A cohesive-element-based model to evaluate interfacial behavior of casing–cement sheath for high-pressure, high-temperature wellbore integrity considering casing eccentricity

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Abstract
In this article, the finite element model considering the casing eccentricity of high-pressure, high-temperature wellbore integrity is established, where the cohesive zone element is introduced to evaluate the mechanical behavior of the casing–cement sheath interface. In this analysis, the bilinear traction–separation law is used to estimate the interfacial failure, and a damage factor is simultaneously defined to describe the damage evolution of the cohesive element. In addition, to achieve the interfacial separation, the pressure fluctuation inside the casing is applied. Using the finite element approach, we investigate the effect of mechanical parameters including Young's modulus, Poisson's ratio, thermal conductivity of the cement sheath, and pressure fluctuation inside the casing on the interfacial failure of the casing–cement sheath. The simulation results show that the damage factor increases with the increase in the mechanical parameters including Young's modulus and Poisson's ratio of the cement sheath and the casing pressure fluctuation. We also observe that the maximum damage factor under higher thermal conductivity is higher than that under lower thermal conductivity for the casing concentricity, while it is lower than that under lower thermal conductivity for the casing eccentricity. This indicates that the casing eccentricity has an important impact on the damage factor. What's more, the casing eccentricity can change the location where the maximum damage factor occurs.

Keywords
High-pressure, high-temperature wellbore integrity, casing eccentricity, casing–cement sheath interface, mechanical behavior, cohesive zone element

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Introduction
Casing eccentricity is the necessary prerequisite and important condition to improve cementing quality for high-pressure, high-temperature (HPHT) wells in unconventional oil and gas fields and hot dry rock fields. So, the casing must be placed in the center of the wellbore through some centralizers. However, due to the change of well trajectory angle, improper

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arrangement of casing centralizer, the borehole enlargement, the borehole washout, nonstandard operation during cementing, and so on, the casing might not be centered in the wellbore. With the exploration and development of shale gas, tight sandstone gas, and offshore oil and gas resources, horizontal well, extended reach well, highly deviated well, or horizontal branch well are widely used in these fields. The construction of these wells makes casing eccentricity more complicated. The casing eccentricity causes many bed effects, such as influence on interface stability and efficiency of displacement fluid, influence on the measurement result of sonic logging instrument and reducing the wellbore integrity safety, casing collapse strength, and casing-cement bond surface strength. And, the final one is the biggest impact on the production process of the wellbore among these impacts. Through investigation and research, the separation of the interface between casing and cement sheath directly produced one way to escape for oil and gas. Such behaviors will cause air pollution, water pollution, soil pollution, greenhouse effect, or production accidents, such as oil spill in the Gulf of Mexico in 2010. In this case, the casing eccentricity as an inevitable issue directly affects the wellbore integrity. In addition, the interfacial behavior (separation or debonding) of the casing–cement sheath also plays an important role in the HPHT wellbore integrity. Thereby, it is crucial to investigate the interfacial behavior of the casing–cement sheath of the eccentric cased wellbore to evaluate the wellbore integrity of HPHT gas wells in unconventional oil and gas fields and hot dry rock fields.

Currently, the finite element method is primarily used to analyze the issue of the casing eccentricity due to the difficulty in acquiring the analytical solution. Akgun et al. established a finite element model to estimate the degree of the casing eccentricity at inclined section of a directional well, accounting the hole inclination angle, the applied tension, and the measured depth. This work demonstrates that the inclination angle remarkably affects the significance of the casing eccentricity. Berger et al. employed a finite element analysis to investigate the impact of the casing eccentricity on the collapse resistance of casing. Yuan et al. proposed a finite element model to analyze the effect of the casing eccentricity on the wellbore integrity. Shahri et al. simulated a case that the cement is not centered in the wellbore and concluded that it is highly possible that the mechanical failure occurs in the wide side of the cement. Nabipour et al. adopted the finite element approach to study the effect of the casing eccentricity on the induced stress in the cement sheath. Salehabadi et al. analyzed the correlation of the eccentricity and the casing stability utilizing a numerical method. Wang et al. also utilized the finite element approach to investigate the effects of the non-uniform in situ stress and the casing eccentricity on the casing strength. Salim and Amani studied a number of engineering cases in the area of HPHT cementing and found that the casing eccentricity decreases the shear stress and the tensile stress of the cement sheath while increasing its compressive stress. Tardy and Bittleston investigated the influence of the casing eccentricity on the flow and displacement of completion fluids using a numerical scheme. Although much effort has been devoted in this area, almost all the computational models used in the work discussed above are based on the assumption that the casing, cement, and formation are perfectly bonded with each other, leading to the significant difference between the prediction and the practice.

