Mechanisms of Casing Deformation during Hydraulic Fracturing in the Horizontal Wells of the Weirong Shale Field

Ze Li, Gao Li,* Hongtao Li, Long He, and Xiyong Wang

ABSTRACT: Casing deformation is frequent during hydraulic fracturing in the Weirong shale gas field, which impedes shale gas production. We investigated the effect of shale elastic modulus on casing deformation based on shale swelling in this work. According to field data, the silicon content in the Weirong shale gas field has a considerable impact on casing deformation during hydraulic fracturing. Furthermore, the results of the experiment show that the silicon content is positively related to the elastic modulus of shale. We conducted numerical simulations to analyze the casing deformation based on shale swelling. We observed that the shale elastic modulus was negatively correlated with the casing stress without shale swelling; however, the shale elastic modulus was positively correlated to casing stress with shale swelling. Furthermore, when the elastic modulus remained constant, casing stress was positively correlated with shale swelling. The numerical simulation results were validated using field data from the WY23-5 shale well. Moreover, factors such as injection pressure, formation pressure, and cement sheath elastic modulus can increase the impact of the shale elastic modulus on casing deformation with shale swelling. Casing deformation is greatly influenced by the distribution of the stimulated reservoir volume (SRV) area. Different SRV area behaviors result in different types of casing deformation. The symmetric distribution of the SRV area causes casing extrusion deformation, whereas the asymmetric distribution of the SRV area causes casing bending deformation. Moreover, casing stress is positively correlated with the length of the SRV area.

1. INTRODUCTION

The rise in global natural gas consumption has promoted the recovery of unconventional natural gas, such as shale gas. The Sichuan Basin is regarded as China’s major source of shale gas. Horizontal wells and multistage fracturing techniques are essential for recovering shale gas from the tight formation. However, multiple casing deformations have been reported in the Sichuan Basin during multistage hydraulic fracturing in horizontal shale gas wells. Moreover, casing deformation is a significant issue in five of the six wells in the Weirong gas field. Casing deformation disrupts the fracturing operation, and a few subsequent stages must be abandoned because of the reduction in the casing diameter and the inability to install bridge plugs to the required depths. Therefore, a comprehensive analysis of the mechanisms of casing deformation in the Weirong gas field is urgently needed.

Several studies have been conducted on casing deformations in shale gas wells during multistage fracturing. According to Lian et al. and Lin et al., stress deficiency is zero stress, and tension stress areas could produce “hanging” in the casing, resulting in partial radial deflection and axial S-shape deformation. Tian et al. and Yan et al. discovered that the temperature of the retention fluid in the cement voids inside casings decreased sharply during hydraulic fracturing. This, combined with the pressure drop inside the cement sheath voids, induced casing deformation. Liu et al. suggested that the local load induced by hydraulic fracturing was the main cause of casing deformation. Meyer et al. studied the effect of differential stress on casing deformations using seismic inversion. Zhang et al. discovered that the casing deformation was caused by additional stress generated by the large temperature difference.

