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Original Paper

Digital twin driven ram BOP shear capability analysis

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ABSTRACT

As a critical component of the oil drilling control system, blowout preventers (BOPs) shear failure accidents can occur in case of blowout incidents. Existing methods based on simulation and empirical formula do not perform well in systematically evaluating the shear capacity of ram BOPs, and relevant research and testing are conducted under static ideal conditions, leading to a lack of effective guidance in field operations. Aiming at the above problems, this paper proposes a shear capability evaluation method of ram BOPs based on digital twin. The shear mechanism of ram BOPs is analyzed and the digital twin model of a ram BOP driven by real-time drilling data is constructed through joint simulation and model reduction. Finally, the shear capacity of ram BOP is evaluated multi-dimensionally in real-time by using the built digital twin model. The model can also simulate shearing process offline under different preset conditions. The results provide a theoretical basis for field operation and performance evaluations of the shear capability of ram BOPs.

1. Introduction

In the context of oil and gas exploration in complex fields, such as underwater, ultra-deep, and unconventional wells, the requirements for well control safety in on-site surface operations are growing increasingly stringent. The blowout preventer (BOP) is a critical component of the well control system for drilling, and its function is to shut down the well in the event of an emergency, such as overflow, kick, and blowout during drilling. However, due to the complex structure of the ram BOP, harsh well environment, and numerous influencing factors, the probability of shear failure in ram BOPs during actual operations reaches up to 50% (BSEE, 2004). For instance, the "Deepwater Horizon" incident in the U.S. Gulf of Mexico, 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 (Green et al., 2016). Therefore, developing a multi-dimensional evaluation method for the shear capacity of ram BOPs is crucial (Meziou et al., 2020; Jamali et al., 2019), and correctly evaluate key parameters such as shear force and shear time during the shear process of ram BOPs in real-time. The shear results of the BOP under various complex working conditions such as different well pressures, pipe types and hydraulic control devices can be calculated at any time, so as to improve the reliability of ram BOPs and ensure the safety of oil and gas drilling.

The ram BOP is mainly composed of two shear rams, two ram shafts, and a shell, as shown in Fig. 1(a). In the context of field operations, the well pressure can exceed the wellbore pressure, resulting in the entry of a hazardous mixture comprising underground oil, natural gas, sand, and stone debris into the wellhead. The hydraulic control system is started urgently to regulate the high-pressure oil into the cylinder closing chamber on both sides of the BOP, and the upper and lower shear rams are pushed inwards to cut the drill pipe timely and seal the wellbore. The joint of the section of the drill pipe expands and breaks (Vujasinovic, 1986), as shown in Fig. 1(b).

At present, the shear capacity evaluation of ram BOP mainly focuses on empirical formula analysis, finite element analysis (FEA), and experimental test. A combination of indoor experiments was used to validate the precise shearing process simulation using simulation software, and the response surface method was employed to improve its efficiency (Xu et al., 2024). Han et al. studied shear force influential factors through finite element

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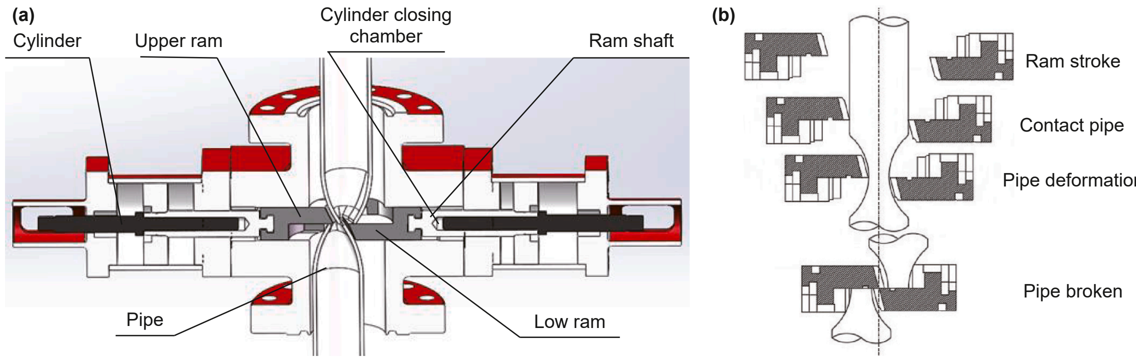

Fig. 1. (**a**) BOP structure; (**b**) pipe shearing process (Zhang et al., 2023).