In the process of fracture propagation simulation of hydraulic fracturing, the cohesive element does not represent any material. And meanwhile, because the cohesive force in cohesive element can resist the tensile stress produced by the separation of fracture tip, various models based on cohesive element have been widely used in the process of hydraulic fracture simulation, and the interfacial mechanical response of composite materials. The casing eccentricity is easy to cause the interface separation between casing and cement sheath, which is very similar to fracture propagation in formation. Therefore, this article uses the cohesive element to simulate the interface separation. In this article, the cohesive zone element is introduced to simulate the interface of the casing–cement sheath, and a finite element approach is applied to evaluate the mechanical behavior of the casing–cement sheath interface for the eccentric cased HPHT well, taking the solid-temperature coupling into account. In addition, the impact of mechanical properties of the cement sheath and the pressure variations inside the casing on the mechanical behavior of the casing–cement sheath interface is also studied in detail.

Cohesive zone models

The cohesive layer composed of cohesive element is in the middle of continuous elements of the two materials, as shown in Figure 1. For the cohesive zone model, the bilinear traction–separation law is used to describe the mechanical behavior of the interface, which is shown in Figure 2.

As seen from Figure 2, the traction increases linearly with the increase in the displacement at segment OA, while it decreases monotonically with the increase in the displacement at segment AB. Point A is a critical point where the initiation damage/softening occurs, and point B is another critical point where the separation occurs completely. The dashed line OM represents
an unloading–reloading behavior for the traction–separation.

The stress–distance relationship of cohesive element in linear elastic stage before damage can be represented by an elastic matrix

$$\mathbf{t} = \begin{pmatrix} t_n \\ t_t \end{pmatrix} = \mathbf{K}\mathbf{\delta} = \begin{bmatrix} k_{nn} & 0 & 0 \\ 0 & k_{ss} & 0 \\ 0 & 0 & k_{tt} \end{bmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix}$$

(1)

where $\mathbf{t}$ is the nominal stress; $\mathbf{\delta}$ is the nominal distance; $\mathbf{K}$ is stiffness matrix; $t_n$ is the normal stress; $t_t$ and $t_s$ are the tangential stresses in two directions, respectively; $\delta_n$ is the normal displacement; and $\delta_s$ and $\delta_t$ are the shear displacements in two directions, respectively.

For the cohesive zone element, the initial damage can be evaluated by the stresses acting on the interface, as shown in equation (2)

$$\left(\frac{t_n}{t_n^c}\right)^2 + \left(\frac{t_t}{t_t^c}\right)^2 + \left(\frac{t_s}{t_s^c}\right)^2 = 1$$

(2)

where $t_n^c$ is the critical strength of the interface along the normal direction; $t_t^c$ and $t_s^c$ are the critical strengths of the interface along the tangential directions; and $\langle \rangle$ is the Macaulay brackets, defined as $\langle x \rangle = \max(0, x)$.19

After the initial damage, the mechanical properties of cohesive zone element gradually decrease, and the stress–distance relationship is inversely proportional

where $\mathbf{r}_n^d$ is the normal stress after the initial damage; $t_n^d$ and $t_t^d$ are the tangential stresses in two directions after the initial damage, respectively; and $D_S$ is a damage factor.

The damage factor $D_S$ is introduced to reflect the reduction of the stiffness of the cohesive zone element. While $D_S = 0$ represents that no damage occurs for the cohesive zone element, $D_S = 1$ represents that the separation occurs completely for the cohesive zone element. The damage factor is defined as

$$D_S = \frac{\delta_m^f (\delta_m^f - \delta_m^c)}{\delta_m^s (\delta_m^s - \delta_m^c)}$$

(4)

where $\delta_m^f$ is the separation displacement of the cohesive element in complete damage; $\delta_m^c$ is the separation displacement of the cohesive element in initial damage; and $\delta_m^s$ is the separation displacement of the cohesive element in damage process, and it is defined as

$$\delta_m = \sqrt{\delta_n^2 + \delta_s^2 + \delta_t^2}$$

(5)

**Mechanical models and finite element models**

**Mechanical models**

Based on the work of former researchers,26–33 we make the following assumptions:

1. The wellbore system for eccentric cased wells can be analyzed in the state of the plane strain;
2. The thickness of the interface of the casing–cement sheath is quite small;
3. The interface of the cement sheath–formation is assumed to be bonded perfectly, mainly because the mechanical properties between them are close to each other;
4. The stress induced by the temperature variation is assumed to be in a steady state, that is, independent on time.