Furthermore, based on the available field data, shear deformation is the most common type of casing deformation. As a result, recently, several researchers have explored the shear deformation caused by fault slides during hydraulic fracturing. During hydraulic fracturing, Chipperfield et al. proposed that the initiation and propagation of fractures formed tensile fractures and caused shear deformation. Fluid injection-induced aseismic slip of faults and surface ruptures were proposed by Wei et al. Based on the analysis of microseism data, Qian et al. observed that the casing deformation...
deformations in the Sichuan basin occurred primarily due to shear slips in the large-scale natural fracture areas.\textsuperscript{19} Bao and Eaton suggested that different mechanisms could trigger fault activation during and after hydraulic fracturing.\textsuperscript{20} Chen et al. studied the relationship between fault slip and casing shear deformation.\textsuperscript{21} Meyer et al. observed that the risk of casing deformation was correlated with stress anisotropy and the microseism moment magnitude of the fracture reactivation event.\textsuperscript{15} Yin et al. suggested that the rock deformed asymmetrically with respect to the wellbore due to the shear failure of natural fractures, and the fracture slip induced the casing shear deformations during hydraulic fracturing.\textsuperscript{22} Xi et al. proposed a mathematical model to establish the relationship between microseism moment magnitude and slip distance, indicating that the radius and slip distances increase with an increase in the moment magnitude.\textsuperscript{23} Liu et al. observed that the fault slip caused by hydraulic fracturing was the main reason for casing deformation in shale gas wells and established a semianalytical model for calculating induced stress along the fault caused by hydraulic fracturing.\textsuperscript{24} Dong et al. analyzed all the casing deformation locations in the affected area and observed that most of the deformation locations corresponded to fault locations.\textsuperscript{25} Chen et al. suggested that fracturing fluid could pass through the fault between the casing and formation.\textsuperscript{26} This triggered the fault, resulting in casing deformation. In addition to faults, the importance of weak bedding planes and the influence on casing deformation have become the focus of researchers. Tang et al. stated that the weak bedding planes have a significant impact on the formation of the fracture network during hydraulic fracturing and that the fracturing fluid can penetrate the weak bedding planes and force them to open.\textsuperscript{26} To investigate the propagation and opening of the weak plane during hydraulic fracturing, Xie et al. developed a 3D fracture propagation model.\textsuperscript{27} Tang et al. developed a 3D fracture model to simulate the interactions between fracture and oblique weak bedding planes during hydraulic fracturing.\textsuperscript{26} The above study shows that the weak bedding plane opens under the action of the liquid phase during and after hydraulic fracturing, which impacts the complexity of the fracture network. Furthermore, the activation of the weak bedding planes is caused by the opening of the weak bedding planes, resulting in casing shear deformation.\textsuperscript{29}

Most of the above studies are based on casing shear deformation caused by faults or natural fractures activation. However, the faults and natural fractures are undeveloped in the Weirong shale gas field. Moreover, only one deformed point exists at the good interval near natural fractures in the Weirong field. Furthermore, symmetrically distributed hydraulic fractures in the wellbore region caused by seismic events demonstrated that shear slip is rare in the area surrounding the WY23-5 well, as shown in Figure 1.\textsuperscript{30} Therefore, we concluded that shear slippage was not the primary reason for casing deformations in the Weirong shale gas field.

In contrast, we discovered that the casing deformation locations were related to the silicon content in the region because 11 of the 13 casing deformation locations contained high amounts of high silicon, as shown in Figure 2. Figure 2 shows the relationship between the casing deformation points and the silicon content. The silicon content distribution and casing deformation points of multiple wells are depicted in this graph. Different colored points show the distribution of silicon content of each well in different depths, and the casing deformation points of each well are represented by red solid points. Past studies establish the positive correlation between the silicon content and the shale elastic modulus.\textsuperscript{31,32} Therefore, the impact of the shale elastic modulus on the mechanism of casing deformation in the Weirong shale gas field needs to be studied further.

In the Weirong shale gas field, we conducted tests and numerical simulations to investigate the effect of the shale elastic modulus on the casing deformation owing to shale swelling. Initially, we conducted tests to investigate the relationship between the shale mineral composition and the
elastic modulus. Then, we created numerical simulations to investigate the effect of the shale elastic modulus on the casing deformation caused by shale swelling. We explained the occurrence of high silicon content casing deformation locations and presented a novel perspective on casing deformation mechanisms in the Weirong shale gas field.

2. RELATIONSHIP BETWEEN SILICON CONTENT AND ELASTIC MODULUS

The elastic modulus is an important mechanical property of shale. We conducted triaxial compression experiments to measure the elastic modulus of shale cores from the Weirong shale gas field. The experiment was performed at the State Key Laboratory of Oil and Gas Reservoir Geology and Exploration; the experimental confining pressure was set at 30 MPa. The temperature was normal during the experiment. The elastic modulus of the tested cores was calculated using the stress–strain curve at the end of the experiment. Natural gas is extracted primarily from the lower Silurian Longmaxi formation in the Weirong shale gas field.33 Hence, we selected the cores from this formation. As shown in Figure 3, the elastic modulus of the cores varies from 15 to 40 GPa. Moreover, most samples were in the range of 35–45 GPa, demonstrating hardness. Furthermore, we performed the XRD experiments on each sample and conducted the triaxial compression experiments to obtain the mineral content. The mineral content of each shale sample corresponds to the elastic modulus, as shown in Figure 3. The shale elastic modulus is positively correlated with the quartz content. Quartz is mainly composed of silicon in the shale;34 thus, the shale elastic modulus is positively correlated with the silicon content in the region. In addition to this manuscript, Feng et al. and Ye et al. also reached the same conclusion.31,32 Therefore, the casing deformation locations positively correlate with the shale elastic modulus and silicon content in the Weirong shale gas field. In Section 1, we found that casing deformation is related to silicon content. Through the analysis in Section 2, we also found that the silicon content is positively correlated with the elastic modulus. In the finite element numerical simulation, it is difficult to analyze the mineral content directly. Therefore, the influence of the shale elastic modulus on the casing deformation will be analyzed in a future manuscript.

