed on the output shaft of the rail bolt wrench, which is a universal tool for fastening the rail bolt, and the strain gauge is used to form the strain flower, the detection circuit is shown in Figure 1. The output torque of the output shaft can be detected by measuring the strain



change of the output shaft through the Wheatstone bridge, and the output torque is recorded by the host computer[4,5].

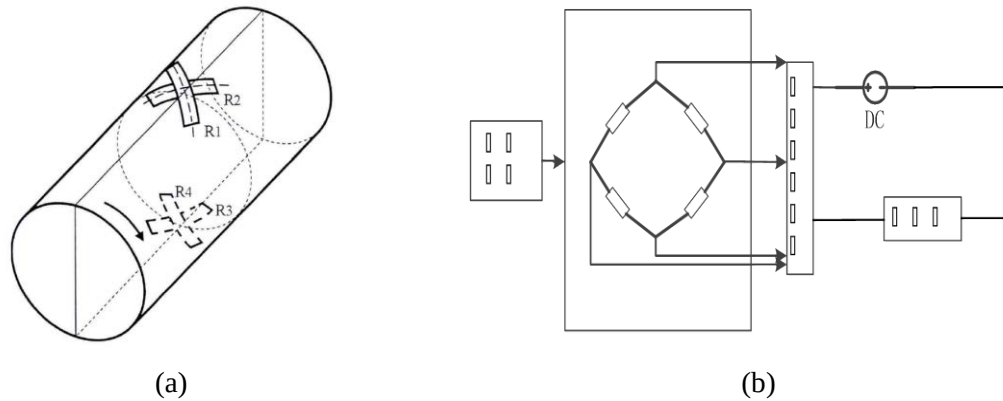


Figure 1. Schematic diagram of current detection

In this paper, the field data test is carried out by using NBL650 rail bolt machine, the strain gauge detection circuit used on a chapter of the construction of the Wheatstone bridge, fastening bolts shall be selected M24[6]. It is mainly aimed at the common failure forms of rail bolts. Based on the basic model of bolt fastening, we analyze the torque waveform of each failure bolt, as shown in Figure 2.

2.2. Support Surface Wear and Thread Tooth Damage

Based on the adhesion furrow friction theory and boundary friction, the surface friction coefficient of different supporting surfaces has the greatest influence on the torque coefficient, no matter how good the fastener mechanical and chemical properties (e.g. tensile strength, wedge load, hardness, chemistry, etc.), surface friction coefficient, coupled with the installation process is not correct, it is possible to satisfy the requirement of the actual installation. This is often one of the common forms of rail bolt failure. In the process of the track bolt installation and maintenance, situation thread damage occurs, and the control process of fastening axial force is actually a process torque convert to axial clamping force by screw thread, the problem of screw part may directly lead to deviation of the tension relation[7]. In order to study the failure mechanism, we destroyed the bolt artificially, and the screw damage is mainly concentrated on the bolt and the support surface. The results of detection results are shown in figure 3.

The experimental data show that the thread damage will increase the friction, thereby increasing the torque coefficient value, while increasing the standard deviation. Analysis of the reasons, thread damage changed the original thread with the contact surface, the contact surface is not flat, usually in the external compression, tooth top deformation, and the protrusion is formed, when the thread is matched with the protrusion, the friction increases, and the value of the torque coefficient is increased. If the installation does not paid attention to the problem, and do not remove the threaded damage of fasteners, while all use the same construction torque, there may be the situation of not reached security clamping force[8].

