Hyperelastic Constitutive Model Determination and Structural Optimization Based on High Vacuum Elastomer Sealing Structure

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Abstract. The stress analysis of rubber liner is widely used in the design of high vacuum elastomer sealing structure. It is very important to determine a reasonable constitutive model and establish a strength evaluation method suitable for failure mode. A series of mechanical properties tests of JY7766 fluororubber were completed in this paper, and material parameters under different constitutive models and strain levels were fitted. A model selection method based on stiffness relative deviation of liner as evaluation index was proposed, and the high precision constitutive model and material parameters with only 0.2% stiffness relative deviation was determined. At the same time, the consistency of crack propagation path and Mises stress distribution of liner was confirmed based on the comparison between theoretical calculation and the actual structure. Under the condition of ensuring the contact total stress of main sealing surface, the maximum Mises stress was reduced by 43.6% and the safety margin of structural strength was improved by optimizing the sealing groove size of a vacuum equipment. The test result showed that the optimized structure meet the requirement of sealing performance.

Keywords: Fluororubber; Hyperelastic constitutive model; Strength evaluation;

1. Introduction

Rubber is very important material for high vacuum elastomer sealing structure because of its good elasticity, interfacial compliance and low permeability. Many theoretical models have been developed to simulate its superelastic behavior. According to the different establishment methods, it can be roughly divided into phenomenological models and statistical models. Typical representatives include Neo-Hooke model[1], Mooney-Rivlin model[2] and Yeoh model[3] that based on strain invariants, and Ogden model[4] based on elongation. For the above models, Xiaoling Hu[5] conducted a comprehensive study on model selection strategies by calculating the fitting error of material performance test data. However, in practical application, because the measurement of material constants is relatively, Wei Wang[6] put forward the method of obtaining material constants by simple uniaxial tensile test under hypothetical conditions, and provided several approximate material constants calculation methods. In the design optimization of elastomer seal structure, the sealing performance is generally determined by the specific pressure, structural stress[7] and contact stress[8]...
of the liner. The strength of sealing structure is qualitatively evaluated by equivalent stress and shear stress[9].

In view of the strength failure of a vacuum equipment sealing structure, the JY7766 fluororubber constitutive model constants measurement and model determination are studied in this paper. And the Mises stress is determined to evaluate the strength of the liner by comparing the calculation results with the actual failure mode. By optimizing the design of the sealing structure, the purpose of improving the structure strength is achieved under the premise of ensuring the sealing performance.

2. Hyperelastic constitutive model determination

2.1 Material mechanical properties test

The stress-strain relationship of fluororubber under pure stretching, compression, shear and hydrostatic pressure was obtained by uniaxial stretching, equibiaxial stretching, plane stretching and volume compression test (Figure 1). These above tests were carried out by E-rubber Technology (Beijing) Co., Ltd.

![Figure 1](image1.png)

**Figure 1.** Diagram of mechanical properties test: (a) uniaxial stretching, (b) equibiaxial stretching, (c) plane stretching, (d) volume compression

The method described in reference[5] was used to carry out the tests, and the sample size was determined according to the test experience. The standard dumbbell-shaped specimen was used for uniaxial tensile test. A special circular specimen with diameter of 60mm and thickness of 2mm was used for biaxial tensile test. A 150mm×5mm×2mm giant specimen was used for plane tensile test. The volume compression was obtained by a single circular specimen layer with diameter of 8mm and thickness of 2mm. According to the calculation, the central region of the above samples can show pure stress state during the test process, which meets the requirements of material mechanical properties.

During the test, the temperature of rubber was kept at (23±2)℃, and the loading strain rate was about 0.01/s. For each sample, four strain levels (25%, 50%, 75%, 100%) were applied, and five cycles of loading were carried out continuously at each strain level.

The curves of engineering stress and strain obtained from various tests are given in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Diagram of engineering stress and strain: (a) uniaxial stretching, (b) equibiaxial stretching, (c) plane stretching, (d) volume compression
According to Figure 2, the mechanical response of rubber showed a certain Mullins effect. Considering that the material in sealing structure is subjected to a long-term stable static load, in order to eliminate the influence of creep and relaxation behaviour as much as possible, the data of the stretch section in the last loading cycle at each strain level are selected to fit the constants of the hyperelastic constitutive model. The results are shown in Table 1.

