Research on Simulation and Structural Optimization of the Anchoring Force of Multiple Packers in the Stage Fracturing String

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Abstract

The multi-packer staged fracturing string is a key tool for the staged fracturing and exploitation of "three-low" oil and gas reservoirs in the Changqing Gas Field. The magnitude of the packer's anchoring force is closely related to the stability of the staged fracturing string, and directly affects the on - site fracturing operation effect. In response to the problems such as the lack of a quantitative design basis for packer anchoring during the staged fracturing process in the Changqing Oilfield and the difficulty in ensuring the service safety of the staged fracturing string, this paper selects the Y241 compression - type packer and the K344 expansion - type packer. Through theoretical mechanical analysis and finite - element numerical simulation, the distribution characteristics and variation laws of the anchoring force of the compression - type/expansion - type multi - packers in the staged fracturing string are studied. And combined with the on - site fracturing operation technology, the structure of the multi - packer string is optimized. The research results show that: during the first - stage, second - stage, and third - stage fracturing processes, the Y241 packer provides anchoring forces of 640.64 KN, 566.42 KN, and 566.72 KN respectively. The anchoring forces are all insufficient and cannot meet the requirements of staged fracturing. A hydraulic anchor with a pressure capacity of 300 KN needs to be configured throughout the process. For the K344 packer, during the first - stage fracturing, when the operating pressure is greater than 55 MPa, the packer's anchoring force meets the requirements; during the second - stage and third - stage fracturing processes, when the operating pressure is greater than 50 MPa, there is no need to connect a hydraulic anchor. Through the linear interpolation method, the critical values for connecting the hydraulic anchor of the K344 packer during staged fracturing are calculated to be 53.43 MPa, 46.47 MPa, and 46.17 MPa respectively.

Keywords

Staged Fracturing; K344 Type Packer; Y241 Type Packer; Anchoring Force; Hydraulic Anchor.

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1. Introduction

The Ordos Basin Changqing Gas Field is an important unconventional natural gas production area in China, characterized by a "three low" property in its main reservoir. To achieve economic extraction, the Changqing Oilfield utilizes a pressure-divided joint production string that is modified in one operation for 2 to 3 layers. Although the reliability of the string construction is high, there are two major technical bottlenecks: first, a high incidence of sticking during drilling, with hydraulic sand sticking and sediment accumulation leading to abnormal increases in unsealing load, resulting in a drilling failure rate as high as 18%; second, the risk of anchoring failure, where insufficient anchoring force of the packer during three-stage fracturing causes movement of the string. The introduction of multiple packers has addressed the drilling difficulty, but the mechanical performance of the anchoring still requires systematic optimization.[1]

Domestic scholars have primarily focused their research on the anchoring force of the packer in three areas: material optimization, improvement of mechanical models, and on-site application verification, aiming to solve anchoring failure issues under complex conditions. L.J Zhang[2] and others have addressed the low successful drilling rate issue of the Y241 type packer in the Changqing Gas Field's pressure-divided joint production string. Through mechanical modeling and stability analysis, they revealed that hydraulic sand sticking is the main cause of failure and provided recommendations for the use of hydraulically anchored sand in multi-stage fracturing. G.M Zhao[3] and colleagues have investigated the mechanical properties and process compatibility of the Y241 type packer in pressure-divided strings, successfully achieving efficient segmented fracturing for 2-3 layers, which enhanced the success rate of drilling to 92% and improved fracturing efficiency by 35%[4] after on-site application. L.Z Dai and others tackled the challenge of calculating the anchoring force of the K344 packer in segmented fracturing strings for horizontal wells. By establishing a mechanical model and conducting finite element simulations, they proposed a calculation formula for the anchoring force and validated its accuracy, managing to control the prediction error of the anchoring force within 5%. This paper combines the characteristics of the Changqing Gas Field, starting from the structures of the K344 and Y241 type pressure-divided packers, using mathematical calculations and software simulation to analyze the anchoring force and provide references for optimization.

2. Analysis of the Anchoring Force of Expansion-type and Compression-type Packers

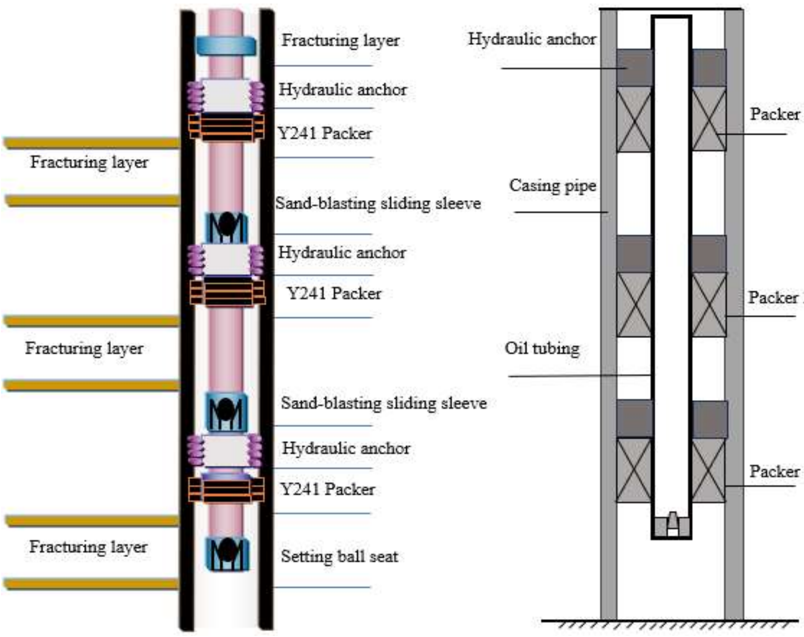

Figure 1. Structure Diagram and Mechanics Model Diagram of Mult-Packer Fracturing String

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With the in-depth research and continuous breakthroughs in oil and gas extraction technology, the number of high-yield conventional oil and gas reservoirs that can be exploited shows a decreasing trend, and extraction targets have largely shifted to low-yield reservoirs. Traditional vertical well extraction techniques are inadequate for economically effective development; thus, segmented fracturing technology has become the core method for increasing single well production rates. As a key means of enhancing recovery rates in low-permeability oil and gas reservoirs, this approach selectively fractures different strata within the same wellbore to achieve more efficient reservoir modification and increased production. As illustrated in Figure 1, the essence of this technology lies in the use of multiple packers to divide the wellbore into several independent fracturing sections, which are then fractured sequentially. This paper presents an analysis of the anchoring forces concerning both expandable and compressible packers within the completion string structure.

