Analysis of Friction-Slip Characteristics of Pot Bearings in Continuous Curved Girder Bridges

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Abstract: In order to study the influence of friction and slip effect of bearing on transverse deviation of concrete curved beam bridge, the solid model of basin rubber bearing was established by ANSYS. Based on this, the stress and deformation of PTFE plate, basin ring, compressed rubber block and base plate were analyzed in detail; the vertical of the bearing was simulated by finite element method. The load-displacement curves are compared with the bearing capacity test results of 2.5MN basin rubber bearing completed by the Highway Science Research Institute of the Ministry of Transportation. The results show that the basin rubber bearing has stable mechanical properties, and the maximum principal stress, vertical compression deformation and radial deformation of the bearing under the design vertical load satisfy the design requirements; the maximum error between the calculated value and the experimental value of the vertical compression deformation is 4.8%, which verifies the accuracy of the finite element model and is for the follow-up. Foundation for analysis of friction and slip characteristics of traveling bearings.

1. Introduction

Compared with straight-line bridges, curved bridges are fully developed along with the design and construction of ramp bridges in urban traffic lines because of their natural advantages in adapting to complex terrain conditions and relieving traffic pressure [1]. The bending bridge has complex force, obvious coupling effect of bending and torsion, and the lateral displacement of the beam is too large, which will cause the main girder lateral tilt when it is serious [2]. Bridge bearing is an important force transfer component. The damage of bearing will cause the change or interruption of the path of force transfer, which will have a great impact on the bearing capacity and safe operation of bridge structure. Filipov et al. [3] established the finite element model of the whole bridge and studied the influence of friction and sliding effect of bearings on the overall mechanical performance of the bridge. Olaf Huth [4] analyzed the mechanical characteristics of the basin bearing after 32 years of service by conducting long-term monitoring and laboratory simulation test on the bearing system of Swiss railway bridge. Giuseppe Lomiento [5] proposed a model for calculating the friction effect of bearings.

In this paper, the three-dimensional solid model of the basin rubber bearing and the finite element model of the concrete curved beam bridge are established using the large-scale finite element analysis software, and the mechanical properties of the basin rubber bearing are analyzed. The finite element model is verified by comparing with the bearing capacity test results of 2.5MN basin rubber bearing completed by the Highway Science Research Institute of the Ministry of Transportation. The accuracy of the model lays a foundation for subsequent analysis of friction and slip characteristics of bearings.
2. Theoretical Analysis and Numerical Simulation of Basin Bearing

2.1. Basic Structure of Basin-type Rubber Bearings

Ordinary basin rubber bearing mainly consists of roof plate, stainless steel cold-rolled steel plate, PTFE plate, intermediate steel plate, Brass Seal ring, rubber plate, steel basin, anchor bolt, dust ring and dust-proof fencing plate.

In the basin rubber bearing, the roof and the bottom of the beam are consolidated. This connection makes them deform synchronously after the main beam is stressed, so that the top plate of the bearing will transfer the upper force of the structure to the PTFE plate, and then the load will be transferred to the bearing rubber and the bottom plate of the bearing successively, and then to the lower structure such as the pier. In this process, the bearing is usually subjected to compressive stress. When the bearing bears pressure, the phenomenon of stress concentration at the bottom of the basin is obvious, resulting in higher local stress, which is much larger than the stress of the basin ring[6—9].

It can be seen from the above analysis that the basin rubber bearing mainly completes the force transfer and deformation through the bearing capacity of rubber block, the binding force of basin ring, the friction slip between PTFE plate and stainless steel slide plate.

2.2. Finite Element Model of Basin Bearing

In the past, most finite element models usually do not establish PTFE plate structure, but only consider the contact stiffness, friction coefficient and other parameters between the stainless steel plate and the contact surface of PTFE plate. But the horizontal displacement of the basin bearing is realized by the sliding between PTFE plate and stainless steel plate. Therefore, the working performance of PTFE plate directly affects the sliding performance of the bearing, is one of the friction-sliding essential structure. In this paper, ANSYS, is used to carry out refine simulation of ordinary basin rubber bearing, and the solid model including roof plate, PTFE plate and steel basin is established to analyze the basic mechanical characteristics of bearing.

2.2.1. Basic Assumptions of Modeling

Bassin bearing capacity can be divided into 33 grades. This paper selects GPZ(2009)2.5SX±50mm bearings with a height of 129mm; The height and diameter of the pressure rubber block are \( H = 26 \text{mm} \) and \( D = 360 \text{mm} \) respectively; The bearing roof size is \( L \times L = 590 \times 590 \text{mm}^2 \); Base thickness \( H = 17 \text{mm} \); Basin ring thickness \( D = 40 \text{mm} \). The thickness of PTFE plate \( H = 7 \text{mm} \), diameter \( D = 300 \text{mm} \). The schematic diagram of bearing structure is shown in Figure 2.1.