### Table 1. Table of JY7766 fluororubber material constant

| Constant | Strain level | \( 25\% \) | \( 50\% \) | \( 75\% \) | \( 100\% \) |
|----------|--------------|-----------|-----------|-----------|-----------|
| Neo-Hooke | \( C_{10} / \text{MPa} \) | 5.865×10^{-1} | 6.852×10^{-1} | 7.244×10^{-1} | 7.299×10^{-1} |
|          | \( d_1 \) | 3.459×10^{-4} | 3.459×10^{-4} | 3.459×10^{-4} | 3.459×10^{-4} |
| Mooney-Rivlin | \( C_{10} / \text{MPa} \) | -1.667×10^{-1} | 3.730×10^{-1} | 4.856×10^{-1} | 4.856×10^{-1} |
|          | \( d_1 \) | 3.459×10^{-4} | 3.459×10^{-4} | 3.459×10^{-4} | 3.459×10^{-4} |
|          | \( \mu_1 / \text{MPa} \) | -6.358×10^{0} | -4.130×10^{0} | -1.257×10^{1} | 7.466×10^{1} |
| Ogden    | \( \alpha_1 \) | -1.295×10^{0} | 6.641×10^{0} | 1.185×10^{0} | 3.412×10^{0} |
|          | \( d_1 \) | 2.425×10^{-4} | 2.425×10^{-4} | 2.425×10^{-4} | 2.425×10^{-4} |
|          | \( \mu_2 / \text{MPa} \) | 3.406×10^{1} | 2.165×10^{1} | 6.644×10^{0} | 1.272×10^{5} |
|          | \( \alpha_2 \) | 1.222×10^{1} | 1.688×10^{0} | 2.501×10^{0} | 2.500×10^{1} |
|          | \( d_2 \) | -7.626×10^{0} | -7.626×10^{0} | -7.626×10^{0} | -7.626×10^{0} |
| Yeoh     | \( \mu_3 / \text{MPa} \) | 3.047×10^{1} | 2.077×10^{1} | 7.154×10^{0} | 5.356×10^{1} |
|          | \( \alpha_3 \) | -2.629×10^{0} | -3.428×10^{-1} | -1.051×10^{-1} | -2.929×10^{0} |
|          | \( d_3 \) | 3.098×10^{-11} | 3.098×10^{-11} | 3.098×10^{-11} | 3.098×10^{-11} |
|          | \( C_{10} / \text{MPa} \) | 4.656×10^{-1} | 5.280×10^{-1} | 5.951×10^{-1} | 6.298×10^{-1} |
|          | \( d_1 \) | 2.425×10^{-4} | 2.425×10^{-4} | 2.425×10^{-4} | 2.425×10^{-4} |
|          | \( C_{20} / \text{MPa} \) | 1.237×10^{0} | 7.461×10^{-1} | 3.050×10^{-1} | 9.506×10^{2} |
|          | \( d_2 \) | -7.626×10^{0} | -7.626×10^{0} | -7.626×10^{0} | -7.626×10^{0} |
|          | \( C_{30} / \text{MPa} \) | -2.292×10^{-1} | -4.900×10^{-1} | -9.617×10^{-2} | 2.139×10^{-2} |
|          | \( d_3 \) | 3.098×10^{-11} | 3.098×10^{-11} | 3.098×10^{-11} | 3.098×10^{-11} |

#### 2.2 Model determination

A vacuum container sealing structure was selected to test the compression stiffness of the JY7766 fluororubber liner. The sealing structure of the liner and sealing groove are rectangular in section, liner inner diameter is 25mm, width and height are 5mm. The inner diameter of the sealing groove is 28mm and the outer diameter is 42mm. The compression ratio is controlled to 40%. The test results are compared with the compression stiffness calculated based on the constitutive model in Table 1. The results are shown in Figure 3.
The stiffness relative deviation is defined:

$$K^* = \left| 1 - \frac{K_{cal}}{E(K_{test})} \right|$$

(1)

$K^*$ —— stiffness relative deviation between calculation and test results.

$K_{cal}$ —— the linear fitting stiffness of theoretical calculation results in the range of (0~1.6)mm compression amount.

$E(K_{test})$ —— mean linear fitting stiffness of test results.

The stiffness relative deviations of different constitutive models at several strain levels are shown in Table 2.

