Methods for Measuring Permanent Deformation and Error Analysis of in-service Connecting Pieces of Narrow-gauge Mine Car

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Abstract. According to the analysis of the different methods for measuring set deformation volume, this paper finds out the reason of these errors. New method is applied in terms of the latest standard and based on which, a small flock is designed and manufactured, thus solving the measurement precision and instrument installation problems. Through further theoretical analysis, the various forms of the errors are displayed, and the errors are figured qualitatively. Deformation of calibration point is analyzed and verified by finite element software, and the results are in line with expectations. Measurements of decreasing the errors are taken, obtaining experience for such tests.

1. Introduction
Connecting pieces of narrow-gauge mine car play a vital role in coal mine transportation lifting systems. As a directly involved part in safety, car couples are widely used in mine transportation. Connecting pieces generally include single-ring chain, double-ring chain, three-ring chain, multi-ring chain, universal chain, wire rope sleeve and corresponding connection pins. In order to protect coal mine transportation and personal safety, some regulations are made for various safety chains and connecting rings, and connection pins for mine cars, which are clearly stipulated in Safety Regulations for Coal Mines.

For mass production, sampling and breaking tests must be carried out. If the requirements are not met, connecting pieces shall not be used. Before the first use and every two years in service, the test must be carried out one by one with a tensile force, which is twice the maximum static load. If cracks are found or permanent elongation exceeds 0.2%, connecting pieces shall not be used[1].

In order to standardize the inspection requirements of the connecting pieces, the State Administration of Work Safety has issued the AQ mandatory standards “Testing specification of in-service connecting bolt of narrow-gauge mine car” and “Testing specification of in-service connecting chain of narrow-gauge mine car”, these two standards are mainly used in pre-use inspection and in-service inspection for various forged connecting chains, welded connecting chains, insurance chains and connecting bolts of mining cars for inclined shafts and lanes of coal mine [2].
2. Comparison of different test methods

2.1 Traditional standard measurement method
For the method of measuring the permanent elongation, “Car couple of decauville for mines connecting chain” contains some corresponding regulation, as shown in figure 1. In figure 1, the number 1-Left test platform, 2-Test bolt, 3-Connected chain, 4-Tested bolt, 5-Ruler fixed on the test platform, 6-Pointer fixed on the right test platform, 7-Clamp, 8-Right test platform.

![Figure 1. Connection test chart for the bolt permanent deformation measurement.](image)

According to the above method, determining the amount of bending deformation includes the actual deformation amount of the bolt and the amount of deformation of the clamp. The actual deformation of the bolt mainly contains the deformation of the contact point, while the deformation amount of the clamp mainly contains the contact point extrusion deformation and the geometric deformation elongation. Contact point extrusion deformation elongation error consists of two parts; the first part is between the chain and the contact point of the connecting bolt, while the second part is between the contact point of the connecting bolt and the clamp hole. Elongation error caused by geometric deformation of test clamp consists of the bolt deformation, the clamp deformation and the chain deformation [3~4].

This test method determines that the standard of permanent deformation is less than 7 mm and the resolution is 1 mm. While in AQ standard, permanent bending deformation is less than 0.2% of the nominal diameter. For example, the permanent bending deformation of φ40 connecting bolt is less than 0.08mm. Obviously, the method in “Car couple of decauville for mines connecting chain” is already unable to meet the requirements.

2.2 The latest standard measurement method
According to “Testing specification of in-service connecting bolt of decauville car for coal mine”, test method is as follows: Place the bolt on the clamp, continuously load to the maximum static load without impact, calibrate the position of point A in the graph, load at a constant speed to twice the maximum static load, and gradually unload to the maximum static load, then calibrate the position of point A. Measure the distance between the two calibrations of point A, this distance is the permanent bending deformation of the bolt. The amount of displacement at point A can be read directly using a measuring instrument that meets the requirements, as shown in figure 2. In figure 2, the number 1-Universal testing machine fixed clamp, 2-Universal testing machine mobile clamp, 3-Test piece.

![Figure 2. Connection bolt test schematic.](image)
The amount of permanent bending deformation specified in this standard is actually the displacement of the calibration point, which is the amount of displacement of the bolt on the non-direct force side of the bolt of the calibrated point A along the diameter direction. According to the definition of the deformation amount in this standard, the displacement amount is selected as the maximum value of the permanent bending deformation of the connecting bolt. Therefore, the correctness of the calibration point position is crucial, which determines the accuracy and test error.

