Influence of Casing Eccentricity on the Mechanical Integrity of Cement Sheaths in Fractured Wells
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ABSTRACT: During the fracturing process of oil and gas wells, casing eccentricity directly affects the mechanical integrity of cement sheaths, but the law and degree of influence are not clear at present, and there are no measures to address the influence of casing eccentricity on the mechanical integrity of cement sheaths. This paper took the lead in developing a set of experimental devices for cement sheath integrity. A comparative experimental study on the mechanical integrity of cement sheaths was carried out for the first time under casing concentric and eccentric conditions, and the influence of casing eccentricity on the mechanical integrity of cement sheaths in fractured wells of the Wushi 17-2 oilfield was also investigated. The numerical simulation method was used to perform stress analysis on cement sheaths of fractured wells under casing concentric and eccentric conditions. The influences of casing wall thickness, cement sheath thickness, the elastic modulus of cement sheath, and formation on radial stress of the cement sheath were analyzed, and the mechanical integrity safeguard or remedy measures of the cement sheath under the casing eccentric condition were proposed for the first time. The results show that casing eccentricity can easily lead to stress concentration at the narrow edge of the cement sheath. Under the condition of the same strength of the cement sheath, the integrity of the cement sheath is more likely to fail under the casing eccentric condition. The tensile failure cracks are concentrated at the narrow edge of the cement sheath. With the increase in casing eccentricity, the stress at the narrow edge of the cement sheath increased, the critical failure pressure of the cement sheath decreased, and the failure pressure of cement sheath integrity decreased by 17.72% at a casing eccentricity of 33% compared within a casing eccentricity of 0%. Improving the casing center degree, increasing the casing wall thickness and cement sheath thickness, and reducing the elastic modulus of the cement sheath can minimize the stress of the cement sheath and prevent mechanical integrity failure. This study is helpful to evaluate the mechanical integrity of the cement sheath in fractured wells accurately and can provide a technical reference for optimizing the casing center degree.

1. INTRODUCTION

Recently, with the further exploitation of oil and gas resources, the difficulty in oil and gas exploration is increasing. As a result, fracturing is turning into a means of conventional production. In fractured well development, the mechanical integrity of a cement sheath is an essential factor that restricts the efficient development of oil and gas. However, casing eccentricity is a crucial indicator affecting the mechanical integrity of a cement sheath. Casing eccentricity leads to uneven thickness of the cement sheath and uneven stress distribution, thereby producing stress concentration. The greater the degree of eccentricity, the more pronounced the nonuniformity is, and the lower is the critical failure pressure of the cement sheath.1−5

Al Ramadan et al. designed a wellbore model setup to mimic the gas migration in a cemented annulus. A series of experiments were conducted on this setup to examine the cement sealability of neat Class H and neat Class G cements and to also evaluate the effect of antigas migration additives on cement sealability.6 He also investigated the critical length of the casing−liner overlap by modeling gas leakage through the cement placed within the overlap using analytical and experimental approaches. Leakage scenarios were developed to mimic gas migration within the cement in the casing−liner overlap. The results showed that the longer the casing−liner overlap, the higher the leakage time; the results also showed that the current casing pressure test duration of 30 min may not be adequate to verify the integrity of the cement within the
Hui et al. established a finite element analysis, and experimental investigation; he pointed out that casing eccentricity would reduce the unloading capacity of a cement sheath under different eccentricity conditions using theoretical calculation, finite element analysis, and experimental investigation; he pointed out that casing eccentricity would reduce the unloading capacity of a cement sheath.9–13 Han analyzed the influence of casing eccentricity on the loading capacity of a cement sheath using the finite element model.14 Wei studied the unloading effect of a cement sheath on external extruding load under different casing eccentricity conditions using theoretical calculation, finite element analysis, and experimental investigation; he pointed out that casing eccentricity would reduce the unloading capacity of a cement sheath.15–17 Hui et al. established a mechanical–thermal coupling model under the condition of casing eccentricity. They pointed out that the maximum stress of the casing inner wall increases with the eccentric angle.16 Sheng and Zhang et al. established the finite element model of a casing–cement sheath–formation assembly. They pointed out that casing eccentricity has a direct influence on casing and cement damage.17,18 De Andrade et al. conducted experiments on the effect of thermal cycling on cement sheath integrity when casing eccentricity occurred.19 Yanjun et al. carried out experiments on the influence of casing eccentricity on the sealability of a cement sheath. They pointed out that casing eccentricity has a significant impact on the sealability of a cement sheath.20 Zhao et al. considered casing eccentricity to carry out finite element analysis on the wellbore integrity of HP/HT wells and pointed out that casing eccentricity would affect the location of the maximum damage factor.21