simulation and experimental verification (Han et al., 2015). Tekin et al. estimated the influence of BOP working conditions and ram parameters on the shear operation through finite element simulation, so as to optimize the geometry and improve the shear performance of the rams (Tekin et al., 2015). Li et al. established a shear force prediction model by applying the Treace yield criterion, sliding line field, and wedge mechanics theory, and optimized the parameters of the shear rams (Li et al., 2021). Western Oil Services Company of New Zealand proposed a statistics-based shear force calculation formula by considering the main influential factors (e.g., yield strength, ultimate strength, and ductility of material), of the mechanical properties of the pipe string combined with field data (New Zealand, 2004). Zhu et al. evaluated the shear oil pressure during the operation of the BOP based on a BOP system simulation analysis model (Zhu et al., 2020). Quispe et al. studied the oil-based system composed of a set of accumulators, a pressure regulator, two rams, valves, and connectors, and presented a theoretical formula for the shear time in the shear process of the BOP (Quispe et al., 2018). Cain et al. developed a novel shear RAM geometry and shear calculation method based on legacy considerations. The method was verified by the design shear test (Cain et al., 2021). Wang et al. analyzed the failure mechanism of ram BOP and concluded that the change of well pressure affected its safety factor (Wang et al., 2022).

Recently, the digital twin has been applied to well-control equipment operation and maintenance, and achieved certain results abroad, while domestic-related research is still in its infancy. Wassar et al. constructed a digital twin model of the ram BOP to conduct a real-time assessment of the degradation and failure of the BOP system (Wassar et al., 2018). Mayani et al. built a data-based borehole digital twin model to provide early warning of downhole risks by combining the twin data (Mayani et al., 2018). Srikonda et al. built a digital twin model of oil and gas equipment based on physics and machine learning, and constantly corrected and calibrated the twin model through real-time data to achieve virtual flow metering, equipment fault diagnosis, and optimal operating parameter prediction, to increase the uptime of equipment (Srikonda et al., 2020). Thoresen et al. built a digital twin model of a drilling platform which contained the model of all sensors, actuators, valves, and drivers connected to the control system (Thoresen et al., 2019). By collecting data including noise, deviation value, and response time, the downhole pressure was controlled under different flow rates and string movements, while estimating the expected instantaneous backflow to improve drilling pressure by correcting surface backpressure. Shen et al. built a digital twin of an oil and gas production system based on big data and artificial intelligence technology, and visualized the drilling process through virtual reality (VR) and augmented reality (AR) (Shen et al., 2021). Milanoski et al. established a digital twin model of a multilayer stiffened panel based on finite element results and calculated its axial load (Milanoski et al., 2022).

To sum up, current analysis methods for the shear capacity lack the consideration of critical parameters such as shear time and oil pressure during the shear process. Moreover, the finite element simulation method is limited by the amount of calculation, the method based on the empirical formula is difficult to handle the influence of complex operating conditions, and experimental research requires suitable experimental conditions and a lot of time. By constructing a digital twin model of the ram BOP, real-time and multidimensional twin data can be provided for the capability evaluation of the ram BOP given its real-time connectivity with the physical entity. Virtual shearing of BOP under different operating conditions can also be simulated in the digital twin model. This helps gain a clear and intuitive understanding of the pipe fracture process as well as predict potential complex scenarios that may occur. Therefore, this paper proposed a digital twin modelling method based on joint simulation, and the finite element model is reduced by a surrogate model, which is trained with I/O pairs generated by the finite element model (Belding et al., 2022). The digital twin model can be used to assess the real-time shearing capacity of BOPs by calculating key parameters such as shear force and shear time. It can also provide decision support for emergency situations involving BOPs under complex and unknown working conditions.

2. BOP shear capability evaluation method framework

The digital twin-based shear capacity evaluation framework for ram BOPs is illustrated in Fig. 2. Firstly, the finite element simulation and system simulation of the shear process are carried out. The digital twin model of ram BOP is constructed in a unified environment that incorporates both finite element simulation and system simulation. Secondly, the shear capacity evaluation method of the ram BOP is analyzed based on the shear operation principle. Finally, real-time drilling data is integrated to drive the twin model, enabling real-time calculation of key shear performance parameters during the shearing process. The shear capacity of the ram BOP is then evaluated using the multidimensional twin data, with the aim of guiding field operations.

2.1. Digital twin modelling of ram BOP

The core of constructing the digital twin of ram BOP is to build a digital twin model. It encompasses not only the modeling of basic unit models but also integration of models across different mechanisms and data layers, as well as model fusion from a multi-field and interdisciplinary perspective to achieve comprehensive characterization across diverse domains (Pocheau et al., 2023). The