2.1 Anchor Force Analysis of K344 Packer

The K344 packer is a fully hydraulically-controlled inflatable tool without mechanical anchoring mechanisms, relying entirely on element expansion for setting.[5] its core sealing component consists of elastomer elements whose expansion degree is directly controlled by internal pressure. The anchoring force comprises two components: 1) friction generated by axial compression forces at both ends of the elements during fracturing operations through casing contact, and 2) friction derived from contact pressure between the hydraulically expanded elements and casing inner wall.[6] The total anchoring force of the K344 packer is the sum of these two frictional components:

$$F_A=F_1+F_2 \tag{1}$$

Among them,F1 can be directly calculated by the formula:

$$F_1=\mu_1 P_1 A_1 \tag{2}$$

In the formula F_1 is the contact friction force between the rubber element sheath and the casing, in *N*; f_2 is the contact friction force between the rubber element and the casing, in *N*; μ_1 is the friction coefficient between the sheath and the casing, dimensionless; p_1 is the contact stress between the sheath and the casing, in MPa; a_1 is the contact area between the sheath and the casing, in mm^2. The calculated values of the anchoring force are shown in Table 1.

Table 1. The partial anchoring force of the K344-type packer is F_1.

Element internal pressure(MPa)	Anchoring force(kN)	Element internal pressure(MPa)	Anchoring force(kN)
45	241.8	65	355.2
50	264.5	70	369.7
55	297.5	75	402.3
60	322.6	80	428.4

2.2 Anchor Force Analysis of Y241 Packer

The Y241 type packer is a compression-type packer that is hydraulically set and released by lifting.[7] it works through the synergistic effect of the slip mechanical anchoring and the rubber element sealing. When setting the packer, the hydraulic pressure drives the slip teeth to embed into the casing wall, and at the same time, the rubber element is axially compressed to produce radial expansion.[8] Its anchoring force is composed of the friction force of the slips and the contact stress of the rubber element. It is calculated by the following formula:

$$F_A=F_1+F_2 \quad (3)$$

In the formula, F_1 is the anchoring force generated between the slip structure and the casing, in kN; F_2 is the anchoring force generated by the contact between the rubber element and the casing wall, in kN.[9]

3. Finite Element Simulation of the Anchoring Force of Packers

3.1 K344 Type Packer

The contact calculation between the rubber element of the K344 - type packer and the casing wall is rather complex. Numerical analysis and computations rely on finite - element software. Considering the working principle of the K344 - type packer, during the fracturing process, the interior of the rubber element expands and makes contact with the pipe wall. The sheaths at both ends ensure that the rubber element only experiences radial deformation. Thus, the rubber - element model is simplified (as shown in Figure 2). Finite - element analysis of the rubber element, which is the core component of the K344 - type packer, is conducted using the finite - element software Abaqus. The basic dimensions of the central tube, slider, casing of the sealing structure, and the core - component rubber element are presented in Table 2.

Table 2. Parameters of Key Components of K344-type Packer

component	Elastic modulus E(MPa)	Poisson's ratio μ	Coefficient of friction	Inner diameter(mm)	Outer diameter(mm)
Sheath	2.14	0.3	0.1	70	120
Casing	2.14	0.3	0.1	121.7	139.7
Central pipe	2.14	0.3	0.1	54	70
Rubber sleeve	C_{10}	C_{01}	0.3	70	114
	1.87	0.47			

The rubber element is made of hydrogenated nitrile rubber. The C3D8R element is used for meshing, and the mesh division is shown in Figure 3. Regarding the constraints and boundary conditions, the packer sheath and the central tube are set as fixed constraints, and the top and bottom of the rubber element are also set as fixed constraints [10]

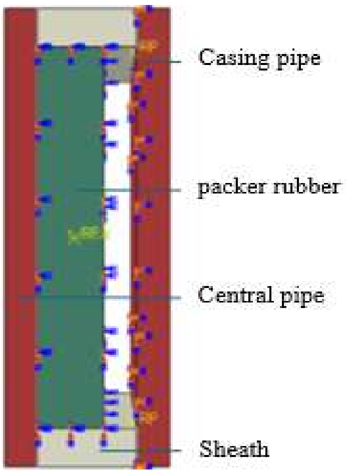

Figure 2. Mechanical Model of the Rubber Element of K344-type Packer

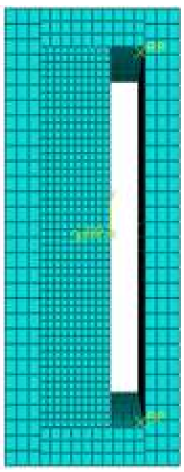

Figure 3. Mesh Division Diagram

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The pressure was applied incrementally. Values were taken at intervals of 5 MPa within the range from 45 MPa to 80 MPa for calculations, resulting in a total of eight sets of contact stress nephograms. Figure 4 presents the contact stress nephograms corresponding to internal pressures of 45 MPa, 50 MPa, 60 MPa, 70 MPa, and 80 MPa. Evidently, due to the contact between the casing and the rubber element, a relatively high contact stress is observed.[11]