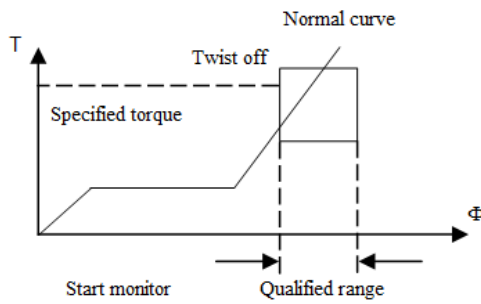


Figure 2. Torque curve of rail bolt fastening process

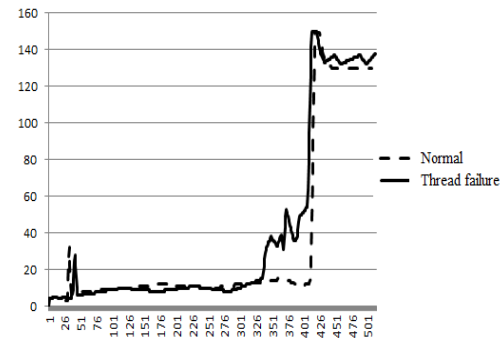


Figure 3. Torque distribution of thread damage

3. Automatic Recognition and Tightening Strategy of Failure Bolt Waveform

For the connection of rail bolts, there are several main failure forms, its fastening waveforms are recorded in this paper. The failure of the form is mainly on the friction coefficient and torque coefficient. The friction coefficient is divided into the friction coefficient of the bearing surface and the coefficient of friction of the thread, the size of the friction coefficient can measure the size of the friction. The torque coefficient indicates the relationship between the rotational torque and the fastening force, compared to the coefficient of friction, the torque coefficient can be directly used to guide the installation, however, the coefficient of friction can analyze the cause of the torque factor, which may cause the torque coefficient increasing or decreasing, especially for the key parts, there will be a greater degree of change. We can get the formula of the torque coefficient through quoting Test method of high strength bolt torque factor for steel structures.

$$K = \frac{d_2}{2d} \tan(\lambda + \varphi) + \frac{f}{3d} \left[\frac{D_0^3 - d_0^3}{D_0^2 - d_0^2} \right] \quad (1)$$

In the formula: d is the nominal diameter of the bolt, d_2 is the pitch diameter of the thread, mm; D_0 is the outer diameter of the nut support surface, mm; d_0 is the diameter of the bolt hole, mm; λ is the thread angle; f is the friction coefficient of friction surface; φ is the equivalent friction angle of the bolt vice. The total coefficient of friction is:

$$\mu_{\text{tot}} = \frac{\frac{T}{F} - \frac{P}{2\pi}}{0.577d_2 - 0.5D_b} \quad (2)$$

In the formula:

$$D_b = \frac{D_0 + d_h}{2} \quad (3)$$

T is the tightening torque, N·m, F is clamping force, kN, P is pitch, mm, d_2 is the pitch diameter of the thread, mm, D_b is the friction diameter of the nut or bolt head under the bearing surface (theoretical or measured), cm, D_0 is the outer diameter of the nut support surface, d_w or d_x , d_h is the aperture (nominal) of the gasket or support part of the bolt.

In the analysis and identification of the bolt torque curve, it can be divided into A and B, as shown in Figure 4. Area A represents the process of helical movement of bolts and nuts, while zone B represents the process of applying preload to the support surface [9].

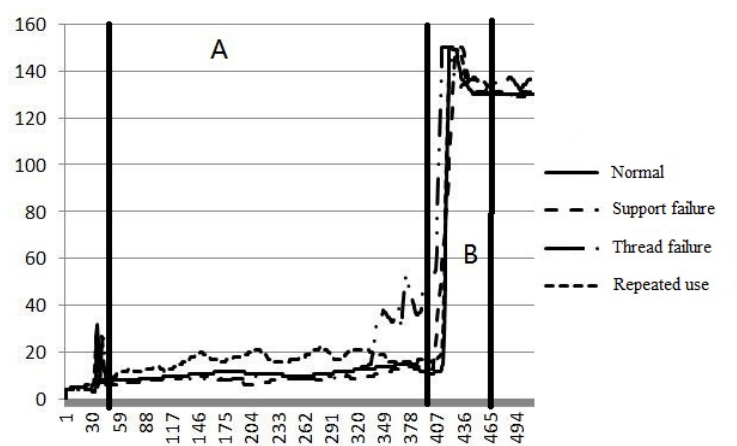


Figure 4. Torque distribution under different circumstances

4. Study on the Judgment Strategy of Track Bolt Failure Form

4.1. Model 1: Failure Form Judgment Strategy based on Mechanism Analysis of Bolt Fastening Process

The following figure is the four torque curve of normal working conditions and three failure forms of the bolt in the fastening process. In this paper, the comparison process of the whole fastening process is divided into three intervals: A, B and C, and the failure forms are analyzed in different intervals.