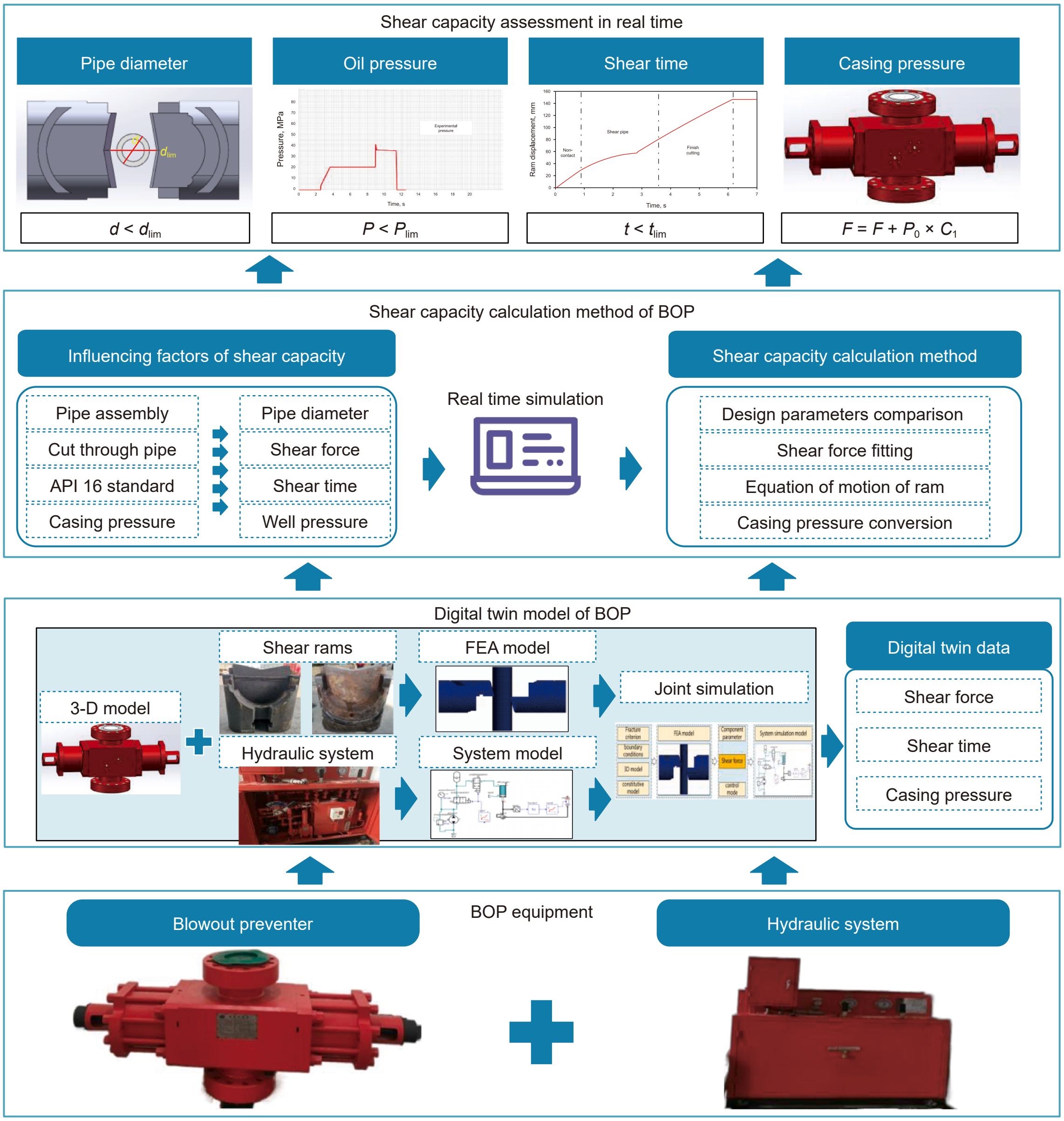

Fig. 2. Digital twin-driven ram BOP shear capability evaluation method framework.

multi-domain model fusion and joint simulation process aligns with ISO 23247 standards for digital twin interoperability, ensuring normative compliance in data integration and system-level validation. Finally, the construction of the real ram BOP object model is realized through joint simulation. In this paper, finite element simulation and system simulation methods are used to describe the behavior changes of the ram and hydraulic control system in the shearing process.

Firstly, the finite element analysis is carried out on the shear process of the ram-BOP, and three-dimensional modelling software is used to construct the three-dimensional models of different shear ram-pipe combinations. The assembled models are then imported into the finite element analysis software in a standard format, and the J-C (Johnson-Cook) constitutive model is selected to describe the shear failure process of pipe string materials. Finally, the boundary conditions of the model are set in combination with the actual working conditions for analysis and calculation, so as to obtain the change of shear force in the shear process.

Secondly, the operational process of the hydraulic control device is described by system simulation. The hydraulic control device of the ram BOP is composed of an oil pump, a set of accumulators, a pressure regulating device, and a blowout preventer. Initially, the oil pump supplies adequate pressure to the accumulators, after which it is deactivated. The control signal is transmitted to the control valve through the control manifold. When the control valve is opened, the accumulators release high-pressure fluid into the closing chamber of the BOP, thus closing the BOP. In this paper, the main components of the hydraulic control system are modelled and the component parameters are set according to field conditions, and the component parameters are set according to field conditions. Finally, the motion modes of the different components are controlled according to the action process, and the system simulation modeling is completed. The shear time, oil pressure, and displacement of the ram BOP during the shear process are analyzed.