![Figure 2.1 Diagram of structural dimensions of Basin Bearing.](image)

In order to simulate the bearing structure correctly and increase the calculation speed, this paper makes some assumptions:
- Assume that the bearing base plate and bearing pad stone just connected.
- The upper roof of the bearing is rigidly connected with the main girder and deforms at the same time. The upper load of the main girder is evenly transmitted to the upper roof of the bearing.
- Contact analysis was performed around the rubber and inside of the inner ring of the steel basin, around the middle steel lining plate and inside of the steel basin.
2.2.2. Basin Bearing Material Simulation

1) Characteristics of PTFE Material

The friction coefficient between PTFE plate and cast iron is very low, and the allowable compressive strength is 30 MPa. PTFE plate can be regarded as linear elastic material in finite element calculation. Both steel basin and PTFE plate are simulated by solid185.

2) Material Properties of Pressure Rubber Blocks

Scholars at home and abroad have proposed different models to simulate rubber. For example, the models based on strain energy function theory include Mooney-Rivlin model, Yeoh model, Valanis-Landel model, Ogden model, etc. The models based on statistical thermodynamics theory include: Gauss chain network model, Non-Gauss chain network model, hybrid model, etc.[10—11].

Mooney-Rivlin constitutive model is often used to simulate the constitutive properties of rubber. Assuming that the material is incompressible, its strain energy density function is:

\[
W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)
\]  

(2.1)

where \(C_{10}\) and \(C_{01}\) is the material constant, they can be determined by experiment or fitted by empirical formula.

In this paper, Mooney-Rivlin model with two parameters is used to study the constitutive relationship of rubber layer in steel basin. The Mooney-Rivlin model parameters of rubber were determined by empirical formula method.

Assume that rubber is an incompressible material, that is, poisson ratio \(\mu\) tends to 0.5, then \(G = E / 3\). The relationship between shear modulus and elastic modulus of rubber and Mooney-Rivlin model parameters is respectively:

\[
G = \frac{E}{3} = 2(C_{10} + C_{01})
\]  

(2.2)

\[
E = 6C_{10}(1 + C_{01} / C_{10})
\]  

(2.3)

In the small deformation range, the ideal fitting effect can be achieved when \(C_{01}/C_{10}\) is 0.25. According to the measured rubber hardness, two parameters of the model can be obtained by substituting into equations (2.2) and (2.3).

In this paper, the values of \(C_{10}\) and \(C_{01}\) will be determined by empirical formula, and the hardness of rubber will be 60. According to the formulas given in the previous paper, \(C_{10} = 0.4825\) MPa and \(C_{01} = 0.1206\) MPa. Because of the incompressibility of rubber, the poisson ratio is 0.4998. From the above analysis, it can be seen that the values of bearing parameters are shown in Table 2.1:

| Material                          | Modulus of elasticity (MPa) | Poisson ratio |
|-----------------------------------|-----------------------------|---------------|
| Rubber                            | \(4.00 \times 10^4\)        | 0.4998        |
| Steel basin (cast steel)          | \(2.05 \times 10^5\)        | 0.3           |
| Polytetrafluoroethylene board    | \(1.5 \times 10^5\)         | 0.4           |

2.2.3. Simulation of Bearing Contact Surface

The contact between rubber and steel basin belongs to rigid body-flexible body contact, steel is regarded as rigid "target surface", which is simulated by TARGE170 element in ANSYS, while rubber is regarded as flexible "contact surface", which is simulated by CONTA173 in ANSYS. At the same time, the friction coefficient between steel basin and rubber is 0.7, while the friction coefficient between PTFE plate and finish rolled stainless steel plate is 0.03. Controlling contact mode by controlling KEYOPT (12) parameters.

2.2.4. Finite Element Model of Bearing

In this paper, a three-dimensional solid model of the bearing is established. The mechanical characteristics of the basin bearing and the friction and slip characteristics between the contact surfaces are mainly analyzed. The basin bottom is regarded as a rigid connection on the pier abutment, and the restraint mode of complete fixation is adopted. The model is shown in Figure 2.2.
2.3. Basic Performance Analysis of Pot Rubber Bearing

2.3.1. Analysis of Mechanical Behavior of Polytetrafluoroethylene (PTFE) Plate
The thickness of PTFE plate is very small, which mainly provides horizontal displacement. The model is modeled according to the actual bearing. The thickness of PTFE plate is 4/7 embedded in the top groove of the middle steel plate. At this time, the compressive ratio limit of PTFE plate is about 99 MPa. Figures 2.3 and 2.4 show the stress and deformation nephograms of PTFE plates.