After analyzing the interval A, we can know that the phenomenon caused by thread damage and support surface wear is not significant when the bolt is at the beginning of the fastening. However, for the bolt which is reused for ages, because the original protective layer has been changed and corroded, working environment has become bad, the friction coefficient will increase, leading to its torque coefficient and standard deviation larger, so its torque should be larger than the other three curves'. After analyzing the interval B, we can know some phenomenon, such as the contact surface is not flat, the top of the tooth deformation, tightening instability, the torque coefficient is extremely large and so on, its torque should be larger than the other three curves'. For the interval C, at the final stage of the fastening process, the preload is less than the expected torque due to the wear of the support surface, so the bolt preloading force on the support surface is smaller than in other cases, the smaller value is the support surface wear failure form.

4.2. Model 2: Failure Form Judgment Strategy based on Bayes Discrimination Analysis Theory

In scientific research, if a new sample data (usually a multivariate) is obtained and it need to be determined which known class it belongs to, it is a discrimination problem in the field of mathematical statistics. For the identification problem, generally, there are some methods such as distance discrimination, stepwise discrimination and Bayes discrimination, Bayes discrimination method is more mature than other methods, the consideration of the problem is more comprehensive and the application is more extensive, therefore, Bayes discrimination method is used to judge the failure form of the bolt in this paper. Bayes statistics is an important branch of modern statistics. The Bayes theory is applied to the discrimination analysis, which constitutes the Bayes judgment[10].

The basic mathematical model is that, setting the probability density of k general (class) $G_1, G_2, \dots, G_{k-1}, G_k$ is $f_j(x)$, $j = 1, 2, 3, \dots, k$, and the prior probabilities of the totals are known.

$$p_j = P(G_j) \quad j = 1, 2, 3, \dots, k \quad (4)$$

Setting the i -th overall data space be: $G^{(i)} = [g_1^{(i)}, g_2^{(i)}, \dots, g_n^{(i)}]$, where n is the data observation, then the i -th covariance matrix is

$$S^{(i)} = \frac{1}{n-1} \sum_{j=1}^n (g_j^{(i)} - \bar{g}^{(i)})(g_j^{(i)} - \bar{g}^{(i)})^T \quad (5)$$

Then the unbiased estimation matrix between the two populations is

$$S = \frac{(n_1-1)S_1 + (n_2-1)S_2}{n_1 + n_2 - 2} \quad (6)$$

According to the Bayes formula, the posterior probability of the i-th overall G_i is

$$P(G_i|x) = \frac{p_i f_i(x)}{\sum_{i=1}^k p_i f_i(x)} \quad (7)$$

Assuming that the object of study is a normal distribution, that is $G_i \sim N_p(\mu_i, e_i)$, $j=1,2,3,\dots$, then the posterior probability formula is:

$$P(G_i|x) = \frac{\exp(-\frac{1}{2}d_j^2(x))}{\sum_{i=1}^k \exp(-\frac{1}{2}d_j^2(x))}, j=1,2,3,\dots \quad (8)$$

In the above equation $d_j^2(x)$ is a generalized square distance function, the formula is

$$d_j^2(x) = (x - \mu_j)^T E^{-1}(x - \mu_j) + \ln|E_j| - 2\ln p_j \quad (9)$$

In the above equation $j=1, 2, 3, \dots$, E is the covariance matrix of each data space.