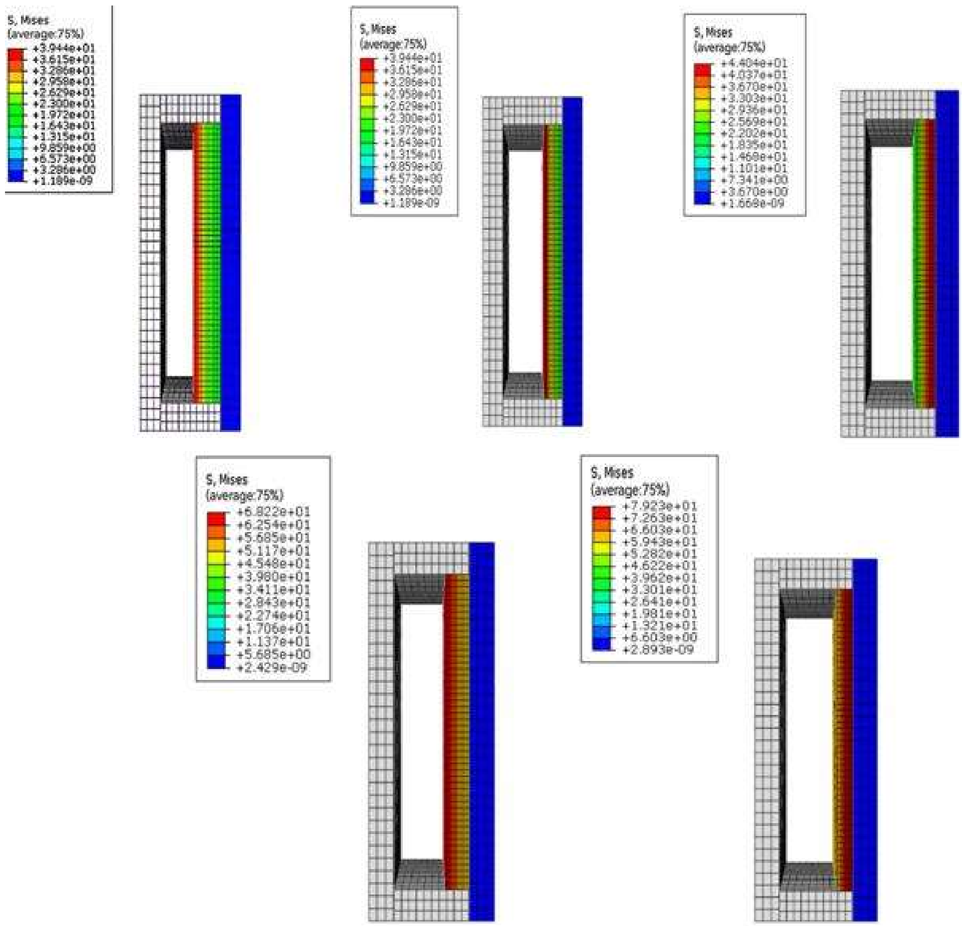

Figure 4. Contact stress nephograms at 45MPa, 50MPa, 60MPa, 70MPa and 80MPa

The anchoring force between the outer rubber element and the casing wall was calculated (Table 3). Based on the data in the table, the curve relationship between the internal pressure and the contact stress was plotted (Figure 5). It can be observed from the figure that when the internal pressure of the rubber element is greater than 80 MPa, the contact stress is very close to the internal pressure.[12]

Table 3. The anchoring force F_2 of the rubber element part of the K344-type packer.

Element internal pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)	Element internal pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)
45	39.4	63.3	65	59.4	95.2
50	42.7	73.4	70	68.22	101.1
55	44.0	80.4	75	73.65	109.1
60	49.5	88.1	80	79.23	117.4

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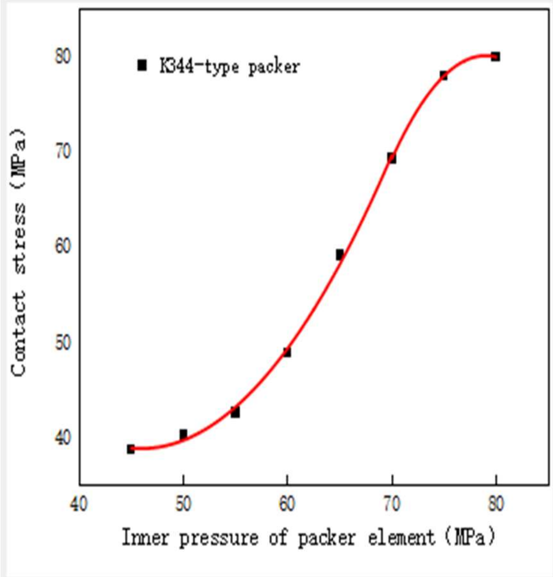

Figure 5. The relationship between the internal pressure of the rubber element and the contact stress curve

Combining the anchoring force data in Table 1 and Table 2, the total anchoring force of the K344 type packer under different working pressures can be obtained, as shown in Table 4.

Table 4. The total anchoring force F_A of the rubber element of the K344-type packer

Element internal pressure(MPa)	Total anchoring force (kN)	Element internal pressure(MPa)	Total anchoring force (kN)
45	507.83	65	738.06
50	568.03	70	793.2
55	624.3	75	850.75
60	681.35	80	908.74

3.2 Y241 Type Packer

Table 5. Parameters of Key Components of Y241-type Packer

component	Inner diameter(mm)	Outer diameter(mm)	Elastic modulus E(MPa)	Poisson's ratio μ	Coefficient of friction
slider	70	115	2.14	0.3	0.1
Casing	121	140	2.14	0.3	0.1
Central pipe	55	70	2.14	0.3	0.1
Rubber element	70	110	C_{10}	C_{01}	0.3
			1.87	0.47	

The key structures of the Y241 type packer include the slips and the rubber element. The slips belong to the anchoring mechanism of the packer. In the fracturing working state, the slips support the packer and lock the rubber element to prevent the axial movement of the packer. The elastic modulus of the key structures, such as the cone and the slips, is 2.3×10^5 MPa, the Poisson's ratio is 0.3, and the density is 7800 kg/m^3 . The rubber element expands in the radial direction by being compressed under an axial load and comes into contact with the inner wall of the casing.[13] The parameters of the key component structures are shown in Table 5.

