Sealing Failure Mechanism and Control Method for Cement Sheath during Hydraulic Fracturing

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ABSTRACT: This study focused on the sealing failure mechanism and control method for a cement sheath during hydraulic fracturing. Taking a shale gas well as an example, whole wellbore numerical models of the casing-cement sheath-formation assembly were established, failure modes of the cement sheath at different depths were clarified, and control methods were proposed based on the calculation results. The following conclusions were drawn. (1) The maximum radial/tangential stress of the cement sheath increased/decreased with an increase in the depth, and the cement sheath above the intermediate casing shoe posed the risk of tangential tensile failure, resulting in tensile cracks. The cement sheath below the intermediate casing shoe produced a micro-annulus under a cyclic casing pressure, and the tensile cracks and micro-annulus constituted passages for the sustained casing pressure. (2) The swelling stress of the expansion cement slurry could offset the circumferential tensile stress and increase the radial compressive stress. Because a cement sheath with a high Young’s modulus usually exhibits high tensile and compressive strengths, it is recommended to use a high Young’s modulus cement slurry system above the intermediate casing shoe and optimize the free expansion ratio. (3) In comparison with ordinary cement stone, low residual strain cement stone exhibited a larger elastic deformation interval. The cumulative residual strain caused by cyclic loading was smaller, and the Young’s modulus demonstrated a lesser decrease. The results of an equivalent physical experiment demonstrated that an ordinary cement sheath lost its integrity after 13 loading cycles with a maximum casing pressure of 60 MPa. A low residual strain cement sheath could guarantee integrity after 30 loading cycles when the maximum casing pressure was 90 MPa, and sealing failure occurred after 11 loading cycles when the maximum casing pressure was 130 MPa. It is recommended to use a low residual strain cement slurry below the intermediate casing shoe to prevent a micro-annulus.

1. INTRODUCTION

Shale gas reservoirs are characterized by low porosity and permeability, which prevent conventional development methods from being used for the commercial production of gas. Therefore, hydraulic fracturing technology is required to achieve higher yields. However, this method can seriously threaten the sealing integrity of the cement sheath as a result of the large displacement, high pump pressure, and cyclic loading. During the shale gas development process for the Fuling shale gas block in Sichuan Basin, China, there has been a significant sustained casing pressure (SCP) phenomenon after staged fracturing. The SCP ratio before fracturing was 14.85%, but the ratio after fracturing was more than 50%, and the wellhead pressures of some shale gas wells exceed 10 MPa, which has produced significant risk to the wellhead safety, staff safety, and environmental protection.

The failure modes of a cement sheath include debonding, tensile failure (radial cracking), compressive/shear damage, and axial disking. Such sealing failures can lead to leakage, HSE (health, safety, environment) hazards, suspended production/injection, and loss of profits. In order to analyze the sealing failure mechanism of a cement sheath, scholars have conducted numerous studies using both theoretical analyses and laboratory tests. The analyses have included drilling, cementing, fracturing, and production. In terms of theoretical analysis, Shi et al. provided an analytical model to evaluate the stress state of a casing-cement sheath-formation assembly, and both the initial loaded state and wellbore temperature variation were considered in their model. Mueller et al. proposed an analytical model to predict the magnitude of the tensile or compressive...
Wang et al.16 used a cohesive zone method to simulate the corrosion properties have been extensively studied.22 The in the well; therefore, its hydration, mechanics, and anti-corrosion properties in different well sections during drilling, perforation, fracturing, or production.26 The SCP refers to the formation-assembly at different depths is used to analyze the integrity of the cement sheath between the tubing and intermediate casing.1 The numerical calculation model can be divided into three parts. The calculation model in Figure 1a is used to analyze the integrity of the cement sheath from the ground to the surface casing shoe. The calculation model in Figure 1b is used to analyze the integrity between the surface casing shoe and the intermediate casing shoe, and the calculation model in Figure 1c is used to analyze the integrity of the cement sheath between the intermediate casing shoe and the landing off point (the inclination angle is 90°). Because the SCP pressure between the tubing and intermediate casing annulus is the highest after fracturing, the target cement sheath in this study was the cement sheath between the tubing and intermediate casing.

2. WHOLE WELLBORE CEMENT SHEATH STRESS CALCULATION MODEL

This section considers an actual shale gas well as an example. The measurement depth, vertical depth, and landing point depth are 5010, 3550, and 3850 m, respectively. The depths of the surface casing shoe and intermediate casing shoe are 1270 and 3200 m, respectively. The casing and borehole size for different spudding operations are listed in Table 1. The cement sheath is considered to be an ideal elastic material. The casing-cement sheath-formation assembly at different depths is shown in Figure 1. The numerical calculation model can be divided into three parts. The calculation model in Figure 1a is used to analyze the integrity of the cement sheath from the ground to the surface casing shoe. The calculation model in Figure 1b is used to analyze the integrity between the surface casing shoe and the intermediate casing shoe, and the calculation model in Figure 1c is used to analyze the integrity of the cement sheath between the intermediate casing shoe and the landing off point (the inclination angle is 90°). Because the SCP pressure between the tubing and intermediate casing annulus is the highest after fracturing, the target cement sheath in this study was the cement sheath between the tubing and intermediate casing.