In order to evaluate the shear performance of the ram BOP, it is necessary to take into account the shear force, shear time, and oil pressure. In order to facilitate this, the shear force evaluation model must be capable of carrying out the finite element and system simulation calculations in real-time. Nevertheless, the traditional finite element method for solving multi-physics models possesses a high degree of freedom and necessitates the discretization of the spatial and temporal domains, consequently resulting in substantial calculation requirements and protracted calculation times, typically spanning 6–7 h. In order to facilitate the real-time monitoring of device status by digital twin technology, it is necessary to develop models that are both accurate and can be solved quickly. Despite advances in computing power, using multi-physics simulation models to achieve this is still out of reach. At present, the commonly used order reduction methods include the data-based least squares fitting method, the response surface method, the Galerkin-POD method, and the machine learning method. The response surface method is simple in form and convenient in calculation, and is suitable for the multi-parameter working condition in this paper (Chatterjee and Hadi, 1986). Therefore, this paper proposes a joint simulation method to reduce the order of the finite element model by constructing a response surface model. The shear force data is fitted and estimated to address the issue of the simulation model's extensive computational demands.

The response surface method is a widely used data fitting method, which can study the experimental results most economically. It can effectively and quickly determine the optimal conditions of multi-factor systems. This method has been widely used in various experimental analyses. The quadratic polynomial response surface model is:

$$y(X) = \beta_0 + \sum_{i=1}^{n} \beta_i d_i + \sum_{i=1}^{n} \beta_{ii} d_i^2 + \sum_{i=2}^{n} \sum_{j=1}^{i-1} \beta_{ij} d_i d_j \tag{1}$$

where $X = (d_1, d_2, \ldots, d_n)$, d_i $(i = 1, 2, \ldots, n)$ are the design variable, β_0, β_i, β_{ii}, β_{ij} is the position coefficient, and its number is $L=(n+1)(n+2)/2$. If the match results deviate significantly from the origin data, it is necessary to consider increasing the order of the model for better results. In this paper, a second-order equation is sufficient to meet the requirements.

The shear force response surface model is imported to a unified environment in the form of a surrogate model, and the built system simulation model is published as an FMU file through the Functional Mock-up Interface (FMI) standard protocol (Wang et al., 2023), which is connected with the response surface model to realize the joint simulation of the ram BOP finite element model and the system simulation model. In the process of joint simulation, the estimation of the displacement-shear force curve of the BOP motion obtained by the response surface model is inconsistent with the time-variable data types required for input and output in the system simulation model. Therefore, data types need to be processed. By adding a custom module with the ram displacement as input and the shear force corresponding to different displacements as output in the system simulation model, and then applying the output to the ram as shear force, a force-displacement-force feedback loop is formed to solve the problem of uniformity of different system data types. The joint simulation model of the ram BOP is finally obtained.

Finally, to ensure digital twin model fidelity, real-time data acquisition protocols are rigorously implemented. Pressure and displacement sensors are installed on the hydraulic manifold and ram shafts, respectively, to measure oil pressure and ram displacement. Data streams are transmitted via the MQTT protocol to a centralized server. Prior to integration into the joint simulation environment, raw data undergoes real-time noise filtering and unit normalization. The flow data is used as input to drive the ram BOP joint simulation model for real-time simulation and real-time calculation of key shear performance characterization parameters such as shear force, shear time, and oil pressure during the shear process of the ram BOP.

Following the installation of the ram BOP and sensors, the monitoring system employs a Peifu CX5130 data acquisition controller paired with an EL6021 communication module to collect sensor data via the MQTT protocol. Acquired signals undergo conditioning (including filtering and noise reduction) and digitization before being stored on the server. The full architecture is illustrated in Fig. 3.

Furthermore, real-time multidimensional data is provided for the shear capacity evaluation of the ram BOP. The twin modelling method is shown in Fig. 4.

2.2. Shear capacity analysis of BOP

Before the shear capability evaluation of a ram BOP begins, it is necessary to determine whether the pipe can be sheared. That is, the wall thickness and outside diameter of the pipe to be sheared should be analyzed first. If the pipe diameter d does not exceed its designed limit $d_{\min}$, the ram BOP can accomplish the shearing task.

$$d \le d_{\min} \tag{2}$$

Secondly, the shear force is obtained through the finite element analysis in the shear process. The minimum required shear oil pressure $P_{\min}$ is subsequently calculated using the derived shear force and compared with the system's operating pressure P. When $P \le 0.9\ P_{\min}$, it indicates that the pipe can be successfully sheared under the current working condition. When $0.9\ P_{\min} < P \le P_{\min}$, the pipe may be successfully sheared under the current working condition, but it must be verified through a shear test. When $P > P_{\min}$, the pipe cannot be cut under the current working condition (see TL BOP stack operation and maintenance manual).