3. NUMERICAL SIMULATION METHODOLOGY

We conducted a numerical simulation to study the impact of the shale elastic modulus and shale swelling on the casing deformation. The swelling of the shale generated by the interaction between working fluids and clay was a crucial aspect in assessing casing deformations, which was ignored in the previous research. The shale in the Weirong field does not contain smectite but contains some Illite and a small amount of smectite layers. The Illite softens and collapses the shale under the action of the liquid. Previous studies indicated that an obvious penetrating fracture exists along the bedding plane due to the interaction between the Illite and the liquid,35 as shown in Figure 4.36 The interaction subsequently causes fractures to expand and propagate due to clay swelling, and then the shale swelling occurs.36 Furthermore, the complex fracture network formed during and after hydraulic fracturing, leading to the liquid interaction with more bedding planes and natural fractures. In addition, the smectite layer can also expand under the action of water, resulting in shale swelling. Therefore, shale swelling cannot be ignored because numerous fractures are generated and connected during hydraulic fracturing. The limited porosity and permeability of the shale matrix prevent the working fluid from permeating the shale matrix. During and after hydraulic fracturing, however, the working fluid permeates into the SRV area. Therefore, shale swelling only occurs in the SRV areas in our research.

The WY23-5 well is critical for understanding casing deformation in the Weirong shale gas field. In this study, we used data from the WY23-5 well to create a numerical simulation model. Therefore, the SRV area in this simulation model was established based on the microseismic data in Figure 5, which showed the trajectory of the WY23-5 well and the microseismic surveillance data of the WY23-5 well. The SRV area was determined using the microseismic monitoring data profile.10

Furthermore, previous research believed that shale deposits were transversely isotropic. Therefore, the mechanical properties of shale formations were assumed to be constant along the horizontal direction of the well. The mechanical properties of
the shale formation, on the other hand, showed substantial variances even along the horizontal direction.\textsuperscript{37,38} We obtained the distribution of the elastic modulus along the horizontal direction in the WY23-5 well from the logging data in Figure 6. The elastic modulus in the WY23-5 well at the measured depth (MD) of 4000–4200 m was between 15 and 35 GPa, indicating that the shale has higher strength. Furthermore, the inhomogeneous mechanical properties of the shale were confirmed by the fluctuation in the elastic modulus in the horizontal direction.

The simulation model based on the anisotropy of the shale elastic modulus and shale swelling is depicted in Figure 7. We used COMSOL Multiphysics for numerical simulation. The generated shale swelling during hydraulic fracturing was used to evaluate the effect of shale swelling on the casing deformation. The parameters for analyzing shale swelling introduced in prior studies were applied in our study.\textsuperscript{30,39,40} The other model information and boundary condition settings are shown below. In this model, the structural mesh was used to boost computational performance and convergence. The meshes around the wellbore were encrypted to improve the accuracy of the calculation results on the casing. The outer wall of the simulation model was fixed by imposing displacement constraints. The in situ stress and formation pressure values obtained from the field data were used in the model. The fracturing fluid is injected directly into the formation through the casing, and the injection pressure was set at the casing inner wall. Because COMSOL can achieve better fluid–solid coupling, formation pressure and injection pressure were applied as fluid pressure. Furthermore, the direction of minimum horizontal stress was parallel to the borehole’s axial direction. The injection pressure was applied to the casing inner wall. The values of the

Figure 4. Influence of the bedding plane on shale swelling.

Figure 5. Microseismic surveillance data and casing deformation point of the WY23-5 well.

Figure 6. Distribution of the elastic modulus along the horizontal direction in the WY23-5 well.
load conditions are listed in Table 1. In Table 1, * indicates variable parameters in the numerical simulation. The distribution of the shale elastic modulus along the wellbore direction is shown in Figure 6, and the relationship between the elastic modulus and well depth was embedded in the COMSOL model by the interpolation function. It is worth noting that the elastic modulus is not distributed uniformly in the model in Figure 7. Although the elastic modulus with depth is only shown on the model’s left side, this is only to highlight the SRV area better. The entire shale formation in the model follows this elastic modulus distribution. In the SRV area of the model, shale swelling was simulated by opening the hygroscopic swelling interface in COMSOL.