2.1. Material and Stress Parameters. The shale gas well has a large vertical span, and there are significant differences in the formation's mechanical parameters. The formation's mechanical profiles at different depths could be obtained based on acoustic logging and rock mechanics experiments. As shown in Figure 2, the constitutive equation of the formation conforms to the Mohr–Coulomb yield criterion, the mechanical stresses created by changing the wellbore and reservoir conditions. Xi et al.5 and Liu et al.15 thought that the cement sheath was prone to tensile failure at the inner face and carried out a sensitivity analysis. Numerical calculations can be very advantageous because of their ability to incorporate material non-linearity and multi-factor coupling analyses. Zhu et al.15 and Wang et al.10 used a cohesive zone method to simulate the migration of the fracturing fluid along the bonding surface and performed a sensitivity analysis. Yin et al.9 used a cohesive zone method to analyze the initiation of a micro-annulus in the process of water injection/fracturing. Based on the simplified Kirsch equation and numerical simulation method, the failure possibilities for the cement sheath under different conditions were simulated based on the shrinkage.17

In terms of laboratory tests, Goodwin and Crook analyzed the effects of excessive pressure and temperature fluctuation on the cement sheath.10 Roy et al.11 constructed a thermal platform to evaluate the effect of thermal stress on the well integrity as a function of the size and material properties. Le Roy-Delage et al.12 performed large-scale laboratory tests on a cement sheath with an annular geometry, and the influences of the contraction and expansion of the inner casing were investigated. Li et al.13 found that radial cracks were generated in the cement sheath under a low confining pressure, with a micro-annulus formed under a high confining pressure. Zhou et al.5 established a cement sheath sealing integrity simulation device, and it was believed that the residual strain generated by the casing pressure gradually accumulated with an increase in the number of cycles, which led to the appearance of a micro-annulus. One of the main functions of the cement sheath is to isolate the oil, gas, and water in the well; therefore, its hydration, mechanics, and anti-corrosion properties have been extensively studied.22 The optimization of cement slurries is a complicated problem, which is closely related to the nature of the reservoir and development conditions, for example, the cement sheath is generally required to have acid resistance and self-repair ability in acid reservoirs;23 the cement sheath in thermal recovery wells is required to have high temperature resistance and fatigue resistance;24 and the cement sheath is required to have lower porosity and larger cementation strength in the high pressure gas reservoir.25 However, in the process of shale gas development, the requirements for the cement sheath are very general, without clear requirements for mechanical parameters or physical properties in different well sections during hydraulic fracturing.

Researchers have generally focused on the integrity of the cement sheath at the target location, which is usually the production layer or horizontal section during drilling, perforation, fracturing, or production.26 The SCP refers to the down-hole gas passing through a certain seepage channel, such as a radial crack, micro-annulus, casing thread, or packer, to the wellhead.27 The occurrence of the SCP indicates the failure of the wellbore barrier; however, an analysis of the integrity of the cement sheath at the production layer cannot ensure the sealing failure mechanism. For shale gas wells, the fluid column pressure acts on the outer wall of the entire casing; however, the well structure, in situ stress, and formation mechanics parameters are different at different depths, which lead to different stress states and failure forms. Additionally, the control methods proposed by previous studies also focused on specific circumstances, such as casing eccentricity, perforation, and casing shoes,27 without analyzing the wellbore cement sheath as a whole.

In this study, the casing-cement sheath-formation assemblies at different depths were first established based on the in situ stress profile, formation mechanics parameters, and wellbore structure, and the radial and tangential stress profiles of the cement sheath were analyzed. Combined with the Mohr–Coulomb failure criterion, the failure modes of the whole wellbore cement sheath were clarified. Second, the control methods were divided into two parts. For the cement sheath above the intermediate casing shoe, the feasibility of using the expansion cement slurry to reduce the circumferential stress was investigated. For the cement sheath below the intermediate casing shoe, the feasibility of using a low residual strain cement slurry to reduce the accumulative plastic strain was investigated in combination with laboratory tests and numerical simulations. Finally, the control methods proposed in this study were verified on site.

Table 1. Geometric Parameters of Casing-Cement Sheath-Formation Assembly

| well depth (m) | surface casing OD (mm) | surface casing ID (mm) | intermediate casing OD (mm) | intermediate casing ID (mm) | tubing OD (mm) | tubing ID (mm) | wellbore diameter (mm) |
|---------------|------------------------|------------------------|-----------------------------|-----------------------------|----------------|----------------|-----------------------|
| 0–1270        | 339.7                  | 315.3                  | 244.5                       | 222.4                       | 139.7          | 118.6          | 444.5                 |
| 1280–3210     | 244.5                  | 222.4                  | 139.7                       | 118.6                       | 311.2          |                | 215.9                 |
| 3220–5010     | 139.7                  | 118.6                  | 215.9                       |                             |                |                |                       |

OD refers to the outer diameter, and ID refers to the inner diameter.
parameters include Young’s modulus, Poisson’s ratio, the internal friction angle, and the cohesion.

The compaction degree of the formation in the vertical direction becomes increasingly obvious, resulting in increases in the Young’s modulus and cohesion. Because the in situ stresses increase with depth, the lateral deformation ability of the rock gradually decreases, causing the Poisson’s ratio to gradually decrease with depth.

The in situ stresses are assumed to increase linearly with an increase in depth. In the horizontal section, the vertical, maximum horizontal, and minimum horizontal in situ stresses can be obtained by density logging method and formation fracturing test, which are 85, 95, and 82 MPa, respectively. Thus, the magnitudes of the in situ stresses at different well depths can be calculated using eqs 1–3:

\[
\sigma_H = h \cdot \frac{95}{3850} \\
\sigma_h = h \cdot \frac{82}{3850} \\
\sigma_V = h \cdot \frac{85}{3850}
\]

where \(\sigma_H, \sigma_h, \text{ and } \sigma_V\) are the vertical, maximum horizontal, and minimum horizontal in situ stresses (MPa), respectively, and \(h\) is the vertical depth (m).

As shown in Figure 1, the maximum, minimum horizontal in situ stress, and vertical in situ stress act in the \(X\), \(Y\), and \(Z\) directions, respectively. In the deviating section, the coordinate transformation of the in situ stress is required. The calculation method is shown in eq 4:

Figure 1. Well structure and numerical model for different spudding operations: (a) from ground to surface casing shoe, (b) from the surface casing shoe to intermediate casing shoe, and (c) from the intermediate casing shoe to landing off point.

Figure 2. Profile of formation’s mechanical parameters: (a) Young’s modulus vs depth, (b) Poisson’s ratio vs depth, (c) cohesion vs depth, and (d) internal friction angle vs depth.
where \( \Omega \) is the angle between the azimuth of the well and the orientation of the maximum horizontal in situ stress (°). In this study, \( \Omega = 90° \), and \( \varphi \) is the deviation angle, which varies from 0° to 90°.

