Visualization of Casing Stress Characteristics under Non-Uniform In-situ Stress and Non-uniform Cement Sheath

Chen Tao¹, Zhu Wei², Chen Feng*², Di Qinfeng³, Qin Guangxu³ and Li Qing¹

¹ School of Computer Engineering and Science, Shanghai University, Shanghai 200072, China
² School of Mechatronics Engineering and Automation, Shanghai University, Shanghai 200072, China
³ Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, China

*Corresponding author’s e-mail: chenfeng536@126.com

Abstract. Casing damage is a common problem in oil and gas fields due to the complicated stress state of casing. Especially in the horizontal well section, the casing is difficult to be centered, and the eccentric casing is prone to failure under non-uniform in-situ stress. In order to study the influence of non-uniform in-situ stress and non-uniform cement sheath on the stress state of casing, a numerical model of the coupling of casing, cement sheath and formation is established. The stress distribution characteristics of casing under four conditions of uniform in-situ stress uniform cement sheath, uniform in-situ stress non-uniform cement sheath, non-uniform in-situ stress uniform cement sheath and non-uniform in-situ stress non-uniform cement sheath are compared. The results show that the non-uniform cement sheath will cause the stress distribution of casing to be uneven, and the maximum stress on the casing is proportional to the amount of eccentricity. The non-uniform in-situ stress will cause the casing stress to be uneven and affect the extreme value of the stress on the casing inner wall. The results will provide the theoretical basis for the casing damage prediction effectively.

1. Introduction
As an unavoidable problem in petroleum engineering, casing damage has been restricting the development of oil and gas industry. According to data statistics of large domestic oilfields: as of August 2013, Daqing oilfield had a total of 18,000 casing damaged wells, with an annual increase of more than 1,200 wells[1]; In the 27,000 production wells of Shengli oilfield, Casing damage occurred in 5,400 Wells, and the casing damage ratio is as high as 20%[2]. The main causes of casing damage include corrosion of downhole fluid, non-uniform extrusion force and non-uniform in-situ stress caused by formation deformation, and shear deformation caused by formation sliding, etc. It involves geological factors, engineering factors and chemical corrosion. The common forms of casing damage include corrosion perforation, casing deformation and casing fracture. Casing damage not only affects the development progress of oil field but also may cause the abandonment of production wells and injection wells, causing huge economic losses to oil field [3]. Therefore, it is of great significance to study the mechanism of casing damage for casing protection.

The stress analysis of casing has been a key problem for scholars at home and abroad. Jerome Schubert studied the defect model with plastic cement sheath and brittle cement sheath, and he analysed
the bearing performance of the casing in view of the coexistence of casing eccentricity and defects [4]. Lssas kalil carried out numerical simulation analysis on the stress situation of the casing when part of the cement sheath was missing, and he studied the influence of the cement sheath missing on the casing strength [5]. Gao Lijun studied the effect of cement sheath stiffness on casing through three-dimensional finite element analysis, and then he found that changing the mechanical properties of cementing cement had little effect on alleviating the shear casing loss [6]. Li Jun considered the influence of factors such as non-uniform in-situ stress on the stress distribution of casing and analysed the casing damage mechanism in the segmented fracturing process of horizontal wells. The results show that as the non-uniform in-situ stress ratio increases, the stress extreme value of the casing wall and non-uniformity of circumferential stress increases significantly [7]. Zhao Lei proposed a method for calculating the equivalent uniform external pressure of the outer wall of casing under the combined effect of non-uniform in-situ stress and inner pressure. The theoretical value was consistent with the maximum equivalent stress obtained by numerical simulation method [8]. Xue Jinghong studied the influence of non-uniform load on the stress distribution of casing by finite element method. The analysis results show that with the decrease of uniformity coefficient of non-uniform external load, the maximum stress value of the casing and the non-uniformity of stress distribution also increased [9]. Fu Pan studied the influence of stratigraphic slip on casing in horizontal well fracturing process. The analysis results can effectively help prevent casing damage [10].