In the study of cyclic load and its influence on cement strength, Tariq et al. proposed a new approach to reduce the breakdown pressure of tight rocks and compared it with the conventional method of fracturing. Results showed that the breakdown pressure of the rock decreases with the increasing number of cycles. The proposed method of cyclic thermochemical fracturing reduced the breakdown pressure by 33% in one cycle, 41% in two cycles, 53.5% in three cycles, and 69% in four cycles when compared with the conventional method of fracturing. An empirical relationship was also presented between the number of cycles of thermochemical fluid injection and the breakdown pressure of the rock.22 In addition, Tariq et al. proposed a new environment-friendly approach to reduce the breakdown pressure of the unconventional rock. The new method incorporated the injection of chemical-free fracturing fluid in a series of cycles with a progressive increase of the pressurization rate in each cycle. The results showed that the new method of cyclic fracturing can reduce the breakdown pressure to 24.6% in ultratight rocks, 19% in tight rocks, and 14.8% in medium- to low-permeability rocks.23 Murtaza et al. developed a novel silicate system, aqueous alkali aluminosilicate (AAAS), which was tested in oil well cementing. It was observed that the addition of a novel silicate system increased the compressive strength. In addition to that, the novel silicate provided an accelerating effect on the development of compressive strength. The application of a novel silicate could be a strong alternative for sodium silicate in the area of oil well cementing because of its promising results of compressive strength and rheology.24 In addition, Murtaza et al. studied the results of scratch tests carried out on oil well cement using type G cement, and the specimens were modified using nanoclay as an additive; the scratch test was applied to evaluate the strength of the oil well cement successfully.25 Yan and Yong et al. carried out experiments on the influence of cyclic load on the seal integrity failure of cement sheaths according to an evaluation of cement sheath seal capability.26–29 Lin and Li et al. also tested the cycle time of seal integrity failure under different strong alternating thermal loads, as well as the mechanical properties of the casing–cement sheath interface before and after sealing integrity failure.30–32 Yanan et al. tested the seal integrity of a cement sheath under the condition of high temperature, high pressure, and casing pressure cyclic load using the method of gas channeling. The experimental results showed that the cement sheath is prone to seal failure in the unloading process after a certain number of loading/unloading cycles under the condition of casing pressure cyclic load, and

| Condition                   | 50% of casing eccentricity | 33% of casing eccentricity |
|-----------------------------|-----------------------------|-----------------------------|
| Simulation result           | ![Image](https://example.com/image1) | ![Image](https://example.com/image2) |

**Figure 1.** Radial stress cloud chart of the cement sheath under various conditions of casing eccentricity.
with the increase of the casing pressure cyclic load, the cement sheath seal failure cycle gradually became less.\textsuperscript{33}

According to investigations and analyses, some scholars had researched the influence of casing eccentricity on the integrity of a cement sheath. Still, no comparative experimental study has been carried out under casing concentric and casing eccentric conditions. No engineering solution has been proposed to compensate for the influence of casing eccentricity on the mechanical integrity of a cement sheath. This paper took the lead in developing a set of experimental devices for cement sheath integrity; a comparative experimental study on the mechanical integrity of cement sheaths was carried out for the first time under casing concentric and eccentric conditions, and the influence of casing eccentricity on the mechanical integrity of cement sheaths in fractured wells was also investigated. The investigated results showed that the integrity of the cement sheath was more likely to fail under the condition of casing eccentricity. The stress calculations of the cement sheath in fractured wells under the conditions of central casing and eccentric casing were carried out combined with the numerical simulation method. The influences of casing wall thickness and cement sheath thickness, the elastic modulus of the cement sheath, and the formation on the radial stress of the cement sheath were analyzed, and the mechanical integrity safeguard or remedy measures of the cement sheath under the condition of casing eccentricity were proposed for the first time, which provides technical reference for a cementing construction design.