Numerical calculations must similarly be combined with finite element software. By simplifying the model of the slips and rubber cylindrical components based on the working principle of the Y241 type packer, finite element analysis is conducted on the key components of the Y241 type packer-specifically the slips and rubber cylinder-using the Abaqus software, with the rubber cylinder material being hydrogenated nitrile rubber. The mesh division is illustrated in Figure 6.[14]

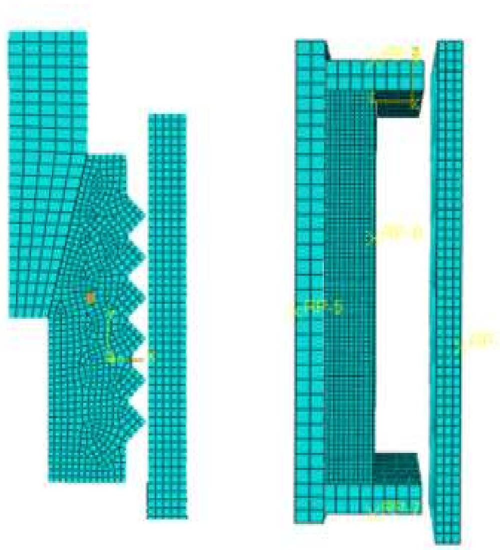

Figure 6. Mesh Division Diagram of the Slip and Rubber Element of Y241-type Packer

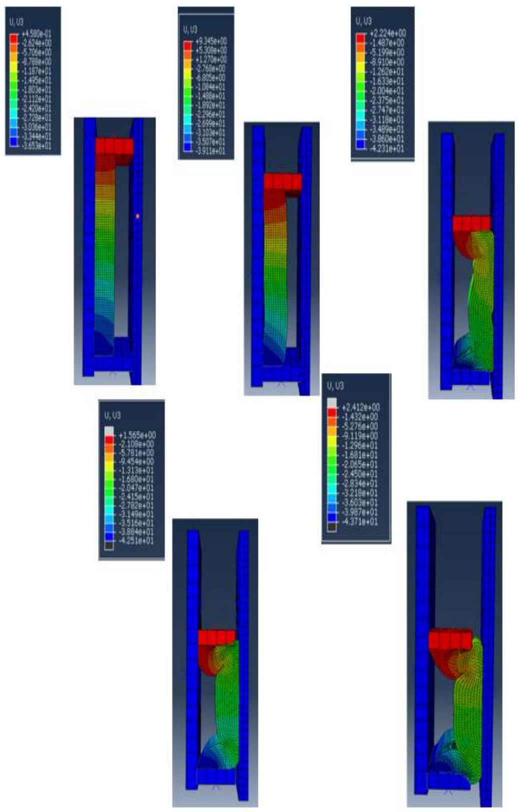

Figure 7. The compression distance of the rubber element at 50MPa, 55MPa, 65MPa, 70MPa and 80MPa

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move in the Y direction, restricting the bottom end's displacement in the Y direction, while the casing's bottom and outer wall are constrained in both Y and X direction displacements. For the rubber cylinder: during the operation of the Y241 type dissolvable packer, the constraints are as follows: the central pipe, casing, and lower shoulder are fixed; the inner surface of the rubber cylinder makes initial contact with the outer surface of the central pipe; the rubber cylinder and the upper and lower shoulders also have initial contact. After the load increases, the contact between the rubber cylinder and the casing wall is noted.[15] The analysis of the operating pressure for the rubber cylinder follows the same methodology as that used for the K344 type packer anchoring force analysis. Figure 7 shows the compression distance cloud map of the rubber cylinder under different working pressures.

From Figure 7, it can be observed that both the compression distance of the rubber cylinder and the contact stress with the casing increase with the external force. The axial compression distance of the rubber cylinder exhibits non-uniform variation, showing significant changes when initially loaded. As the working pressure increases, it gradually becomes more stable, as depicted in Figure 8.[16]

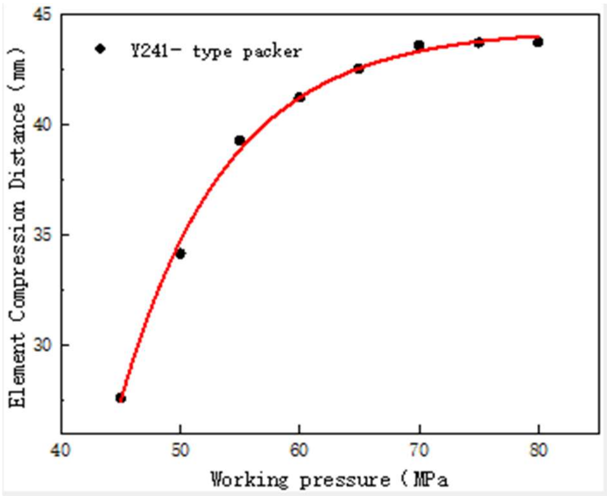

Figure 8. The curve of the compression distance of the rubber element varying with the operating pressure

At the same time, the data table of the contact stress between the rubber element and the casing under different working pressures is provided.

Table 6. The anchoring force F_1 between the rubber element of the Y241 dissolvable packer and the pipe wall

Working pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)	Working pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)
45	6.4	9.48	65	10.5	16
50	7.1	10.52	70	12.4	18.37
55	7.7	11.41	75	13.5	20
60	8.7	12.89	80	14.8	21.93

Draw a contact stress curve graph between the rubber element and the casing, with the working pressure as the abscissa and the contact stress as the ordinate.

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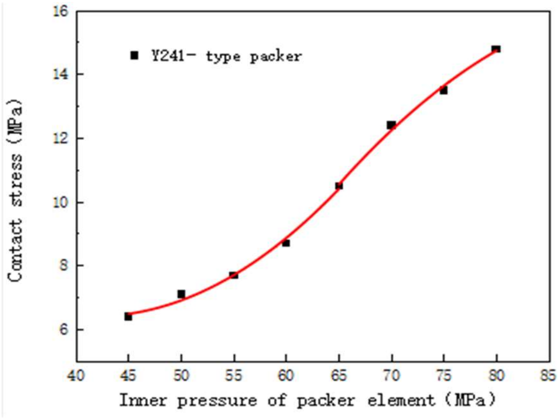

Figure 9. The contact stress curve between the rubber element and the casing

The setting of the packer relies on the key component, the slips. During the setting process, the slips are opened by axial working pressure, making contact and engaging with the casing. Analyzing the slips under different axial working pressures of 45MPa, 50MPa, 60MPa, 70MPa, and 80MPa, the displacement contour of the slips is shown in Figure 10, with displacements of 0.0241mm, 0.0267mm, 0.0321mm, 0.0374mm, and 0.0428mm.

