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Study on Failure Length of Cementing Interface in Horizontal Wells During Fracturing

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Abstract
The cementing interface of oil and gas wells is often the weak link between oil and gas turbulence. Due to the low cementation strength at the fracturing interface, the two interfaces have been crushed to form turbulence channels before the target layer is opened during fracturing. If the closure is not good, there will be inter-layer channeling. Therefore, the pressure bearing capacity of the fracturing interface is an important indicator for designing the fracturing construction parameters. The pressure capacity of the two interfaces during the fracturing process is the key to evaluating the success of the fracturing construction. This paper establishes the calculation model for the stress distribution of horizontal wells in horizontal wells under the effect of non-uniform stress. At the same time, the influence of the pressure change in the wellbore during the fracturing process on the stress distribution in the borehole wall was analyzed. The calculation model of the interfacial stress distribution in the horizontal well during the fracturing process was established, and the debonding pressure and debonding length of the two interfaces under different cementing strengths were calculated. After the establishment of the horizontal well fracturing two interface crack propagation mechanics model, calculate the pressure required for cracks along the two interfaces to expand at different failure lengths.

Key words : Second interface; Cementation strength; Shear stress; Mechanical model

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INTRODUCTION

Cementing operation is one of the most important aspects of oil and gas well drilling engineering. The second interface of oil and gas well cementing is a highly variable interface. The second interface of cement ring is often the weak link of oil and gas slag. Cementing second interfac, it is actually a cemented interface between the solidified cement solids and the filter cake formed on the surface of the borehole wall and the cemented interface formed between the filter cake and the borehole wall. It has many influencing factors[1-3].The fundamental reason why the horizontal well cementing interface is still outstanding is that there are two objective facts about the wellbore actually drilled:One is that the borehole diameter is irregular, and the other is that the mud cake is thick, and both of them form a mud cake that is embedded between the cement slurry and the wall surface of the formation[4].Studies have shown that as long as there are mud cakes, no matter how thin, there will be a certain degree of peeling between the cement ring and the formation rock to form micro-cracks, resulting in decreased interface cementation strength.

The horizontal interface failure mechanics model for horizontal wells during the fracturing process is divided into two parts: one is the two-interface debonding mechanical model, and the other is the fracture along the interface expansion model.

1. INTERFACE DEBONDING MECHANICAL MODEL(ZHAO,2009)

In this paper, when the force calculation is performed, the two interfaces and the cement ring are considered separately, and the second interface is considered to be a low-strength cement ring sandwich.Take the horizontal section of length L as the study object, and set the length of the debonding area of the two interfaces to l_1.and $l_1 < L$,first make several assumptions about the model:

(1) The interface between stratum and cement ring is only subjected to shear stress;

(2) Ignore the bending effect;

(3) Section stress, displacement and section shear stress of two interface sealing system components are uniformly distributed.

(4) The bushing does not produce displacement under the action of the fracturing fluid.