The standard specifies that the resolution of the measuring instrument used in the test shall be not more than 0.01 mm, and the accuracy of the test machine shall not be less than ±1%. Therefore, we used a 200t tensile tester and a dial gauge for measurement taking into account the test accuracy and operating methods, which are the current laboratory equipments.

Although the accuracy of the measuring equipment is achieved, the measurement principle is similar to that of “Car couple of decauville for mines connecting chain”. Because of the measuring instrument connected with the test machine fixture, the error is large, as shown in figure 3. Considering the fixing method independent of the testing machine, the dial gauge is independent of the testing machine. Because the base is cumbersome, it is inconvenient to adjust, as shown in figure 4.

2.3 Test tooling for measuring permanent deformation

Considering the gradual increase in the number of joints tested, we designed and fabricated a set of simple tooling according to the test conditions, as shown in figure 5, figure 6 and figure 7.

The basic operation steps are as follows. First, After many tests with the designed tooling, one person can be installed, the adjustment is simple and convenient, and meanwhile the rigidity of the tooling is
good. Under slight impact vibration, the accuracy is not affected, and the measurement results also meet the relevant standards, as shown in figure 8.

![Figure 8. Tooling diagram.](image)

3. Error analysis of test results
Through the first part of the discussion, when applying the test method specified in “Testing specification of in-service connecting bolt of deauville car for coal mine”, there will be no error factors such as extrusion deformation and clamp deformation. Further analysis from the experimental principle, the error of this method is only derived from the position of the calibration point A.

3.1 Analysis of theoretical and practical measuring points
Among the relative positions, the I position is the theoretical test position, and the II position is the test position where the error is actually measured. The two figures a and b are the theoretical measurement positions, that is, the dial of the dial indicator and the axis of the pin are completely coincident, and the measured deformation value is the maximum deformation value, which satisfies the standard definition. The c–g diagram is the basic diagram of the actual measurement position (the so-called basic diagram refers to the projection of the dial gauge on the front view and the top view when actually measuring). In actual measurement, the position of the dial indicator may be any one of c–g or a combination of two. The dial of the dial indicator does not coincide with the axis of the pin, and there is a certain angle or spacing to cause measurement error, as shown in figure 9.

![Figure 9. Dial indicator placement diagram.](image)

3.2 Error analysis of actual measurement
For figure 9(c), the dial indicator has only a certain angle in the direction of the top view, as shown in figure 10(a).

![Figure 10. Error analysis.](image)

The actual amount of deformation is line segment AB, the measured deformation is line segment AA'. The bending deformation of the bolt is currently not mathematically derived on the horizontal axis of the bolt. It is related to the force, the material, the spacing of the force at both ends of the bolt and the
diameter of the bolt. Based on known data, the relationship between $AB$ and $AA'$ cannot be accurately derived. However, it can be seen from the mapping method that the deflection of the dial of the dial indicator causes the measured deformation to increase, that is $AA' > AB$.

The dial indicator has a certain off angle $\beta$ only in the direction of the main view. Since the load is small, it can be considered that the bolt is uniformly deformed in cross section, as shown in figure 10(b).

We have a relational formula, as in equation (1).

$$\Delta L = AB, \angle BAA' = \beta, \Delta L = AA'$$  \hspace{1cm} (1)

In the triangle $O'AA'$, it can be obtained from the cosine theorem, as in equation (2).

$$\Delta L' = \left[ (r - \Delta L)^2 \cos^2 \beta + 2r\Delta L - \Delta L^2 \right]^{1/2} - (r - \Delta L) \cos \beta$$  \hspace{1cm} (2)

In equation (2), $r$ represents the bolt radius. After calculation, the measured deformation amount is greater than the actual deformation amount, that is, the error is a positive value, and the error magnitude is related to the dial indicator yaw angle and the bolt radius.

For figure 9(e), since the deformed pin outline cannot be mathematically described, the error cannot be accurately quantified. Since the actual calibration point position is not at the maximum deformation, the measured deformation amount will be smaller than the actual deformation amount. It is obviously to obtain the relationship between the measured deformation and the actual deformation amount, that is $\Delta L' < \Delta L$.

For figure 9(f), due to the small load, the bolt is uniformly deformed in the cross section. Thus the measured deformation amount is basically the same as the actual deformation amount, that is $\Delta L' = \Delta L$. However, when the load is larger, the deformation of the bolt in the cross section becomes uneven. At this time, since the deformed bolt outline cannot be mathematically accurately described, the error cannot be quantitatively calculated.

