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Original Paper

BOP shear force evaluation under complex scenarios

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ABSTRACT

As the “throat” of the drilling well control system, ram blowout preventers (BOPs) can effectively prevent blowout accidents. However, the ram shear mechanism under complex working conditions is unclear, and it is difficult to evaluate the ram BOP shear force, leading to frequent shear failure accidents in oilfields. Aiming at the above problems, this paper takes the double-V ram BOP as the research object, and integrates the methods of theoretical analysis, simulation modeling, and test verification to analyze the shear force in the pipe shear process under both static and moving conditions. A ram BOP shear force evaluation method is proposed based on equivalent stress. Finally, by comparing with calculation data and experimental data, the error between them is less than 5%, demonstrating the applicability and effectiveness of the proposed method. The research results can provide a theoretical basis for oilfield operations of ram BOPs.

1. Introduction

As oil drilling and production gradually move towards deep water, ultra-deep water and unconventional wells, the operating conditions are extremely harsh. As the most critical equipment for well control, ram BOPs serve as the last resort to avoid blowouts from happening, as shown in Fig. 1. In case of an emergency, the upper and lower shear rams of a ram BOP are pushed inwards to cut the pipe timely and seal the wellbore. However, due to the harsh working environment of ram BOPs and the unclear state of the pipe, oilfield shear failure occasionally occurs, and the failure probability can reach 50% according to statistics (Wu et al., 2018). For example, the “Deepwater Horizon” accident in the Gulf of Mexico in the United States, the worst marine oil spill in history, was caused by the failure of the shear rams to completely cut off the pipe in time, leading to the explosion of the drilling platform (Cai et al., 2012; Meng et al., 2019).

Extensive studies have been carried out on the shear mechanism analysis of ram BOPs in literature. Research methods can be roughly divided into theoretical calculation and simulation analysis. In terms of theoretical calculation, Koutsolelos (2012) analyzed the shear force during the movement of a ram shearing pipe according to the distortion energy density theory and introduced a relevant empirical coefficient to put forward the shear force estimation formula of double-V rams. Based on this method, Zhao (2016) proposed a shear ability evaluation method of deepwater shear ram BOPs by comprehensively considering the influential factors such as drilling fluid density and shut-off casing pressure on shear force. Wang et al. (2019) and Li et al. (2021) comprehensively considered the influence of various parameters such as the key structure of shear ram, the properties of the pipe, and shearing conditions on the shear force, and established a shear force prediction model based on the Treace yield criterion, wedge-shaped stress theory, and slip line field theory by applying a compressive stress formula in an indentation experiment. Albright and Christian (2004) analyzed the main factors (including but not limited to material yield strength, ultimate strength, and ductility) that affected the mechanical properties of pipes, and proposed a statistical-based ram shear force calculation formula using field data. Georgios et al. (2014) proposed a shear force calculation method with a specific size pipe based on the analytical expression of displacement in the pipe shearing process.

Simulation methods can be used to analyze the shearing process of ram BOPs and explore the influence law of main control factors

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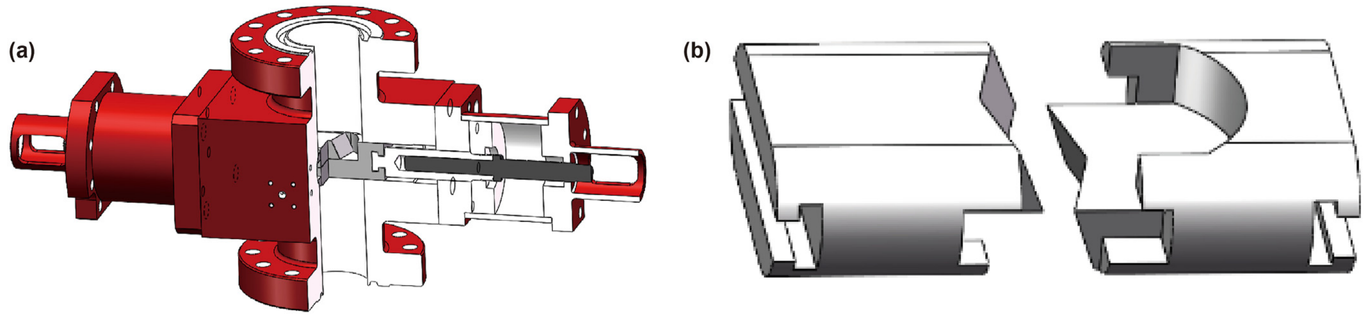

Fig. 1. BOP and shear rams (**a**) BOP (**b**) double-V rams.

on its shearing performance under various working conditions. Meng et al. (2014), Huang (2014) and Han et al. (2015) established a finite element model of the ram shear process by ABAQUS/Explicit module based on Johnson-Cook constitutive model, failure criterion, and shear-damage fracture damage strain model. The influence law of stress-strain distribution, ram structure (e.g., V-shaped angle, bevel angle, and bevel chamfer), pipe dimensions (e.g., outer diameter, thickness, and length), and material properties (e.g., yield strength), etc. on the peak stress and the shear force are studied during the shearing process. The optimal angle parameter is obtained to guide the structure design of rams. Zhao et al. (2017) used the display dynamics module in ANSYS to numerically simulate the shearing process of rams. For a shear blind ram (SBR), which has a V-shaped blade as the upper ram and a straight blade as the lower ram, the influence law of factors such as lower jaw length, blade shape, and tensile load on ram shear force and shearing effect was also analyzed. Tekin (2010) used the Finite Element Method (FEM) to estimate the influence of actual working conditions of BOPs on ram shear force and clarified the influence law of factors such as temperature gradient, pressure gradient, load at shear position, ram shear velocity and area. In this way, the geometric structure of the rams was optimized and the shearing performance was improved. Ju et al. (2022) established a simulation model of gas-liquid transient drift flow in the well during a blowout process, which provided theoretical support for the design and construction of the well kill after the blowout.

To sum up, although simulation methods can effectively obtain more accurate results when evaluating ram BOP shear force in a shearing process, the analysis time is relatively long, making the methods are not suitable for field application because they cannot timely provide guidance for ram shearing operation. Additionally, the existing shear force calculation formulas are built purely from the perspective of pipe material mechanics and need to be modified based on a large amount of shear test data, and the influential factors of complex working conditions in the shearing process are insufficiently considered. To solve the above problems, this paper constructs a double-V ram BOP shearing force calculation model suitable for complex working conditions. The model comprehensive considers the influence of ram structure size, borehole hydrostatic pressure, friction force, and pipe movement, and is verified by a shear test and simulation. Finally, the parameter description of the ram BOP shear force estimation method is realized, which provides theoretical guidance for ram BOP field shearing operation.