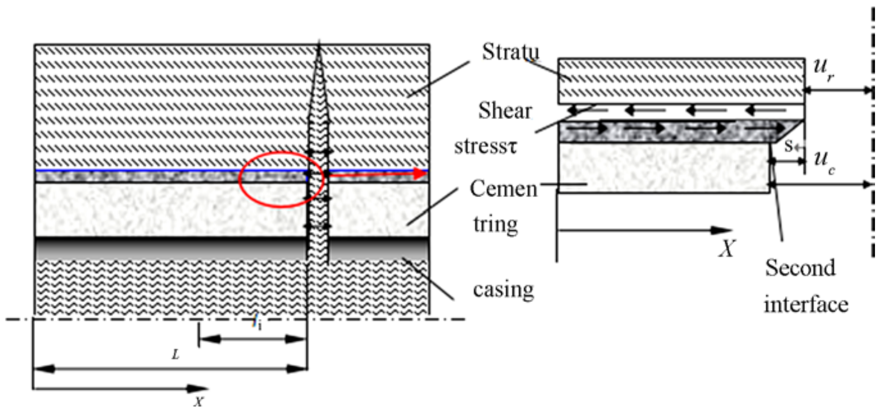


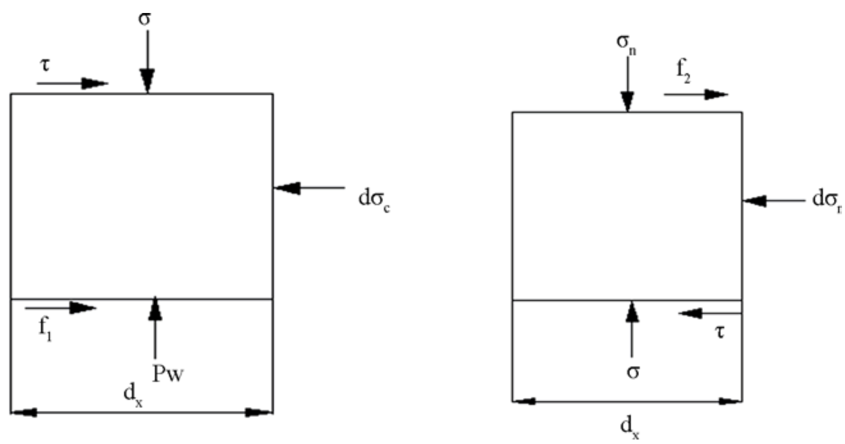
Figure 1
Schematic Diagram of the Relative Sliding of the Second Interface

Based on the assumptions and Figure 1, the formula for the relative slip of the interface between the formation and the cement ring can be listed:

$$u = u_r - u_c - \frac{h\tau}{G} \tag{1-1}$$

Where: h is the thickness of the two interfaces, m; G is the shear modulus of the two interfaces, MPa;Ur is the displacement of the formation rock under the action of the fracturing fluid, m;Uc is the displacement of cement ring under the action of fracturing fluid,m

The cement ring at the perforation hole was taken as the research object, and cement ring microelements were taken for force analysis.



Figgure 2
The Stress State of the Micro-Element Segment of the Cement Ring

The analysis shows that the left and right sides of the cement ring at the perforation are subjected to the compressive stress of the fracturing fluid, and the front and rear sides are affected by the borehole internal pressure and the in-situ stress, respectively, to list the cement ring microelement force equilibrium equation:

$$\left(\sigma_c - d\sigma_c\right) A_c + \tau dxC_1 + p_w dxC_2\mu_2 + \tau_0 dxC_1 = \sigma_c A_c \tag{1-2}$$

The formula will be expanded:

$$\begin{aligned} &\frac{n}{360}\left(\sigma_c - d\sigma_c\right)\pi\left(r_1^2 - r_2^2\right) + \tau dx\frac{n}{180}\pi r_1 + p_w dx\frac{n}{180}\pi r_2\mu_2 \\ &= \sigma_c\frac{n}{360}\pi\left(r_1^2 - r_2^2\right) \end{aligned} \tag{1-3}$$

In the formula:Ac is the force cross section of the cement ring microelement,m^2 C1 is the arc length outside the cement ring,m. C2 is the inner arc length of the cement ring, m; n is the degree of the circle angle, °;σ_n is the normal force along the outside of the cement ring, MPa;r_1 is the outer diameter of the cement ring, m;r_2 is the inner diameter of the cement ring, m; P_w is wellbore internal pressure, MPa; μ_1 is the coefficient of friction at an interface, dimensionless;τ_0 is the interface bond strength, MPa.