Using the cohesive zone model to describe mechanical behavior of the interface of the casing–cement sheath, the mechanical model of HPHT wells in unconventional oil and gas fields and hot dry rock fields is established (see Figure 3). In Figure 3, the following symbols are used: the in situ stresses $\sigma_{H1}$, $\sigma_{H2}$; the internal pressure of the casing $p_0$; the temperature of the casing inner surface $T_0$; and the temperature of formation $T_f$. In addition, point O and point A are the
centers of the cement sheath (i.e. the wellbore center) and the casing, respectively. Thus, the distance between point O and point A represents the eccentric distance.

**Finite element models**

For the selection of element types of the finite element model, in order to simulate the interface separation between the casing and cement sheath, the cohesive zone element is adopted to analyze the mechanical behavior of the interface. And the casing, the cement sheath, and formation are discretized by four-node axisymmetric thermally coupled quadrilateral, bilinear displacement, and temperature elements. Meanwhile, the bilinear stress-strain relation with isotropic hardening is used to address the plastic deformation of the casing, and the Mohr–Coulomb model is used to investigate the mechanical behavior of the cement sheath and formation.

For the boundary conditions and load conditions of the finite element model, the wellbore system is fully fixed at point B, and the motion along the y-direction is restricted at point C. In addition, the in situ stresses $\sigma_{i1}$, $\sigma_{i2}$ and the formation temperature $T_f$ are applied on the outer boundary, and the casing temperature $T_0$ is applied on the inner surface of the casing. Besides, in order to simulate the pressure variation inside the casing, the casing pressure is first increased to $p_1$ and then reduced to $p_0$ in this analysis.

**Results and discussion**

**Numerical results**

In this numerical analysis, we take HG-X1 well, a typical HTHP gas well drilled in Xinjiang oilfield as an example. Due to the borehole enlargement, the casing eccentricity occurs at the depth of 3180–3220 m, bringing about a complex interfacial behavior of the casing–cement sheath. The specific parameters are mentioned in Table 1.

For the interface of the casing–cement sheath, the basic parameters are listed in Table 2.

| Parameters                                      | Data         |
|------------------------------------------------|--------------|
| The bottom depth (m)                           | 3220         |
| The eccentric distance OA (mm)                 | 40           |
| The eccentric direction (°)                    | 60           |
| The inner radius of the casing (mm)            | 73.0         |
| The casing pressure variation (MPa)            | 90–32.2      |
| The horizontal maximum in situ stress (MPa)    | 67           |
| in situ stress (MPa)                           | 62           |
| The horizontal minimum in situ stress (MPa)    | 45           |
| The casing inner surface temperature (°C)      | 180          |
| The reference temperature (°C)                 | 20           |

**Table 1. HG-X1 well parameters.**

| Parameters                                      | Data         |
|------------------------------------------------|--------------|
| The wall thickness (mm)                         | 0.1          |
| The normal critical strength $t_c$ (MPa)        | 40           |
| The eccentric direction (°)                     | 60           |
| The inner radius of the casing (mm)             | 73.0         |
| The casing pressure variation (MPa)             | 90–32.2      |
| The horizontal maximum in situ stress (MPa)     | 67           |
| in situ stress (MPa)                            | 62           |
| The horizontal minimum in situ stress (MPa)     | 45           |
| The casing inner surface temperature (°C)       | 180          |
| The reference temperature (°C)                  | 20           |

**Table 2. The basic parameters of the interface of the casing–cement sheath.**
The maximum damage factor is equal to 0.84, located in the 90° and 270° directions. However, when the eccentric distance increases to 40 mm, the interface separation occurs at the narrow side of the cement sheath, with a range of [198°, 342°]. Meanwhile, the maximum separation displacement occurs at 290° direction, with a value of 1.2 mm. Further increase in the eccentric distance (i.e. 70 mm) makes the interface separation occur at the narrow side of the cement, with a wider range of [198°, 371°] around the wellbore. In addition, we also observe that the maximum separation displacement reaches 1.4 mm, obviously higher than the one for the eccentric distance of 40 mm.

The casing eccentricity also affects the stresses of the casing and the cement sheath. Figure 6 exhibits the radial stress along the radial and hoop directions under different eccentric distances. Especially, in Figure 6(b), signs “A”–“C” represent the radial stresses along the outer surface of the casing with \( e = 0, 40, \) and 70 mm, while signs “D”–“F” represent the radial stresses along the inner surface of the cement sheath with \( e = 0, 40, \) and 70 mm, respectively.