Both the wellhead pump pressure and hydrostatic column pressure generated by the fracturing fluid would act on the inner wall of the casing. The casing pressures are different depths can be calculated using eq 5:

\[
P_t = P_0 + \rho gh/10^6
\]

where \( P_t \) is the casing pressure (MPa), \( P_0 \) is the pump pressure (MPa), \( \rho \) is the fluid density (kg/m³), and \( g \) is the gravity acceleration (9.8 m/s²). The fluid friction is neglected here.

2.2. Contact Model and Meshing Method.

For the contact relationship between the casing and the cement sheath and between the cement sheath and the formation, the cohesive zone method (CZM) was used to simulate the bonding property. The mechanical behavior includes linear elastic phase, damage initiation criterion, and damage evolution phase. The bilinear tensile displacement curve is shown in Figure 3.

![Figure 3. Failure process of the cohesive zone method: (a) Traction-separation law. (b) Shear-separation law.](image)

In the linear elastic phase, the slope of the line AB represents the stiffness, the damage in this phase is 0, the constitutive relation is shown in eq 6:

\[
t = \begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = K\varepsilon = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{sn} & K_{ss} & K_{st} \\ K_{tn} & K_{ts} & K_{tt} \end{bmatrix} \begin{bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{bmatrix}
\]

where \( t_n, t_s, t_t \) are the component of the stress in three directions (MPa), including one vertical direction and two tangential directions, \( \varepsilon_n, \varepsilon_s, \varepsilon_t \) are the component of the displacement in three directions (m), and \( K_{ij} \) represents the stiffness matrix (GPa).

When the deformation reaches to a certain degree, the cohesive zone method will begin to damage; due to the fact that damage is affected by the damage components in three directions, the quadratic nominal stress criterion is more applicable than the maximum stress criterion, and the quadratic nominal stress criterion is shown in eq 7:

\[
\left( \frac{t_n}{t_{n0}} \right)^2 + \left( \frac{t_s}{t_{s0}} \right)^2 + \left( \frac{t_t}{t_{t0}} \right)^2 = 1
\]

where \( t_n, t_s, t_t \) are the tractions in the normal, the first shear direction, and the second shear direction, respectively (m), and \( t_{n0}, t_{s0}, t_{t0} \) are the peak values of the nominal stress purely in the directions, respectively (m). The symbol < > indicates that the CZM will not be damaged when subjected to compressive stress.

The damage of the CZM means that its stiffness degrades, the dimensionless parameter \( D \) can be used to describe the damage degree, there is no damage when \( D = 0 \), and the CZM fails completely when \( D = 1 \):

\[
D = \frac{d_m^\text{max} - d_m^0}{d_m^\text{max} - d_m^0}
\]

where \( d_m^\text{max} \) is the maximum displacement (m), \( d_m^0 \) is the displacement when the CZM is completely destroyed (m), and \( d_m^0 \) is the displacement corresponding to initial damage (m).

The failure mode of B-K fracture energy is used to describe the damage evolution:

\[
G_i^\text{c} + (G_i^\text{T} - G_i^\text{c}) \left( \frac{G_i + G_i^\text{T}}{G_i + G_i^\text{c} + G_i^\text{T}} \right)^\beta = G_i^\text{T} + G_i^\text{c} + G_i^\text{T}
\]

where \( G_i \), \( G_i^\text{T} \), and \( G_i^\text{c} \) are the energies dissipated in the three directions (J/m²), \( G_i^\text{T} \) and \( G_i^\text{c} \) are the critical energies in the three directions (J/m²), and \( \beta \) is the power factor (dimensionless).

The cohesive properties of the casing-cement-formation system assembly are listed in Table 2, which were taken from a reference.

| parameter                        | casing-cement interface | cement-formation interface |
|----------------------------------|-------------------------|----------------------------|
| normal strength (MPa)            | 0.5                     | 0.42                       |
| shear strength (MPa)              | 2                       | 2                          |
| cohesive stiffness (GPa)          | 30                      | 30                         |
| critical energy (J/m²)            | 100                     | 100                        |

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Variable density and structured meshing method are used for the casing, cement sheath, and formation, with a unified grid using CPE4 elements. Displacement constraints are applied to the formation boundary, and the size of the formation is 4.5 m × 4.5 m, which prevented the boundary from affecting the stress results.

Python scripts could be used to generate the finite element models for the whole wellbore casing-cement sheath-formation assembly. First, INP files are generated with numerical software ABAQUS based on the finite element model (shown in Figure 1a-c) for each spudding. Second, the formation’s mechanical parameter, in situ stress, and casing internal pressure values in the INP files are replaced by Python scripts, which made it possible to obtain INP files corresponding to different depths. Third, the post-processing code could be generated by the Python scripts based on the log file generated by ABAQUS. In terms of output, the maximum tangential stress and radial stress of the cement sheath at different depths are needed to be obtained.
2.3. Failure Criterion. Except the debonding between the cement sheath and casing or formation, the failure of the cement sheath could be mainly divided into tensile failure, compressive failure, and shear failure; the failure of the cement sheath can be judged with the criteria of maximum principal stress when suffering the pure tensile or compressive loading. When both tensile stress and compressive stress exist in different directions, the Mohr–Coulomb failure criteria can be used to judge the integrity. In a cylindrical coordinate system, $\sigma_1 = \sigma_\theta$, $\sigma_3 = \sigma_r$, where $\sigma_\theta$ and $\sigma_r$ are the tangential and radial stress, respectively.

Here, $\sigma_1$ and $\sigma_3$ are the maximum and minimum principal stresses (MPa), respectively, and $\sigma_t$ and $\sigma_c$ are the tensile strength and compressive strength (MPa), respectively. Based on the mathematical relationship between the failure standard and judgment value, it can be concluded that a sealing failure occurs when the judgment value is greater than 1.

