Analysis of Low Temperature Compression Characteristics of Rubber Seal Strip of Shelter based on ABAQUS

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Abstract. The extreme low temperature of the alpine region is easy to have a bad effect on the sealing performance of the rubber seal strip of the shelter. In this paper, ABAQUS software is used to simulate and analyse the compression characteristics of the seal strip of the shelter at 23℃ and -55℃, the Von Mises stress and the surface contact stress at two different temperatures are obtained. The result shows that the compression performance of rubber seal strip is sensitive to the extreme low temperature, and it is prone to low-temperature failure. The simulation results in this paper can provide an important reference for the subsequent low-temperature environmental test, so as to more comprehensively analyse the low-temperature failure mechanism of the rubber seal strip of the shelter in the alpine region.

1. Introduction
Rubber seal strip is the key component to achieve the sealing performance of the shelter. It mainly fills the gap between components by the compression deformation caused by extrusion, which improves the working environment of the sealed part or device, and is widely used in the shelter hatch, window, hole cover and other parts. The lowest temperature in China's alpine region can reach -55℃. In this extreme low ambient temperature, rubber seal strip will produce large compression set, and increase hardness and brittleness. Long time use may lead to sealing failure and cracking of the seal strip. If not handled in time, the sealing environment of the shelter equipment is easy to be damaged, the equipment failure rate will be greatly increased, and the service life of the equipment will be reduced.

Scholars at home and abroad have got some results by using finite element software to analyze the compression characteristics of rubber seal strips. D A Wagner studied the relevant factors affecting the sealing performance of automobile sealing strips, by using ABAQUS, the nonlinear finite element analysis of sealing strips was carried out, and the stress deformation characteristic curve of sealing strips was obtained [1]. Ma Tianbing used the foam model in MARC to analyze the compression force of the door sealing strip, and obtained the compression load characteristic curve of the sealing strip through the experiment, Compared with the simulation results, the error was small, which verified the consistency between the theory and the experiment [2]. Fu Jicun used ANSYS to analyze the sealing strip of a certain vehicle, investigated the geometric structure, material characteristics, compression deformation and compression force of the sealing strip in the process of door closing, and optimized the sealing strip structure according to the analysis results [3]. At present, the simulation analysis of rubber seal strip mainly focuses on the geometric design of sealing structure, material characteristics, process assembly and other aspects [4-7], less attention is paid to the
influence of working temperature on the compression performance of rubber seal strip, especially in low ambient temperature.

To sum up, this paper focuses on the simulation analysis of the compression deformation of rubber seal strip in the alpine region. The simulation results can be used as the comparison basis of environmental tests, and also provide some reference for the optimization of sealing strip structure size and the improvement of shelter environmental adaptability design.

2. Geometric structure and stress analysis of rubber seal strip

2.1. Geometric structure
The shape and specification of rubber seal strip of shelter vary according to the type of the shelter. According to the parts used in the shelter, the sealing strip can be divided into hatch frame sealing strip, window inner and outer sealing strip, engine compartment cover sealing strip, hatch and window glass guide groove sealing strip, air bone sealing strip, scuttle sealing strip and decoration sealing strip, etc. In this paper, we select the hatch frame sealing strip used in the dynamic sealing occasion which needs frequent switch action as the research object. The geometric model of sealing strip intersecting surface is shown in Figure 1.