As seen from Figure 6(a), with the increase in the eccentric distance, the radial stress increases within the casing and decreases within the cement sheath. In addition, increasing the distance from the wellbore center yields the increase in the radial stress initially and, subsequently, the reduction of the radial stress. Meanwhile, due to the non-uniform in situ stress, the radial stress along 0° direction is lower than that along 90° direction. It is also observed that the interface of the casing–cement sheath (i.e. at the distance of
80.5 mm) is subjected to a tensile state, leading to the occurrence of the interfacial separation. Figure 6(b) plots the radial stress distribution at the outer surface of the casing and the inner surface of the cement sheath. For the eccentric distance of 0 mm, the radial stress along the hoop direction is homogeneous at the
outer surface of the casing or the inner surface of the cement sheath. It can be seen that the largest difference of the radial stress between the outer surface of the casing and the inner surface of the cement sheath occurs at the 0° and 180° directions, revealing that the interfacial separation occurs first at these two directions. In addition, the smallest difference of the radial stress occurs at the 90° and 270° directions, indicating that it is very difficult to occur at the interfacial separation at these two directions. With the casing eccentricity (i.e., an eccentric distance of 40 mm), the radial stress is 0 at the range of [198°, 342°]. That is, the interfacial separation appears at this range, as seen in Figure 6(b). Meanwhile, the largest difference of the radial stress between the outer surface of the casing and the inner surface of the cement sheath appears in 0° and 360° directions, showing that the following interfacial separation occurs at these two directions. When the eccentric distance increases to 70 mm, the interfacial separation further extends to the ranges of [0°, 11°] and [198°, 360°]. Overall, the radial stress dominates between the outer surface of the casing and the inner surface of the cement sheath. Therefore, the casing eccentricity yields a large radial stress within the casing and the cement sheath.

Figure 7 shows the hoop stress results along the radial and hoop directions for different eccentric distances of 0, 40, and 70 mm. In Figure 7(b), symbols “A”–“C” represent the hoop stresses along the outer surface of the casing with \( e = 0, 40, \) and 70 mm, while symbols “D”–“F” represent the hoop stresses along the inner surface of the cement sheath with \( e = 0, 40, \) and 70 mm, respectively.

As shown in Figure 7(a), with the increase in the eccentric distance, the hoop stress decreases within the casing and the cement sheath. Note that a significant change of the hoop stress mainly occurs near the interface of the casing–cement sheath. This is due to the fact that the elastic modulus of the casing is obviously higher than the one of the cement sheath (see Table 3). In addition, the hoop stress does not vary remarkably around the wellbore (see Figure 7(b)).

Figure 8 shows the Mises stress variation along the radial and hoop directions for different eccentric distances. Similar to the trend of the hoop stress, Mises stress decreases with the increase in the eccentric distance along both the radial direction and the hoop direction. This is probably due to the fact that Mises stress is primarily dominated by the hoop stress. To summarize, the casing eccentricity yields the radial tensile stress at the interface of the casing–cement sheath, directly resulting in the interfacial separation. It is harmful for the wellbore integrity. However, both the hoop stress and Mises stress within the casing and cement sheath decrease, which is beneficial to the safety of the casing and the cement sheath.

**Parametric study**

In this section, we will study the sensitivity of mechanical parameters to the damage factor of the casing–cement sheath interface.

**Effect of Young’s modulus of cement sheath.** In this case, Young’s modulus of the cement sheath varies from 15 to 25 GPa with an increment of 5 GPa. For the casing concentricity (see Figure 9(a)), increasing Young’s modulus of the cement sheath leads to the significant increase in the damage factor of the cohesive element, indicating that a stiffer cement sheath will jeopardize interfacial safety. Furthermore, the
Figure 8. Mises stress results along the (a) radial and (b) hoop directions.

Figure 9. The effect of Young’s modulus of cement sheath on the damage factor of the cohesive element: (a) eccentric distance of 0 mm, (b) eccentric distance of 40 mm, and (c) eccentric distance of 70 mm.
maximum and minimum damage factors occur at the 90° and 180° directions, respectively. Considering the casing eccentricity (see Figure 9(b)), we find that the damage factor also shows an increasing trend as Young’s modulus of the cement sheath increases. The maximum damage factors reaches 1, located at a range of [225°, 345°] around the wellbore. Unlike the casing concentricity case, the position where the minimum damage factor is located moves along the 105° direction. If we keep increasing the eccentric distance, the range of the interfacial separation will extend to the range of [195°, 360°] around the wellbore. This suggests that the increase in the casing concentricity will increase the structural risk.