The wellbore diameter, casing diameter, and thickness were 215.9 mm, 145.6 mm, and 13.49 mm, respectively. We fixed the length of the numerical model at 200 m to simulate the MD of 4000−4200 m. The width and height of the model were also fixed at 200 m.

The shale matrix and the SRV areas are elastoplastic and follow the Mole Coulomb criterion. During the numerical simulation, the cohesion was set at 20 MPa, and the internal friction angle was set at 30°. The casing grade of the WY23-5 well was 125 SG. In our study, the casing yield stress was 861 MPa and followed the Von Mises yield criterion. The casing was set to frictional contact with the cement sheath in the finite element software. In COMSOL, the governing equation for shale swelling is as shown in eq 1.

$$\varepsilon_{hs} = \beta_h (C_{mo} - C_{mo,ref})$$  \hspace{1cm} (1)

where $\beta_h$ is the coefficient of hygroscopic swelling, $C_{mo}$ is the moisture concentration, and $C_{mo,ref}$ is the strain-free reference concentration. In this paper, the shale swelling can be simulated only by setting appropriate parameters and making $\varepsilon_{hs}$ an appropriate shale swelling degree.

### Table 1. Main Parameters in the Numerical Simulation

| material          | elastic modulus (GPa) | Poisson’s ratio (1) | swelling (%) | maximum horizontal stress (MPa) | minimum horizontal stress (MPa) | vertical stress (MPa) | formation pressure (MPa) | injection pressure (MPa) |
|-------------------|-----------------------|---------------------|--------------|---------------------------------|---------------------------------|-----------------------|--------------------------|--------------------------|
| shale formation   | *                     | 0.23                |              | 100                             | 80                              | 90                    | 50                       | 80                       |
| SRV area          | *                     | 0.23                | *            | 100                             | 80                              | 90                    | 50                       | 80                       |
| casing            | 210                   | 0.30                |              | -                               | -                               | -                     | -                        | -                        |
| casing sheath     | 10                    | 0.30                |              | -                               | -                               | -                     | -                        | -                        |

### 4. RESULTS AND DISCUSSION

#### 4.1. Influence of Shale Elastic Modulus and Shale Swelling on Casing Deformation

4.1.1. Impact of Shale Elastic Modulus on Casing Deformation without Shale Swelling.

To investigate the effect of the shale elastic modulus and shale swelling on casing deformation, a univariate analysis is required. As a result, as shown in Figure 8, we initially computed casing stress without considering shale swelling. Because the shale elastic modulus varied along the horizontal direction of the well, the casing stress changed along the horizontal direction of the well. The casing stress ranged from 375 to 465 MPa at MDs ranging from 4000 to 4200 m. The casing stress without shale swelling was negatively linked with

Figure 7. Numerical model for casing deformation based on mechanical anisotropy and shale swelling

Figure 8. Casing stress without shale swelling at the MD of 4000−4200 m.
the shale elastic modulus, implying that the higher the elastic modulus, the lower the casing stress. A high shale elastic modulus resulted in low shale deformation, which in turn resulted in low casing stress.

Similarly, for the same in situ stress, a low shale elastic modulus resulted in an increased casing stress. Furthermore, the greatest casing stress was 465 MPa between 4000 and 4200 m. This was lower than the yield strength of the 125
SG grade casing (861 MPa). According to the field data, however, casing deformation occurred between 4164 and 4169 m. As a result, the numerical simulation results contradicted the field data. As a result, we investigated the mechanism of casing deformation as well as the effect of shale elastic modulus on the casing stress with shale swelling.