Thus, the relationship between the interfacial shear stress and the compressive stress on the cement ring is obtained:

$$\tau = \frac{\left(r_1^2 - r_2^2\right)}{2r_1}\frac{d\sigma_c}{dx} - p_w\frac{r_2}{r_1}\mu_2 \quad (1\text{-}4)$$

Assuming 0≤x≤L-l1 in the bonding elastic zone, the relative slippage of the interface is u=0.

$$\frac{G\left(u_c - u_r\right)}{h} = \frac{\left(r_1^2 - r_2^2\right)}{2r_1}\frac{d\sigma_c}{dx} - p_w\frac{r_2}{r_1}\mu_2 - \tau_0 \quad (1\text{-}5)$$

Known by Hooke's Law:

$$\varepsilon_c = \frac{\sigma_c}{E_c}\ ,\ \ \varepsilon_r = \frac{\sigma_r}{E_r} \quad (1\text{-}6)$$

After x differentiation, we get:

$$\frac{\left(r_1^2 - r_2^2\right)}{2r_1}\frac{\mathrm{d}^2\sigma_c}{\mathrm{d}x^2} = \frac{G}{h}\left(\frac{\sigma_c}{E_c} - \frac{\sigma_r}{E_r}\right) \quad (1\text{-}7)$$

Assume that the stress in the section and the cement ring system are uniformly distributed.

$$A_r\left(\sigma_r - \sigma_h\right) + A_c\left(\sigma_c - \sigma_h\right) = 0 \quad (1\text{-}8)$$

Where: A_r is the vertical section of the stratum at the hole, m^2; A_c is the longitudinal section of the cement ring at the hole, m2; σ_n is the horizontal stress in the section along the wellbore, MPa.

After finishing:

$$\frac{d^2\sigma_c}{dx^2} = \frac{2r_1G}{\left(r_1^2 - r_2^2\right)h}\left[\left(\frac{1}{E_c} + \frac{A_c}{E_rA_r}\right)\sigma_c - \left(\frac{1}{E_r} + \frac{A_c}{E_rA_r}\right)\sigma_h\right] \quad (1\text{-}9)$$

In the case of no softening, after the interface is debonded, due to the interlocking of the cementite ring and the micro-convex peaks on the surface of the formation, the residual adhesive stress remains at the interface.With the increase of the interface slip, the residual bond stress will eventually become constant with the wear of the surface micro-convex peak group, so when the model is solved, the shear stress in the debonded area is considered to be a constant value τ_0.

At the same time, when perforating a horizontal hole, in the debonded area, the boundary conditions are debonded,L-l_1<x<L. Shear stress fails, considered equal to zero, σ_c=p_w Here p_w refers to fracturing fluid pressure;

The final solution is:

$$\sigma_c = p_w - \frac{2r_1}{\left(r_1^2 - r_2^2\right)}\left(\tau_0 + p_w\frac{r_2}{r_1}\mu_2\right)\left(L - x\right) \quad (1\text{-}10)$$

Boundary conditions in the bonded elastic zone, 0≤x<L-l_1 In x=0 locations not affected by the fracturing fluid,σ_c =-σ_h At x =L-l, the cement stone has continuous transverse stress, which is $\sigma_c\big|_{x=(L-l_1)^-} = \sigma_c\big|_{x=(L-l_1)^+}$ make

$$P = \frac{2r_1G}{h\left(r_1^2 - r_2^2\right)}\left(\frac{1}{E_c} + \frac{A_c}{E_rA_r}\right)\quad Q = \frac{-2r_1G}{\left(r_1^2 - r_2^2\right)h}\left(\frac{1}{E_r} + \frac{A_c}{E_rA_r}\right)\sigma_h$$

$$M = p_w - \frac{2r_1}{\left(r_1^2 - r_2^2\right)}\left(\tau_0 + p_w\frac{r_2}{r_1}\mu_2\right)l_1 \quad (1\text{-}11)$$

Get σ_c calculation formula:

$$\sigma_c = \frac{e^{\sqrt{P}x} - e^{-\sqrt{P}x}}{e^{-\sqrt{P}(L-l_1)} - e^{\sqrt{P}(L-l_1)}}\left[\left(\frac{Q}{P} - \sigma_h\right)e^{-\sqrt{P}(L-l_1)} - \left(\frac{Q}{P} + M\right)\right] - \frac{Q}{P}$$
$$= \frac{\left(\frac{Q}{P} + M\right) - \left(\frac{Q}{P} - \sigma_h\right)e^{-\sqrt{P}(L-l_1)}}{\sinh\left[\sqrt{P}\left(L - l_1\right)\right]}\sinh\left(\sqrt{P}x\right) - \frac{Q}{P} \quad (1\text{-}12)$$