2. Ram BOP shear mechanism

To explore the shear mechanism of ram BOPs under complex working conditions, the explicit dynamic FEA method is applied to simulate and model the static and dynamic shearing process of ram BOPs, so as to obtain accurate and effective variation law of performance characterization parameters, such as stress, strain, shear force.

First of all, it is necessary to clarify the constitutive models of the pipe and rams, which macroscopically reflect the mechanical properties of materials, show the essential changes of materials during loading, and affect various physical phenomena such as heat, force, and mechanical in the process of deformation under load. Among the existing material constitutive models, the Johnson-Cook constitutive model is relatively simple in form, and takes into account the plastic model related to the strain rate and stability of the material, making it suitable for materials with relatively large strain rate changes and diverse crystal structures. Therefore, this paper takes the Johnson-Cook constitutive model as the basis for analysis. Its basic function is as follows:

$$Y=\left[A+B\varepsilon_p^n\right]\left[1+C\ln\dot{\varepsilon}^*\right]\left[1-(T^*)^m\right] \tag{1}$$

where Y is the strength type, ε_p is the equivalent plastic strain, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}^*=\dot{\varepsilon}/\dot{\varepsilon}_0^*$ is the dimensionless strain rate (usually the reference strain rate $\dot{\varepsilon}_0^*=1\ \mathrm{s}^{-1}$), $T^*=(T-T_{ref})/(T_{melt}-T_{ref})$ is the corresponding temperature, T is the current temperature of the material, T_{ref} is the reference temperature, and T_{melt} is the melting temperature of the material. The constants A, B, C, n and m represent five material properties: initial yield stress, hardening constant, strain rate constant, hardening exponent, and thermal softening exponent, respectively, which are usually determined by mechanical testing.

In addition, to better fit the fracture state of the pipe, reference is made to the Shock EOS Linear state equation:

$$u_s=D_1+S_1u_p \tag{2}$$

where u_s is the impact velocity, u_p is particle velocity, D_1 is the intercept of curve u_s-u_p representing volume sound velocity, and S_1 is the slope coefficient.

Generally speaking, material constitutive model parameters are derived from mechanical tests, literature, and technical judgments. For S135 pipe material, this paper refers to (Green et al., 2016) and determines the main parameters of the pipe as presented in Table 1.

Secondly, the model is meshed. Hexahedral mesh elements are mainly used to encrypt meshes in the pipe shear failure areas to guarantee model accuracy considering the mesh deformation and element failure during pipe shearing [Fig. 2(a)]. Compared with pipe deformation, shear deformation of the rams is negligible, so the shear rams are set to rigid bodies, and the pipe is set to a flexible body. Mesh independence analysis is required to analyze the peak shear force changes of the model with different mesh numbers. The optimal number is around 10^5 [Fig. 2 (b)]. The FEA (finite element

Table 1
S135 pipe material model parameters.

Index	Formula	Value
Initial yield stress	A	1021.896 MPa
Hardening constant	B	744.192 MPa
Strain rate constant	C	0.014
Hardening exponent	n	0.55
Thermal softening exponent	m	1
Fusing temperature	T_{melt}	1520 °C
Acoustic volume velocity	D_1	4578 m/s
Curve slope coefficient	S_1	1.33

Analysis) model of the pipe shear fracture process is shown in Fig. 3.

Since the rams' movement in the ram chamber is constrained by the inner wall of the ram chamber under static shear conditions, only their horizontal motion is reserved when setting the boundary conditions of the FEA model, while the degrees of freedom in all other directions are constrained. The displacement of the rams in the X direction is set according to the distance between the upper and lower shear rams and the center of the pipe. Finally, a gravitational field referring to the negative orientation of the Z axis is added to the boundary conditions. The finite element model of the static shear process of the ram BOP is obtained. The shear force variation curve is shown in Fig. 4.

When the rams are not in contact with the pipe, the stress and shear force are close to zero. During the elastic phase, the stress on the pipe increases sharply. As the rams continue to advance, the acting load between the rams and the pipe gradually increase. The increasing rate of the stress and shear force of the pipe in the plastic phase is relatively slow and gradually approaches the maximum, which is caused by the increase in plastic deformation degree of the pipe shear area and the increase of shear deformation resistance due to the increase in material hardening. During the fracture process, the stress and shear force on the pipe decrease significantly. Afterwards, due to the large deformation of the tips on both sides of the fractured pipe section, the broken pipe has a tendency to return to its original state, and there is always residual stress in the broken pipe. As a result, the pipe stress after fracture does not directly drop to zero, but fluctuates within a certain range. While the shear action between the rams and the pipe disappears and the shear force drops to zero.

For dynamic shear conditions, upward force constraints are added to the upper and lower surfaces of the pipe to simulate the tension load under channeling conditions, so as to realize the channeling movement of the pipe. By changing the magnitude of the tension load, different channeling conditions are simulated. Finally, the shear force data of the ram BOP under dynamic working conditions are obtained, as illustrated in Fig. 5.

Compared with the static shear cases, the stress of the pipe under the turbulent condition is relatively larger, but the peak shear force of the model decreases. Among them, the stress of the pipe is mainly generated by the tension and compression loads on the upper and lower surfaces of the pipe before the shear rams

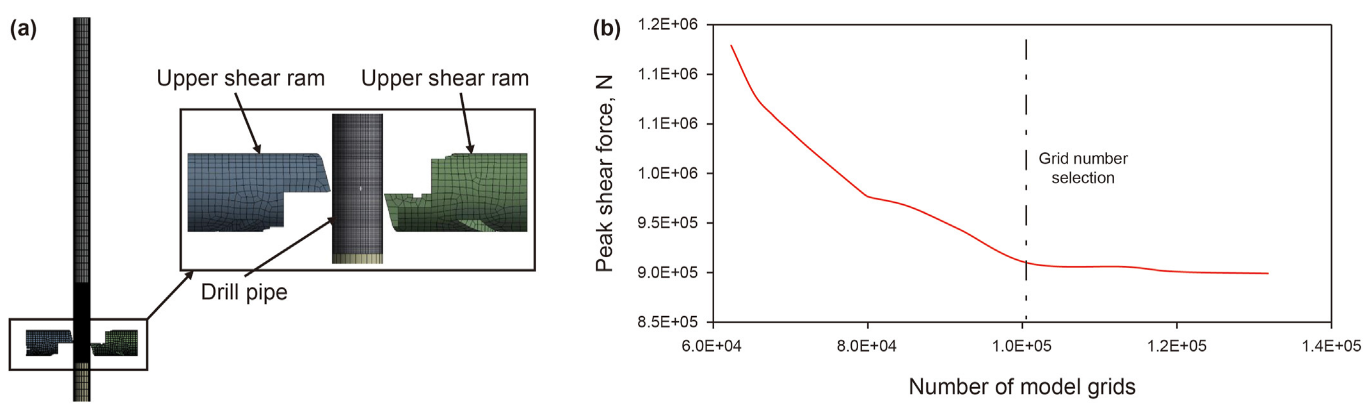

Fig. 2. FEA modeling of ram BOP shear process (**a**) BOP FEA model (**b**) mesh independent analysis.