From the stress distribution in Figure 2.4, the maximum equivalent stress of PTFE plate is 27 MPa, which is less than the allowable stress value of 30 MPa. The PTFE plate work normally. The stress in the center of PTFE plate is small, and the stress in the outer ring is increased, and the stress in the edge is the largest. The maximum stress of PTFE plate is far less than the limit of compression ratio and plastic deformation is not enough. Therefore, the basic assumption of linear elastic model is correct in finite element analysis.

From Figure 2.4, the distribution of displacement nephogram is different. The central deformation of PTFE plate is larger, the outer ring is smaller, and the edge displacement is the smallest. The displacement of PTFE plate is between 0.08 mm and 0.24 mm, which has little effect on the overall deformation of the bearing.

2.3.2. Analysis of the Force Characteristics of Rubber Blocks
Rubber block is the main compression component of basin bearing, which is used to bear the reaction force of the bearing, transfer the horizontal displacement and rotation angle. Therefore, it is required that rubber block has reliable compression performance and smaller elastic compression. In the model, the diameter of rubber is 360 mm, the compressive modulus of elasticity is 4000 MPa, and the allowable stress value is 25 MPa.

The maximum principal stress under design load is 22.65 MPa, which is less than the allowable
compressive stress value of 25MPa. The distribution law of compressive stress of rubber block is that the equivalent compressive stress in the center of rubber plate is small, and increases annularly to the edge. Local stress concentration occurs on the contact surface between rubber block and basin ring. Uniform distribution of stress concentration points along rubber edge.

From the Figure 2.6, it can be seen that the vertical deformation of rubber is between 0.067 mm and 0.26 mm, and the compression deformation accounts for 1%~2% of the total deformation. The maximum deformation occurs at the bottom edge of the rubber block, and the displacements in all directions are not very different and uniformly distributed. The location of the point with larger displacement is basically the same as that of the stress concentration point. The stress values of each point on the edge of rubber block are extracted and analyzed as shown in Figures 2.7 and 2.8.

![Figure 2.6](image)

**Figure 2.6** Vertical deformation of rubber

From Figure 2.7, it can be seen that the stress distribution of rubber edge is serrated, and the stress is positive or negative. The tension stress may be due to the deformation of the basin ring. Figure 2.8 shows that the stress value of the upper edge of rubber is greater than that of the bottom edge, and the distribution of the stress value of the upper and lower surfaces is consistent. Distribution of stress on the upper and lower surfaces of rubber is the same along the diameter. The maximum stress on the upper and lower surfaces is near the center of the rubber sheet, and the maximum difference is 4 MPa.

2.3.3. **Analysis of Mechanical Characteristics of Basin Ring**

The stress-strain equivalent nephogram of the basin ring is shown in Figure 2.9 and the stress distribution is shown in Figure 2.10:

![Figure 2.9](image)

**Figure 2.9** Stress-deformation Nephogram of Basin Ring.
The distribution of the equivalent stress of the basin ring is shown in Figure 2.9 (a). The equivalent stress of the basin ring is between 9 MPa and 83 MPa. The basin ring bears tension under the lateral pressure provided by rubber in the steel basin. The maximum tension stress occurs on the contact surface between the top of the rubber and the basin ring. Vertical compression deformation of the basin ring is very small, the maximum is 0.37 mm, and the maximum radial displacement is 0.014 mm, which is less than the allowable deformation of 0.22 mm. Equivalent stress values of basin rings with different heights are extracted along the height of basin rings. The results are shown in Figure 2.10. The stress distribution of basin rings at different heights is the same, and the compressive stress appears at the mouth of basin rings.