4.3. Model 3: Failure Form Judgment Strategy based on Curve Regression

According to the significance test theory of curve regression, residual squared sum and regression squared sum can directly respond to the effect of curve fitting, the larger the SSR, the smaller the SSE, the better the curve. The calculation formulas of SSE and SSR are as follows.

$$SSE = \sum_i (x_i - \hat{x}_i)^2 \quad SSR = \sum_i (\hat{x}_i - \bar{x}_i)^2 \quad (10)$$

Where X_i is the vector value, $\hat{x}_i$ is the regression function value, and $\bar{x}_i$ is the sample mean value. To determine whether the two sets of vectors can be clustered into one class or not, one of the vectors can be followed by a curve regression, then substitute into another group of data to calculate SSE and SSR, Judging whether the two groups of vectors are a class or not through examining the size of SSE and SSR.

5. Threaded Fastening Failure Forms Judgment Strategy Simulation

In order to prove the feasibility and effectiveness of the mathematical model, a large amount of data is required for testing. The following sets of data are from the torque data of the rail bolt wrench in the field construction. These data come from the first section.

Under normal operating conditions, the torque vector is:

$N=[4\ 5\ 4\ 32\ 7\ 8\ 8\ 8\ 9\ 9\ 10\ 10\ 10\ 11\ 11\ 12\ 12\ 12\ 11\ 11\ 11\ 11\ 11\ 10\ 10\ 10\ 11\ 11\ 12\ 12\ 12\ 13\ 13\ 14\ 14\ 15\ 14\ 13\ 11\ 12\ 49\ 150\ 135\ 130\ 130\ 130\ 130\ 130\ 130]G_i \sim N_p(\mu_i, e_i)$, $j=1,2,3,\dots$

$H=[4\ 5\ 6\ 20\ 6\ 6\ 7\ 7\ 8\ 8\ 8\ 9\ 10\ 11\ 10\ 9\ 8\ 8\ 6\ 6\ 7\ 8\ 8\ 9\ 10\ 10\ 11\ 11\ 10\ 10\ 9\ 9\ 10\ 11\ 12\ 13\ 15\ 14\ 14\ 34\ 68\ 139\ 147\ 132\ 131\ 131\ 131\ 130\ 131]$

$C=[5\ 5\ 5\ 4\ 6\ 7\ 7\ 8\ 8\ 9\ 9\ 10\ 10\ 9\ 9\ 9\ 8\ 8\ 9\ 10\ 10\ 11\ 11\ 10\ 9\ 10\ 8\ 8\ 10\ 11\ 12\ 14\ 16\ 35\ 34\ 39\ 46\ 36\ 50\ 63\ 150\ 141\ 134\ 136\ 132\ 134\ 135\ 136\ 133]$

$R=[5\ 5\ 5\ 26\ 9\ 10\ 12\ 13\ 13\ 13\ 14\ 13\ 15\ 16\ 19\ 20\ 17\ 17\ 18\ 19\ 20\ 21\ 17\ 16\ 17\ 18\ 19\ 22\ 21\ 17\ 19\ 21\ 21\ 20\ 19\ 16\ 16\ 16\ 17\ 15\ 17\ 84\ 150\ 143\ 136\ 135\ 132\ 130\ 130\ 129]$

$A=[5\ 5\ 5\ 2\ 5\ 7\ 8\ 9\ 8\ 7\ 7\ 9\ 11\ 10\ 9\ 8\ 7\ 9\ 9\ 10\ 8\ 12\ 9\ 10\ 12\ 10\ 11\ 13\ 10\ 8\ 8\ 12\ 16\ 28\ 36\ 31\ 38\ 45\ 43\ 52\ 64\ 149\ 143\ 137\ 132\ 135\ 135\ 133\ 135\ 132]$

$B=[4\ 5\ 5\ 26\ 8\ 10\ 11\ 13\ 14\ 14\ 15\ 13\ 14\ 17\ 17\ 21\ 20\ 18\ 17\ 18\ 22\ 21\ 18\ 19\ 15\ 20\ 22\ 23\ 22\ 23\ 18\ 17\ 17\ 20\ 21\ 23\ 18\ 15\ 16\ 15\ 18\ 89\ 152\ 147\ 132\ 131\ 130\ 129\ 128\ 128]$

In this paper, we will use three models to simulate and analyze the above six sets of torque data vectors, and prove the feasibility and effectiveness of the mathematical model in comparison with the actual engineering results. Can make some suggestions after contrasting data.

