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FEM analyses of stress and deformation of a flexible inner pressure bolt

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Abstract: The flexible inner pressure bolt is a new kind and new structural bolt (anchor rod). A number of structural improvements and performance test have been carried out. The bolt has superior compatibility to the soft crag and the large distortion tunnel with its flexibility. In order to study its stress, deformation and interaction mechanism thoroughly, a number of large distortion calculations and analyses have been carried out on the bolt by FEM (finite element method), especially with the ANSYS software, based on the updated Lagrangian law. The results show that the maximum stress of the inner wall of the bolt is consistent with an elastic analytic solution. The maximum stress on the body occurs in the vicinity of the enhancement material. The link enhancement of the body seems to be quite essential. The experimental results indicate that the maximum injection pressure in the bolt is 2.5 MPa without link enhancement and 8.3 MPa with the enhancement. This link enhancement effect is highly significant. These results provide some basis for the design, application and anchoring stress analysis of the bolt.
Key words: flexible inner pressure bolt; stress and deformation; FEM; large distortion calculation

1 Introduction

The flexible inner pressure bolt is a new kind and structural bolt (anchor rod), whose interaction mechanism is unique. It is shown in Fig. 1. The bolt is authorized by SIPO and given the Chinese invention patent ZL 200310105525.3. By now, a number of practical tests have been carried out, such as structural improvement and performance tests[1–2]. The body cavity of the bolt is mainly made of high polymer material. High tensile steel wire and some linear material are used as longitudinal enhancement in the body of the bolt under inner pressure (p_i). The body of the bolt may experience a large distortion in the overall radial-direction but almost no longitudinal deformation. The anchoring force is realized by a friction force between the body of the bolt and the adjacent wall rock through radial-direction pressure. The pressure produces the extrusion reinforcement effect to the adjacent wall rock; the span anchoring stress is not easily ineffective because of its fine compatibility with the adjacent formation distortion. Ground and mine experiments indicate that the bolt has superior compatibility to the soft crag and the large distortion tunnel with its flexibility. In practical projects, the bolt hole is often affected by drilling and the condition of adjacent geological formations. The rate of distortion in radial-direction of the body of the bolt is more than 10%, under extreme conditions up to 30%~50%. Anchoring stress analyses made by finite element methods (FEM), such as NCAP and NOLM procedures, are restricted to small distortion analyses. The updated Lagrange law was used to carry out a finite element analysis of a large distortion to the bolt, which can guarantee its plane deformation, stress conditions and provide instructions for the design of bolt applications and the anchoring stress analysis[1–2].

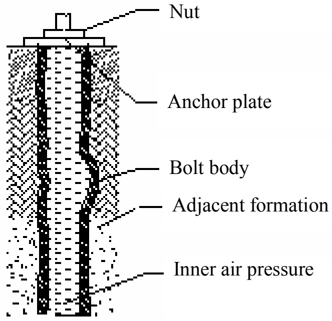

Fig. 1 Sketch of the bolt in application

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2 Application of finite element method in large distortion

Under different reference coordinate systems, the finite element fundamental equations of large distortion problems vary, which usually are carried out under Euler's law and the updated Lagrange law. The updated Lagrange law was used to analyze the stresses and the distortion of the flexible inner pressure bolt[3–6].

The fundamental equation of the finite element of the large distortion problems is:

$$([\boldsymbol{K}]_L)+([\boldsymbol{K}]_N)[\Delta\boldsymbol{q}]=[\Delta\boldsymbol{F}] \tag{1}$$

where $[\boldsymbol{K}]_N$ is the geometric rigidity matrix at time t; $[\boldsymbol{K}]_L$ the conventional finite element rigidity matrix at time t; $[\Delta\boldsymbol{q}]$ the nodal displacement incremental matrix; $[\Delta\boldsymbol{F}]$ the nodal load increment matrix.