Effect of Poisson’s ratio of cement sheath. Poisson’s ratio of the cement sheath varies from 0.35 to 0.45 with an increment of 0.05 in this analysis. As seen from Figure 10, Poisson’s ratio is insensitive to the damage factor of the cohesive element. However, the casing eccentricity plays an important role in the damage factor, as shown in Figure 10(a) and (b). We also observe that the change of the eccentric distance from 0 to 40 mm leads to the increase in the damage factor from 0.114 to 0.968 at the 0° direction, and the decrease from 0.842 to 0.196 at the 90° direction. Therefore, we should choose the material with a lower Poisson’s ratio as the casing–cement sheath.

Effect of thermal conductivity of cement sheath. The thermal conductivity of the cement sheath varies from 1.34 to 2.14 W/(m K) with an increment of 0.4 W/(m K) in this analysis.

For the casing concentricity case, the distribution of the damage factor around the wellbore is insensitive to the thermal conductivity (see Figure 11(a)), that is, the maximum damage factor for the structure with a higher thermal conductivity is obviously higher than that with a lower thermal conductivity. However, the distribution of the damage factor varies obviously at the range of [0°, 105°] around the wellbore (see Figure 11(b)) when the casing eccentricity occurs. The minimum damage
factor for the structure with a higher thermal conductivity is higher than that with a lower thermal conductivity, while the maximum damage factor for the material with a higher thermal conductivity is lower than that for a lower thermal conductivity. Meanwhile, the interfacial separation occurs at the range of $[225^\circ, 345^\circ]$ for the material with a higher thermal conductivity, while at the range of $[195^\circ, 360^\circ]$ for that with lower thermal conductivity (see Figure 11(b)). The analysis above indicates that decreasing thermal conductivity will improve the interface safety for the casing concentricity, while it is harmful for the interfacial safety for the casing eccentricity. This is consistent with the conclusion by Salehabadi et al.\textsuperscript{13}

**Effect of casing pressure variation.** The casing pressure variation varies with different peaks from 70 to 110 MPa. As seen from Figure 12(a), the increase in the pressure remarkably increases the damage factor of the cohesive element. The maximum damage factor is 0.842 for the peak of the pressure fluctuation of 70 MPa, while it increases to 0.902 for the peak of the pressure fluctuation of 110 MPa. Note that the maximum damage factor is equal to 1 for the peak of 70 MPa (see Figure 12(b)) for the casing eccentricity of 40 mm, revealing that the casing eccentricity is capable of further rising for the damage factor of the cohesive element. In addition, it is highly possible that the interfacial separation for higher peaks of the pressure variation for the casing eccentricity occurs. For a peak of the pressure fluctuation of 70 MPa, the interfacial separation occurs at the range of $[270^\circ, 315^\circ]$ (see Figure 12(b)). However, the interfacial separation expands to the range of $[210^\circ, 360^\circ]$ when the peak of the pressure reaches 110 MPa. In summary, larger pressure fluctuation is harmful for the interface safety of the wellbore system; therefore, it should be controlled strictly in practice engineering.

Figure 11. The effect of thermal conductivity of cement sheath on the damage factor of the cohesive element: (a) eccentric distance of 0 mm, (b) eccentric distance of 40 mm, and (c) eccentric distance of 70 mm.
Conclusion

In this article, the cohesive zone element is introduced to simulate the interface of the casing–cement sheath, and by numerical simulation of three different casing eccentricity distances, we can directly obtain that the radial stresses is continuous in radial direction, and the hoop stress and the Mises stress are discontinuous in radial direction. And meanwhile, the stresses of the outside of casing and the inside of cement sheath are different in the position where the damage factor $D_s = 1$. According the results of the numerical simulation, it is believed that the method of using the cohesive element to simulate the separation of the interface of casing–cement sheath is effective.

By studying the sensitivity of mechanical parameters to the damage factor of the casing–cement sheath interface, we have drawn the following conclusions:

1. The damage factor significantly increases with the increase in Young’s modulus of the cement sheath and the casing pressure fluctuation, while the stiffness is not sensitive to the Poisson ratio of the cement sheath.
2. Reducing the thermal conductivity of the cement sheath is beneficial for the interfacial safety for the case of the casing concentricity. However, it jeopardizes the interfacial safety of the casing–cement sheath when considering the casing eccentricity.
3. The casing eccentricity highly influences the damage factor of the casing–cement sheath interface, and it is capable of changing the location where the maximum damage factor occurs.

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