2. RESULTS AND DISCUSSION

2.1. Numerical Simulation Results and Discussion. In the cementing process of fractured wells, casing eccentricity is caused by factors such as wellbore trajectory and casing weight, so it is easy to form a cement sheath with uneven thickness after cementing. As a result, the casing—cement—formation combination is not a symmetrical model with a uniform circumferential force, and the combination is not uniform in circumferential force under internal and external pressures.

Figure 1 is the calculation cloud chart of the cement sheath radial stress at the first interface under various conditions of casing eccentricity. As shown in Figure 1, S stands for stress, and “S11” means the radial stress of the model in a specified coordinate system. The radial stress at the narrow edge of the cement sheath under the casing eccentric condition is significant. Additionally, the maximum radial stress occurs at the inner wall of the cement sheath, which shows that casing eccentricity can lead to uneven stress distribution in the cement sheath. Combined with the calculation of the stress distribution under various casing eccentricities, the radial stress distribution curve of the cement sheath inner wall is drawn under different casing eccentricities, as shown in Figure 2. Here, $\Phi = 0^\circ$ means that the calculation point is located on the inner wall of the wide side of the cement sheath. The measurement $\Phi = 180^\circ$ means that the calculation point is located on the inner wall of the narrow side.

Figure 2 shows that the radial stress on the inner wall of the cement sheath is uniformly distributed under the casing concentric condition, and the risk of mechanical integrity failure of the cement sheath at various phase angles is equal. When the casing is eccentric, the radial stress at the narrow edge of the cement sheath is much larger than that at the wide edge, which shows that casing eccentricity increases the risk of mechanical integrity failure under the same cement strength condition. Additionally, the greater the degree of eccentricity, the greater the failure risk.

To comprehensively reflect the influence of casing eccentricity on the mechanical integrity of the cement sheath, the stress distribution calculation results of the cement sheath under various casing eccentricities were extracted, and the results are shown in Table 1.

From Table 1, we can see that under the condition of the same cement strength, casing eccentricity affects the radial stress distribution of the cement sheath, and it has a significant influence on its circumferential stress, Mises stress, and deformation amount. With the increase of casing eccentricity, radial stress, Mises stress, and deformation of cement sheath, the compression failure risk of the cement sheath also increases. Meanwhile, the cement sheath tends to change from the compression to tensile direction in the circumfluence.

Similarly, the influence law of different casing wall thicknesses, different cement sheath thicknesses, different elastic moduli of the cement sheath, and different elastic moduli of formation on the radial stress of the cement sheath under the condition of casing eccentric can be obtained through a numerical simulation calculation, as shown in Figures 3–6.

It can be seen from Figures 3–6 that the radial compressive stress at the inner wall of the cement sheath increases with the increase of casing eccentricity. Under the same casing eccentricity condition, the radial compressive stress at the inner wall of the cement sheath decreases with the increase of casing wall thickness, cement sheath thickness, and elastic formation on the radial stress of the cement sheath were extracted, and the results are shown in Table 1.

| casing eccentricity (%) | 50 | 33 | 15 | 0 |
|-------------------------|----|----|----|---|
| maximum radial stress (MPa) | 35.24 | 34.37 | 33.73 | 33.27 |
| maximum circumferential compressive stress (MPa) | 3.342 | 3.411 | 3.524 | 3.792 |
| maximum Mises stress (MPa) | 37.22 | 36.31 | 35.24 | 34.68 |
| maximum deformation amount (mm) | 0.0928 | 0.0829 | 0.0757 | 0.0623 |
modulus of formation and increases with the increase of elastic modulus of the cement sheath.

2.2. Experimental Results and Discussion. 2.2.1. Experimental Result. 2.2.1.1. Uniaxial Compressive Strength Test of the Cement Sheath. Cement sheath samples for the uniaxial test were prepared based on this cement slurry system. The length of samples was 50.0 mm, and the diameter was 25.0 mm. The sample before the test is shown in Figure 7a, and the sample after the test is shown in Figure 7b. The uniaxial compressive strength was 34.8 MPa.

2.2.1.2. Integrity Failure Test Result of the Casing Concentric Condition. The experimental results show that cement sheath failure did not occur at 35−65 MPa, alternating 20 cycles. Subsequently, the alternating pressure was increased to 79 MPa, and gas channeling appeared at the top of the cement sheath after 10 cycles of altering the pressure of 35−79 MPa. After disassembling the experimental device, a tensile crack was found at the end face of the cement sheath. The crack was uniformly distributed in the circumferential direction, as shown in Figure 8. Therefore, it was analyzed that uniform tensile failure occurred in the cement sheath.