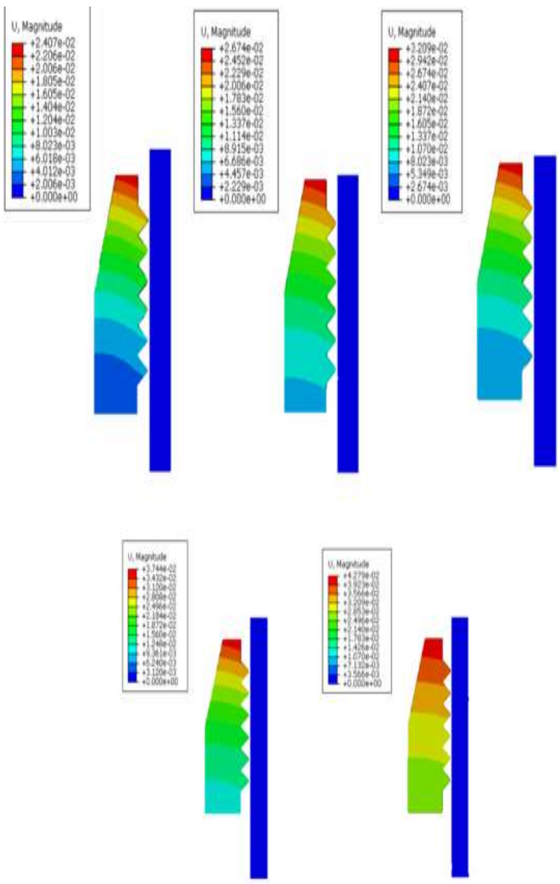

Figure 10. Displacement Nephogram of the Slip of Y241-type Packer

respectively. By statistically comparing this data, the resulting variation curve is illustrated in Figure 11. It can be observed that the displacement of the slips increases with the rise in axial working pressure, and the displacement of each slip tooth is different, with the maximum displacement occurring at the top slip tooth and gradually decreasing from top to bottom.

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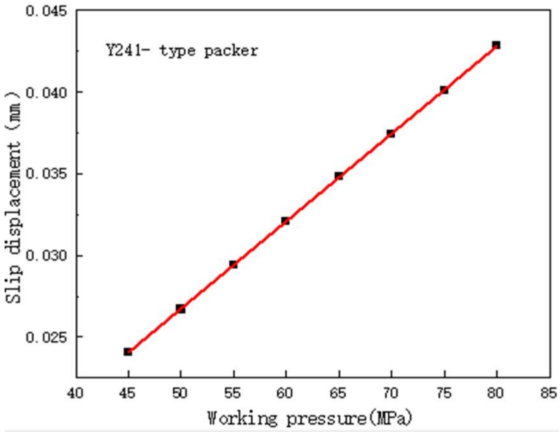

Figure 11. The displacement curve of the slip of Y241-type packer

Additionally, the contact stress of the slips at different axial working pressures was analyzed. Figure 12 presents the contact stress contour between the slips and the inner wall of the casing under varying loads. Combining the data from Table 7, we can derive the variation curve shown in Figure 13. It is evident that the stress on the slips also increases with the increased load, and similarly, the forces acting on different slip teeth vary, with the maximum stress occurring at the top slip tooth and decreasing progressively downward. By correlating the anchoring forces of the slips and the rubber sleeve.

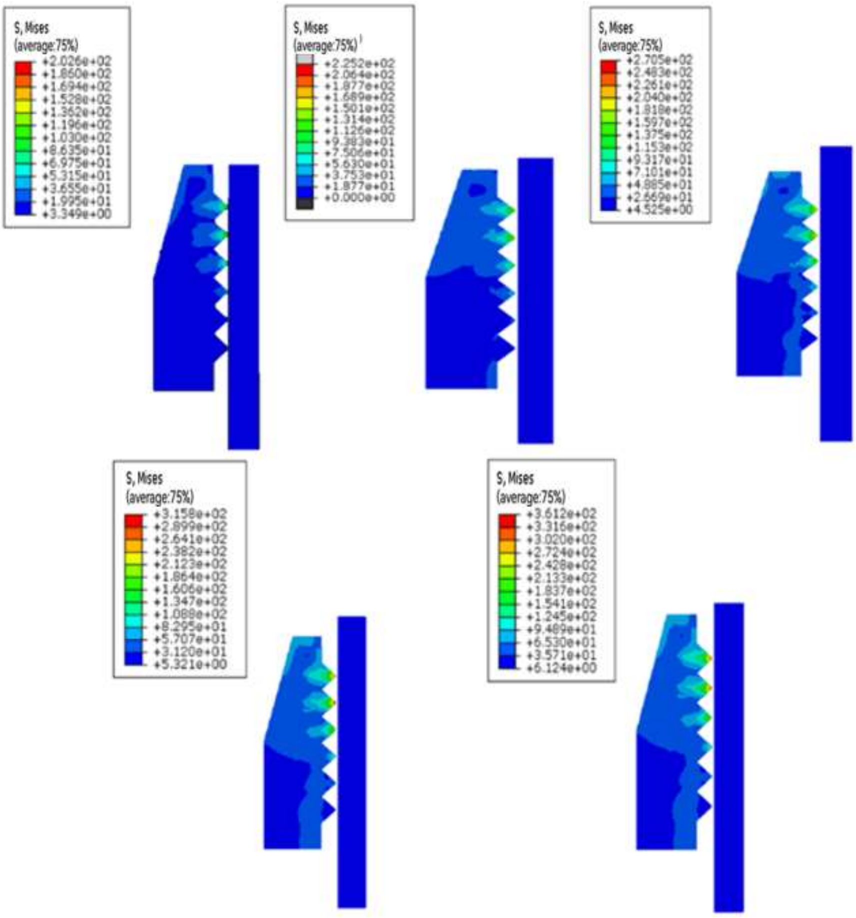

Figure 12. The contact stress curve of the slip of Y241-type packer

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Table 7. The total anchoring force F_2 of the slip structure of the Y241 packer