China's shale gas development widely uses the form of “segmented fracturing and horizontal well”. Considering that the casing is difficult to be centered under the influence of gravity in the horizontal well section, the stress state of the eccentric casing is very complicated under non-uniform in-situ stress. Analysing the stress characteristics of casing under non-uniform in-situ stress and non-uniform cement sheath is important for protecting casing and preventing casing damage. We establish a numerical model of the coupling of casing, cement sheath and formation by finite element method and analyse the stress state of the casing. The influence of non-uniform in-situ stress and non-uniform cement sheath on the mechanical characteristics of casing is studied, which provides a theoretical basis for casing damage prediction in horizontal wells.

2. The casing, cement sheath and formation model

2.1. Finite element model

The finite element models of the casing, cement sheath and formation are established as shown in figure 1 and figure 2. The outer diameter of the casing is 139.7mm, the wall thickness of the casing is 10.54mm, the outer diameter of the cement sheath is 215.9mm, and the length and width of the formation are 900mm. Figure 1 shows the casing centered and Figure 2 shows that the casing is 20mm eccentric. Assuming that the interface of casing and cement sheath (hereinafter referred to as the first interface) and the interface of cement sheath and formation (hereinafter referred to as the second interface) are of good cementing quality. Interface nodes are processed as common nodes. In this paper, the mechanical characteristics of the casing, cement sheath and formation under eccentricity of 5mm, 10mm, 15mm, 20mm, 25mm, 30mm and 35mm are considered respectively. Due to limited space, not all computational models are shown here. The stress on the finite element model under uniform in-situ stress is 30MPa in the X direction and 30MPa in the Y direction. The stress on the finite element model under non-uniform in-situ stress is 30MPa in the X direction and 50MPa in the Y direction.
2.2. Mechanical properties of materials

According to the test data, the Young's modulus, poisson ratio, yield limit and strength limit of P110 steel casing are $210 \times 10^5$ MPa, 0.29, 734.9MPa and 920.0MPa respectively. The relationship between the real stress and the plastic strain is shown in table 1. Considering the elastic-plastic properties of cement sheath and formation, mohr-coulomb criterion is selected as failure criterion. The material properties of cement sheath and formation are shown in table 2.

Table 1. The relationship between the real stress and the plastic strain.

| real stress (MPa) | plastic strain | real stress (MPa) | plastic strain |
|------------------|----------------|------------------|----------------|
| 734.9            | 0              | 957.5            | 0.0440         |
| 764.3            | 0.0001         | 967.9            | 0.0503         |
| 869.0            | 0.0057         | 976.5            | 0.0562         |
| 885.7            | 0.0122         | 983.9            | 0.0620         |
| 901.3            | 0.0186         | 990.0            | 0.0677         |
| 917.7            | 0.0252         | 994.7            | 0.0730         |
| 932.2            | 0.0315         | 998.4            | 0.0780         |
| 945.8            | 0.0379         | 1000.3           | 0.0830         |

Table 2. The material properties of cement sheath and formation.

| Modulus of elasticity (GPa) | poisson ratio | Angle of internal friction (°) | Cohesive force (MPa) |
|-----------------------------|---------------|--------------------------------|----------------------|
| cement sheath               | 9.2           | 0.15                           | 17.1                 | 21.6                 |
| formation                   | 27.0          | 0.20                           | 30.0                 | 59.3                 |

3. The characteristics of casing stress distribution under different parameters

The casing string in the horizontal section of shale gas is affected by complex in-situ stress in the process of refracturing. After hydraulic fracturing, the formation hydration expansion will produce greater uniform in-situ stress, and the fault slip of stratum will produce non-uniform in-situ stress. Under the action of gravity, horizontal casing tends to be close to the lower side of the well. Casing eccentricity is easy to be formed during cementing, which leads to the complicated stress state of casing. In this paper, the effects of casing eccentricity on the stress distribution characteristics of the casing complex under uniform in-situ stress and non-uniform in-situ stress are calculated respectively. We analyse the von Mises stress distribution characteristics, the equivalent stress of the casing inner wall, the radial stress and tangential stress distribution rules at the first interfaces and the second interfaces.
3.1. The effect of casing eccentricity on stress distribution characteristics of casing under uniform in-situ stress

When the casing is centered, the stress distribution of the casing under uniform in-situ stress is shown in figure 3. The stress distribution on the casing is uniform, and the maximum stress is 583.9MPa, which is located on the inner wall of the casing. While the casing eccentricity is 35mm, the stress distribution under uniform in-situ stress is shown in figure 4. The stress distribution on the casing shows obvious non-uniformity. The maximum value appears on the inner wall on the thicker side of the cement sheath, and the value is larger than that the casing in the center, reaching 600.9MPa.