2.2.1.3. Integrity Failure Test Result of the Casing Eccentricity Condition. The experimental results show that slight gas channeling occurs at the top of the cement sheath in the simulated casing after 20 cycles of alternating pressure of 35−65 MPa. After disassembling the experimental device, a tensile crack was found at the end face of the cement sheath. The crack was uniformly distributed in the circumferential direction, as shown in Figure 8. Therefore, it was analyzed that uniform tensile failure occurred in the cement sheath.

2.2.2. Experimental Discussion. By comparing experimental data in Section 2.2.1, the cement sheath integrity failure pressure was found to be 79 MPa under the casing concentric
condition. The integrity failure pressure of the cement sheath was 65 MPa under the casing center degree of 67%, and it decreased by 17.72% compared to that under the casing center degree of 100%. This indicates that casing eccentricity will decrease the loading capacity of the cement sheath and the cement sheath is more likely to fail during fracturing.

On comparing Figures 8 and 9, cement sheath cracks were found to be distributed uniformly in the circumference direction when the casing center degree was 100%. Cement sheath cracks occurred at the narrow edge of the cement sheath when the casing center degree was 67%. This change indicates that the cement sheath’s radial stress distribution is uniform when the casing is entirely concentric, and casing eccentricity will cause stress concentration at the narrow edge of the cement sheath. As a result, the failure risk of mechanical integrity of the cement sheath increased at its narrow edge. The experimental results are consistent with the numerical simulation results, which verifies the correctness of the conclusion.

2.3. Engineering Solutions Results and Discussion.

2.3.1. Optimal Design for Casing Center Degree. Numerical simulation of stress distribution was used in the cement sheath under the different casing eccentricities, and the change curve of radial stress at the inner wall of the cement sheath is shown in Figure 10. According to the failure criterion of the cement sheath, when the radial stress of the cement sheath is greater than its compressive strength, the cement sheath will be at risk of integrity failure. The compressive strength test of the cement sheath showed that the compressive strength is 34.8 MPa. According to Figure 10, ensuring that the casing center degree is no less than 58.5% can ensure the mechanical integrity of the cement sheath.

2.3.2. Optimal Design for Casing Wall Thickness. When the wellbore conditions are poor, the casing center degree is difficult to guarantee, and the integrity failure risk of the cement sheath can be reduced by increasing the casing wall thickness. The numerical simulation method was used to calculate the radial stress at the inner wall of the cement sheath when the casing center degree was 67%, and the casing wall thicknesses were 9.19, 10.36, 11.51, and 12.68 mm. The curve of radial stress at the inner wall of the cement sheath changing with the casing wall thickness is shown in Figure 11.

Figure 11 shows that with the increase of casing wall thickness, the radial stress at the inner wall of the cement sheath decreases. The compressive strength test of the cement sheath showed the compressive strength to be 34.8 MPa. The casing wall thickness should be more than 9.94 mm to ensure mechanical integrity of the cement sheath.

2.3.3. Optimal Design for the Thickness of the Cement Sheath. Based on the numerical analysis, the radial stress at the inner wall of the cement sheath was calculated when the casing center degree was 67%, and the thicknesses of the cement sheath were 19, 29.8, 40.6, and 51.4 mm. The curve of radial
stress at the inner wall of the cement sheath changing with cement sheath’s thickness is shown in Figure 12.

![Figure 12. Curve of radial stress at the inner wall of cement sheath changing with cement sheath’s thickness.](image)

Figure 12 shows that with the increase of cement sheath thickness, the radial stress at the inner wall of the cement sheath decreases; when the thickness of the cement sheath is 19 mm, the radial compressive stress at the inner wall of the cement sheath is 32.2 MPa. The compressive strength test of the cement sheath showed that the compressive strength is 34.8 MPa; the analysis showed no risk of cement sheath failure under the conventional thickness of the cement sheath (>19.0 mm).

2.3.4. Optimal Design for Mechanical Properties of the Cement Sheath. Based on the numerical analysis, the radial stress at the inner wall of the cement sheath is calculated when the casing center degree is 67%, and the cement sheath’s elasticities are 3, 5, 7, and 9 GPa. The curve of radial stress at the inner wall of the cement sheath changing with cement sheath’s elasticity is shown in Figure 13.