The ideal mechanical performance of a cement sheath includes a high compressive strength and low Young’s modulus, which means that the cement sheath has a larger elastic range, which is conducive to the sealing integrity. However, achieving this is very difficult because even though adding a certain amount of elastic particles, fibers, polymers, and the like to the base cement slurry will decrease the Young’s modulus, these materials also decrease the compressive strength. As shown in Figure 4, De Andrade et al. estimated the correlation between the uniaxial compressive strength (UCS)/tensile strength and Young’s modulus ($E$) based on the data from a series of experiments and fitted the relationship between the Young’s modulus and the strength (eqs 10 and 11).

$$\text{UCS} = 0.0354E^2 + 3.1509E + 4.0642 \quad (10)$$

$$T_0 = 0.1502\text{UCS} - 0.5732 \quad (11)$$

where UCS is the uniaxial compressive strength (MPa), $E$ is the Young’s modulus (GPa), and $T_0$ is the tensile strength (MPa).

This integrity analysis method is very important for the optimization of the cement slurry system. A lower Young’s modulus means a lower strength. Young’s modulus needs to be optimized while considering the strength for different wellbore types or production conditions.

2.4. Model Verification. A full-scale cement sheath sealing capacity assessment device was used to evaluate the sealing performance under cyclic casing pressure, as shown in Figure 5a. This simulation device was mainly composed of a control system and testing module. The control system mainly controlled the pressure and circulation times acting on the inner wall of the casing, while the testing module mainly monitored the stresses on the inner and outer walls of the cement sheath and the flow of air through the annulus. The experiment was conducted as follows. The casing-cement sheath-outer casing assembly was used to simulate the casing-cement sheath-formation assembly, and the fracturing process was simulated by applying pressure to the casing through the control system. There were bubble detection and gas flow detection devices on top of the annulus and stress sensors on the outer and inner casing walls.

The inner diameter, outer diameter, and height of the inner casing were 124.26, 139.7, and 1200 mm, respectively. The inner
diameter, outer diameter, and height of the outer casing were 193.7, 244.5, and 1200 mm, respectively. The grades of the inner casing and outer casing were P110 and N80, respectively, and the Young’s modulus and Poisson’s ratio values of the casing were 210 GPa and 0.3, respectively. The casing and the cement sheath were simplified as an ideal elastic material, which obeys Hooke’s law ($\sigma = E \cdot \varepsilon$, where $\sigma$ represents stress, MPa; $E$ represents the Young’s modulus, MPa; and $\varepsilon$ represents strain, dimensionless). The Young’s modulus, Poisson’s ratio, tensile strength, and UCS values of the cement sheath can be measured by a uniaxial compression test, which were 8 GPa, 0.17, 4.2 MPa, and 40.8 MPa, respectively. The casing inner pressure varied from 70 to 0.1 MPa. The measurements from the stress sensor located between the inner casing and the cement sheath are shown in Figure 6.

A finite element model of the casing-cement sheath-outer casing assembly corresponding to the assessment device was established. The numerical model is shown in Figure 5c. The contact model and meshing method were the same as those discussed in Section 2.2. A liquid column pressure of 70 MPa was applied to the inner wall of the casing, and the radial and tangential stresses of the cement sheath are shown in Figure 7.

The stress of the cement sheath in Figure 6a varies periodically owing to the cyclic pressure. When the pressure is 70 MPa, the radial compressive stress measured by the stress sensor is 22.7 MPa and the tangential tensile stress is 4.6 MPa. As shown in Figure 6b, the cement sheath bears a high tangential tensile stress under a high casing inner pressure, which results in tangential tensile cracks.

As shown in Figure 7a,b, the radial and tangential stresses at the inner wall of the cement sheath are 23.26 and 4.74 MPa, respectively. The assessment device and numerical calculation results demonstrated differences of 2.5 and 3.0%, respectively, which validated the accuracy of the meshing method, load setting, and contact model of the numerical model.

3. RESULTS AND DISCUSSION

3.1. Calculation Results. The circumferential stress, radial stress, and Mohr–Coulomb judgment value profile could be calculated based on the well structure, in situ stress profile, formation mechanics parameter profile, and casing pressure profile. Because the SCP between the tubing and intermediate casing was the most severe after fracturing, the target cement sheath in this study referred to the cement sheath between the tubing and intermediate casing. The cementing slurry used in the shale gas well was the same as that used in the experiments discussed in Section 2.4, and the calculation results are shown in Figure 8.

The stress was positive for tension and negative for compression, as shown in Figure 8a. The radial compressive stress increased with the depth because the internal pressure and in situ stress increased with the depth, which increased the compression degree. However, as shown in Figure 8b, the circumferential stress had the opposite pattern. It decreased with an increase in depth and even changed from tension to compression.
This was because the enveloping effect of the in situ stress was greater than the outward spreading effect of the casing pressure, which caused the circumferential stress to gradually decrease. At the same time, the stresses changed abruptly at the positions of the intermediate casing shoe and surface casing shoe because of the change in the well structure.

It can be seen from Figure 8c that the integrity of the cement sheath cannot be guaranteed. Tangential tensile cracks would occur under the action of the circumferential and radial stresses from 0 to 3210 m. When the well depth was greater than 3210 m, the radial compressive stress was greater than 40.8 MPa, which was larger than the uniaxial compressive strength. The cement sheath was at risk of plastic yield and compression failure. In the multi-stage fracturing process, the micro-annulus may appear between the casing and cement sheath, which will be verified in Section 5.2. Therefore, the ordinary cement slurry system used in shale gas wells cannot meet the isolation requirements.

3.2. Sensitivity Analysis. 3.2.1. Young’s Modulus. Previous studies have shown that Young’s modulus can significantly affect the stress state of the cement sheath. If the Young’s modulus is set to 4, 6, 8, 10, or 12 GPa, the Poisson’s ratio remains constant at 0.17. In addition, according to eqs 10 and 12, the compressive strength is 17.2, 24.2, 31.5, 39.1, or 47 MPa, respectively, and the tensile strength is 2.0, 3.0, 4.2, 5.3, or 6.4 MPa, respectively. The calculation results under different values for Young’s modulus are shown in Figure 9.