4.1.2. Impact of Elastic Modulus on Casing Deformation with Shale Swelling. We considered the shale swelling in the SRV areas as a strain, and the shale swelling values at 0.2%, 0.4%, and 0.6% were used in numerical simulations. Figure 9 shows the casing stress for different shale swelling percentages. We observed that the casing stress was directly proportional to the shale swelling percentage. However, because of the lack of shale swelling, casing stress did not increase over the MD of 4000–4095 m. After considering shale swelling, the casing stress was positively correlated with the shale elastic modulus. The strain on the shale formation at a specific shale swelling percentage remained constant for a predetermined SRV area. Therefore, the casing stress was directly proportional to the shale elastic modulus for the same strain on shale formation. At the MD of 4165 m, the maximum casing stress was 1059 MPa for 0.6% shale swelling. This far exceeded the yield strength of 125 SG casing leading to casing deformation. Figure 9c is the log signature of the WY23-5 well, showing casing deformation. Figure 9c shows that the GR curve of the WY23-5 well in the casing deformation is positioned gently without obvious lithologic change. Multifinger calliper logging shows that casing deformation occurs at 4165–4169 m.

Numerical models with shale swelling were corroborated by field data, which showed that casing deformation occurs at MDs ranging from 4164 to 4169 m. The contour plots of casing stress for different shale swelling at MDs of 4164–4166 m are shown in Figure 10. The casing did not deform at no shale swelling, while the degree of casing deformation increased with shale swelling. The casing suffered bending deformation at 0.6% swelling because of the asymmetric distribution of the SRV area in the WY23-5 well, as shown in Figure 4. The numerical simulation results demonstrate the effect of the elastic modulus and shale swelling on the casing deformation in the Weirong shale gas field.

Casing displacement is an important metric for measuring casing deformation. The casing displacement corresponding to varied shale swelling is achieved using numerical simulation in this paper, as shown in Figure 11. It is worth noting that, to demonstrate better the impact of the shale swelling on casing deformation, only simulation results of 4164 to 4166 m are shown in Figure 11. Furthermore, to better highlight the comparison of the casing displacement under different shale swelling, the range of casing displacement corresponding to different shale swelling values is maintained at 0–25 mm. As shown in Figure 11, casing displacement increases with an increase in the shale swelling. When the shale swelling is 0.6%, casing displacement is 25 mm in many positions, showing strong casing deformation characteristics. When the shale swelling is small, the casing displacement is small, and casing deformation characteristics are not obvious.

4.2. Influence of Construction Parameters on Casing Deformation. 4.2.1. Impact of Injection Pressure on Casing Deformation. Hydraulic fracturing has been widely used to boost the natural gas output from shale resources. Furthermore, microseismic data and postfracturing production studies show a favorable relationship between fracture complexity and gas output in fractured wells.\(^{43}\) In hydraulic fracturing design, the injection pressure is a critical parameter. To investigate the impact of injection pressure on casing deformation, the casing stresses for different injection pressures and 0.4% shale swelling in the SRV area were determined, as shown in Figure 12. From Figure 12, we observed that the distribution of casing stress is consistent under different injection pressures with a peak in the SRV area. The maximum casing stress with an injection pressure of 100 MPa is 1031 MPa, which increases from 903 MPa by 70 MPa. The higher the injection pressure, the greater the formation of deformation due to porous medium pressurization and fracture pressurization. Therefore, the effect of the shale elastic modulus on the casing deformation increased with an increase in the injection pressure, and the high injection pressure used in the hydraulic fracturing process was a major cause of casing deformations.

4.2.2. Impact of Formation Pressure on Casing Deformation. Formation pressure is an important factor that can influence stress distribution. We maintained the injection pressure of 80 MPa and shale swelling at 0.4% throughout this simulation. The impact of formation pressure on the casing stress along the axial length at MDs of 4000–4200 m was
measured as shown in Figure 13. We observed that the casing stress was inversely proportional to the formation pressure.

The maximum casing stress at 40 MPa formation pressure was 1004 MPa. However, the maximum casing stress at 70 MPa formation pressure was 814 MPa. The stress acting directly on the casing—the effective stress on the shale rock skeleton—was determined by subtracting the formation pressure from the total stress. The effective stress decreased with increased formation pressure when the in situ stress remained constant.

4.2.3. Impact of Cement Sheath Elastic Modulus on Casing Deformation. The cement sheath’s elastic modulus has a substantial impact on casing deformations, which can be adjusted using different cement slurry mixtures. Figure 14 presents the casing stress values for cement sheath elastic moduli of 6000, 8000, 10 000, and 12 000 MPa. We observed that the casing stress was directly proportional to the elastic modulus of the cement sheath. The maximum casing stress at a 6000 MPa elastic modulus is 912 MPa, and the maximum casing stress at 120.00 MPa is 978 MPa. Therefore, some experts believe that decreasing the elastic modulus of the cement sheath could protect the casing. The in situ stress combined with the stress induced by shale swelling transfers to the casing through the cement sheath. Therefore, the casing stress is low when the elastic modulus of the cement sheath is low. Thus, the elastic modulus of the cement sheath can play an important role in the countermeasures of casing deformation.