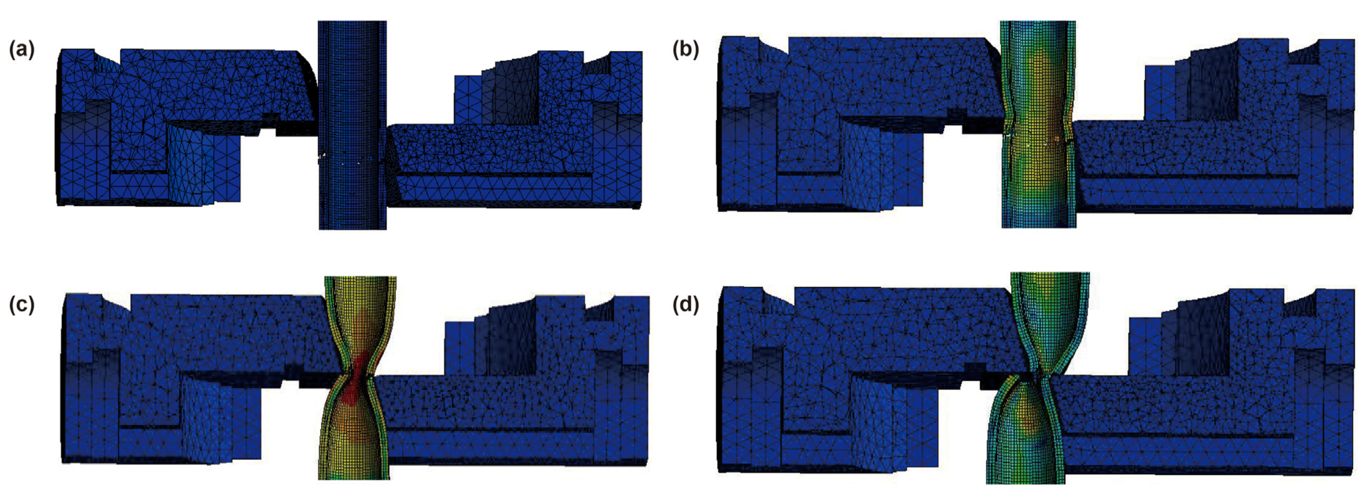

Fig. 3. FEA modeling of BOP shear process (**a**) non-contact (**b**) elastic deformation (**c**) plastic deformation, and (**d**) fracture.

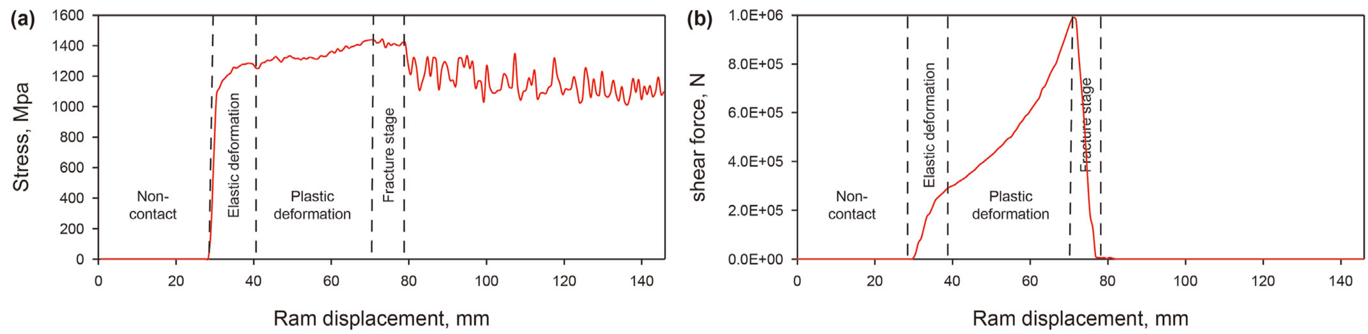

Fig. 4. Ram BOP shear results under static conditions (**a**) shear force curve (**b**) stress curve.

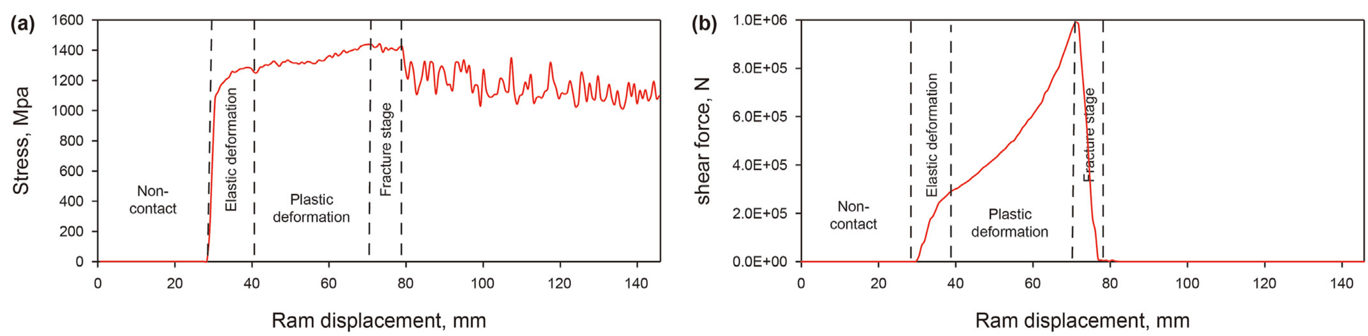

Fig. 5. Results under dynamic conditions (**a**) shear force curve (**b**) stress curve.

contact the pipe. The larger the loads, the greater the stress. However, since there is no contact between the rams and the pipe at this time, the shear force of the model is always zero. In the elastic deformation stage, both the pipe stress and the model shear force increase rapidly, and the larger the tension and compression loads, the greater the increase in the pipe stress. In the plastic deformation phase, the stress and shear force slowly increase and gradually approach the peak values as the rams continue to cut in. However, the larger the tension and compression loads, the smaller the peak of the model shear force. During the fracture process, both the stress and the shear force trend to decrease. However, due to downward shift of the shear position caused by the pipe movement, the shear force fluctuates during the descent, and the required ram displacement increases when the pipe is completely fractured. And the greater the tension and compression loads under channeling conditions, the larger the displacement required. Finally, due to the residual stress on both sides of the pipe shear section, the pipe stress after fracture still fluctuates within a certain range.