2.2. Stress analysis of sealing strip
This kind of sealing strip is generally composed of EPDM dense rubber, EPDM foam rubber and U-shaped metal framework. Among them, EPDM dense rubber is vulcanized on the metal framework to form a "U" shape structure, which plays the role of clamping and fixing on the shelter sheet metal depending on the friction force generated by the close extrusion between the deformed contact angle and the sheet metal. EPDM foam rubber plays a reliable sealing effect by the compression reaction generated by the extrusion with the hatch sheet metal, and at the same time makes up for the uneven gap between the hatch and the side wall sheet metal. The stress of EPDM foam rubber in the compression process is shown in Figure 2, which mainly includes: the normal force \( F_1 \) generated by the contact between the sealing strip and the hatch sheet metal, which is perpendicular to the top surface of the foam rubber, mainly causes the sealing strip to produce compression deformation to achieve sealing. The extrusion force \( F_2 \) caused by the contact between the sealing strip and the shelter sheet metal mainly causes the bending moment change of the sealing strip. In the process of closing the shelter hatch, the sealing strip bears the normal force \( F_1' \) and the shear force \( F_3 \) generated by the rotation around the hinge axis, which mainly causes the sealing strip to overturn and twist. According to the comprehensive analysis of the stress conditions, the compression load that causes compressive strain of the sealing strip when the hatch is closed mainly comes from the normal force \( F_1 \).
In practical application, there is a certain contradiction between the expectation and the restriction of the normal force $F_1$. For example, when the shelter hatch is closing, we hope that the smaller the compression load is, the better, so as to obtain the lower closing force. When the hatch is closed, we expect that the sealing strip has a larger compression reaction force, so as to achieve a good sealing effect. In actual design, we need to balance the requirements of the two aspects, not too much or too small. In this paper, the simulation analysis of the compression performance of the rubber seal strip is mainly about the normal force that causes the compression deformation of the foam rubber of the sealing strip.

3. Finite element modeling

3.1. Material properties

Rubber is a kind of nonlinear hyperelastic material, and its mechanical behavior is usually characterized by the constitutive model of hyperelastic material. ABAQUS provides various constitutive models such as Arruda Boyce, van der Waals, Mooney Rivlin, Neo Hookean, Yeoh, Ogden, Marlow, etc. For the hyperelastic and incompressible properties of the dense rubber part of the sealing strip, the Mooney Rivlin model can be used to characterize its material properties. The model is simple and convenient to use, and has a good fitting effect on the medium strain of the rubber material. The model is as follows:

$$W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3)$$  \hspace{1cm} (1)

Where $C_{10}$ and $C_{01}$ is the material constant, which can be determined by the following empirical formula.

$$\lg E = 0.0198H - 0.542$$  \hspace{1cm} (2)

$$E = 6(C_{10} + C_{01})$$  \hspace{1cm} (3)

$$C_{01} = 0.1C_{10} \sim 0.25C_{10}$$  \hspace{1cm} (4)

Where $H$ is the hardness of rubber material and $E$ is the modulus of elasticity. The parameters of EPDM dense rubber used in this paper are shown in Table 1.

| Temperature  | 23℃ | -55℃ |
|--------------|-----|------|
| $C_{10}$/MPa | 1.015 | 2.012 |
| $C_{01}$/MPa | 0.145 | 0.287 |
EPDM foam rubber is generally considered to have compressibility. The constitutive model of the hyperelastic compressible foam material in ABAQUS is determined by the deformation derivation of Ogden model. The model is as follows:

\[
U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} \left[ \lambda_i^{n_1} + \lambda_i^{n_2} + \lambda_i^{n_3} - 3 + \frac{1}{\beta_i} (J_i^{\alpha_i} - 1) \right]
\]

(5)

Where \( \mu_i \), \( \alpha_i \), \( \beta_i \) is the material constant, which is obtained by fitting the uniaxial compression test data of EPDM foam rubber material.

3.2. Model building and mesh generation

Because the cross-section size of rubber seal strip is far smaller than its length direction, and the compression load borne by the sealing strip is parallel to the cross-section and evenly distributed along the length direction, the sealing strip can be simplified as a plane two-dimensional model. A straight line can be used to represent the rigid body with infinite rigidity when the seal strip is under simulation. The process of rigid body approaching to the seal strip is the process of simulating the closing of the hatch. When meshing, the cell shape is mainly quadrilateral, and the cell size is 0.5mm, the quadrilateral element type is CPS4R, and the triangle element type is CPS3, the total number of units is 740, the finite element model is shown in Figure 3.