![Figure 13. Curve of radial stress at the inner wall of the cement sheath changing with cement sheath’s elasticity.](image)

Figure 13 shows that with the increase of cement sheath’s elasticity, the radial stress at the inner wall of the cement sheath increases. The compressive strength test of the cement sheath showed that the compressive strength is 34.8 MPa. The cement sheath’s elasticity modulus should be less than 6.5 GPa to ensure the cement sheath’s mechanical integrity.

3. CONCLUSIONS

The numerical simulation and experimental investigation showed that casing eccentricity could lead to uneven stress on the cement sheath during fracturing, and stress concentration at the narrow edge easily leads to mechanical integrity failure.

With the increase in casing eccentricity, the stress at the narrow edge of the cement sheath increased and the critical failure pressure of the cement sheath decreased. The failure pressure of the cement sheath integrity decreased by 17.72% at a casing eccentricity of 33% compared with a casing eccentricity of 0%. Therefore, the casing center degree should be as high as possible when cementing.

Suppose it is challenging to ensure the casing center degree. In that case, the stress state of the cement sheath can be improved by increasing the casing wall thickness and cement sheath thickness and reducing the elastic modulus of the cement sheath; these changes can decrease the integrity failure risk of the cement sheath.

Mechanical integrity of the cement sheath is very important to ensure safe production of oil and gas. Protection for the mechanical integrity of the cement sheath should be considered in future fracturing well designs, and the design standards or guidelines should be developed accordingly.

4. NUMERICAL SIMULATION

4.1. Model Building. Assuming that the mechanical properties and material properties of the combination remain unchanged along the axial direction of the wellbore, the integrity problem of the cement sheath analyzed can be transformed into a two-dimensional plane strain problem. Structural analysis numerical software ANSYS was used to establish a two-dimensional finite element model of casing–cement sheath–formation combination, as shown in Figure 14.

A thick-walled ring shape was used to simulate the formation to apply uniform in situ stress, and the formation diameter was set to 3 m, which was more than 10 times the hole diameter; the formation size was much larger than the hole size to eliminate the end effect based on St. Venant’s principle.

![Figure 14. Casing–cement sheath–formation combination model with casing eccentricity.](image)
4.2. Inputs of the Simulator. In terms of loads and constraints, the first and second interfaces of the combination were set as contact pairs, and the contact behavior was set to rough. The pressure module was used to apply the far-field stress, and casing pressure was applied to the inner wall of the casing. The in situ stress was set at 30 MPa, and the maximum-casing pressure during fracturing was set at 65 MPa. The geometric and mechanical parameters of casing–cement sheath–formation combination are shown in Table 2.

Table 2. Geometric and Mechanical Parameters of the Combination

| name       | outer diameter (mm) | elastic modulus (GPa) | Poisson ratio | cohesive force (MPa) | internal friction angle (deg) |
|------------|---------------------|-----------------------|---------------|----------------------|-------------------------------|
| casing     | 177.8               | 210                   | 0.3           | 0                    | 11.2                          |
| cement sheath | 215.9           | 6.0                   | 0.16          | 11.9                 | 27.4                          |
| formation  | 19.61               | 0.24                  | 1.9           | 23.43                |                               |

4.3. Failure Criterion. The typical failure forms of the cement sheath are compression failure and tensile failure; most studies take the Mohr–Coulomb failure criterion as the primary basis to determine whether the cement sheath has been damaged at present, as shown in Table 3.

Among them, $\sigma_1$ and $\sigma_3$ are the maximum and minimum principal stresses respectively, MPa; $\sigma_t$ is the tensile strength of the cement sheath, MPa; and $\sigma_c$ is the compressive strength of the cement sheath, MPa.

5. EXPERIMENTAL VERIFICATION

5.1. Experimental Device. 5.1.1. Introduction of the Experimental Device. An evaluation device for cement sheath integrity failure was developed. It can perform the mechanical integrity test of the cement sheath under concentric and eccentric casing conditions, as shown in Figure 15. The device mainly includes a wellbore simulation system, pressure and control system, temperature and control system, fluid-channeling simulation system, and data acquisition and control system. The simulated wellbore height was 0.8 m, the confining pressure and casing pressure applying capacity was 100 MPa, the fluid-channeling pressure applying ability was 20 MPa, and the temperature applying capacity was 200 °C. The simulated casing center degrees were 67 and 100%. The upper and lower lids with the casing concentric and eccentric conditions are shown in Figures 16 and 17. This device can be used to evaluate the integrity failure of a cement sheath under various temperatures, pressures, casing eccentricity, and alternate temperature and pressure cycles.