3. BOP shear force evaluation method

3.1. Mechanical analysis of pipe shear process

During the shearing operation, the BOP is controlled by a hydraulic system, composed of a hydraulic pump, a pressure regulating valve, a set of accumulators, two hydraulic cylinders, etc. During field operations, the accumulators are first charged to rated pressure by the hydraulic pump, and then the valve is closed. The accumulators provide pressure to push the rams to shear the pipe when the control system issues a shearing signal. The shearing process and the shear force of the rams during shearing are shown in Fig. 6.

In Fig. 6, P_0 is the hydraulic oil pressure in the accumulators, F_f is the friction between the hydraulic cylinder piston rod and rams, F_i is a hydrostatic pressure, F is the shear force in the process of shearing, F_l is the fluid force in the well, and C_1 and C_2 are the cross-sectional areas of the left and right side pistons, respectively. The shear force F_i is only applied when the rams contact the pipe, which is represented as:

$$F_s = \begin{cases} F_f + F_i + F_l & l < a \\ F_f + F_i + F_l + F & a \le l \le b \\ F_f + F_i + F_l & l > b \end{cases} \tag{3}$$

where l is the ram displacement, a is the ram displacement when the rams of the BOP contact the pipe, and b is the ram displacement when the rams cut the pipe.

In an increasingly complex drilling environment, hazardous high-pressure mixtures such as petroleum, natural gas, and sandstone chips flow together to the wellhead when the drilling fluid pressure in the well is not sufficient to balance the formation pressure. As a result, an upward pushing pressure is generated at the lower end of the pipe, and simultaneously the pipe is in a state of upward movement under the action of the wellhead lifting system. To simplify the model, only the effect of the borehole pressure and the lifting system on the pipe is considered, ignoring the influence of impurities such as cuttings particles on shearing. Therefore, the shear movement plane of the rams is taken as the *Oxy* plane, and the pipe axial channeling direction as the positive direction of the *z*-axis to establish a corresponding spatial coordinate system to conduct the force analysis of the pipe, as shown in Fig. 7. In the *Oxy* plane, the pipe is squeezed and deformed by the vertical shear force F_v of the rams. In the *Oxz* plane, the lower end of the pipe is subjected to the upward pressure F_c under the influence of borehole high-pressure liquid, and the upper end of the pipe is

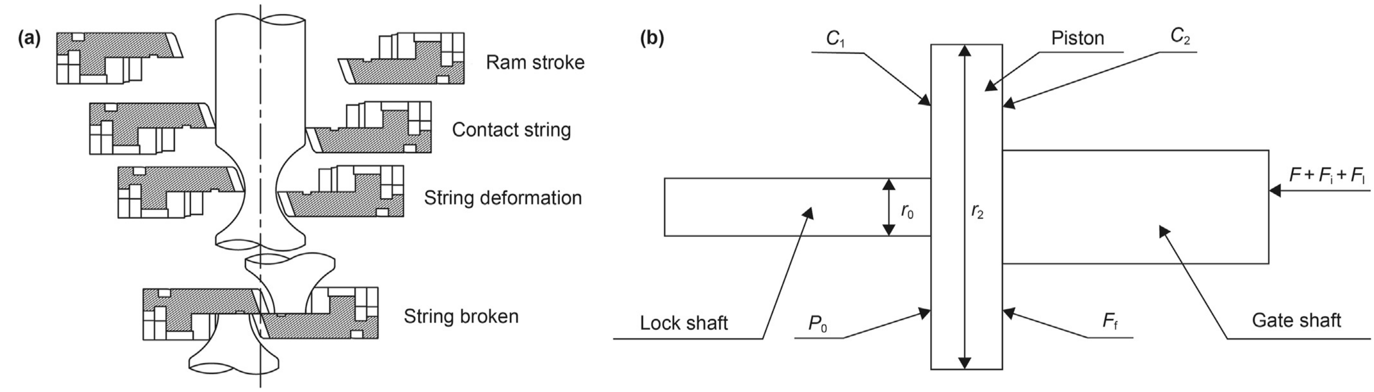

Fig. 6. Shearing process of BOP (**a**) fracture process of pipe (**b**) stress analysis.

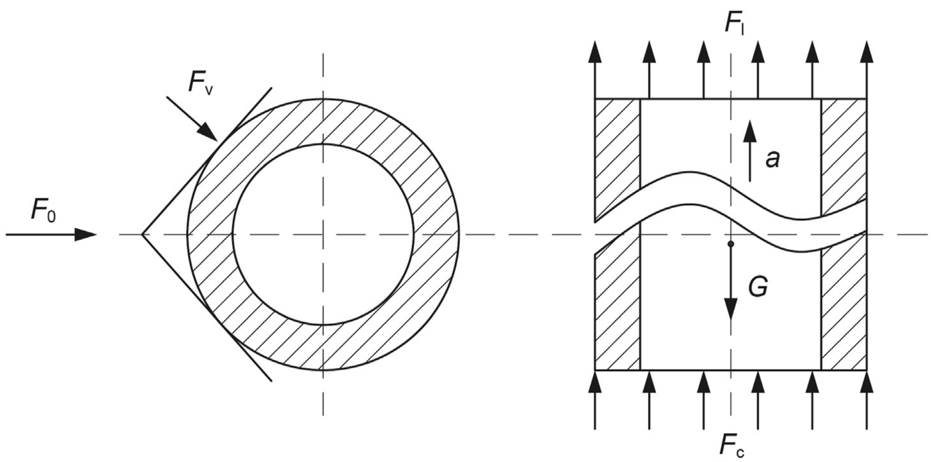

Fig. 7. Force analysis of pipe under dynamic conditions.

subjected to the tension F_t caused by the wellhead lifting system, as well as the gravitational field. Finally, the pipe moves upwards with an acceleration, which affects the ram shearing effect.

Based on the above analysis, a theoretical method for shear force calculation of ram BOPs under complex working conditions is proposed based on the Tresca strength criterion, combined with the stress situation of the pipe under dynamic conditions. The framework of the method is shown in Fig. 8.

3.2. BOP shear force evaluation under static conditions

Through analyzing the shear process of the ram BOP, it is found that whether the BOP can shear the pipe mainly depends on the maximum shear force. Therefore, a shear force evaluation method of ram BOPs under complex working conditions is proposed through a parametric analysis based on the equivalent relation of ram shear compressive stress and material yield criterion by comprehensively considering the influence of friction force, hydrostatic pressure, fluid impact force, and pipe movement.