![Figure 3. Finite element model of rubber seal strip.](image)

3.3. Define contact and boundary conditions

For the compression deformation of the sealing strip, it is mainly the contact deformation between the hatch and the foam rubber. In practical application, the reaction force of compression deformation is measured by compressing the foam rubber after the U-shaped structure is fixed by the clamp. Therefore, in the simulation process, the hatch is regarded as the active surface and infinite rigid body, and the seal strip as the driven surface is regarded as the elastomer. In the contact process between the hatch and the foam rubber of the sealing strip, the compression load and deformation are generated by the movement of the hatch and described by the displacement of the hatch. The rigid body of the hatch moves down for 5mm to compress the sealing strip for 5mm displacement. The type of contact between the hatch and the foam rubber is set as surface to surface contact. The friction generated in the contact area is calculated by the adhesion sliding friction model, and the friction coefficient is set as 0.4, this means that the shear stress on the surface of the contact area is always less than its normal contact stress, which ensures that the deformation of the sealing strip is less affected by the sliding between the hatch and the sealing strip. After the sealing strip is compressed and deformed, the dense rubber and foam rubber will have surface contact, but relative sliding is not allowed. The contact type is set as self-contact. At the same time, the contact between the dense rubber of sealing strip and U-
shaped metal framework is regarded as infinite roughness and the contact surface is not separated. In the modeling, all nodes of U-shaped metal framework are fixed.

4. Analysis of simulation results

After the modeling of the sealing strip is completed, the contact extrusion process between the hatch and the sealing strip is solved and calculated, and the Von Mises stress and contact stress of the sealing strip in the compression process under the environment of 23°C and -55°C are obtained. The following is comparative analysis.

4.1. Distribution of the Von Mises stress

When the hatch sheet metal contacts with the sealing strip and generates compression deformation, and the compression stroke is 3, 5 and 8mm respectively, the Von Mises stress distribution of the sealing strip under 23°C and -55°C are shown in Figure 4-6. The gray part in the figure is the initial state when the sealing strip is not compressed, and the cloud part is the working state when the sealing strip reaches the corresponding compression stroke. Through comparison, it can directly describe the different states of the sealing strip before and after compression under different temperatures.

![Figure 4. The Von Mises stress distribution of sealing strip in different temperature(D=3mm).](image1)

(a) 23°C  (b) -55°C

![Figure 5. The Von Mises stress distribution of sealing strip in different temperature(D=5mm).](image2)

(a) 23°C  (b) -55°C
Figure 6. The Von Mises stress distribution of sealing strip in different temperature (D=8mm).

It can be known from the results that when the hatch sheet metal reaches the predetermined position, the sealing strip is compressed, the foam rubber will slip and deform, and the stress distribution is uneven, and it is mainly concentrated on the outer side of the joint between the foam rubber and the dense rubber of the sealing strip, the two sides of the inner surface of the foam rubber of the sealing strip, which indicates that the above weak links mainly bear the compression load when the hatch is closed. Under the same temperature, the maximum Von Mises stress of the sealing strip appears on the outside of the joint between foam rubber and dense rubber, and increases gradually with the increase of compression stroke. When the temperature is -55°C and the compression stroke is 8mm, the maximum Von Mises stress of the sealing strip reaches 0.4655MPa; Under the same compression stroke, the maximum Von Mises stress increases with the decrease of temperature. When the compression stroke is 5mm, the maximum Von Mises stress of the sealing strip under 23°C is 0.0391MPa, and increases to 0.2191MPa under -55°C, the possibility of tearing inside the foam rubber of sealing strip is obviously increased.

4.2. Distribution of contact stress

The contact stress distribution of the sealing strip at 23°C and -55°C are shown in Figure 7-9.

Figure 7. The contact stress distribution of sealing strip in different temperature (D=3mm).

Figure 8. The contact stress distribution of sealing strip in different temperature (D=5mm).
Figure 9. The contact stress distribution of sealing strip in different temperature (D=8mm).

It can be seen from the simulation results that under the same ambient temperature, the contact stress of the sealing strip increases with the increase of compression stroke, which is due to the increase of deformation caused by compression, and the reaction force of the sealing strip on the shelter sheet metal gradually increases; under the same compression stroke, the contact stress of the sealing strip increases with the decrease of ambient temperature. When the compression stroke is 8mm, the maximum contact stress of the sealing strip is 0.0058 MPa under normal temperature, while the maximum contact stress increases to 0.0397 MPa under -55°C, which shows that when the temperature drops, the elasticity and hardness of the sealing strip increase, the closing force of the hatch also increases gradually, and the possibility of fatigue failure of the sealing strip increases obviously under a long-term action.