**Table 2. The stiffness relative deviations of different constitutive models**

| Constitutive Model | 25% | 50% | 75% | 100% |
|--------------------|-----|-----|-----|------|
| Neo-Hooke          | 45.5% | 25.4% | 46.2% | 313.0% |
| Mooney-Rivlin      | 44.1% | 19.0% | 61.5% | 6.7% |
| Ogden*             | 46.9% | 10.1% | 51.9% | 2.4% |
| Yeoh               | 49.0% | 8.2% | 26.4% | 0.2% |

* Since the calculation is not convergent, the stiffness relative deviation of Ogden model is only for reference

According to the above results, the Yeoh model at 100% strain level can accurately predict the compression deformation of JY7766 fluororubber, its stiffness relative deviation is only 0.2%. The model can be used for stress analysis of seal structure. It is worth noting that the above conclusion is slightly different from the constitutive model selection strategy based on goodness of fit of material stress and strain curves given in literature[5]. The reason may be that the stress state of the liner in seal structure is inconsistent with that of the sample used in the material performance test. Therefore, it is necessary to test the compressive stiffness of the structural parts to be analyzed and screen the constitutive model of rubber material though the stiffness relative deviation.

3. Strength evaluation and optimization of sealing structure

The typical failure mode of the vacuum container sealing structure (the structure size is given in section 2.2) is the penetration crack of liner after long time compression (Figure 4). The Yeoh model at the 100% strain level in Table 1 was used to calculate the stress on the liner, and the results are shown in Figure 5.
At present, there is no unified criterion for strength evaluation of rubber material. Evaluation methods literature[9] mainly rely on equivalent stress and shear stress. By comparing with Figure 4 and Figure 5, it can be found that the distribution of the Mises stress consistent with the crack propagation path, which is consistent with the existing conclusion that “the larger the equivalent stress, the crack is more likely to occur”[10].

According to the calculation results in Figure 5, in the assembled sealing structure, each surface of the liner is extruded and the structure is in a state of volume compression. The Mises stress at the outer tip of the section has exceeded 11.9MPa, which is close to the tensile strength of JY7766. Even without considering the peak stress at the apex, the Mises stress in the middle area of inner surface reaches 4.0MPa, which is close to the engineering stress of the material at 100% strain state. After prolonged compression, cracks may develop from the outer edge, and gradually spread.

In order to solve this problem, the outer diameter of the sealing groove is increased, so as to provide sufficient deformation space for the liner and reduce the stress of the material. Figure 6 and Figure 7 respectively show the calculation results of the sealing structure Mises stress and the contact total stress on the main sealing surface when the outer diameter of the sealing groove is increased to 45mm.

By comparing Figure 5 and Figure 6, the maximum Mises stress of the liner is decreased to 6.2MPa, which is 43.6% lower than unoptimized structure. The liner strength is significantly improved. Meanwhile, according to the calculation results in Figure 7, the contact total stress of the top and bottom main sealing surface are both between 2.5MPa and 6.0MPa, which is greater than the internal and external pressure difference of the sealing structure.
The leak rate of vacuum equipment with optimized structure is tested by HMS leak detector. When the equipment is vacuumed inside and exposed to $10^5$ Pa hydrogen, the leakage rate is stable at about $10^{-8}$ Pa $\cdot$ m$^3$/s before and after structural optimization. It is proved that the optimized structure can meet the sealing performance requirement by ensuring the contact total stress of the main contact surface.

4. Conclusions
In this paper, the mechanical properties of rubber material were tested, and the high-precision constitutive model and material parameters were selected. Further, based on the sealing structure of a vacuum equipment, the relationship between the Mises stress and the strength failure of the liner was analyzed, and the strength design optimization of the sealing structure was completed.

In terms of determining the constitutive model of rubber material, the relative deviation evaluation of compression stiffness between theoretical calculation result and real structural part could be used as an effective screening method of constitutive models and material parameters. For JY7766 fluororubber liner, the Yeoh model at 100% strain level could be used to predict the deformation of liner with high precision, and the stiffness relative deviation was only 0.2%, which was suitable for sealing structure theoretical analysis and design.

In terms of strength optimization of sealing structure, for the rectangular liner given in this paper, the results showed that the Mises stress distribution was consistent with the crack propagation path. The maximum Mises stress could be reduced by 43.6% by increasing the sealing groove size to obtain sufficient liner deformation space. And the contact total stress at the main sealing surface could be ensured to be higher than the internal and external pressure difference of the vacuum equipment. The results of vacuum test by HMS leak detector showed that the optimized structure meets the requirement of sealing performance.

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