Similarly, for figure 9(g) and figure 9(h), the projections of the dial gauge in the top view and the main view are deflected and moved relative to the respective axes. At this time, since the deformed bolt outline cannot be accurately described by mathematical, the error cannot be quantitatively calculated either.

Through further measurement experiments, it is found that the actual measurement process is more likely to be the combination error shown in the two figures c and d as shown in figure 9. For combined errors, the dial indicator not only has a certain off angle $\alpha$ in the direction of the top view, but also a certain off angle $\beta$ in the direction of the main view without offset distance. Set the angle between the dial indicator rod and the pin axis of the bolt is $\gamma$, as shown in figure 10(c).

In triangular pyramid $OABA'$,

$$\Delta L = AB, \angle BAO = \alpha, \angle OAA' = \beta, \Delta L' = AA', \angle BAA' = \gamma, AB = AA' \cos \gamma$$  \hspace{1cm} (3)

By solid geometry knowledge, we can obtain an equation (4).

$$\cos \gamma = \cos \alpha \cos \beta$$  \hspace{1cm} (4)

It can be seen that the combination error dial indicator rod is related to the angle of the bolt force axis in the space and $\Delta L' > \Delta L$.

In summary, the position of the calibration point is determined by the angle and distance of the relative axis. The difference between the angle and the distance changes the measured value, causing the measurement error to be positive or negative.

4. Finite element verification
4.1 Establishment of finite element model

The finite element method can well verify the problems that cannot be easily solved by the relevant theory. The loading process is simulated by using the finite element software [5–6]. The whole process includes three-dimensional model building, mesh generation, constraint building, solution calculation and data analysis, as shown in figure 11.

![Figure 11. Finite element model.](image)

The bolt finite element model information is shown in Table 1.

| Young's Modulus (GPa) | Poisson’s Ratio | Density (kg/m³) | Nodes | Elements | Elements size (mm) |
|-----------------------|----------------|-----------------|-------|----------|-------------------|
| 206                   | 0.3            | 7850            | 134951| 50028    | 4                 |

4.2 Analysis of finite element results

It can be seen that the equivalent stress range of the axially lateral path of the pin is 0.48MPa to 200.84MPa, and that of the calibration point A is 200.84MPa, as shown in figure 12.

The variation trend of equivalent stress along the lateral path is as follows: from -90mm to -69mm, the equivalent stress decreases slowly to 3.9MPa, from -69mm to -31mm, the equivalent stress increases rapidly to 78.4MPa, from -31mm to -23mm, the equivalent stress decreases rapidly to 47.4MPa, and from -23mm to 0mm, the equivalent stress increases rapidly to 200.84MPa, that is, the equivalent stress reach its maximum at the calibration point A. The change rule from 90 mm to 0mm is basically symmetrical with that from -90mm to 0mm, as shown in figure 13.

![Figure 12. The equivalent stress of the lateral path.](image)

![Figure 13. The equivalent stress trend of the lateral path.](image)

The axial lateral path of the pin deforms along the X direction in the range of -0.011mm to 0.055mm, and the deformation of the calibration point A is 0.055mm, as shown in figure 14.

The variation of radial deformation is as follows: from -90mm to -23mm, the radial deformation increases slowly to 0.027mm, and from -23mm to 0mm, the radial deformation of the pin increases rapidly to 0.055mm, that is to say, the maximum value is reached at the calibration point A. The change rule from 90mm to 0mm is basically symmetrical with that from -90mm to 0mm, as shown in figure 15.

![Figure 14. Axial displacement of bolt.](image)

![Figure 15. Radial displacement of bolt.](image)
From the results of the finite element analysis, it can be concluded that the calibration point A is the maximum radial deformation position on the outside of the pin. Therefore, it is important to measure the position of calibration point accurately to reduce the experimental error.

5. Conclusion

In this paper, two standard deformation measurement methods are analyzed. The test method specified by the new standard is selected according to the test purpose required by Safety Regulations for Coal Mines. According to this experimental method, a small tooling is designed and manufactured to solve the original method measurement accuracy and instrument installation problems. Through theoretical analysis, the cause of the error of this method is found, and the magnitude of the error is qualitatively analyzed. Deformation of calibration point A is analyzed and verified by finite element software, and the results are in line with expectations.

Through many experiments, some methods to minimize the error are found, and the accuracy of the test is further improved in the future to accumulate experience in such experiments. Later, the shape of the bolt arc will be further studied by the finite element analysis software, in order to quantitatively describe the error size.

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