The experimental device was designed based on the principle of stress equivalence, and a small-size simulated casing was used to ensure the safety and convenience of the experiment. The radial stress of the inner wall of the cement sheath under the experimental condition is equal to that under the field working condition by changing the pressure inside the casing to ensure a similar stress state of the cement sheath.

5.1.2. Principle of Experimental Design. 5.1.2.1. Mechanical Model of Cement Sheath Integrity under the Field

Table 3. Failure Criteria of Mohr–Coulomb

| stress range | mechanical description                  | principal stress relation | failure criteria |
|--------------|----------------------------------------|---------------------------|-----------------|
| 1            | tensile–tensile–tensile                | $\sigma_1 \geq \sigma_3 \geq 0$ | $\sigma_1 \geq \sigma_t$   |
| 2            | compression–compression–compression    | $0 \geq \sigma_1 \geq \sigma_3$ | $-\sigma_3 \geq \sigma_c$ |
| 3            | tensile–tensile–compression             | $\sigma_1 \geq 0 \geq \sigma_3$ | $\frac{\sigma_1}{\sigma_c} - \frac{\sigma_3}{\sigma_c} \geq 1$ |
**Working Condition.** The mechanical model of cement sheath integrity under the field working condition is the combination of casing, cement sheath, and formation, as shown in Figure 18.

![Figure 18. Mechanical model of casing–cement sheath–formation combination.](image)

The radial stress $G_1$ at the inner wall of the cement sheath can be calculated according to Lammer’s formula:

$$G_1 = \frac{k_{11}^e (k_{12}^e + k_{12}^f)P + k_{11}^e k_{12}^f F}{k_{21}^e + k_{22}^e (k_{12}^e + k_{12}^f) - k_{11}^e k_{12}^f}$$  \hspace{1cm} (1)

$$k_{11}^e = \frac{1 + \nu_t}{E_t} \cdot \frac{2(1 - \nu_s) a^2}{b^2 - a^2}$$  \hspace{1cm} (2)

$$k_{21}^e = \frac{1 + \nu_t}{E_t} \cdot \frac{(1 - 2\nu_s)b^2 + a^2}{b^2 - a^2}$$  \hspace{1cm} (3)

$$k_{21}^t = \frac{1 + \nu_t}{E_t} \cdot \frac{(1 - 2\nu_s)b^2 + c^2}{c^2 - b^2}$$  \hspace{1cm} (4)

$$k_{12}^t = \frac{1 + \nu_t}{E_t} \cdot \frac{(1 - 2\nu_s)c^2}{c^2 - b^2}$$  \hspace{1cm} (5)

$$k_{12}^f = \frac{1 + \nu_t}{E_t} \cdot \frac{2(1 - \nu_s)d^2}{d^2 - c^2}$$  \hspace{1cm} (6)

$$k_{22}^f = \frac{1 + \nu_t}{E_t} \cdot \frac{(1 - 2\nu_s)b^2 + c^2}{c^2 - b^2}$$  \hspace{1cm} (7)

$$k_{22}^t = \frac{1 + \nu_t}{E_t} \cdot \frac{(1 - 2\nu_s)c^2 + d^2}{d^2 - c^2}$$  \hspace{1cm} (8)

In the formula, $a$ is the inside radius of the casing, mm; $b$ is the outside radius of the casing, mm; $c$ is the outside radius of cement sheath, mm; $d$ is the outside radius of the formation, mm; $E_t$ is the elasticity modulus of the casing, MPa; $\nu_t$ is Poisson’s ratio of the casing, dimensionless; $E_s$ is cement sheath’s elasticity, MPa; $\nu_s$ is Poisson’s ratio of the cement sheath, dimensionless; $P$ is the casing pressure, MPa; and $F$ is the formation confining pressure, MPa.