Young’s modulus. However, as shown in Figure 9c, although the reduction of Young’s modulus is conducive to relieve the stress state, the compressive and tensile strengths will also be reduced. Therefore, the integrity of the cement sheath in the whole wellbore cannot be guaranteed simply by reducing the Young’s modulus.

3.2.2. Pump Pressure. In the multi-stage fracturing process, the mechanical parameters of the shale in different stages may be different, resulting in differences in the fracture initiation pressure and expansion pressure, which is ultimately reflected as a difference in the pump pressure. Based on the numerical model in Section 2, the pump pressure was changed to 70, 80, and 90 MPa, with the other parameters remaining unchanged. The calculation results under these different pump pressures are depicted in Figure 10.

Figure 10a,b shows that the maximum radial and circumferential stress profiles under different pump pressures are basically parallel. The stress can obviously be relieved with a smaller pump pressure. However, it can be seen from Figure 10c that the integrity of the cement sheath cannot be fully guaranteed even if the pump pressure is reduced to 70 MPa.

4. SOLUTION ANALYSIS: ABOVE THE INTERMEDIATE CASING SHOE

Cement stone is a typical material that can resist compressive stress but not tensile stress. The tensile strength is usually 1/8—1/12 the compressive strength, which is generally less than 5 MPa. Therefore, it is unrealistic to simply increase the tensile

Figure 8. Calculation results of the whole wellbore cement sheath: (a) maximum radial stress profile (b) maximum tangential stress profile, and (c) judgment value profile.
strength to solve the sealing failure problem above the intermediate shoe. This paper proposes a method for relieving the circumferential tensile stress that involves using the expansion cement slurry system in the annulus between the tubing and intermediate casing. The expansion cement slurry has a small amount of expansive agent added to the base cement slurry to offset the volume shrinkage during the hardening process to ensure the cementing quality. In this study, the swelling stress generated by the cement sheath itself was used to offset the tensile stress in the circumferential direction, thereby alleviating the stress state. Because the stiffness of the casing was much larger than that of the cement sheath, the swelling stress could relieve the circumferential tensile stress and increase the radial compressive stress. Therefore, it was necessary to optimize the free expansion ratio. The cement material gradually expands with time as a result of the expansion agent, but its expansion speed gradually decreases to zero. The free expansion ratio is the ratio of the length increment to the initial height.

In this study, the thermal stress caused by heating was used to simulate the expansion process of the cement sheath. The volume expansion process of the cement sheath was simulated for every time period with a certain temperature change. This method did not really produce a temperature variation but artificially defined a coefficient of thermal expansion and temperature change. Thus, the equivalent thermal expansion of the cement sheath was equal to the actual chemical expansion effect. Based on the numerical calculation model in Section 2, the numerical calculation model of the swelling stress could be obtained by modifying the following terms.

1. Thermodynamic parameters needed to be added to the casing-cement sheath-formation assembly, including the heat transfer coefficient, coefficient of thermal expansion, and specific heat capacity. The specific parameters are listed in Table 4.

The heat transfer coefficient, specific heat capacity, and density used in the casing-cement sheath-formation assembly were obtained from Xi et al. The chemical expansion of the cement sheath was simulated by the thermal expansion process, and no chemical expansion occurs in the casing and formation; therefore, the thermal expansion coefficient of casing and formation were set to zero.

2. In the analysis step settings, the original static general analysis step needed to be changed to the temperature-displacement coupling analysis step in ABAQUS.

3. In terms of the load setting, it was necessary to set the temperature boundary of the cement sheath between the tubing and the intermediate casing. The temperature change value was set to $\Delta t$, which can be calculated using eq 12:

$$ a\Delta t = \Delta l/l $$

Figure 9. Influence of Young’s modulus on the stress profile: (a) maximum radial stress profiles with different values for Young’s modulus, (b) maximum tangential stress profiles with different values for Young’s modulus, and (c) judgment value profiles with different values for Young’s modulus.
where $\alpha$ is the thermal expansion coefficient ($10^{-6} \cdot \text{C}^{-1}$), $\Delta l$ is the length increment (mm), and $l$ is the original length (mm).

(4) In terms of the meshing method, the structure and variable density meshing method remained unchanged, but the meshing type of all the components needed to be changed to C4PT.

4.1. Calculation Method Verification. Yang et al.$^{35,36}$ analyzed the effect of the expansion cement sheath on the circumferential strain of the casing and formation during the hardening process. The testing process was mainly divided into the following steps. The dynamic change laws for the Young’s modulus and Poisson’s ratio of cement stone with two types of expansion cement slurry systems (expansion agent content of 8%) during the hardening process were first determined. The length of the cement material rod (initial length of 1000 mm) mixed with the expansion agent was measured by the length gauge to calculate the free expansion ratio. Finally, the effect of the cement slurry on the circumferential strain of the casing and formation during the hardening process was monitored using a special testing device, as illustrated in Figure 11a,b.

Influence of pump pressure on stress profiles: (a) maximum radial stress profiles with different pump pressures, (b) maximum tangential stress profiles with different pump pressures, and (c) judgment value profiles with different pump pressures.

