Analysis of the Pressure Expansion of Bridge Plug Tools and Packers by Equivalent Material Method

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Abstract. For the bridge plug tool and packer, the pressure expansion process and differential pressure loading process of the bridge plug and packer have been simulated by finite element method. The numerical structural stress analysis of the bridge plug and the packer are carried out, and the structure of the bell mouth of the cartridge assembly is optimized. The results show that the replacement of the laminated steel structure in the bridge plug/packer with equivalent materials can greatly improve the calculation efficiency, thus completely calculating the pressure expansion and differential pressure loading of the bridge/packer. After the bridge plug/packer expands, the excessive stress is concentrated at the bell mouth. The optimized structure of the elliptical curve at the bell mouth has relatively low stress. This calculation provides theoretical support for the sealing and optimization of bridge plugs and packers.

1. Introduction
Bridge plug tools and packers are sealing devices used in oil and gas wells. Their principle is that the internal pressure is pressurized, the rubber cylinder assembly composed of the inner rubber tube and outer rubber tube made of laminated steel strip and rubber is expanded after being pressed, then the outer rubber tube is in contact with the casing of the well wall. Under the action of internal pressure extrusion and upper and lower pressure difference, the oil and gas wells are sealed [1-2]. In order to understand the load distribution condition of each part of the bridge plug/packer, the pressure expansion process of the bridge plug/packer is simulated by finite element calculation. After the structural stresses calculation, structural optimization is performed on the overstressed parts.

2. Material and Methods
The main working part of the bridge plug and packer is the rubber cylinder assembly (inner rubber tube, outer rubber tube, laminated steel strip, floating head, upper sleeve joint). Therefore, when building the finite element model, the other parts of the bridge plug tool and packer are simplified. The simplified bridge plug tool and packer finite element models are shown in Fig. 1 and Fig. 2, respectively. The bridge plug tool/packer laminated steel strip has an outer diameter of Ø52 mm, Ø60 mm for the outer rubber tube, and Ø160 mm inner diameter for the outer sleeve that needs to be sealed (hidden in the model).
In the models, the steel sheet structure is replaced by an equivalent material, which can greatly reduce the number of contacts and small-sized local units, thus completely reduce the calculation time of the pressure expansion and the differential pressure loading of the bridge plug/packer [3-6]. Since the steel sheet structure is easily expanded in the radial direction, but the deformation in the longitudinal direction is relatively small, the steel sheet is formed according to the orthotropic material [7]. Orthotropic material means that there are three mutually perpendicular symmetry planes at any point of the material, and the direction perpendicular to the symmetry plane is called the main direction of elasticity. In the main direction of elasticity, the elastic properties of the material are the same, and the axis parallel to the main direction of the elasticity is the elastic main axis or the material main axis, and the three material main axes are represented by 1, 2 and 3. Since the properties of orthotropic materials are different in different directions, it is necessary to set the direction of the material. As shown in Fig. 3, the equivalent structure of the steel sheet is generated in three directions according to the cylindrical coordinates, 1 is the radial direction r, 2 is the circumferential rotation direction φ, and 3 is the height direction z. Therefore, different material parameters can be defined in the three directions.

| Density | Poisson's ratio | Thermal expansion coefficient | Elastic Modulus |
|---------|----------------|-------------------------------|----------------|
| kg/m³   | /              | K⁻¹                          | MPa            |
| 8030    | 0.31           | 16.6E-6                      | 1860000        |