In the case of demanding to seal the wellbore, pipe shearing should be completed within 30 s to achieve rapid sealing (see API SPEC 16D (2018)). Therefore, the shear time during the shear process also needs to be evaluated after the shear force meets the requirement. By studying the hydraulic control system as shown in Fig. 5(a), the changes in oil pressure and shear time in the shear process are analyzed. The system is composed of a pump, a set of accumulators, a pressure-regulating valve, a direction control valve and a ram BOP. Initially, the pump supplies sufficient pressure for the accumulators, and then shuts off. A control signal is issued by the drilling control system when the BOP needs to be closed, and it is transmitted to the direction control valve through the control manifold to open the valve. Subsequently, the accumulators release high-pressure fluid into the closing chamber of the BOP, thus facilitating its closure. The pressure-regulating valve is utilised to ensure that the pressure remains within an acceptable range. The force on the rod in the shear process is shown in Fig. 5(b), where P_a is the oil pressure of the hydraulic system, F_f is the friction force on the piston rod and the ram of the cylinder, F is the shear force in the shearing process, C_1 is the cross-sectional area of the left piston, r_0 is the diameter of the shaft of compression, r_1 is the diameter of the shaft of ram, r_2 is the diameter of the shaft of piston, and C_2 is the cross-sectional area of the right piston rod.

Note that the fracture shear force of the drill pipe F_c only acts when the ram contacts the pipe, and the backpressure applied on the piston is lumped in F_f. So, the shearing process can be expressed as:

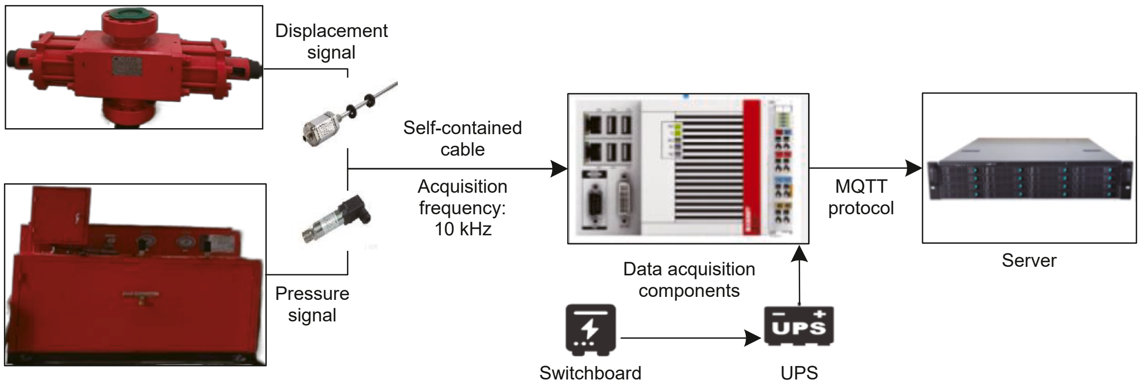

Fig. 3. The architecture of the data acquisition system.