In order to determine the effect of cement sheath inhomogeneity on casing stress characteristics, the von Mises stress distribution characteristics on casing under different casing eccentricity were calculated respectively. The maximum von Mises stress on the casing corresponding to different casing eccentricity under uniform in-situ stress are shown in table 3. The results show that the greater the eccentricity is, the greater the maximum von Mises stress is, and the more likely the casing failure is. The variation of casing’s maximum von Mises stress under different eccentricity is shown in figure 5. It can be seen from the figure 5 that casing’s maximum von Mises stress is proportional to the casing eccentricity.

Table 3. The effect of casing eccentricity on casing’s maximum von Mises stress under uniform in-situ stress.

| Casing position | center | 5mm eccentric | 10mm eccentric | 15mm eccentric | 20mm eccentric | 25mm eccentric | 30mm eccentric | 35mm eccentric |
|-----------------|--------|---------------|----------------|----------------|----------------|----------------|----------------|----------------|
| The maximum stress (MPa) | 583.94 | 586.52 | 588.90 | 591.12 | 593.30 | 595.53 | 597.96 | 600.88 |

In order to determine the effect of cement sheath inhomogeneity on casing stress characteristics, the von Mises stress distribution characteristics on casing under different casing eccentricity were calculated respectively. The maximum von Mises stress on the casing corresponding to different casing eccentricity under uniform in-situ stress are shown in table 3. The results show that the greater the eccentricity is, the greater the maximum von Mises stress is, and the more likely the casing failure is. The variation of casing’s maximum von Mises stress under different eccentricity is shown in figure 5. It can be seen from the figure 5 that casing’s maximum von Mises stress is proportional to the casing eccentricity.

Figure 5. The effect of casing eccentricity on casing’s maximum von Mises stress under uniform in-situ stress.

The equivalent stress of the casing inner wall when the casing is centered under uniform in-situ stress is shown in figure 6. The equivalent stress distribution on the casing inner wall is uniform, and the
maximum value is 583.6MPa. When casing eccentricity is 35mm, the equivalent stress is shown in figure 7. Distribution of the equivalent stress in the casing inner wall was obviously uneven, and the minimum equivalent stress appeared on the thinner side of the cement sheath, with a size of 539.7MPa. The maximum equivalent stress is 600.5MPa, which appears the thicker side of the cement sheath.

The equivalent stress of the two casing inner walls in figure 6 and figure 7 are plotted along the circumference of the casing inner wall, as shown in figure 8. When the casing is centered, the equivalent stress curve is basically horizontal and the equivalent stress on the casing wall is uniform. When the casing eccentricity is 35mm, the equivalent stress curve changes greatly and presents obvious fluctuation characteristics. At this time, the maximum value of the equivalent stress on the casing inner wall is larger than the maximum value of the equivalent stress when the casing is centered.

3.2. The effect of non-uniform in-situ stress on stress distribution characteristics of casing
The stress distribution of the casing centered under uniform in-situ stress is compared with the stress distribution of the casing centered under non-uniform in-situ stress, as shown in figure 9 and figure 10. When the in-situ stress is uniform, the stress distribution on the casing is uniform, and the maximum stress is located on the casing inner wall. When the in-situ stress is non-uniform, the stress distribution on the casing shows obvious non-uniformity. The maximum value appears in the direction of smaller in-situ stress, and the value is higher than that under uniform in-situ stress.
Figure 9. The stress distribution of the casing under uniform in-situ stress when the casing is centered.

Figure 10. The stress distribution of the casing under non-uniform in-situ stress when the casing is centered.