5.1.2.2. Mechanical Model of Cement Sheath Integrity under the Experimental Condition. The mechanical model of cement sheath integrity under the experimental condition is the combination of casing and cement sheath, as shown in Figure 19. The radial stress $\sigma_r$ and circumferential stress $\sigma_\theta$ at the inner wall of the cement sheath can be calculated according to Lammer’s formula:

$$\sigma_r = -S_1$$  \hspace{1cm} (10)

$$\sigma_\theta = \frac{a_1^2 + a_2^2}{a_2^2 - a_1^2} \cdot S_1 - \frac{2a_2^2}{a_2^2 - a_1^2} \cdot F$$  \hspace{1cm} (11)

$$S_1 = \frac{C \cdot P + B \cdot F}{A + D}$$  \hspace{1cm} (12)

$$A = \left(1 - \nu_s\right) a_1^2 + \left(1 + \nu_s\right) a_2^2$$  \hspace{1cm} (13)

$$B = \frac{2a_2^2}{E_s \cdot a_1 \left(\frac{a_1^2}{a_1^2} - 1\right)}$$  \hspace{1cm} (14)

$$C = \frac{2a_1}{E_s \cdot a_1 \left(\frac{a_1^2}{a_1^2} - 1\right)}$$  \hspace{1cm} (15)

$$D = \left(1 - \nu_s\right) a_1^3 + \left(1 + \nu_s\right) a_2$$  \hspace{1cm} (16)

In the formula, $a_1$ is the inside radius of the casing, mm; $a_2$ is the outside radius of the casing, mm; $a_2$ is the outside radius of the cement sheath, mm; $E_t$ is the elasticity modulus of the casing, MPa; $\nu_t$ is Poisson’s ratio of the casing, dimensionless; and $S_1$ is the absolute value of radial stress at the inner wall of the cement sheath, MPa.

5.1.2.3. Casing Pressure Design Based on the Principle of Stress Equivalence. The curves of radial stress at the inner wall of the cement sheath changing with the casing pressure under the experimental condition and the field working condition were drawn separately based on the theoretical model, as shown in Figure 20. To realize that the radial stress at the inner wall of the cement sheath under the experimental condition is equal to that under the field working condition, there is

$$G_1 = S_1$$  \hspace{1cm} (17)

Therefore, various working conditions in the field can be simulated by changing the casing pressure in the experiment based on Figure 20.

5.2. Experimental Material. The experimental material is mainly cement slurry; the cement used in the experiment is Portland cement, the class of cement is G, and its formula is shown in Table 4.

5.3. Experimental Procedures. 5.3.1. Experimental Investigation of the Casing Concentric Condition. The
lower lid was installed with the casing center degree of 100% (Figure 16), and a casing with a wall thickness of 10.36 mm was inserted into the simulated wellbore. The cement slurry was prepared according to the formula shown in Table 4 and was injected into the simulated annulus; the heat conduction oil was injected into the casing. The upper lid was sealed, the test device was sealed, and the temperature was set at 120 °C for maintenance for 48 h. After the cement sheath was completely cured, the fracturing operation of the Wushi 17-2 oilfield was simulated. The confining pressure of the cement sheath was set at 30 MPa, the pressure in the casing was set in the range of 35–65 MPa, alternating for multiple cycles, and the pressure at the bottom of the cement sheath was maintained at 1–2 MPa to test fluid channeling.

5.3.2. Experimental Investigation of the Casing Eccentricity Condition. The lower lid was installed with a casing eccentricity of 67% (Figure 17); the experimental procedures and parameter settings are the same as those in the experimental investigation of the casing concentric condition.

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**Table 4. Cement Slurry Formula of the Wushi 17-2 Oilfield**

| Material Name          | Weight (g) | Volume (mL) | Dosage (g) |
|------------------------|------------|-------------|------------|
| Water                  | 40.40      | 40.40       | 404.00     |
| PC-X60L (defoaming agent) | 0.40      | 0.40        | 4.00       |
| PC-F41L (dispersant agent) | 1.50      | 1.46        | 15.00      |
| PC-H21L (cement retarder) | 0.80      | 0.68        | 8.00       |
| PC-G80L (fluid loss agent) | 3.50      | 3.24        | 35.00      |
| PC-B10 (expansion agent) | 1.00      | 0.28        | 10.00      |
| Cement                 | 100.00     | 31.25       | 1000.00    |

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**Figure 20. Schematic diagram of equivalent casing pressure.**

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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported by grants from the major project of CNOOC (China) Co., Ltd., “Research on key technologies of drilling and completion of 20 million m³ oilfield in the west of South China Sea”, and the National Natural Science Foundation of China (Project No. 51804043).

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