2.3.4. Analysis of Stress Characteristics of Basin Bottom

Stress nephogram and stress distribution map of basin bottom are shown in Figures 2.11 and 2.12:

From the stress cloud Figure 2.11, it can be seen that the maximum stress value of the lower support plate under the design load is 70.2 MPa, which is lower than the allowable stress value of the cast steel material. The stress values from the center of the basin bottom along the diameter to the edge of the steel basin are extracted. See Figure 2.12. It can be found that the compressive stress increases gradually to the edge within 1/2R from the center of the basin bottom, but the increase is small. At 180-220 mm basin ring, the stress increases suddenly, the maximum value is 103.23 MPa. Because of the large stress concentration in the basin ring. The bottom of the steel basin warps slightly and produces tensile stress.

| Parameter                        | PTFE plate | Pressure Rubber Block | Basin Ring | Base Plate of Bearing |
|----------------------------------|------------|-----------------------|------------|-----------------------|
| Maximum Equivalent Stress (MPa)  | 27         | 22.65                 | 83         | 70.2                  |
| Maximum Vertical Displacement (mm)| 0.24       | 0.26                  | 0.37       | 0.33                  |

From Table 2.2, it can be seen that all parts of the bearing meet the design requirements and have stable force and deformation capacity under normal service load.

2.4. Verification of Finite Element Model

In order to verify the correctness of the above calculation and whether the model itself is consistent with the constraints and stress characteristics of the actual bearing, the bearing capacity test results of 2.5MN basin rubber bearing completed by the Highway Science Research Institute of the Ministry of Transportation are compared with the finite model calculation results in this paper. In order to illustrate the feasibility of the validation, a comparison is made between the experimental conditions and the finite
element simulation conditions. The comparison results are shown in Table 2.3.

Table 2.3 Comparison of Test Conditions and Finite Element Parameters.

| Research Instruments       | Bearing Type     | Bearing Height/mm | Design Bearing Capacity/MN | Ambient Temperature          | Boundary Condition                        |
|----------------------------|------------------|-------------------|-----------------------------|------------------------------|------------------------------------------|
| Experimental Research GPZ(09T)2.5SX | 129              | 2.5               | Normal atmospheric temperature | Contact between support base plate and steel plate |
| Finite Element Simulation GPZ(09T)2.5SX | 129              | 2.5               | Normal atmospheric temperature | Fully Fixed Support Base Plate |

The Basic test conditions given in Table 2.4 are consistent with the basic conditions of finite element simulation in this paper. Therefore, it is feasible to verify each other between test data and finite element calculation results.

Two 2.5MN basin bearings were tested by the Highway Science Research Institute of the Ministry of Transportation. The loading was divided into pre-loading and formal loading. Three times of preloading was carried out before the formal loading. The preloading load was 2500kN. Displacement meters were arranged between the base plate and the roof of the support. The formal loading time is 10 steps, loading to 3500 kN. In this paper, the load step is divided into 10 steps and applied to the support roof in the form of uniform load. The vertical compression deformation corresponding to each loading step is extracted, and the load-deformation curve is obtained and compared with the experimental results. The results are shown in Figure 2.13.

![Figure 2.13 Comparison of theoretical and experimental results.](image)

As can be seen from Figure 2.13, the theoretical maximum value of vertical compression deformation of this type of bearing is 0.62 mm, and the experimental maximum value is 0.65 mm. Both of them satisfy the permissible value of vertical compression of the bearing. The maximum compression deformation measured by the test is 4.8% different from that calculated by the finite element method, which belongs to the acceptable error range. The experimental results are in good agreement with the load-deformation curve obtained by theoretical calculation. The radial deformation of the basin ring is very small. The radial deformation value of the basin ring is 0.015 mm under the design vertical load. The calculated results in this paper are 0.014 mm, and there is little difference between the two. Therefore, it can be proved that the finite element calculation model can accurately simulate the actual bearing force and deformation.

3. Conclusion

(1) The basin bearing relies on three-dimensional compression rubber blocks in the steel basin to bear vertical loads. The deformation of rubber blocks causes the contact ring to be pulled. There exists a phenomenon of local stress concentration on the contact surface between the base plate and the basin ring of the bearing, but the maximum stress value is far less than the yield strength of the cast steel material, which does not affect the normal work of the bearing. The deformation of PTFE sheet under design load is very small, and this micro-deformation has little effect on the stress distribution of intermediate steel sheet and rubber sheet. The PTFE sheet can be used as linear elastic material when analyzing the mechanical characteristics of bearing.

(2) The maximum stress, vertical compression deformation and radial deformation of the basin bearing all meet the design requirements. The basin bearing has a large safety reserve, stable force and
small deformation. Usually, the ultimate failure of bearing capacity will not occur. The horizontal force characteristics of the bearing are very important.

(3) In this paper, the finite element calculation results of the bearing are compared with the experimental values. The results show that the finite element calculation results of the vertical compression of the bearing are 0.03 mm different from the experimental values, and the error is not large. It shows that the model can accurately simulate the force and constraint conditions of the basin bearing, and lay a foundation for the subsequent analysis of the friction and slip characteristics of the bearing.

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