The Green strain increment is:

$$\Delta\boldsymbol{E}_{ij}=\frac{1}{2}\left[\frac{\partial\Delta u_j}{\partial x_i}+\frac{\partial\Delta u_i}{\partial x_j}+\frac{\partial\Delta u_k}{\partial x_i}\cdot\frac{\partial\Delta u_k}{\partial x_j}\right] \tag{2}$$

As for the updated Lagrange law constitutive equation, namely the second Piaura-Kirchhoff stress increment and Green strain relational equation, may be expressed as the following tensor form:

$$\Delta\boldsymbol{S}_{ij}=\boldsymbol{C}i_{jkl}\Delta\boldsymbol{E}_{kl}-\boldsymbol{S}_{ik}\Delta\boldsymbol{E}_{kj}-\boldsymbol{S}_{jk}\boldsymbol{E}_{ki} \tag{3}$$

which can be expressed as the matrix form:

$$[\Delta\boldsymbol{S}_{ij}]=([\boldsymbol{C}]+[\boldsymbol{C}]_\mathrm{S})[\Delta\boldsymbol{E}_{ij}] \tag{4}$$

where $[\boldsymbol{C}]$ material conventional matrix, $[\boldsymbol{C}]_\mathrm{S}$ matrix related with stress conditions.Regarding the plane problems, $[\boldsymbol{C}]_\mathrm{S}$ can be expressed as Eq.(5).This analysis is the concrete application of the big distortion finite element theory based on the updated Lagrangian law.

$$[\boldsymbol{C}]_\mathrm{S}=\begin{bmatrix}-2S_{11} & 0 & -2S_{12}\\ 0 & -2S_{22} & -2S_{12}\\ -S_{12} & -S_{12} & -[S_{11}+S_{22}]\end{bmatrix}=\begin{bmatrix}-2\sigma_{11} & 0 & -2\sigma_{12}\\ 0 & -2\sigma_{22} & -2\sigma_{12}\\ -\sigma_{12} & -\sigma_{12} & -2(\sigma_{11}+\sigma_{22})\end{bmatrix} \tag{5}$$

3 Bolt stress and FEM distortion analysis

3.1 Description and analysis

The bolt anchoring form is shown in Fig. 1. The inner pressure of the body of the bolt was 5.0 MPa and the steel wire axial anti-pull out force 70 kN. The outer wall nodal stress of the bolt and its displacement according to the above parameters were simulated. The body of the bolt is made of rubber and super-elastic material. The outer diameter is 27 mm, the inside diameter 13 mm, the thickness 7.0 mm and the length 2.0 m. The material used in the analysis could approximately be considered as Mooney-Rivlin material[3,7]. The related material parameters are shown in Table 1.

Table 1 Rubber (TPE) material parameters [7]

T_1	A_1	B_1	T_2	A_2	B_2	PRXY
20	40	10	40	120	30	0.45

Note: T_1, T_2 material temperature (°C); A_1, B_1; A_2, B_2: lasticity coefficients under T_1, T_2 respectively (MPa); PRXY: Poisson ratio.

The modulus of elasticity of the longitudinal enhancement steel wire was 210 GPa, the Poisson ratio 0.30, the diameter 2.5 mm and the distributed diameter 20 mm in the pipe wall of the body of the bolt. The axial anti-pull out force, exerted on the 12 steel wire was 100 kN and the axial anti-pull out force 70 kN. The modulus of elasticity of the link enhancement material was 80.0 MPa, the Poisson ratio 0.35, the enhancement band width 2.5 mm and the thickness 2.0 mm. The modulus of elasticity of the adjacent formation was 1.0 GPa and the Poisson ratio 0.32. The bolt hole is regarded as a rigid hole. The material cannot be compressed. The effect of temperature can be neglected.

3.2 Models establishments and simplification

The length of the bolt is much larger than its diameter; therefore its end surface effect can be neglected. The analysis was carried out according to plane strain conditions. As a result of its structure and the symmetrical loads, a quarter of the entire bolt was considered to establish the FEM model, as shown in Fig. 2. The link enhancement material had not reached its defined elongated quantity and was distorted along with the rubber. Given its own material behavior establishment analysis, its modulus of elasticity was 80.0 MPa and the Poisson ratio 0.35 [7–9] .

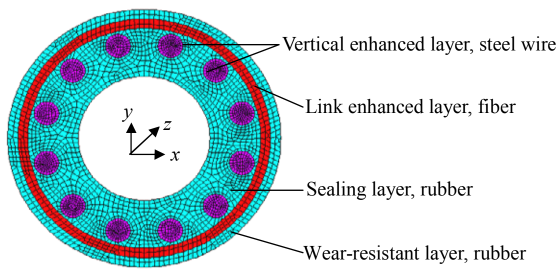

Fig. 2 FEM model of the bolt

3.3 Unit selection and grid division

The HYPER84 unit (8 nodes) was selected as the body of the bolt and the PLANE82 unit (8 pitch points) as the steel wire[7]. We divide the grid and made gradually trial balance adjustments. The stress