Working pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)	Working pressure(MPa)	Contact stress(MPa)	Anchoring force (kN)
45	202.6	300.1	65	293.1	446.6
50	225.2	333.7	70	315.8	467.8
55	247.8	367.2	75	338.5	501.5
60	270.5	400.8	80	361.2	535.2

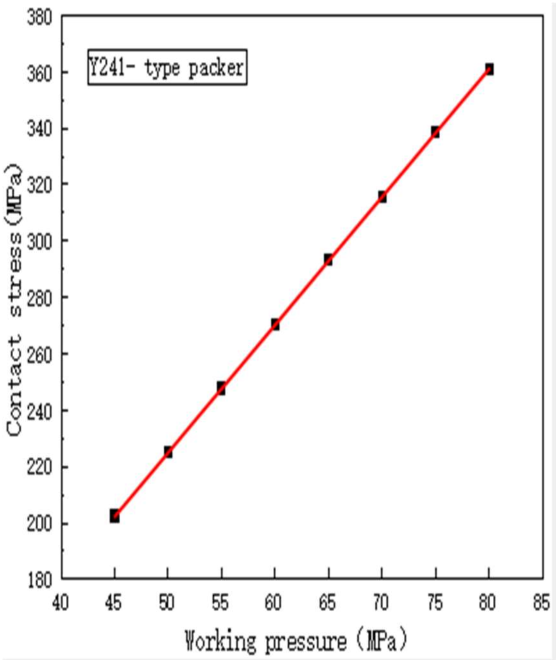

Figure 13. The contact stress curve of the slips of the Y241-type packer

with the casing as presented in Tables 6 and 7, we can derive the total anchoring force of the Y241 type packer during staged fracturing operations, as shown in Table 8.

Table 8. The total anchoring force F_A of the Y241 packer

Working pressure(MPa)	Total anchoring force (kN)	Working pressure(MPa)	Total anchoring force (kN)
45	309.58	65	462.6
50	344.22	70	486.17
55	378.61	75	521.5
60	413.69	80	557.13

4. Force Analysis of Multiple Packers during the Process of Stratified Fracturing

4.1 First-stage Fracturing

Based on the previous numerical simulations, the magnitudes of the anchoring forces borne by packers in different packer strings during staged fracturing operations are obtained. Now, an analysis of the axial forces of the packer strings during the staged fracturing process is to be carried out During the primary fracturing operation, the forces acting on the string are as shown in Figure 14. The axial forces are mainly induced by factors such as temperature and pressure variations. Specifically, they include the axial forces resulting from the temperature effect, piston effect, ballooning effect, and friction drag effect.

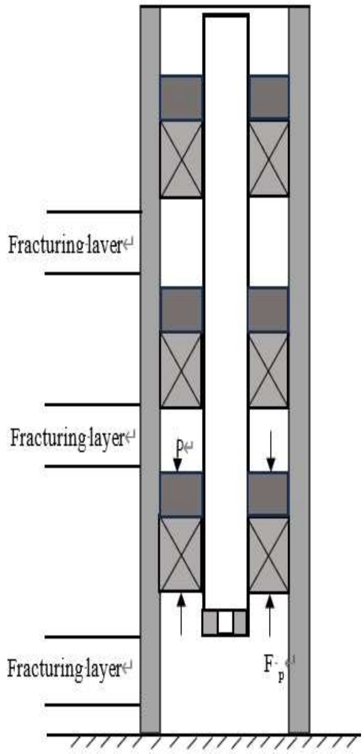

Figure 14. Force analysis during the first-stage fracturing

During the fracturing process, due to the injection of fracturing fluid, the downhole temperature will change. At this time, the axial force on the packer caused by the temperature effect due to the temperature change is.as follows:

$$F_1=-\beta EA_S\Delta T\times 10^{-3} \quad (4)$$

In the formula,F_1 represents the axial force generated by the temperature effect on the upper part of the packer, with the unit in kN;β is the coefficient of thermal expansion, taking a value in 1.2×10^{-5}/℃ ΔT is the temperature change, measured in℃； A_S is the cross-sectional area of the tubing string, in m^2

The tubing string above the packer will be affected by the piston effect due to the change in pressure difference. At this time, the axial force acting on the primary packer is as follows:

$$F_2=\frac{\pi}{4}\left[\left(d_T^2-d^2\right)P_i-\left(d_T^2-D^2\right)P_o\right]\times 10^{-3} \quad (5)$$

In the formula, F_2 is the axial force caused by the piston effect, in kN; P_i is the pressure at the lower part of the packer, in MPa; P_o is the annulus pressure at the upper part of the packer, in MPa; d is the inner diameter of the tubing, in m; D is the outer diameter of the tubing, in m. It can be seen from the formula that the axial force generated under the influence of the piston effect is related to the size of the packer.

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Therefore, the axial forces caused by the piston effect on the K344 type packer and the Y241 type packer during the first - stage fracturing are different. Due to the influence of the pressure difference between the inside and outside of the tubing string, the bulging effect will occur on the tubing string above the packer. The axial force acting on the packer is as follows:

$$F_3=\frac{\mu\pi}{2}(d^2P_i-D^2P_o)\times 10^{-3} \tag{6}$$

In the formula: Pi is the tubing pressure, in MPa; Po is the external pressure of the tubing, in MPa; d is the inner diameter of the tubing, in m; D is the outer diameter of the tubing, in m.