Referring to the ram BOP shear force prediction model in Wang et al. (2019), an initial theoretical calculation model of shear force suitable for double V-shaped shear rams is established. Firstly, taking the shear contact surface between the upper and lower shear rams and the pipe as the *Oxy* plane and the shear movement direction of the rams as the positive direction of the *X* axis, a corresponding coordinate system is established. Because of the axisymmetric structure of double-V rams, it is only necessary to analyze the movement of one shear ram. Accordingly, the movement velocity and displacement of the ram are also analyzed along the direction of the shear edge, as illustrated in Fig. 9.

In Fig. 9, C_0 is the point at which the rams are just in contact with the pipe. Under the hydraulic pressure of the cylinders, the rams continue to move in the positive direction of the *X*-axis, and then this point C_0 is defined as C_t. In this process, the movement velocity v and displacement x of the shear rams are expressed as follows (Li et al., 2021):

$$\begin{cases} v = \dfrac{P_0 C_1}{M} t \\ x = \dfrac{P_0 C_1}{2M} t^2 \end{cases} \tag{4}$$

where M is the mass of a shear ram, and t is the ram shearing time. Setting the time when the rams just touch the pipe as t_0 and the V-angle of the rams as α, the ram shear cut-in displacement at time t is $d = \frac{P_0 A_0}{2M}(t^2 - t_0^2)$. According to the decomposition of shear velocity, the displacement of the rams in the direction of the shear edge is as follows:

$$d' = \frac{P_0 A_0}{2M}\left(t^2 - t_0^2\right)\sin(\alpha/2) \tag{5}$$

According to the structural characteristics of double-V rams, the basic indentation shape during the ram shearing pipe process is analyzed, and the equivalent analysis of stress distribution in the

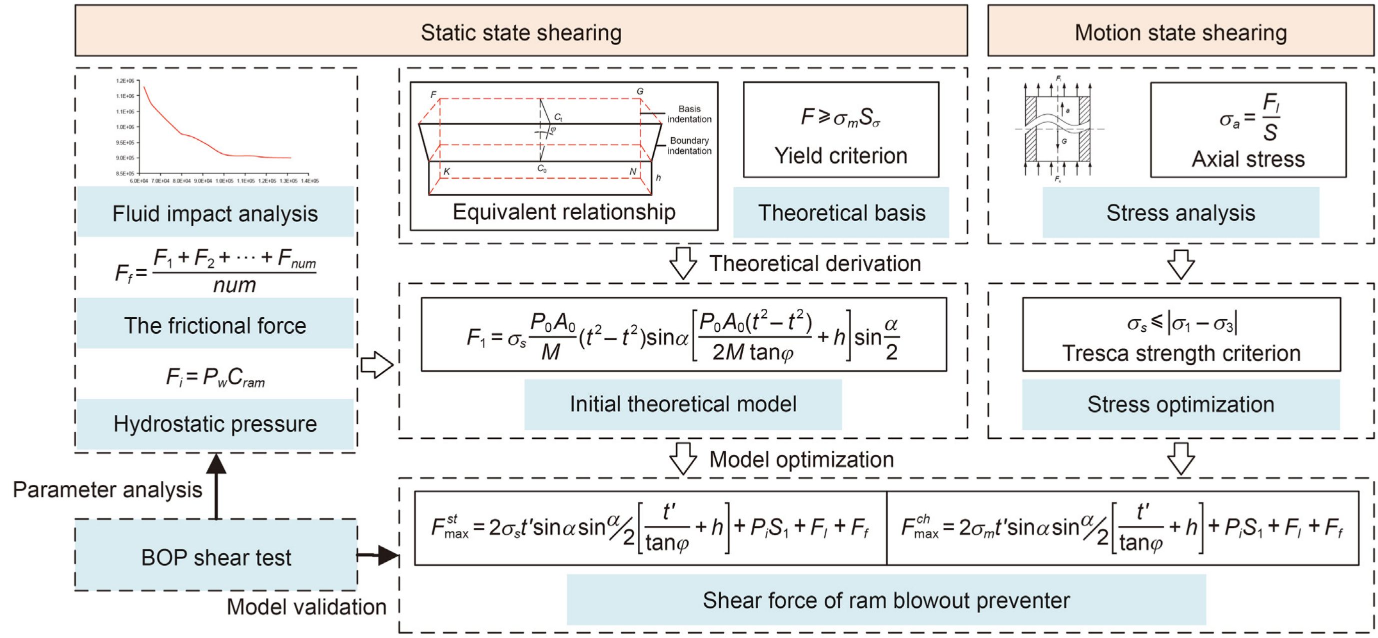

Fig. 8. Ram BOP shear force evaluation method.

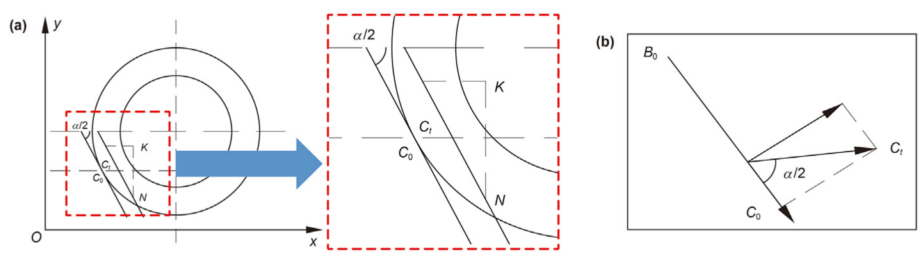

Fig. 9. Ram shear (a) displacement (b) velocity decomposition.

process of ram shearing is carried out by referring to existing foundation models. The equivalent model of shear force distribution of double-V rams is obtained as shown in Fig. 10.

In Fig. 10, the KN segment is the projection length of the part of the shear rams cutting into the pipe in the *Y*-axis direction and φ is the angle of the shear blade surface of the rams, that is, the angle between the cutting edge and the vertical line. According to the symmetry effect, the calculation formula of the length of line *KN* is:

$$L_{KN} = 2d\cos\frac{\alpha}{2}\sin\frac{\alpha}{2} = d\sin\alpha \tag{6}$$

The *FK* segment is the projection length of the shear end face of the ram in the *Y*-axis direction, and its calculation formula is:

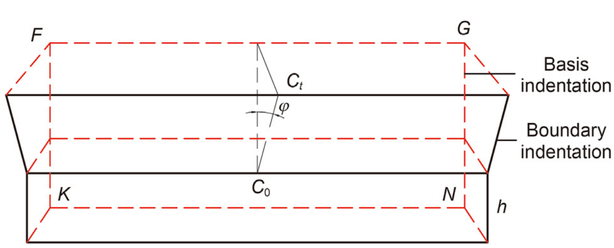

Fig. 10. Equivalent distribution of ram shear force.

$$L_{FK} = \frac{d}{\tan\varphi} + h \tag{7}$$

According to the shape characteristics of the base indentation, the effective action area of ram shear stress is obtained as follows:

$$S_\sigma = L_{KN}L_{FK} = d\sin\alpha\left[\frac{d}{\tan\varphi} + h\right] \tag{8}$$

Then, the ram shear force F_1 is derived from the material yield criterion:

$$F_1 = \sigma_s S_\sigma = \sigma_s d\sin\alpha\left[\frac{d}{\tan\varphi} + h\right] \tag{9}$$

where h is the blade thickness of the ram, and σ_s is the yield strength of the pipe material.