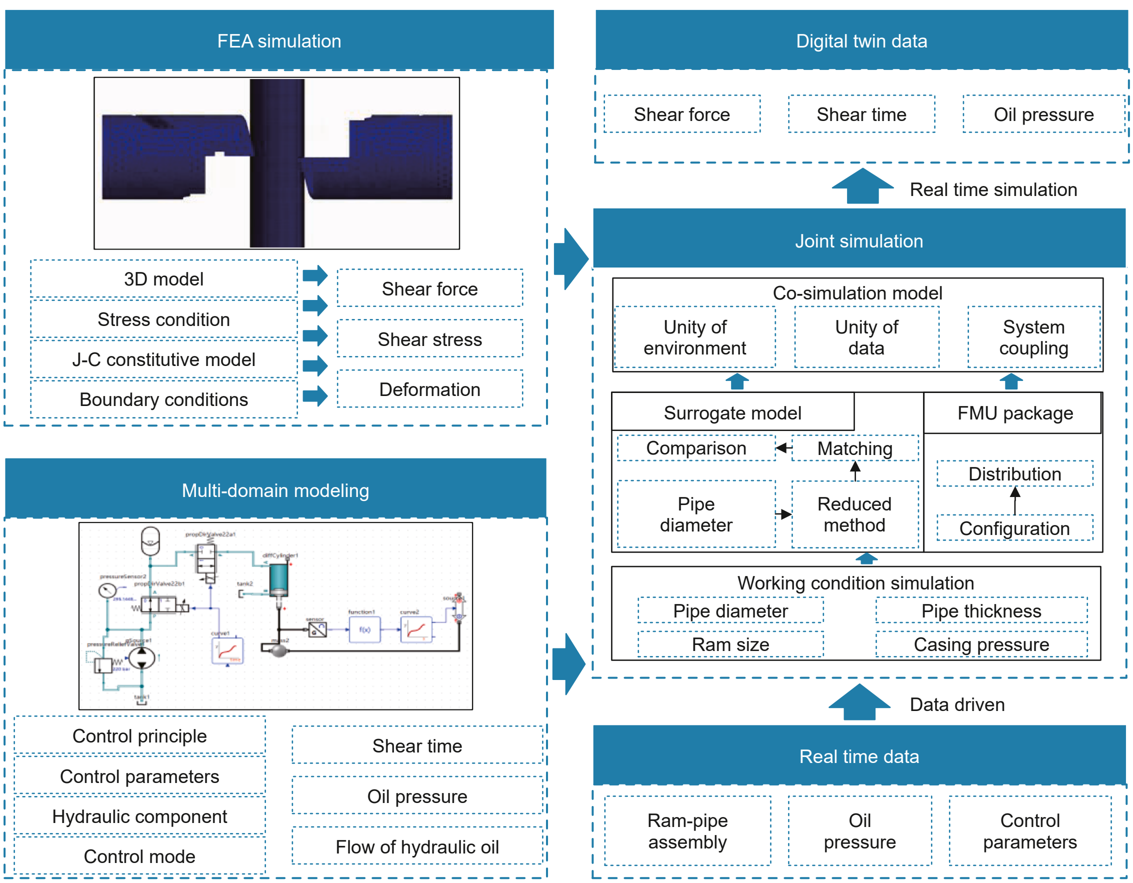

Fig. 4. Digital twin modeling method of ram BOP.

$$P_a C_1 \geq F_f + F_c \tag{3}$$

Inflatable accumulators work according to Boyle's law:

$$P_0 V^n = \text{const} \tag{4}$$

where P_0 is gas pressure in accumulators, MPa; V is the volume of gas, m^3; n is the gas variable index (1 when isothermal, 1.4 when adiabatic). Because the gas state in the accumulators of the BOP changes at a long interval, it is considered that the BOP shear process isothermal, and the value of k is set to 1 (Quispe et al., 2018).

The rate at which fluid is discharged from the accumulators is largely determined by pressure loss and differential pressure in the hydraulic control system, and the flow of oil determines the time required to shut the BOP. Bernoulli equation is introduced for calculation:

$$P + \rho g h + \frac{\rho v^2}{2} = \text{const} \tag{5}$$

where P is the pressure of the hydraulic control system, v is the flow velocity of the point, ρ is the fluid density, g is the gravitational acceleration, and h is the height of the point.

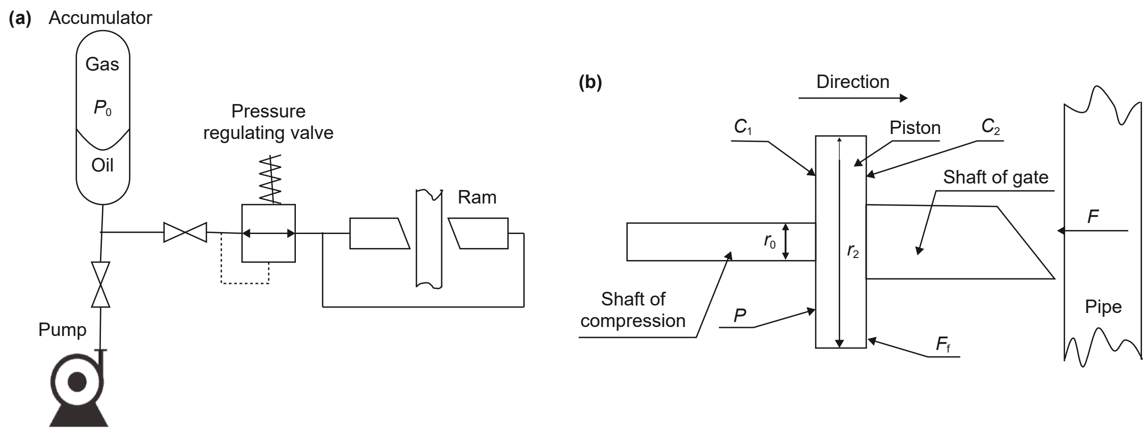

Fig. 5. Schematic diagram of **(a)** the ram BOP hydraulic control system, **(b)** the force on the rod.

At a certain time, the liquid pressure P_1 in the accumulators and the liquid pressure P_2 in the cylinder indicate that the initial velocity of the oil in the accumulators is 0. h_1 and h_2 respectively represent the liquid height of the accumulators, and the cylinder:

$$P_1 + \rho g h_1 = P_2 + \rho g h_2 + \frac{\rho v_1^2}{2} \tag{6}$$

The fluid velocity v_1 in the cylinder can be obtained as:

$$v_1 = \sqrt{\frac{2(P_1 - P_2 - \Delta\rho g h)}{\rho}} \tag{7}$$

Then, the variation of flow in the cylinder is:

$$Q = v_1 C_1 = C_1 \sqrt{\frac{2(P_1 - P_2 - \Delta\rho g h)}{\rho}} \tag{8}$$

According to the working principle of the accumulators, the liquid flow rate in the cylinder is the volume change rate of the accumulators, and the relationship between the shear time t and the flow rate Q can be obtained:

$$t = \int_{Va}^{Vb} \frac{1}{Q} \mathrm{d}V_{\mathrm{dis}} \tag{9}$$

Finally, it is also necessary to consider the influence of pressure in the well on the shear process because of the changing environment, so as to remediate the shear force data. When the ram BOP operates under varying closing pressures, well pressure is assumed to act uniformly on the rams. The force is the product of the pressure and the action area of the ram. Therefore, the relationship between the shear force and the closing pressure is as follows:

$$F = F_{\mathrm{m}} + P_{\mathrm{w}} \cdot C_3 \tag{10}$$

where F is the shear force, F_{m} is the shear force obtained by simulation, C_3 is the cross-sectional area of the ram, and P_{w} is the well pressure. Finally, the shear capacity of the ram BOP is evaluated by combining oil pressure and shear time.

2.3. Calculation method for shear capacity of BOP

The finite element method is used to evaluate the shear capacity of the BOP. Firstly, three-dimensional modeling software is used to construct the three-dimensional models of different shear ram-pipe combinations, and the assembled models are imported into the finite element analysis software in a standard format, and are meshed according to actual requirements. The number of mesh elements is determined through the mesh independence analysis (Zhang et al., 2023).

Secondly, the Johnson-Cook constitutive model is adopted to analyze the material's stress response to parameters such as strain, strain rate, and temperature. The basic function of this model is as follows (Shrot ang Bäker, 2012):

$$Y = \left[A + B\varepsilon_p^n\right]\left[1 + C\ln\dot{\varepsilon}^*\right]\left[1 - (T^*)^m\right] \tag{11}$$

where Y is the strength, 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 referred to as the strain rate $\dot{\varepsilon}_0^* = 1\ \mathrm{s}^{-1}$), $T^* = \left(T - T_{\mathrm{ref}}\right)/\left(T_{\mathrm{melt}} - T_{\mathrm{ref}}\right)$ is the corresponding temperature, T is the current temperature on the material, T_{ref} is the reference temperature, T_{melt} is the melting temperature of the material, A, B, C, m, n are five material constants, usually determined by mechanical tests, and their meanings are as follows: initial yield stress, hardening modulus, hardening index, strain rate strengthening parameters and thermal softening index.

Finally, the boundary conditions are set according to the actual working conditions, and axial force is applied to the upper and lower surfaces of the pipe to move up and down vertically. The pipe's radial degree of freedom is retained, while all degrees of freedom of the rams are constrained except for the shear direction, to simulate the moving states of the rams in the BOP. The finite element simulation model of the ram BOP is then built, and the change of shear force and shear stress in the shear process can thus be obtained through simulation. The corresponding oil pressure can also be calculated based on the obtained shear force according to the hydraulic control conversion principle, and finally, the shear capacity is evaluated.

Moreover, based on the well pressure data and piston cross-sectional area, the effect of the well pressure on the shear force is determined with Eq. (10). In this paper, the system simulation method is employed to simulate and analyze the shear process based on the model parameters of the hydraulic control components. The input is the ram hydraulic control command signals, and the displacement and velocity characteristics of the ram during the shear operation are obtained eventually.

3. Simulations and experiments

3.1. Finite element simulation of ram BOP shear process

On the premise that the rams can cut the pipe normally, the rams are treated as rigid bodies and the pipe as a deformable body for simulation analysis. In the process of model meshing, the rams as a rigid body are divided by tetrahedral mesh elements, and the pipe as a flexible body is divided by hexahedral mesh elements. The intermediate shear area mesh is refined, as shown in Fig. 6.

To determine the number of model grids of the finite element model of the rams, the mesh independence analysis is carried out. First, the model grid number is controlled by modifying the mesh size of the model in the shear region, and the peak shear force of the model is taken as the output reference, so as to obtain the change curve of the peak shear force of the model under different model grid numbers, as shown in Fig. 7. The total number of model grids in the overall model is 118389.

In the setting of load constraint boundary conditions, the shear rams only need to retain the movement in the X direction, while the degrees of freedom in the other directions are all constrained. According to the distance from the upper and lower rams to the pipe center, the displacement of the rams in the X direction is set. It is imperative to set pipe constraints in accordance with the prevailing working conditions, as shown in Fig. 8.

Then, the shear force curve of the ram BOP under different working conditions is obtained, as shown in Fig. 9. It can be seen that the pipe is elastically deformed and the shear force rises rapidly when the rams just touch the pipe. Then plastic deformation takes place and the shear force gradually rises until the pipe breaks. Afterwards, the shear force rapidly decreases to zero and the rams close, completing the sealing of the well.