Meanwhile, the flow of liquid in the pipeline will generate frictional force. This frictional force is related to factors such as the fluid velocity and viscosity. At this time, the axial force acting on the tubing string above the packer is:

$$F_4=8\pi\mu vL \tag{7}$$

In the formula: v is the fluid flow velocity, in m/s; μ is the fluid dynamic viscosity; L is the length of this section of the tubing string.

Combining the above analysis, the total axial forces acting on the K344 type packer and the Y241 type packer during the first - stage fracturing process are as follows:

$$F_A=F_1+F_2+F_3+F_4 \tag{8}$$

In the formula, F1 is the axial force caused by the temperature effect, in kN; F2 is the axial force caused by the piston effect, in kN; F3 is the axial force caused by the bulging effect, in kN; F4 is the axial force caused by the friction drag effect, in kN.[17]

By substituting the data, the axial forces acting on the two types of packers during the first - stage fracturing operation are shown in Table 9.

Table 9. The axial force F_A acting on the packer during the first-stage fracturing operation

	F_1	F_2	F_3	F_4	F_A
Y241 packer	113.42	260.8	51.54	214.88	640.64
K344 packer	113.42	272.8	51.54	214.88	606.68

4.2 Second-stage Fracturing

The forces acting on the tubing string during the second-stage fracturing operation are shown in Figure 15. At this time, the first-stage fracturing has been completed, so the main force is generated at Packer 2. Due to the differences in factors such as the position of the packer and the position of the fracturing formation, the axial forces generated under the influence of the temperature effect, piston effect, bulging effect, and friction drag effect are numerically different even though they are all affected by these factors.[18] By substituting the data into the relevant formulas, the values of the axial forces of the tubing strings of different packers during the second-stage fracturing are shown in Table 10.

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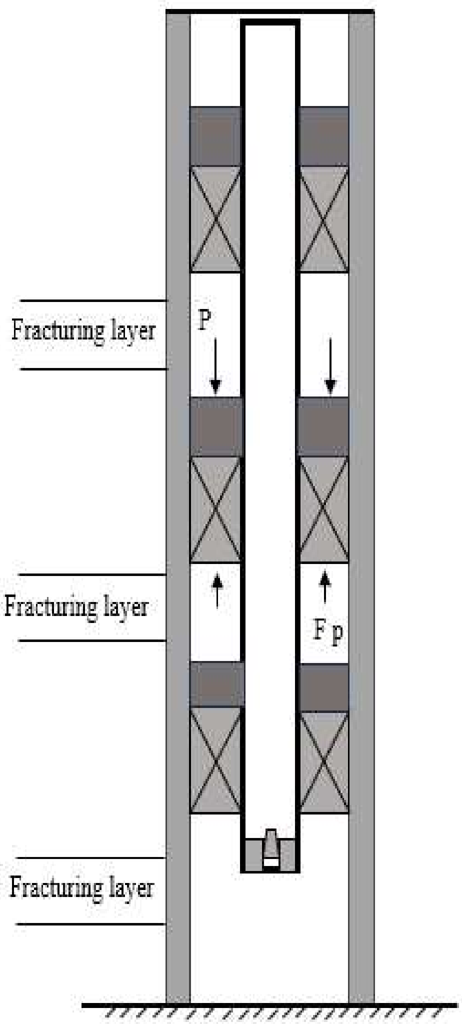

Figure 15. Force analysis during the second-stage fracturing

Table 10. The axial force F_A acting on the packer during the second-stage fracturing operation

	F_1	F_2	F_3	F_4	F_A
Y241 packer	107.82	313.64	54.63	90.33	566.42
K344 packer	108.82	272.8	55.63	91.33	525.58

In the formula, F1 is the axial force caused by the temperature effect, in kN; F2 is the axial force caused by the piston effect, in kN; F3 is the axial force caused by the bulging effect, in KN; F4 is the axial force caused by the friction drag effect, in KN.

4.3 Third-stage fracturing

During the third - stage fracturing operation, both the first - stage and second - stage fracturing operations have been completed. The forces acting on the tubing string are shown in Figure 16. The axial force at Packer 3 is the same as that in the first - stage and second - stage fracturing operations. The total axial force is as follows:

$$F_A=F_1+F_2+F_3+F_4 \tag{9}$$

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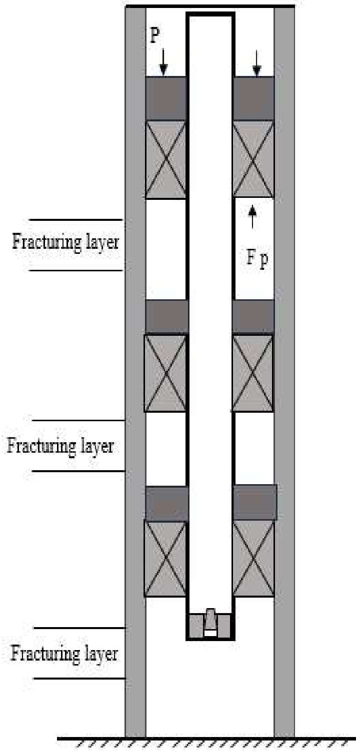

Figure 16. Force analysis during the third-stage fracturing

By substituting the relevant data for the third - stage fracturing operation, the axial forces acting on the tubing strings of the two types of packers are shown in Table 11.

Table 11. The axial force F_A acting on the packer during the third-stage fracturing operation

	F_1	F_2	F_3	F_4	F_A
Y241 packer	107.23	343.79	53.99	61.71	566.72
K344 packer	107.23	299.03	53.99	61.71	521.96

In the formula, F1 is the axial force caused by the temperature effect, in kN; F2 is the axial force caused by the piston effect, in kN; F3 is the axial force caused by the bulging effect, in KN; F4 is the axial force caused by the friction drag effect, in KN

5. Staged Multi - packer Tubing String Structure

The hydraulic anchor is an indispensable and important component in the hydraulic fracturing process. Its main function is to achieve reliable anchoring to the wellbore wall through hydraulic power, thereby fixing the fracturing tubing string and preventing its axial displacement during the fracturing process. its basic structure usually includes components such as springs, slips, and pressure plates. Under different operating conditions, a reasonable selection of the connection of the hydraulic anchor can improve its anchoring effect, ensure the smooth progress of the operation, and ultimately achieve the goal of increasing production.