Table 3. Mohr–Coulomb Failure Criteria

| stress interval | description of interval | relationship between principal stresses | failure standard | judgment value |
|-----------------|--------------------------|----------------------------------------|------------------|----------------|
| 1               | tension–tension–tension  | $\sigma_1 \geq \sigma_1 \geq 0$       | $\frac{\sigma_1}{\sigma_t}$ |
| 2               | compression–compression–compression | $0 \geq \sigma_1 \geq \sigma_3$ | $-\sigma_1 \geq \sigma_3$ | $-\frac{\sigma_3}{\sigma_t}$ |
| 3               | tension–compression–compression; tension–tension–compression | $\sigma_1 \geq 0 \geq \sigma_3$ | $\frac{\sigma_1}{\sigma_3} \geq 1$ | $\frac{\sigma_3}{\sigma_3} \geq 1$ |

Table 4. Thermodynamic Parameters of Casing-Cement Sheath-Formation Assembly

| name            | coefficient of heat conduction (W·(kg·°C)^{-1}) | specific heat (J·(kg·°C)^{-1}) | coefficient of thermal expansion (10^{-6}·°C^{-1}) | density (kg·m^{-3}) |
|-----------------|-----------------------------------------------|--------------------------------|-------------------------------------------------|---------------------|
| casing          | 45                                            | 461                            | 0                                               | 7800                |
| cement sheath   | 0.98                                          | 837                            | 9                                               | 3100                |
| formation       | 1.59                                          | 1256                           | 0                                               | 2600                |

where $\alpha$ is the thermal expansion coefficient ($10^{-6} \cdot \text{C}^{-1}$), $\Delta l$ is the length increment (mm), and $l$ is the original length (mm).
In the numerical calculation process, the selected Young’s modulus and Poisson’s ratio were the values when the cement sheath reached the steady state. Thus, the circumferential strains of the casing and outer cylinder were also relatively stable. Figure 11c shows the corresponding numerical model of the detection device. The material and geometric parameters were obtained from Yang et al., and the contact model between the cement sheath and casing and the outer cylinder was cohesive contact. In terms of the meshing, the meshing type for all the components was CPE4T.

Because the expansion coefficients of cement slurry system 1 and system 2 were set to $9 \times 10^{-6}/\degree C$, and the free expansion ratios were 0.13 and 0.15%, respectively, the temperature variation values were 14.4 and 16.7 $\degree C$, respectively, according to eq 12. The numerical calculation results and test results are compared in Figure 12.

As shown in Figure 12a,b, the numerical calculation results are basically consistent with the experimental results, which proved the correctness of the calculation method. The calculation result was slightly larger than the test result. This was because some part of the expansion volume of the cement sheath during the test was used to fill the internal micro-voids and cracks and could not be completely applied to the casing and outer cylinder.

### 4.2. Free Expansion Ratio Optimization

The Young’s modulus for the cement sheath was set to 8 GPa, the expansion ratio was set to 8 or 0%, and the other parameters remained unchanged. Because this section discusses a method for controlling the integrity of the cement sheath above the intermediate casing shoe, only the integrity from the wellhead to the intermediate casing shoe is analyzed here. The comparison results are shown in Figure 13.

As depicted in Figure 13a, the radial compressive stress increases under the action of swelling stress, which is obviously not conducive to the sealing integrity. Meanwhile, the swelling stress reduces the circumferential tensile stress, which contributes to the sealing integrity (Figure 13b). This is because the swelling stress produces a compressive stress component in the circumferential direction, which can offset the circumferential tensile stress generated by the casing pressure. For example, if the stress component of the swelling stress in the circumferential direction is $-2$ MPa and the casing pressure makes the stress component 5 MPa, then the final tensile stress is 3 MPa. From the judgment value profile, when the free expansion ratio is 8%, the integrity of the cement sheath between 0 and 1270 m can be guaranteed. If the Young’s modulus is set to a range of 4–12 GPa, the UCS and tensile strength can be calculated according to eqs 10 and 11, respectively. The free expansion ratio varies from 0 to 12%, and the other parameters remain unchanged. The effective isolation height from the wellhead to the intermediate casing...
shoe can be analyzed according to the criteria provided in Table 3, and the result is shown in Figure 14.

As shown in Figure 14, when the free expansion ratio is $0\%_e$ and the Young’s modulus varies from 4 to 12 GPa, the effective isolation height is 0 m, which means that simply adjusting the Young’s modulus cannot guarantee the integrity. When the free expansion ratio reaches $0.6\%_e$, the decrease in the circumferential stress and increase in the radial stress are just within the optimal ranges. As the free expansion ratio continues to increase, although the circumferential stress continues to decrease, the radial stress gradually increases, which is also detrimental to the integrity.

When the free expansion ratio is $0.7\%_e$, the effective isolation height increases significantly with an increase in Young’s modulus. Even the stress of the cement sheath increases with Young’s modulus, but the tensile and compressive strengths also increase. Therefore, it is recommended to use a high Young’s modulus value for the cement slurry system above the intermediate casing shoe and control the free expansion ratio within a reasonable range.

5. SOLUTION ANALYSIS: BELOW THE INTERMEDIATE CASING SHOE

In Section 3, it was concluded that the failure mode of the cement sheath above the intermediate casing shoe was circumferential tensile cracks, and in Section 4, the method of using the expansion cement slurry to reduce the circumferential stress was discussed and optimized the free expansion ratio of the cement slurry. The cement sheath below the intermediate casing shoes bears very high radial stress, which may cause plastic accumulation during multi-stage fracturing, and finally produce micro-annulus. In this section, the uniaxial and triaxial compression tests were carried out first, and then the cyclic loading tests were carried out according to the compressive strength, and the equivalent physical experiment and numerical calculations were carried out by a full-scale cement sheath sealing capacity assessment device.

5.1. Cyclic Compression Test. The cyclic compression tests on cement stone of two different formulations were carried out, which are the ordinary cement slurry system used in shale
gas wells and the low residual strain cement slurry system. The detailed ratio of the ordinary cement slurry is as follows: Gezhouba Three Gorges class G oil well cement (500 g), ganister sand (175 g), liquid dehydrating agent (20 g), and water (264 g). The detailed ratio of the low residual strain cement slurry is as follows: Gezhouba Three Gorges class G oil well cement (500 g), organic elastic material (77.2 g), inorganic nanoemulsion (77.2 g), liquid dehydrating agent (20 g), expansion agent (2 g), retarder (1 g), inorganic toughening agent (10 g), and water (260 g).