Where σ_c derivation:

$$\frac{d\sigma_c}{dx} = \frac{\left(\frac{Q}{P} + M\right) - \left(\frac{Q}{P} - \sigma_h\right)e^{-\sqrt{P}(L-l_1)}}{\sinh\left[\sqrt{P}\left(L - l_1\right)\right]}\cosh\left(\sqrt{P}x\right)\sqrt{P} \quad (1\text{-}13)$$

As the pressure of the fracturing fluid continues to increase, the shear stress on the stressed end first reaches the local bond strength at the interface and debonding and slipping occur. Through the previous analysis of the cement ring microelements, when the debonding slip occurs at the second interface, the interfacial shear stress calculation formula can be expressed as:

$$\tau = \frac{1}{2}\frac{r_1^2 - r_2^2}{r_1}\frac{d\sigma_c}{dx} - p_w\frac{r_2}{r_1}\mu_2$$

$$\frac{d\sigma_c}{dx} = \sqrt{P}\left[\left(\frac{Q}{P} + M\right) - \left(\frac{Q}{P} - \sigma_h\right)e^{-\sqrt{P}L}\right]\coth\left(\sqrt{P}L\right) \quad (1\text{-}14)$$

When the shear stress τ reaches the interface cementation strength, the interface begins to debond and produce slip, and the debonding pressure of the second interface can be calculated by the above formula. Taking the stratum at the perforation hole as the research object, the stratum microelements are taken for force analysis, and the force equilibrium equation of the stratum microelements is analyzed and listed:

$$\left(\sigma_r - d\sigma_r\right)A_r + \sigma_n dxC_3\mu_1 + \tau_0 dxC_3 = \tau dxC_4 + \sigma_r A_r \quad (1\text{-}15)$$

Where: μ_1 is the coefficient of friction between rock formations; C_3 is the lateral area of the rock, m2; C_4 is the inner area of rock in the formation, and the size is equal to the outer area of the cement ring, m^2.

Because σ_c and σ_r satisfy the relation:

$$\sigma_r = \frac{A_c}{A_r}\left(\sigma_h - \sigma_c\right) + \sigma_h \quad (1\text{-}16)$$

After finishing:

$$\frac{\left(\frac{Q}{P}+M\right)-\left(\frac{Q}{P}-\sigma_h\right)e^{-\sqrt{P}(L-l_1)}}{\sinh\left[\sqrt{P}\left(L-l_1\right)\right]}\cosh\left(\sqrt{P}x\right)=\frac{2\mu_1\sigma_n R_1+2p_w r_2\mu_2+4\tau_0 r_1}{\sqrt{P}\left[r_1^2-r_2^2-\frac{A_c}{A_r}\left(R_1^2-R_2^2\right)\right]} \tag{1-17}$$

To calculate the debonding length l_1, substitute $x=L-l_1$ into the above formula:

$$\left(\frac{Q}{P}+M\right)-\left(\frac{Q}{P}-\sigma_h\right)e^{-\sqrt{P}(L-l_1)}=\frac{2\mu_1\sigma_n R_1+2p_w r_2\mu_2+4\tau_0 r_1}{\sqrt{P}\left[r_1^2-r_2^2-\frac{A_c}{A_r}\left(R_1^2-R_2^2\right)\right]}\tanh\left[\sqrt{P}\left(L-l_1\right)\right] \tag{1-18}$$

Under the same downhole pressure, the debonding length of the two interfaces increases with the increase of the elastic modulus of the formation. This shows that the greater the difference between the nature of the formation and the cement ring, the easier the debonding occurs at the second interface, resulting in slip damage.