For rubber materials, the hyperelastic constitutive model parameters are determined by uniaxial tensile, plane tensile and biaxial tensile tests. Poisson's ratio can be determined by experimental data of
volume change rate. Commonly used hyperelastic constitutive models include the Neo-Hooke model, the Mooney-Rivlin model, the Yeoh model, the Gent model, the Ogden model, and the Arruda-Boyce eight-chain model. Since the rubber used in the model has exceeded 45% in the initial stage of constrained deformation, it is more suitable to use the Ogden model. The strain energy density function of Ogden model is defined as:

\[ W = \sum_{k=1}^{N} \mu_k \left( \frac{1}{\lambda_1 + \lambda_2 + \lambda_3} \right)^{a_k} \left( \frac{1}{\lambda_1 + \lambda_2 + \lambda_3} \right)^{a_k-3} \]  

where \( \lambda_i \) is the main stretch, \( k, \alpha_k \) are material constants (determined by experimental data), and \( \mu_i \) is the number of terms in the function. The penalty function used in the Ogden formula uses the form of the function used in the Mooney-Rivlin model. The actual strain energy density function is a modified Ogden function, as described by Eq. (2):

\[ W = \sum_{k=1}^{N} \mu_k \left( \frac{1}{\lambda_1 + \lambda_2 + \lambda_3} \right)^{a_k} \left( \frac{1}{\lambda_1 + \lambda_2 + \lambda_3} \right)^{a_k-3} - \ln(J) + \frac{1}{2a} G(J)^2 \]

where \( J \) is the ratio of the deformed volume to the undeformed volume, and \( N \) is the number of terms in the function, \( G(J) = J^2 - 1 \), and

\[ \frac{4}{a} = \frac{1}{3} \sum_{k=1}^{N} \mu_k \left( \frac{(1+4\nu)(1-2\nu)}{2(1-2\nu)} \right) \], \( \nu = Poisson\'s\ ratio \]

A three-item (modified Ogden) model is widely used, and up to four-item models (\( N=4 \)) can be used.

3. Results

3.1 Bridge plug tool

The complete compression simulation of the bridge plug is carried out based on the model and material parameters defined in the previous section. The requirements for the use of the bridge plug are 16 MPa for loading internal pressure and 16 MPa for differential pressure at the upper and lower ends. The calculated stress distribution results of the bridge plug tool are shown in Fig. 4.

According to the calculation results, the maximum stress of the spindle is 399.2 MPa, which is located at the contact of the upper sleeve joint with the steel strip. The maximum stress of the floating head is 1217 MPa, which is located at the contact of the lower sleeve joint with the steel strip. The outer rubber tube has a maximum stress of 234.6 MPa and is located at the edge of the outer rubber.
Figure 5. Simulation results of the packer's expansion process

tube. The steel strip has a maximum stress of 1458 MPa and is located at the end of the steel strip welded to the sleeve joint. The inner rubber tube has a maximum stress of 36.9 MPa and is located at the maximum displacement inside the inner rubber tube, that is, at the ends without the outer rubber tube covering limit.

3.2 Packer
The overall calculation process of the packer is similar to the bridge plug[8]. According to the determined model and material parameters, the expanded state of the final simulated packer is shown in Fig.5, which is the result of displacement distribution of the packer as a whole. According to the simulation results, when the load is applied to 1.54 MPa, the structure at the radial maximum displacement of the expansion tube has been in contact with the outer sleeve. When the load is applied to 2.44 MPa, the expansion tube has been fully opened, and the entire radial reaches 160 mm of the outer sleeve.

When the packer is loaded with internal pressure to 16 MPa and the differential pressure between the upper and lower ends is 16 MPa, the stress distribution diagram of the packer is the same as that of the bridge plug. According to the calculation results, the maximum stress of the main structure of the packer is 2019 MPa, which is located at the contact of the upper sleeve joint with the steel strip. The maximum stress of the floating head is 1247 MPa, which is located at the contact of the lower sleeve joint with the steel strip. The outer rubber tube has a maximum stress of 196.2 MPa and is located at the edge of the outer rubber tube. The steel strip has a maximum stress of 954.9 MPa and is located at the end of the steel strip welded to the sleeve joint. The inner rubber tube has a maximum stress of 24.93 MPa and is located in the middle of the inside of the inner rubber tube.