The cement slurry mentioned above was poured and formed in a cylindrical mold (size $\Phi 50 \text{mm} \times 120 \text{mm}$) and cured at 130 °C and 20 MPa in a water bath for 3 days. Then, the uniaxial and triaxial compression tests with a confining pressure of 15 MPa were carried out, and the results of ordinary cement stone are shown in Figure 15.

As shown in Figure 15, the Young’s modulus and Poisson’s ratio of ordinary cement stone can be calculated as 7.82 GPa and 0.16, respectively, the uniaxial compressive strength is 40.8 MPa, the strains corresponding to the yield/failure of cement stone are 0.4/0.68%. When the confining pressure is 15 MPa, the cement stone exhibits certain plastic characteristics, and the stress–strain curve after the elastic stage will be concave downward because the internal micro-cracks in the cement stone gradually expand; thus, the stiffness gradually decreases. The mechanical parameters of cement stone can be calculated from the experimental results, and the parameters are shown in Table 5.

The uniaxial and triaxial compression tests were carried out on low residual strain cement stone, and the results are shown in Figure 16.

As shown in Figure 16, the average values of Young’s modulus and Poisson’s ratio are 5.45 GPa and 0.17, respectively, the uniaxial compressive strength is 34.7 MPa. The cement stone shows obvious plastic deformation characteristics under triaxial compression, the peak deviation stress is 44.6 MPa, and the corresponding peak strain is 1.48% (Table 6).

On the basis of the above experiments, the cyclic loading and unloading experiments were carried out on ordinary and low residual strain cement stone with a confining pressure of 15 MPa, the cyclic number is 20, the peak loading stress and minimum loading stress are 70% of the peak deviation stress and 5 MPa, respectively, and the axial stress–strain curve and the post-failure morphology are shown in Figures 17 and 18.

It can be seen from Figures 17a and 18a that, when the loading stress of cement stone reaches the yield strength, there was residual strain after unloading. In the subsequent loading process, new plastic strain was generated each time, and the residual strain after unloading was also increasing; the cumulative residual strains of conventional and low residual strain cement stone after the 20th cycle are 0.92 and 0.43%, respectively. Obviously, the residual strain of low residual strain cement stone is smaller than that of ordinary cement stone under cyclic loading. As shown in Figures 17b and 18b, the unloading Young’s modulus can be analyzed according to the stress–strain curve during cyclic loading, ordinary and low residual strain cement stones showed similar properties, and the unloading Young’s modulus gradually decreases with the cycle times and tends to be stable; this is because the micro-pore structure inside the cement breaks down gradually during the loading process, leading to the gradual attenuation of elastic property. For ordinary cement stone, the initial Young’s modulus is 8.37 GPa, and the unloading Young’s modulus after the 20th cycle is 6.12 GPa, which decreased by 26.8%. However, for low residual strain cement stone, the initial Young’s modulus is 5.49 GPa, and the unloading Young’s modulus after the 20th cycle is 4.95 GPa, which decreased by 9.8%. Compared with ordinary cement stone, low residual strain cement stone can fully guarantee its elastic deformation ability during cyclic loading.

Table 5. Mechanical Parameters of Conventional Cement Stone

| confining pressure (MPa) | peak deviation stress (MPa) | peak strain (%) | yield strain (%) | Young’s modulus (GPa) | Poisson’s ratio |
|--------------------------|-----------------------------|----------------|-----------------|----------------------|----------------|
| 0                        | 40.8                        | 0.68           | 0.4             | 7.82                 | 0.16           |
| 15                       | 45.7                        | 0.86           | 0.51            | 8.37                 | 0.18           |

The full-scale cement sheath sealing capacity assessment device in Section 2.4 was used to perform the sealing ability of different cement slurry systems, and the sealing integrity of the conventional cement sheath was analyzed first; the experimental steps were as follows:

1. Pour the cement slurry into the annulus and then cure at a temperature of 130 °C for 72 h.

![Figure 15. Compression test and the post-failure morphology of conventional cement stone. (a) Uniaxial stress–strain curve and (b) cement stone after uniaxial compression experiment. (c) Triaxial stress–strain curve and (d) cement stone after triaxial compression experiment.](image-url)
(2) Control the change of the internal pressure of the casing through the pressure system.

(3) Check the sealing ability by injecting gas at the bottom of the cement sheath. Since the cement sheath formed by the ordinary cement slurry would produce circumferential tensile cracks when the casing pressure was 70 MPa, the maximum and the minimum casing pressure varied from 60 to 0.1 MPa in this section, and the results of the ordinary cement sheath are shown in Figure 19.

It is clearly showed that the ordinary cement sheath will lose integrity after 13th loading, considering that the fracturing stages and pump pressure in shale gas wells are generally greater than 20 and 80 MPa. Therefore, the conventional cement slurry system cannot guarantee the sealing integrity below the intermediate casing shoe.

The sealing integrity of a low residual strain cement sheath was analyzed second, the maximum casing pressure was set to be 90 and 130 MPa, the minimum pressure was 0.1 MPa, and the results are shown in Figure 20.

As shown in Figure 20a, when the maximum pressure was 90 MPa, the sealing integrity can be guaranteed even if the number of cycles was 30, but when the maximum pressure was 130 MPa (Figure 20b), the cement sheath would lose isolation after 11 cycles of loading; it can be concluded that a low residual strain cement sheath was beneficial to the sealing integrity under cyclic casing pressure, although the low residual strain cement stone has lower compressive strength, the elastic strain interval (yield stress/Young’s modulus) is larger than that of ordinary cement stone, and the plastic accumulation strain under cyclic pressure load is smaller, which obviously is conducive to the integrity, so it is recommend to use a low residual strain cement slurry below the intermediate casing shoe.