Based on the axial forces and anchoring forces respectively borne by the Y241 type packer and the K344 type packer during the staged fracturing process, the connection situations of the hydraulic anchors under each stage of fracturing operations are analyzed.

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5.1 Structural Optimization of K344 Type Packer

As can be seen from the calculation and analysis of the above - mentioned data, the magnitudes of the axial forces and anchoring forces of the multi - packer staged fracturing tubing string using the K344 type packer vary during the staged fracturing process. Therefore, the connection conditions of the hydraulic anchors also vary. The fracturing data at each stage and the connection conditions of the hydraulic anchors under different working pressures are shown in Table 12.

Table 12. Connection conditions of the hydraulic anchor for K344-type packer

<table>
<tr><th>Internal pressure (MPa)</th><th>Anchoring force(kN)</th><th>First Fracturing Axial Force(kN)</th><th>Second Fracturing Axial Force(kN)</th><th>Third Fracturing Axial Force(kN)</th><th>first-stage</th><th>second-stage</th><th>third-stage</th></tr>
<tr><td>45</td><td>507.83</td><td rowspan="6">606.68</td><td rowspan="6">525.58</td><td rowspan="6">521.96</td><td rowspan="2">required</td><td>required</td><td>required</td></tr>
<tr><td>50</td><td>568.03</td><td rowspan="5">not required</td><td rowspan="5">not required</td></tr>
<tr><td>55</td><td>624.3</td><td rowspan="4">not required</td></tr>
<tr><td>60</td><td>681.35</td></tr>
<tr><td>70</td><td>793.06</td></tr>
<tr><td>80</td><td>908.74</td></tr>
</table>

Based on the above - mentioned data, it can be seen that during the first - stage fracturing, when the internal pressure is within 50MPa, the anchoring force is insufficient to resist the axial force, and a hydraulic anchor needs to be connected at this time. When the internal pressure is 55MPa, the anchoring force is sufficient, and there is no need to connect a hydraulic anchor.

Under the working conditions of the second - stage and third - stage fracturing, when the internal pressure is 45MPa, the anchoring force is insufficient to resist the axial force, and a hydraulic anchor needs to be connected. When the internal pressure is 50MPa, the anchoring force is greater than the axial force, and there is no need to connect a hydraulic anchor.

In response to this situation, the linear interpolation method is used to calculate the internal pressure value at which a hydraulic anchor is required for each stage of fracturing. The linear interpolation method is a mathematical method based on known data of two points to estimate the value of an unknown point in the middle through a linear relationship. Its core idea is to assume that the data change between two known points is linear, thereby constructing a linear equation to predict the intermediate value. The linear interpolation formula is:

$$P_c = P_1 + \frac{(F_p - F_1)}{(F_2 - F_1)} \times (P_2 - P_1) \tag{10}$$

By substituting the data under each stage of fracturing conditions, the following results can be obtained: the critical pressure Pc for the first-stage fracturing is 53.43MPa; the critical pressure Pc for the second-stage fracturing is 46.47MPa; and the critical pressure Pc for the third-stage fracturing is 46.17MPa.

Then, the conditions for connecting the hydraulic anchor when the K344-type packer is used in layered fracturing are shown in Table 13.

Table 13. Connection conditions of the hydraulic anchor

Fracturing stage	critical internal pressure(MPa)	Hydraulic anchor
first-stage	<53.43	required
second-stage	<46.17	required
third-stage	<46.47	required
first-stage	>53.43	not required
second-stage	>46.17	not required
third-stage	>46.47	not required

5.2 Structural Optimization of Y241 Type Packer

According to the known data, in the three - stage fracturing of the multi - packer pressure - dividing string using the Y241 - type packer, the anchoring force is always less than the axial force, and a hydraulic anchor needs to be configured to make up the difference. The pressure-bearing capacity of the hydraulic anchor is calculated by the formula: pressure-bearing capacity of hydraulic anchor=axial force-anchoring force. Considering comprehensively, the hydraulic anchor needs to be able to cover the difference under the corresponding design pressure in each stage of fracturing, and the pressure-bearing capacity of the hydraulic anchor is selected according to the most stringent condition (i.e., the maximum difference). The following table shows the minimum pressure-bearing calculation for each stage of fracturing.

Table 14. Design of the pressure-bearing capacity of the hydraulic anchor for Y241-type packer

Fracturing stage	Work pressure(MPa)	Packer anchoring force(kN)	Total axial force(kN)	Hydraulic anchor pressure	Safety factor	Designed pressure(kN)
first-stage	80	557.13	640.64	83.51	1.5	125.27
second-stage	70	486.17	566.42	80.25	1.5	120.38
third-stage	60	413.69	566.72	153.03	1.5	229.55

6. Conclusion

Through theoretical modeling and finite - element simulation, a systematic analysis was conducted on the anchoring forces of the Y241 type compression packer and the K344 type expansion packer. The anchoring force of the K344 type packer completely depends on the contact stress of the rubber element expansion. Its total anchoring force increases non - linearly with the internal pressure. The anchoring force of the Y241 type packer results from the synergistic effect of the slip friction and the contact stress of the rubber element.

During the staged fracturing process, the anchoring force of the Y241 type packer is always lower than the axial force. A hydraulic anchor needs to be configured throughout the process. Considering the safety factor of the hydraulic anchor and combining with the data, a hydraulic anchor with a pressure - bearing capacity of about 300 kN can be used. The critical internal pressure of the K344 type packer during each stage of fracturing is lower than 55 MPa. Above 55 MPa, it can achieve a good tubing string anchoring effect, ensuring the safety of the tubing string during the fracturing operation, and there is no need to connect a hydraulic anchor.

This paper simplifies the mechanical models of the K344 type packer and the Y241 type packer, ignoring complex situations such as downhole fluid and casing conditions. The analysis may not be accurate. Subsequently, the K344 type packer and the Y241 type packer can be used in combination according to their anchoring force conditions.

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