Under the condition of uniform in-situ stress, the equivalent stress of the casing inner wall when the casing is centered is shown in figure 11. The equivalent stress distribution on the casing inner wall is uniform. Under the condition of non-uniform in-situ stress, the equivalent stress of the casing inner wall when the casing is centered is shown in figure 12. The equivalent stress distribution in the casing inner wall shows obvious non-uniformity, the minimum value appears in the direction of greater in-situ stress, and the maximum value appears in the direction of smaller in-situ stress.

Figure 11. Vector diagram of the equivalent stress on casing inner wall under uniform in-situ stress when the casing is centered.

Figure 12. Vector diagram of the equivalent stress on casing inner wall under non-uniform in-situ stress when the casing is centered.

The equivalent stress of the two casing inner walls in figure 11 and figure 12 is plotted along the circumference of the casing inner wall, as shown in figure 13. When the casing is centered, the equivalent stress distribution on the casing wall is uniform under uniform in-situ stress. The equivalent stress distribution on the casing wall presents obvious fluctuation characteristics under non-uniform in-situ stress, with four extreme values. The two maximum values occur in the direction of smaller in-situ stress and the minimum values occur in the direction of larger in-situ stress. In addition, the maximum stress is greater than that under uniform in-situ stress.

Figure 13. Distribution rule of the equivalent stress on casing inner wall along circumference.
3.3. The effect of casing eccentricity on stress distribution characteristics of casing under non-uniform in-situ stress

When the casing is centered, the stress distribution of the casing under non-uniform in-situ stress is shown in Figure 14. The stress distribution on the casing is uniform, and the maximum stress is 696.6 MPa, which is located on the inner wall of the casing. While the casing eccentricity is 35 mm, the stress distribution under non-uniform in-situ stress is shown in Figure 15. The stress distribution on the casing shows obvious non-uniformity. The maximum von Mises stress appears on the inner wall on the thicker side of the cement sheath, and the value is increased to 717.0 MPa compared with casing centralization case.

Figure 14. The stress distribution of the casing under non-uniform in-situ stress when the casing is centered.

Figure 15. The stress distribution of the casing under non-uniform in-situ stress when the casing is 35 mm eccentric.

The von Mises stress distribution characteristics on the casing under different casing eccentricity conditions were calculated respectively, and the maximum value of von Mises stress on the casing under non-uniform in-situ stress conditions was obtained, as shown in Table 4. The results show that the greater the eccentricity is, the greater the maximum von Mises stress is, and the more likely the casing failure is. The variation of casing’s maximum von Mises stress under different eccentricity is shown in Figure 16. It can be seen from Figure 16 that casing’s maximum von Mises stress is proportional to the casing eccentricity. The conclusions are consistent with those in Table 3.

Table 4. The effect of casing eccentricity on casing’s maximum von Mises stress under non-uniform in-situ stress

| Casing position | center | 5mm eccentric | 10mm eccentric | 15mm eccentric | 20mm eccentric | 25mm eccentric | 30mm eccentric | 35mm eccentric |
|-----------------|--------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| The maximum stress (MPa) | 696.60 | 700.06 | 703.42 | 706.40 | 709.09 | 711.65 | 714.20 | 716.95 |

Figure 16. The effect of casing eccentricity on casing’s maximum von Mises stress under non-uniform in-situ stress
4. Conclusions
(1) Under the condition of uniform in-situ stress, the stress distribution on the inner wall of the centralized casing is uniform, while non-uniform cement sheath will result in non-uniform stress distribution of the casing.

(2) The maximum value of von Mises stress appears on the inner wall of casing on the thicker side of the cement sheath under the condition of non-uniform cement sheath, and the maximum von Mises stress on the casing is proportional to the casing eccentricity.

(3) Non-uniform in-situ stress makes the stress distribution on the inner wall of casing uneven. The maximum value appears in the direction of smaller in-situ stress, and the value is higher than that of uniform in-situ stress.

(4) The stress distribution on the casing is very uneven under the condition of the coexistence of non-uniform in-situ stress and non-uniform cement sheath. The value of von Mises stress on the casing is proportional to the casing eccentricity. And the maximum stress appears on the inner wall of the casing corresponding to the eccentricity direction. This position is the danger zone of casing inner wall.

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