2. INTERFACE CRACK PROPAGATION MODEL

In the horizontal well fracturing process, the cementation strength and fracture toughness at the second interfaceare less than the cementation strength and fracture toughness of the formation and cement ring, When the hydraulic pressure leaks into the formation and forms cracks in the formation, the weak interface at the second interface will also be leaked. Affecting the bonding quality of the interface, it is easy to cause turbulence and other undesirable phenomena, further affecting the cementing quality. Therefore, it is necessary to study the influence of the pressure of the fracturing fluid on the failure length of the second interface. According to the theory of linear elastic fracture mechanics, crack propagation must have two conditions: First, there must be enough stress at the top of the crack to create some mechanism for crack propagation; second, there must be enough energy to inject the top of the crack to work to create a new surface[6]. In this paper, the mechanical model of crack propagation is established, and the relationship between the pressure of the fracturing fluid and the failure length of the second interface is analyzed.

When establishing the fracture expansion mechanics model, take the azimuth θ = 0. The crack extends along the perimeter of the wellbore, ie, the slot width is 2b, the slot length is 2a, and the fracturing fluid pressure is P. The center of the fracture is the center of the perforation, and the fracture is subjected to the expansion force P of the fracturing fluid and the radial force σ_r around the wellbore. Take the center O of the hole as the origin of the coordinates, along the two interfaces, the direction of the seam length is the x-axis, and the direction of the seam width is the y-axis. Establish the coordinate system as shown in Figure 3.

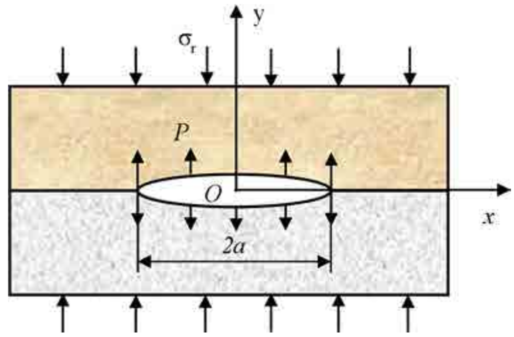


Figure 3
Expansion of Cracks Along the Well Axis at the Second Interface

When establishing the relationship between failure length of the secondary interface and fracturing fluid pressure, In relation to the debonding length 2a of the previous two interfaces, it is considered that the two interfaces are extended on the basis of the debonding length, and the crack propagation type belongs to the type I crack. It also involves the stress intensity factor K_I and fracture toughness K_{IC}. Cracks will only expand when the stress intensity factor is greater than or equal to the fracture toughness[7].

In the hydraulic fracturing process, the stress is more complicated when the crack expands. The distribution law of stress field and displacement field at the crack tip of the two interfaces can be followed without the same mechanical model. For this purpose, the mechanical model at the two interfaces needs to be decomposed into three simple models, and the stress can be superimposed at the end.

(a)There is no crack at the two interfaces, and it is affected by the uniform compressive stress σ_r at a distance;

(b)Long cracks with a length of 2a, far away from the force, the role of uniform tensile stress σ_r on the crack surface;

(c)Long cracks with a length of 2a, far away from the force, act on the surface of the crack and exert a uniform stress p.

By the principle of superposition, the stress intensity factor K_I at the crack tip at the interface can be obtained.

$$K_I=\left(p-\sigma_r\right)\sqrt{\pi a} \tag{2-1}$$

In the fracturing fluid injection process, frictional resistance along the fracturing string, near-well frictional resistance, and frictional resistance within the fracture are generated. In the depth of a certain well, the first two frictional resistances are constant and will not change, and the frictional resistance in the joints will increase with the increase of the crack extension length, so the pressure of the fracturing fluid at the crack tip is continuously decreasing. The fracturing fluid fracturing fluid friction resistance calculation process is as follows. In general, the relationship between surface pump pressure and pressure in the formation during fracturing operations can be expressed as:

$$P_f = P_{well}(t) + P_H - P_B - P_M - P_F - \Delta P_{fra} \qquad (2\text{-}2)$$

Where: P_f is the fracturing fluid at the crack tip pressure, MPa; P_{well} is the ground wellhead pump pressure, MPa; P_H is wellbore liquid column static pressure, MPa; P_B is the bottom formation fracture pressure, MPa; P_F is frictional pressure along the column, MPa; P_M is the near-well friction resistance, MPa; $\triangle P_{fra}$ is the flow friction resistance in the seam, MPa.