### 6. CASE STUDY AND FIELD VERIFICATION

#### 6.1. Case Study

To verify the accuracy of the whole wellbore cement sheath stress calculation model, the cement sheath stresses were calculated and the integrity was evaluated based on the engineering and geological conditions of eight wells. The comparison results are listed in Table 7. These show

![Figure 17. Variation of mechanical parameters with ordinary cement stone under cyclic loading: (a) cyclic stress–strain curve and (b) unloading Young’s modulus vs cycle time.](image)

| Confining pressure (MPa) | Peak deviation stress (MPa) | Peak strain (%) | Yield strain (%) | Young’s modulus (GPa) | Poisson’s ratio |
|--------------------------|-----------------------------|-----------------|------------------|-----------------------|----------------|
| 0                        | 34.7                        | 0.86            | 0.60             | 4.86                  | 0.15           |
| 15                       | 44.6                        | 1.48            | 0.63             | 5.49                  | 0.16           |

![Table 6. Mechanical Parameters of Low Residual Strain Cement Stone](image)
that the field data are consistent with the results calculated using the whole wellbore cement sheath stress calculation model.

6.2. Field Verification. Based on the above analysis, it could be concluded that the combination of the expansive cement slurry system and low residual strain cement slurry could maintain the integrity during fracturing when the new combination of cement slurry was used in seven shale gas wells. The relational parameters are listed in Table 8. The field results showed that none of the seven shale gas wells did not experience the SCP problem before and after fracturing.

7. CONCLUSIONS

(1) The radial compressive degree of the cement sheath increased with the well depth, while the circumferential tension degree decreased with the well depth or even changed from tension to compression. The cement sheath above the intermediate casing shoe posed the risk of tangential tensile failure, which resulted in tensile cracks. The cement sheath below the intermediate casing shoe produced a micro-annulus under a cyclic casing pressure, and the tensile cracks and micro-annulus constituted...
Table 7. Cement Sheath Integrity Evaluation Based on the Whole Wellbore Cement Sheath Stress Calculation Model

| well name | measuring/vertical depth (m) | $\sigma_v/\sigma_h$ | pump pressure (MPa) | casing thickness (mm) | casing OD (mm) | cement slurry type | Young’s modulus (GPa) | calculation/experiment results | field-measured results/SCP (MPa) |
|-----------|-----------------------------|------------------|--------------------|----------------------|----------------|-------------------|---------------------|-----------------------------|-----------------------------|
| W-1 h     | 4780/3620                   | 98.3/106.2/95.4  | 66–95              | 12.7                 | 139.7          | ordinary          | 12                  | failure                     | failure, 8.65                |
| W-2 h     | 5550/3626                   | 94.5/100.5/82.1 | 70–90              | 12.7                 | 139.7          | ordinary          | 10                  | failure                     | failure, 10.78               |
| W-3 h     | 5320/3750                   | 98.2/107.6/89.8 | 75–90.9            | 12.7                 | 139.7          | ordinary          | 8                   | failure                     | failure, 5.54                |
| W-4 h     | 5237/3838                   | 95.8/102.5/95.3 | 85–123             | 10.54                | 139.7          | ordinary          | 8                   | failure                     | failure, 11.84               |
| W-5 h     | 5555/3721                   | 97.6/100.7/85.8 | 70–91              | 10.54                | 139.7          | ordinary          | 10                  | failure                     | failure, 1.94                |
| W-6 h     | 5413/3744                   | 89.9/91.1/85.8  | 76–85              | 12.7                 | 139.7          | ordinary          | 12                  | failure                     | failure, 12.31               |
| W-7 h     | 5430/3744                   | 92.1/100.8/82.0 | 65–89              | 12.7                 | 139.7          | ordinary          | 12                  | failure                     | failure, 13.89               |

$\sigma_v/\sigma_h$ refer to the vertical in situ stress, maximum horizontal in situ stress, and minimum horizontal in situ stress in the target fracturing layer, respectively.

Table 8. Field Implementation and Application

| well name | pump pressure (MPa) | fracturing segment | cement quality | free expansion ratio (upon intermediate casing shoe) (%) | Young’s modulus (below intermediate casing shoe) (GPa) | SCP (MPa) |
|-----------|---------------------|--------------------|----------------|----------------------------------------------------------|------------------------------------------------------|-----------|
| W-8 h     | 82–95               | 18                 | high           | 8                                                        | 5                                                    | 0         |
| W-9 h     | 70–105              | 16                 | high           | 9                                                        | 5                                                    | 0         |
| JX6-4HF   | 75–85               | 18                 | high           | 8                                                        | 5.5                                                  | 0         |
| JX6-5HF   | 72–87               | 22                 | high           | 8                                                        | 5.5                                                  | 0         |
| JX9-1HF   | 78–87               | 22                 | high           | 8                                                        | 5.5                                                  | 0         |
| JX9-2HF   | 75–83               | 25                 | high           | 9                                                        | 4.5                                                  | 0         |
| JX9-3HF   | 81–89               | 19                 | high           | 9                                                        | 4.5                                                  | 0         |
passages for the SCP. Reducing the Young’s modulus of the cement sheath and the pump pressure was beneficial to alleviate the stress state of the cement sheath but could not guarantee the sealing integrity of the whole wellbore.

(2) The swelling stress of the expansion cement slurry after hardening was beneficial to decrease the circumferential stress but increased the radial compressive stress as well. It was necessary to comprehensively evaluate the influence of the Young’s modulus and free expansion ratio on the effective isolation height. Because a cement sheath with a high Young’s modulus value generally exhibited high compressive and tensile stiffness, it was recommended to use a high Young’s modulus cement slurry system above the intermediate casing shoe and control the free expansion ratio within a certain range to maximize the effective isolation height.

(3) Plastic accumulative strain on the cement sheath occurred during the cyclic compression test. The cement sheath below the intermediate casing shoe was subjected to high radial compressive stress, and the cyclic casing pressure caused the plastic accumulation of the cement sheath. The results from an assessment device demonstrated that the sealing ability of an ordinary cement sheath was poor, and a low residual strain cement sheath could withstand a higher casing pressure and more loading repetitions as a result of a larger elastic range. It is recommended to use the low residual strain cement slurry system below the intermediate casing shoe to increase the sealing ability.

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