The shear force calculated by Eq. (9) is the force exerted by one shear ram. Combined with the structural characteristics of the double-V rams, the resultant shear force F of the shear ram in horizontal direction is:

$$F = 2F_1\sin(\alpha/2) \tag{10}$$

Operating oil pressure is the focus of field shearing operations. Therefore, both the shear force between rams and pipe and the movement resistances such as the borehole hydrostatic pressure F_i

and the friction F_f should be comprehensively considered when estimating shear force. The final shear force estimation formula of ram BOPs is thus obtained as follows:

$$F_{\max}^{st} = 2\sigma_s t' \sin\alpha \sin\alpha/2 \left[\frac{t'}{\tan\varphi} + h\right] + P_i S_1 + F_l + F_f \tag{11}$$

where t' is the wall thickness of the pipe.

3.3. BOP shear force evaluation under dynamic conditions

Under dynamic conditions, the yield strength of the pipe changes with the stress state of the pipe, resulting in a large error between the shear force calculated by the above method and the actual one. Therefore, the yield strength σ needs to be corrected.

Combined with the force analysis of the pipe under the state of channeling, the axial tensile force and shear force are applied to the pipe during shearing, and the stress distribution is shown in Fig. 11. The stress parameters of the pipe in each direction are: $\sigma_{zz} \neq 0$, $\sigma_{yy} \neq 0$, and $\sigma_{xx} = \tau_{xx} = \tau_{zy} = \tau_{xz} = 0$.

According to the Tresca yield criterion, the yield strength of the pipe at the time of yielding is:

$$\sigma = |\sigma_{zz} - \sigma_{yy}| \tag{12}$$

where σ_{yy} is a negative value in the compression state, σ_{zz} is a positive value in the tension state, and σ_{zz} is generated by the action of the loads on the pipe. The calculation method of σ_{zz} is as follows:

$$\sigma_{zz} = \frac{F}{A} \tag{13}$$

where F is the axial force on the shear section of the pipe, and A is the cross-sectional area of the pipe.

Based on the above analysis, it is necessary to correct the yield strength in Eq. (9) when evaluating the shear force under the condition of pipe channeling, as follows:

$$\sigma_s = \sigma_{yy} = \sigma_m - \sigma_{zz} \tag{14}$$

where σ_m is the yield strength of pipe material.

Combined with Eq. (11), the final shear force estimation formula of ram BOPs under channeling conditions is obtained as follows:

$$F_{\max}^{ch} = 2\sigma_m t' \sin\alpha \sin\alpha/2 \left[\frac{t'}{\tan\varphi} + h\right] + P_i S_1 + F_l + F_f \tag{15}$$

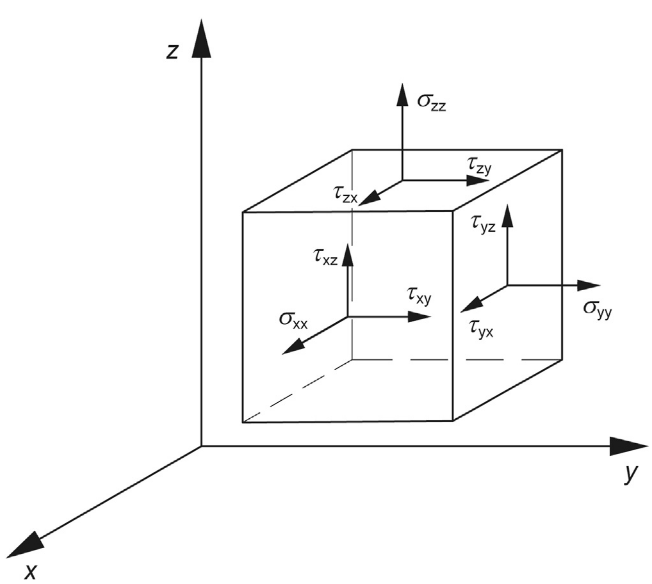

Fig. 11. Stress distribution of pipe material.

4. Experimental study

4.1. Experiment setup

The ram shear test rig mainly includes a hydraulic control device, a shear ram BOP, and a pipe produced by North China Rongsheng Company. The hydraulic control device is composed of an electric pump, a switch valve, a regulating valve and a set of accumulators, and supplies hydraulic power for the BOP. Pressure gauges installed on the console are used to indicate the pressure changes of the accumulators and the manifold, respectively. The ram BOP has two double-V integral shear rams, which is consistent with the theoretical model.

Before start testing, the BOP needs to be installed on a fixed base, and sealed with an end cover. The BOP is connected with the hydraulic control device through the high-pressure manifold. The pipe is vertically suspended from the top and stabilized in the center of the BOP cavity. High-pressure liquid is injected into the BOP cavity through the fixed base. The effect of hydrostatic pressure on the rams is analyzed after the liquid pressure is stabilized. The schematic diagram of the ram shear test is shown in Fig. 12.

After the preparation is completed, the hydraulic control device is started for ram BOP shear tests under different pressures of 20 MPa, 35 MPa, and 50 MPa, respectively. According to the value changes on the manifold pressure gauge, it is found that the pressure tends to decrease when the rams start to move. The pressure increases and stabilizes when the rams contacts with the pipe and perform shearing operation. The pressure drops at the final cut, and then rises again and stabilizes until the rams are fully closed, indicating that the shear is finished. The shear oil pressure under each operating condition is obtained according to the manifold pressure gauge reading. Then, the shear force during compression shear is obtained, and the theoretical formula under compression shear conditions is verified. The shear result is shown in Fig. 13.

4.2. Result analysis and discussion

The traditional shear force estimation method based on the empirical formula proposed by Koutsolelos (2012) is mostly adopted to oilfield production at present. The formula is as follows:

$$F_{\max}^{tr} \geq C\frac{2\pi}{\sqrt{3}} R h' \sigma \tag{16}$$

where C is the empirical coefficient, 0.28736 is preferable for the double-V ram BOPs studied in this paper. R is the outside diameter of a pipe, h' is the wall thickness of a pipe, and σ is the yield strength of pipe material.