5.1. Model 1 Simulation Results Analysis

In the A range, torque matrix N, H, C, R, A, B of simple linear fitting, get the following figure 5.

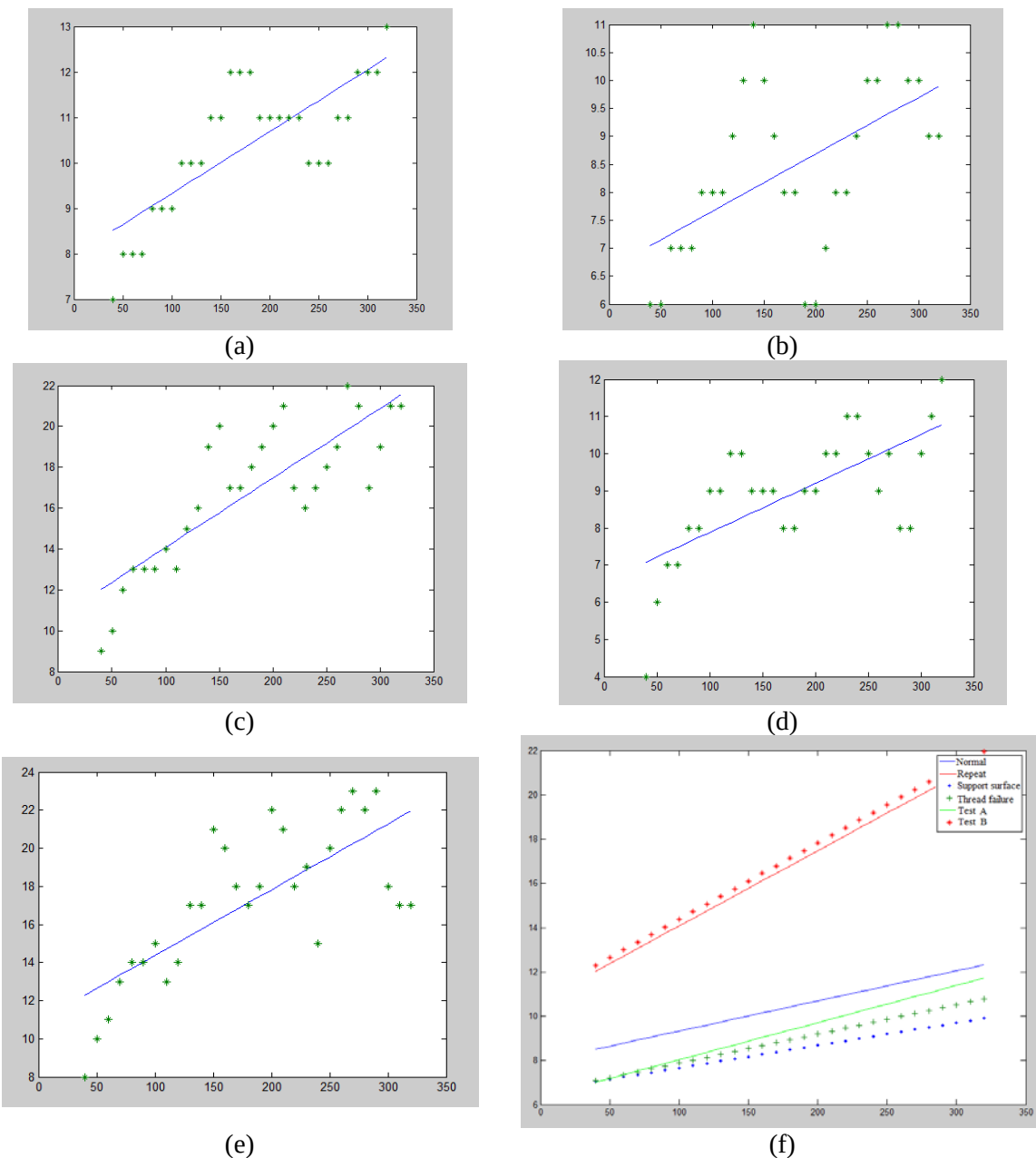


Figure 5. Linear fitting curves of torque matrix N, H, C, R, A and B in A range

In Figure5, Normal curve fitting of A interval(a); Thread damage curve fitting of A interval(b); Repeated use curve fitting of A interval(c); Curve fitting of work piece A measured of A interval(d);

Curve fitting of work piece B measured of A interval(e); Curve fitting contrast diagram of A interval(f).

Put the fitted curve under the same coordinate system, it can be seen, the measured A and the normal working conditions, bearing surface, thread damage, the three cases mix together. It is difficult to find what kind of failure and the measured object B And repeat the use of failure type of curve fit very close, you can determine the failure type of B for the re-use. In the B range, torque matrix N, H, C, R, A, B of simple linear fitting. Similar to the fitting curve obtained in Fig. 5, this paper will not go into details.

5.2. Model 2 Simulation Results Analysis

In the first section, the large number of torque data and the failure bolt are investigated in the construction of the track bolt wrench. It is found that thread failure is the most common in three failure forms. It accounts for about 60 % of the total number of failures, and the repeated use of failure is rare only occasionally, about 10 % of the total failure. Therefore, the prior probability of three failure forms is:

$$\begin{aligned} p\{\text{threadfailure}\} &= 0.6 \\ p\{\text{wearfailureof sup portsurface}\} &= 0.3 \\ p\{\text{repeateduse}\} &= 0.1 \end{aligned}$$

According to the original simulation data can be calculated for each sample space covariance matrix.

$$\begin{aligned} E(A, H) &= \begin{bmatrix} 2399.8 & 2164.2 \\ 2164.2 & 2158.8 \end{bmatrix} & E(B, H) &= \begin{bmatrix} 1991.3 & 2055.7 \\ 2055.7 & 2158.8 \end{bmatrix} \\ E(A, C) &= \begin{bmatrix} 2399.8 & 2398.1 \\ 2398.1 & 2403.2 \end{bmatrix} & E(B, C) &= \begin{bmatrix} 1991.3 & 2072.6 \\ 2072.6 & 2403.2 \end{bmatrix} \\ E(A, R) &= \begin{bmatrix} 2399.8 & 2075.8 \\ 2075.8 & 2020.3 \end{bmatrix} & E(B, R) &= \begin{bmatrix} 1991.3 & 2003.1 \\ 2003.1 & 2020.3 \end{bmatrix} \end{aligned}$$

The linear discriminant function formula can be obtained by the covariance formula.

$$W(x, H) = \hat{a} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} + \hat{b} \quad (11)$$

$a = [112.099 \ 0.642 \ -1.872 \ 1.708 \ -0.965 \ 0.125 \ -0.402 \ -0.389 \ 0.656 \ 1.125 \ 0.714 \ -0.146 \ -0.603 \ -1.833 \ 0.200 \ 1.714 \ 0.715 \ -1.697 \ 0.861 \ -0.010 \ -1.470 \ -1.406 \ 1.132 \ -2.745 \ 0.276 \ -0.09 \ 1.296 \ -0.292 \ 0.932 \ 1.935 \ -0.939 \ 33.993 \ 0.133 \ -0.824 \ -0.540 \ 1.728 \ -2.599 \ 1.187 \ 0.200 \ 11.940 \ 0.565 \ -0.252 \ 1.259 \ 21.233 \ 1.238 \ -0.664 \ -0.321 \ -20.244 \ -0.1800 \ 415 \ 0.225 \ 0.105 \ 1.232 \ -0.160 \ 0.669 \ -14.779 \ -1.163 \ -1.282 \ -3.290 \ 0.876 \ 0.785 \ -21.542 \ 0.375 \ 0.566 \ 0.483 \ 5.921 \ 0.126 \ 0.339 \ -0.855]$