4.3. Influence of the SRV Area Distribution on Casing Deformation. 4.3.1. Impact of Symmetric Distribution of the SRV Area on Casing Deformation. In addition to the construction parameters, the distribution of the SRV area can also influence the casing stress distribution. Figure 15 illustrates the numerical simulation used to investigate the effect of the symmetric distribution of the SRV area and length of hydraulic fractures on the casing deformation. The SRV area is only assumed to change in the MD of 4130−4175 m due to the casing deformation only occurring at the MD of 4164−4169 m. The casing stress was measured at 25, 50, 75, and 100 m lengths of the SRV area on both sides of the wellbore. We used 0.4% shale swelling for the numerical simulation of symmetric fracturing. The remaining parameters used in the simulation are listed in Table 1.

Furthermore, we used the inhomogeneous distribution via interpolation method in the COMSOL program for our numerical simulation based on the elastic modulus derived from logging data. The casing stress at the MD of 4130−4175 m and contour plots of the casing stress under symmetric fracturing are shown in Figure 16 and Figure 17, respectively. The maximum casing stresses for the SRV area lengths of 100 and 25 m are 1073 and 749 MPa, respectively. The length of the SRV area shows an obvious influence on the casing stress. When shale swelling is fixed, the longer the SRV length, the greater the overall deformation of the SRV area. According to Figure 17, the casing experiences extrusion deformation during symmetric fracturing because the even distribution of the casing stress is created due to shale swelling caused by the symmetric distribution of the SRV areas.

4.3.2. Impact of Asymmetric Distribution of the SRV Area on Casing Deformation. As shown in Figure 18, we conducted a numerical simulation to investigate the influence of the SRV area’s asymmetric distribution. The length of the left side of the SRV area was varied at 25, 50, 75, and 100 m. The right side of the SRV area’s length was set at 25 m. The impact of the asymmetric stimulation area induced during multistage fracturing and the asymmetric fracturing on casing deformation was analyzed in previous studies. The impact of asymmetric fracturing on casing deformation is shown in Figure 19 and Figure 20. The maximum casing stress at 100 m SRV area length is 1070 MPa. This exceeds the casing yield strength. We observed that casing stress is directly proportional to the length of the SRV area. However, Figure 20 shows that the casing suffers bending deformation under asymmetric fracturing. This is because asymmetric fracturing results in an asymmetric distribution of casing stress due to the SRV areas’ asymmetric distributions.

5. CONCLUSIONS

Multiple field data sets establish a positive correlation between casing deformation and silicon content in the Weirong shale gas field. This paper investigated the mechanism of casing deformation in the field of interest. By conducting XRD and triaxial compression experiments and analyzing the data, we discovered a positive association.
between the shale elastic modulus and silicon content in the Weirong shale gas field.

Furthermore, we used numerical simulations to examine the effect of shale elastic modulus on casing deformation caused by shale swelling. The casing stress with shale swelling was shown to be precisely related to the shale elastic modulus. Furthermore, when the shale elastic modulus remained constant, casing stress rose with shale swelling. The numerical simulation results were validated using field data from the WY23-5 well. The casing deformation caused by shale swelling must satisfy two factors simultaneously: large shale swelling and large elastic modulus.

Furthermore, we conducted several simulations to investigate the influence of different factors on casing deformation under the effects of the anisotropy of the shale elastic modulus and shale swelling. The higher the injection pressure, the lower the formation pressure, and the higher the cement sheath elastic modulus, the larger the impact of the shale elastic modulus on the casing deformation. Furthermore, the distribution of the SRV area had a significant impact on casing deformation, with casing stress being directly proportional to the length of the SRV area. Symmetric fracturing resulted in symmetric distribution of the SRV area, resulting in extrusive casing deformation. Asymmetric fracturing, on the
other hand, resulted in an asymmetric distribution of the SRV region, resulting in casing bending deformation.

Figure 18. Numerical model for casing deformations induced due asymmetric fracturing.

Figure 19. Impact of asymmetric fracturing on casing stress.

Figure 20. Contour plots of casing stress under asymmetric fracturing.

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