When evaluating ram BOP shear force based on this method, it is necessary to first determine the hydrostatic pressure. Based on of Eq. (3), the hydrostatic pressure in the BOP cavity produces resistance to the inward shear movement of the rams, resulting in the increase of shear force required to cut the pipe. Since the resistance area of the hydrostatic pressure in the well to the ram movement changes with the movement of the rams, the cross-section of the ram shafts is mainly taken as the resistance area of the hydrostatic pressure in the well to simplify calculation. Then, the hydrostatic pressure during shearing is obtained.

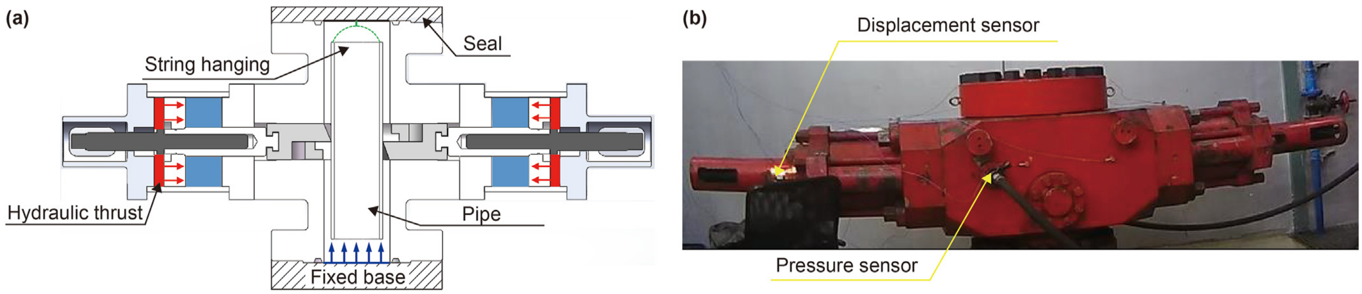

Fig. 12. BOP experiment setup (**a**) schematic diagram of devices (**b**) experimental and monitoring equipment.

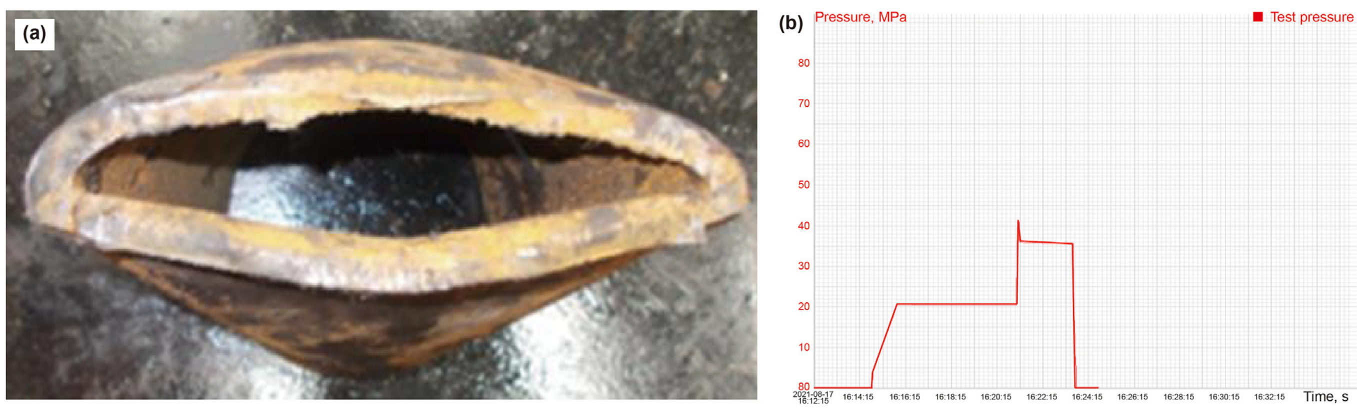

Fig. 13. The final shear result: (**a**) deformation of the pipe (**b**) oil pressure curve.

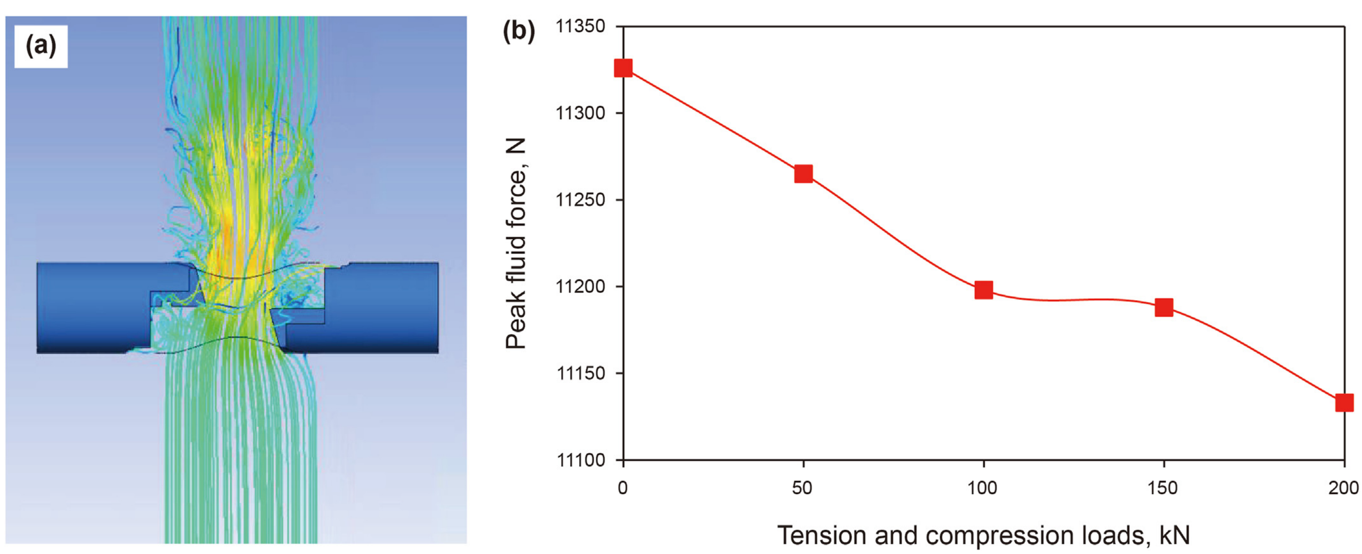

Fig. 14. Fluid-structure coupling simulation model of ram BOP (**a**) flow field analysis, (**b**) peak fluid force curve.

$$F_i = P_w C_{ram} \tag{17}$$

where P_w is the pressure in the well during shearing and C_{ram} is the cross-sectional area of the ram shaft.