$b = [-106.664 \ 0.321 \ -0.244 \ -0.180 \ 3.415 \ -0.225 \ 0.105 \ 1.232 \ -0.160 \ 0.669 \ -1.779 \ -1.163 \ -1.282 \ 21.290 \ 0.876 \ 0.785 \ -1.542 \ -0.375 \ 0.566 \ 41.483 \ 0.921 \ 0.126 \ 10.339 \ -0.855 \ 2.099 \ 0.642 \ -0.872 \ 1.708 \ -0.965 \ 0.125 \ -0.402 \ -33.389 \ 22.656 \ 1.125 \ 0.714 \ -0.146 \ -0.603 \ -12.833 \ 0.200 \ 1.714 \ 0.715 \ 31.697 \ 0.861 \ -0.010 \ -1.470 \ 51.406 \ 1.132 \ -2.745 \ 41.276 \ -0.09 \ 1.296 \ -0.292 \ 0.932 \ -1.935 \ -0.939 \ 50.993 \ 0.133 \ -2.824 \ -0.540 \ 1.728 \ -2.599 \ 1.187 \ 0.200 \ 11.940 \ 0.565 \ -0.252 \ 15.259 \ -1.233 \ 1.238]$

The probability of each sample in each population can be obtained from the linear discriminant function. As listed in Table.1.

Table 1. Probability distribution table of sample failure

	Repeated use	Thread failure	Support area
Sample one	0.033	0.928	0.0327
Sample two	0.9175	0.052	0.0305