4.3. Failure mechanism analysis of low temperature

EPDM is a kind of high polymer material, which is a kind of terpolymer made by copolymerization of ethylene, propylene and a small amount of non conjugated diene. EPDM belongs to amorphous rubber, its main chain is saturated carbon chain, there is no polar substituent in the molecular chain, only a small amount of double bonds in the side chain, the interaction between the molecular chains is small, the cohesive energy is low, and the crystallization process will not occur due to the rearrangement of the structure between the molecular chains. This is obviously different from the general crystalline rubber. At relatively low temperature, it will lose high elasticity due to the orderly arrangement of molecular structure. Therefore, for EPDM, its cold resistance mainly depends on the glass temperature.

As a kind of polymer, the glass transition of rubber material is its unique segment movement. From the viewpoint of molecular motion, the glass transition of rubber means that the molecular segment motion is excited. From the perspective of macro performance, the glass transition of rubber refers to the transition from glass state to high elastic state (from low temperature to high temperature), or from high elastic state to glass state (from high temperature to low temperature). The temperature at which this glass transition occurs is called the glass temperature, which can be expressed as $T_g$. There are many kinds of glass transition phenomena. At $T_g$, many physical and mechanical properties of rubber change greatly from high elastic state to glass state. In this paper, the selected sealing strip shows a good hyperelastic state at room temperature. At this time, the sealing strip has good elasticity, small compression set, moderate hardness and brittleness, which can meet the expected design requirements. However, with the decrease of temperature near $T_g$, the main polymer chain of rubber material is gradually frozen, and the chain segment only moves in its fixed position, resulting in the decrease of the elasticity and hardness of the sealing strip. When the working temperature drops below $T_g$, the movement of the whole polymer chain and segment of the rubber material is frozen, and the sealing strip changes from high elastic state to glass state, and its elasticity is almost lost. At this time, the sealing strip shows a large compression set, and the hardness and brittleness are greatly increased. Long-term use of the sealing strip is easy to lead to functional failure and brittle fracture.

5. Conclusions and Prospects

This paper focuses on the simulation analysis of the compression deformation of rubber seal strip in the extreme low temperature of the alpine region, and obtains the following conclusions:

In the compression process of the sealing strip, the stress concentration always at the outer side of the joint between the foam rubber and the dense rubber of the sealing strip and the two sides of the inner surface of the foam rubber of the sealing strip, which indicates that the above weak links mainly bear the compression load when the hatch is closed.

Ignoring the influence of temperature, the contact stress of rubber seal strip always increases with the increase of compression stroke, which is determined by the hyperelasticity of rubber material itself, with good resilience and small compression set to achieve the sealing performance.
Under the same compression stroke condition, the maximum Von Mises stress and contact stress of rubber seal strip always increase with the decrease of temperature, which is related to the glass transition of rubber material under extreme low temperature. After the change of molecular motion of rubber material, the mechanical properties of sealing strip such as hardness and elasticity have changed, which will lead to the failure of sealing strip at low temperature seriously. For the long-term service in the alpine region, the environmental adaptability of the equipment will face severe challenges.

The above results can provide an important reference for the subsequent low-temperature environmental test, so as to analyse the low-temperature failure mechanism of sealing strips in the alpine region more comprehensively. On the other hand, the research in this paper is only preliminary, there are many aspects need to be more in-depth research, such as the evaluation of the active life of the sealing strip under low temperature, optimization of the sealing strip structure to improve environmental adaptability, etc. In addition, the research of this paper has not formed a closed-loop, and no reasonable solution has been put forward to the problem of low temperature failure.

6. Acknowledgments
The authors gratefully acknowledge the financial support by the National Key R&D Program of China (Grant No. 2017YFC0806300).

7. References
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