4. Discussion
The analysis results show that the excessive stress in the bridge plug/packer is concentrated at the bell mouth (the position where the sleeve joint is in contact with the steel strip) [9-10]. Here, the steel strip is flared and squeezing strongly with the sleeve joint. According to preliminary calculations, the stress here exceeds the allowable stress of the material, which may cause damage in subsequent use. So optimization here can improve the problem of excessive stress. Taking the packer as an example, the original simplified model is too simple to handle here, and it has a certain deviation from the actual one. The original model is shown in Fig.6.
Figure 6. Schematic diagram of unoptimized model
The optimized structure of this location is shown in Fig. 7.

Figure 7. Schematic diagram of the optimization model

The inner arc of the sleeve joint is designed to be elliptical. According to the thickness of the sleeve joint and the contact angle with the steel strip, the semi-major axis $a$ of the elliptical arc is calculated, and the length of the semi-minor axis $b$ is obtained by the difference between the thickness and the chamfer, as shown in Fig. 8.

Figure 8. Optimized shape in the sleeve joint

After optimization according to the elliptic curve, since the thickness of the sleeve joint is 6 mm, the chamfering is removed, and the elliptical arc-shaped semi-short axis $b$ is taken as 5 mm. The semi-major axis $a$ is calculated to be 6.41 mm. The stress distribution result of the packer after calculation is shown in Fig. 9.
According to ASME standards and GB150 regulations for pressure vessel parts [11-12], stress linearization at the maximum equivalent stress of each component before and after optimization. The film stress $P_m$ and film stress plus bending stress $P_m+P_b$ of each component are obtained, and the calculation results are shown in Table 2.

Table 2. Stress of each optimized component

| Optimized component | Upper sleeve joint | Lower sleeve joint | Steel strip at the upper sleeve joint | Steel strip at the lower sleeve joint |
|---------------------|--------------------|--------------------|--------------------------------------|--------------------------------------|
| Unoptimized $P_m$ (MPa) | 520.54             | 177.08             | 318.54                               | 279.94                               |
| Optimized $P_m$ (MPa)  | 577.82             | 159.45             | 175.37                               | 85.48                                |
| Unoptimized $P_m+P_b$ (MPa) | 800.33             | 571.17             | 717.54                               | 616.15                               |
| Optimized $P_m+P_b$ (MPa) | 811.79             | 295.17             | 280.59                               | 119.8                                |

From the results of Table 2, the elliptical arc-shaped sleeve joint can significantly reduce the stress of the steel strip, because the ellipse is more in line with the deformed shape of the steel strip when in contact. Due to the pressure difference at the lower sleeve joint, the elliptical arc structure also reduces its stress. The bearing at the spindle is large, and the elliptical arc structure is equivalent to reducing the thickness of the upper sleeve joint. When the steel strip is superposed on the internal pressure and the pressure difference, the steel strip is finally expanded more than the lower sleeve joint. So as the contact stress decreases, the overall film stress and bending stress increase. Therefore, the optimization of the elliptical structure at the bell mouth has a good effect on reducing the stress.

5. Conclusions

(1) In this paper, the finite element method is used to establish model of bridge plug and packer in proportion to the real thing. The equivalent material is used to replace the laminated steel strip structure in the bridge plug/packer. This simplified method can greatly improve the computational efficiency, thus fully calculating the pressure expansion and the differential pressure loading of the bridge plug/packer.

(2) The pressure expansion process of the bridge plug and packer is simulated separately, and the stress distribution and maximum stress of each component of the rubber cylinder assembly are calculated.

(3) Optimize the structure according to the elliptic curve at the position of the excessively stressed position in the packer. When selecting the appropriate semi-long axis, except for the upper sleeve joint, which overall film stress and bending stress are increased due to the reduced thickness, the overall film stress and bending stress of the lower sleeve joint, steel strip at the upper sleeve joint and steel strip at the lower sleeve joint are reduced. The optimization of the elliptical structure at the bell mouth has a good effect on reducing the stress.

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