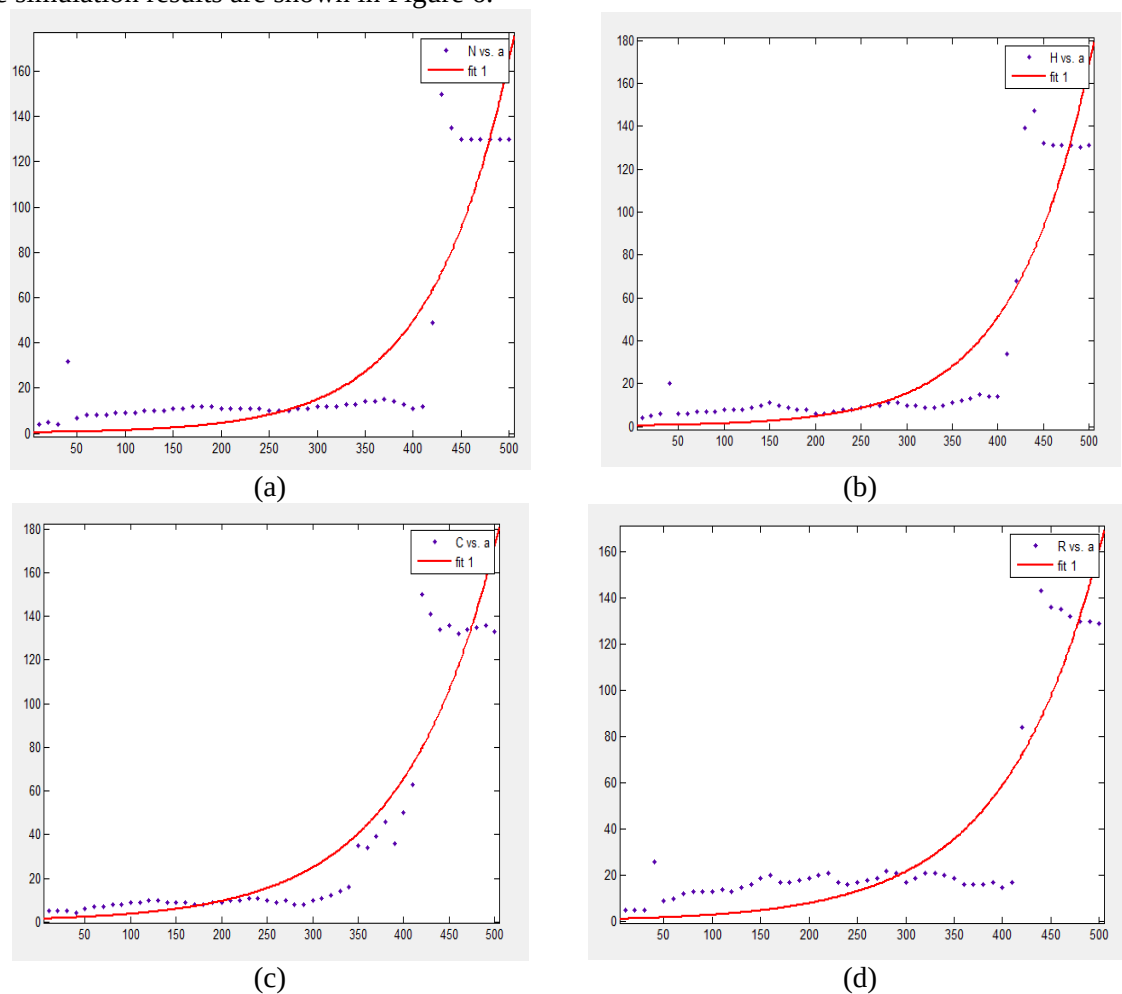
The cross estimate of the error rate is

$$p = \frac{n_{a1} + n_{a3} + n_{b2} + n_{b3}}{n_{a2} + n_{b1}} \quad (12)$$

$P = 0.003 < 1\%$, so the discriminant classification can be considered.

5.3. Model 3 Simulation Results Analysis

The simulation results are shown in Figure 6.

**Figure 6.** The simulation results

In Figure 6, Torque curve in normal working condition (a); Torque curve in invalid bearing surface condition (b); Torque curve in thread damage condition (c); Torque curve in repeated use condition (d).

Residual squared sum (SSE) and regression squared sum (SSR) are calculated respectively by substituting the data matrix of the test pieces A and B into the above fitted curve.

Table 2. Calculation results of A and B under test

		SSE	SSR	SST=SSE+SSR
A	Normal	21178	89170	110348
	Support	20350	92257	112607
	Bolt wear	16490	11677	28167
	Repeat	18153	81732	99885
	Normal	25305	89045	114350
B	Support	25051	92143	117194
	Bolt wear	28189	119190	147379
	Repeat	23573	86899	110472

According to the theory of regression equation significance test, we can see that the smaller SST(total squared sum) means the better fitting effect, that is, the measured data more in line with the curve requirements, can be classified as a class. According to the above table, the measured object A should be judged as a thread damage failure, the measured object B can be judged as the reuse failure form.

6. Summary

The main forms of track bolt failure included support surface wear, thread damage, and reuse. It can be seen that the three failure modes are differences in the torque curves through the qualitative analysis of its mechanical mechanism, the differences is reflected by different curve characteristics. In this paper, three mathematical models are established, and three kinds of thread failure modes are analyzed from the three aspects: the Euclidean distance, the cluster analysis and the regression statistical analysis, the simulation data of the samples collected from samples A and B are simulated and classified, and eventually derive the failure categories of workpieces A and B. The simulation results show that the bolt A is thread damage failure and the bolt B is reuse failure. The results of the discriminant and analysis of workpiece A and workpiece B are consistent with those obtained by actual engineering construction, which proves the feasibility and validity of the constructed mathematical model.

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