Secondly, the frictional force during shearing through the test method is calculated. Frictional resistances in the process of ram shearing are mainly sourced from seals, the friction between the rams and the wall, etc. The friction factors are not considered in the FMA process of the BOP, and the friction resistance in the shearing process is sliding friction, which is defined as a certain value.

$$F_f = |P_0 C_0 - F_i - F| \tag{18}$$

Where F_i is the hydrostatic pressure obtained by Eq. (17), and F is the simulation result of shear force.

The friction resistance in the shearing process is obtained by comparing the test data with the FMA results. In order to ensure the

Table 2
Theoretical peak shear force of BOP under typical operating parameters.

Scenario	Diameter, mm	Wall thickness, mm	Hydrostatic pressure, MPa	Load, kN	Peak shear force, kN
1	127	9.19	0	0	1088
2	127	9.19	20	0	1248
3	127	9.19	35	0	1368
4	127	9.19	50	0	1499
5	139.7	10.54	0	0	1268
6	127	9.19	0	50	962
7	127	9.19	0	100	952
8	127	9.19	0	150	934
9	127	9.19	0	200	919

accuracy of the results, it is necessary to solve multiple groups of data, and finally, the least square method is used for average fitting to get the friction resistance in the BOP shearing process.

$$F_f = \frac{F_1 + F_2 + \ldots + F_{num}}{num} \tag{19}$$

where F_1-F_{num} is the friction data based on multiple measurements.

In addition, considering the impact of borehole fluid on the shear process, the Bureau of Safety and Environmental Enforcement (BSEE) (Green et al., 2017) established a fluid-structure coupled finite element model. The performance of BOPs under the influence of fluid was analyzed, and the results showed that the effect of fluid was less than 1%. The fluid-structure coupling simulation of the shear process is also carried out under the condition of pipe moving. As shown in Fig. 14, the results show that the larger the loads, the smaller the fluid force, and the peak of fluid force are under 12 kN, which is far less than the shear force. Therefore, the fluid impact term is ignored in the final calculation.

Finally, selecting typical working condition parameters as shown in Table 2, the theoretical shear force of the ram BOP under theoretical working conditions is obtained by combining Eqs. (11) and (15). It can be seen that the theoretical calculation results and FEA results have the same trend. Due to the influence of the tensile and compressive loads on the stress state of the pipe, the shear force decreases with the increase of the drilling pipe traversing velocity. As the hydrostatic pressure in the well obstructs the shearing process, the shear force required to cut the pipe gradually increases with the increase of the hydrostatic pressure in the well.

In terms of model verification, the results obtained by the proposed method are compared with West Engineering Services (Albright and Christian, 2004) which has collected a large amount of field shear test data of pipes with different sizes and the traditional method which has no consideration of dynamic and pressure conditions. As shown in Fig. 15, the error of the proposed method is smaller than the traditional method. Detailed results are presented in Table 3.

First of all, the error between the FEA data and the experimental data is within 5%, which verifies the accuracy of the FEA data. Incidentally, the material of the pipes and rams are considered to be continuous and uniform in the FEA process, and a mesh division method of balancing the calculation amount of the model and the accuracy of the FEA results is obtained through the model mesh independence analysis. The error between the experimental and FEA results is mainly sourced from the both aspects. Secondly, the error between the shear force peak value calculated by the proposed method and the test value is within 10%, which ensures the accuracy of the proposed method. Finally, the results indicate that the proposed method is more suitable for the shear force estimation of ram BOP in complex blowout scenarios, although it may be more complicated in calculation by comparing with the traditional method.

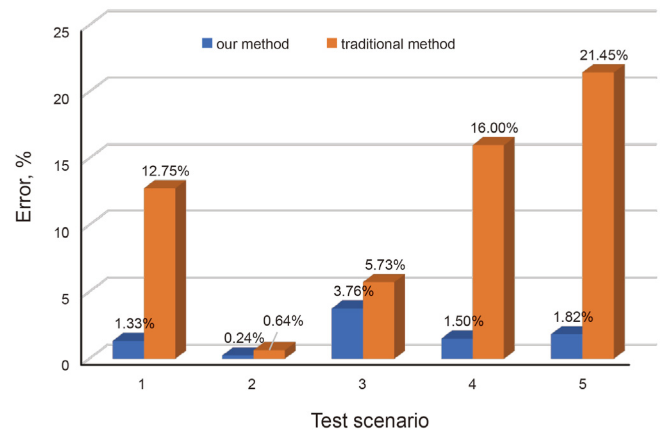

Fig. 15. Comparison of errors of different methods.

5. Conclusion

Aiming at the inaccuracy problem of existing double-V ram BOP shear force calculation methods, this paper proposes a shear force calculation method of ram BOP under complex working conditions based on the equivalent stress and the yield criterion theory. The method is revised by the shear test and FEA method by comprehensively considering ram structure and size, pipe material, hydrostatic pressure in the well, kinetic friction force, and pipe motion state so that the ram shear performance is timely monitored.

To verify the accuracy of the theoretical model, the FEA models of ram BOP shearing process under both static and dynamic conditions are constructed, respectively. It is found that the stress and shear force of the pipe in the shearing process are affected by the tension and compression loads on the upper and lower surfaces of the pipe, and the stress under the dynamic conditions is larger than that under the static conditions, while the shear force is smaller than that under the static shear conditions.

Finally, the proposed shear force estimation method is verified through the shear test and FEA results of the ram BOP. The relative deviation is less than 10%. Compared with commonly-used traditional methods, the deviation is smaller under the complex working conditions, which demonstrates the effectiveness of the proposed method, which provides a theoretical basis for field shearing operation.

Table 3
Results of shear force peak of ram BOP by different methods.

Scenario	Test value, kN	FEA value, kN	Error	Our method, kN	Error of FEA value	Error of test value	Traditional method, kN	Error of traditional method
1	1103	1052	4.81%	1088	1.33%	3.41%	1243	12.75%
2	1251	1212	3.21%	1248	0.24%	2.96%	1243	0.64%
3	1319	1334	1.16%	1368	3.76%	2.56%	1243	5.73%
4	1480	1453	1.88%	1499	1.5%	3.16%	1243	16.00%
5	1291	1290	0.07%	1268	1.82%	1.75%	1569	21.45%
6	–	968	–	962	0.62%	–	1243	22.07%
7	–	911	–	952	4.50%	–	1243	26.69%
8	–	865	–	934	7.98%	–	1243	30.46%
9	–	845	–	920	8.88%	–	1243	33.64%

Ethics approval

Ethics approval (include approvals or waivers) is not applicable, Additional declarations for article (in life science journals that report the results of studies involving humans and/or animals) are not applicable.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Consent to participate

The authors voluntarily agree to participate in this research study.

Consent for publication

The authors sign for and accept responsibility for releasing this material on behalf of all co-authors.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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