According to the law of crack propagation, cracks will continue to expand when the pressure at the fracture tip is higher than the pressure required for the expansion of the fracture. Therefore, when the pressure of the fracturing fluid equals the pressure required for crack propagation, the crack stops expanding, and the length of the expansion at this time is the maximum length of the two interface failure.

Take the direction of the wellbore in line with the direction of the maximum horizontal stress, perpendicular to the minimum horizontal stress, The inner and outer diameters of the cement ring were 77.57mm and 127.57mm, respectively, and the outer radius of the formation was 200mm. The elastic modulus of the formation was Er=2000MPa, and the elastic modulus of the cement ring was Ec=1100MPa. Calculate the debonding length of the second interfaces under different fracturing fluid pressures. The results are shown in the Figure 4.

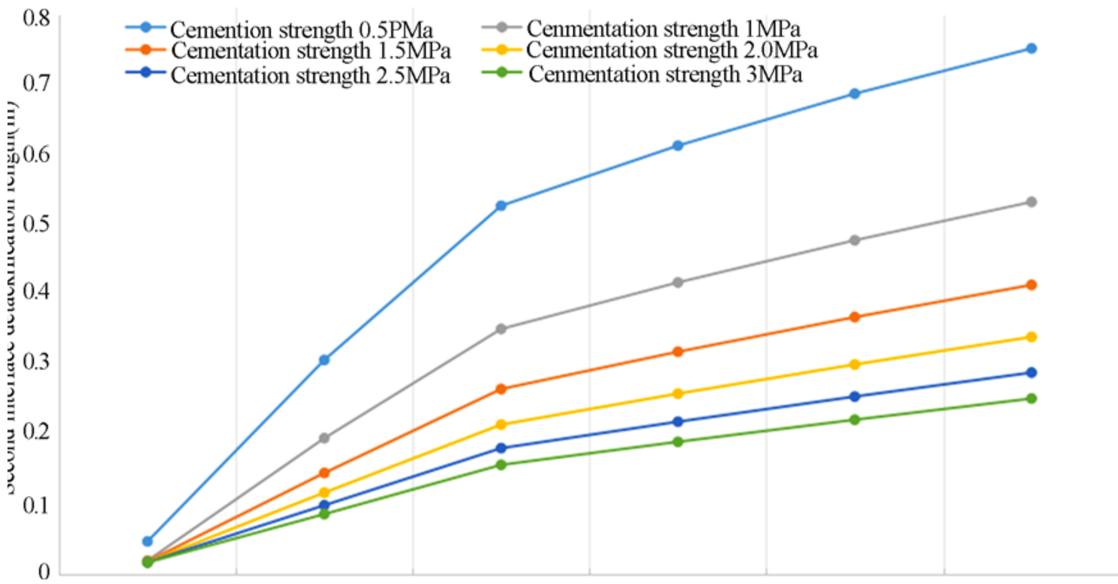


Figure 4
Debonding Length of Two Interfaces Under Different Cementing Strength

The different lines in the figure represent the strengths of the two different interfaces. After the comparison, it can be found that as the cementation strength increases, the debonding length of the seond interfaces decreases, which is consistent with the expected results.

When analyzing the influence of stratum properties on the debonding length of the two interfaces, the fixed cement ring elastic modulus Ec=1000 MPa, the elastic modulus of the formation from 1000 MPa to 2000 MPa, and the debonding length of the two interfaces under different formation elastic moduli are calculated, as shown in the Figure 5:

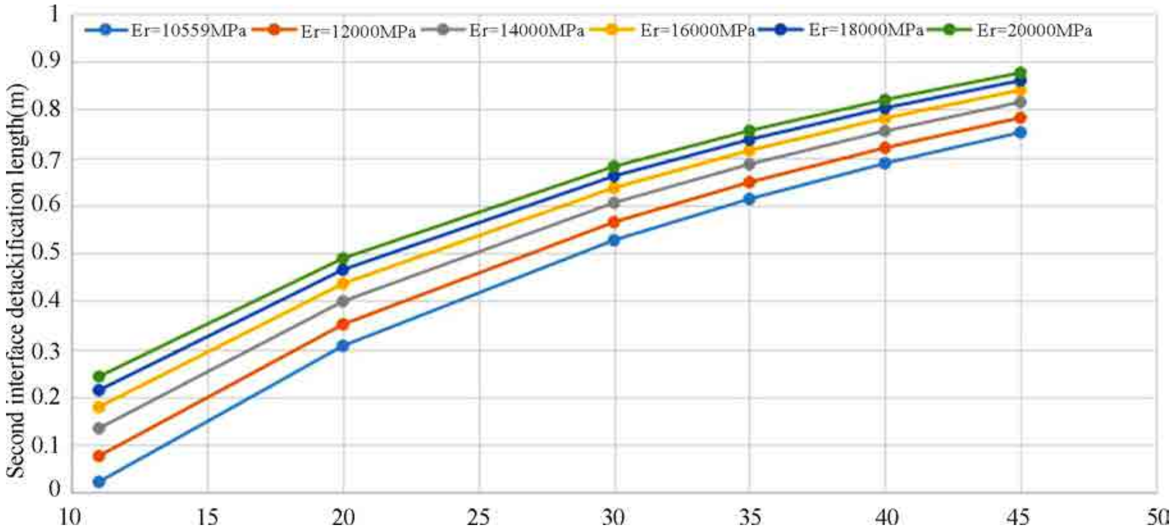


Figure 5
Debonding Length of the Second Interfaces Under Different Elastic Modulus

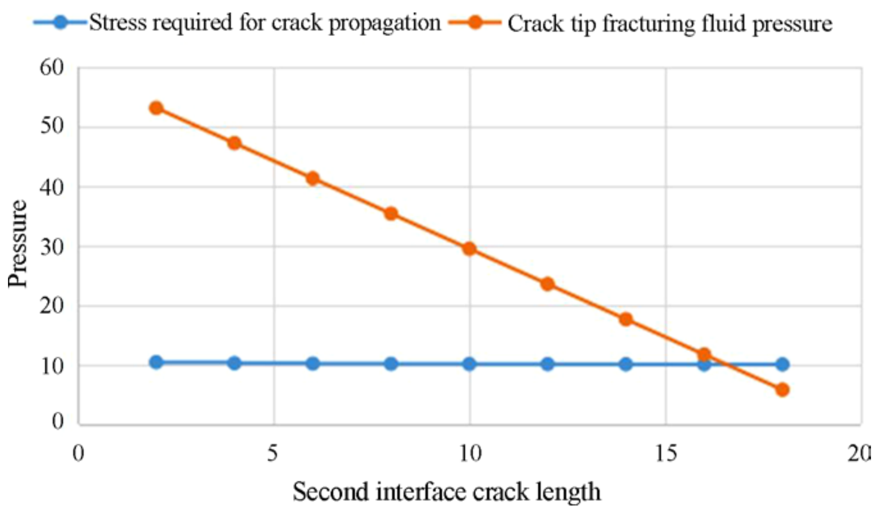


Figure 6
Schematic Diagram of the Calculation of the Length of Failure at Interface

CONCLUSION

(a)Established the calculation model of the interfacial stress distribution of the horizontal well during fracturing, and solved the two mechanical models.

(b)In the fracturing process, the two-way interface failure of horizontal wells is divided into two processes of interface debonding and interface crack propagation. According to the deformation characteristics of cement rings and formation rocks during the fracturing process, the debonding pressure of the horizontal interface of the fractured well is obtained. And the debonding length calculation model.

(c)The failure length of the fracturing interface of a horizontal well is the sum of the debonding length of the two interfaces and the extension length along the interface, and the influencing factors of the failure length of the two interfaces include: The higher the interfacial cementation strength, the cement ring elastic modulus and Poisson's ratio, and the downhole pump pressure, the higher the cement ring elastic modulus and the Poisson's ratio, the shorter the failure length at the interface.

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