3.2. System simulation of ram BOP hydraulic control device

A simulation model of the ram BOP hydraulic control system is established using multi-domain modeling software. In order to simplify the model, the focus is exclusively on the shear process of the ram BOP, wherein the oil pressure exerts a force on the rams, resulting in the separation of the pipe, as shown in Fig. 10(a). The

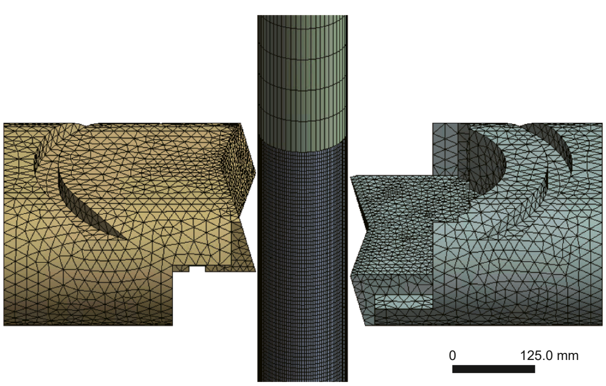

Fig. 6. FEA model of ram BOP shear process.

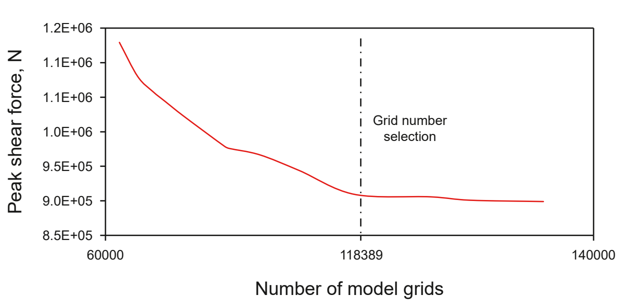

Fig. 7. Model mesh independence analysis results (Zhang et al., 2023).

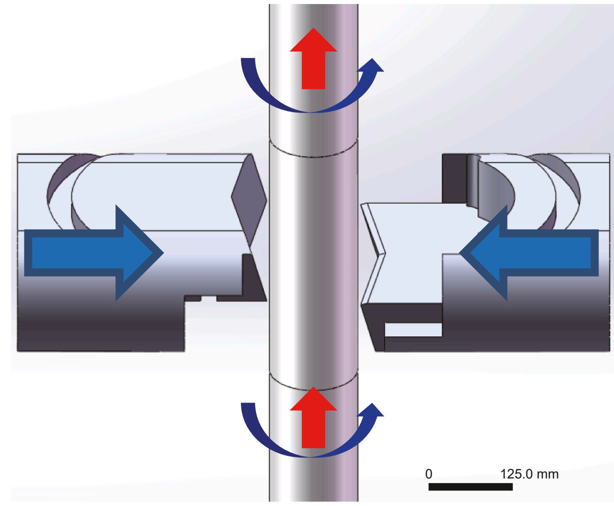

Fig. 8. Load constraint boundary conditions.

hydraulic control system of ram BOP is mainly composed of a pump (providing oil power), a relief valve (controlling the system pressure), a reversing valve (controlling the moving of the rams), a cylinder, a direction control valve (transmit the single), a set of accumulators, and a mass block (representing the ram). As shown in Fig. 10(b), the pump and relief valve constitute a constant pressure source to supply oil pressure to the accumulators. The two signal sources respectively simulate the command signal issued by a PLC (Programmable Logic Controller) to control the switching pressure (the operating pressure of the BOP) of the electromagnetic relief valve and the command signal of the reversing valve. After receiving the signal, the two-position two-way electromagnetic reversing valve acts correspondingly. The mass block simulates the total mass of the BOP rams and the cylinder. A mechanics module simulates the shear force between the BOP rams and the pipe.

By applying different shear force loads to the mechanical simulation module, data such as ram displacement, shear time, and oil pressure of the ram BOP under different shear force loads are obtained. It can be seen in Fig. 11(a) that the rams are approximately in uniform motion caused by the dominating effect of a constant sliding friction force at the beginning and end of shearing. In the process of shearing the pipe, the rams are subjected to the contact reaction force exerted by the pipe, so the speed of the rams tends to decrease. The high-pressure oil, flowing from the accumulators to the BOP cylinder, exerts a force on the rams in opposition to the frictional force when the shear command is initiated, thereby generating kinetic energy as the high-pressure liquid traverses the pipeline. Consequently, an initial minor peak in oil pressure within the cylinder is observed, followed by a subsequent return to a state of normality once the rams commence movement, as shown in Fig. 11(b). When the rams touch the pipe, the oil pressure required to push the rams increases, increasing of the oil pressure in the cylinder. After the pipe is cut, the oil pressure of the cylinder recovers its initial value. Finally, the cylinder and the accumulators form a communicating vessel after the ram is closed, and the oil pressure in them is equal and remains constant.

3.3. Digital twin modeling of ram BOP based on joint simulation

Because the calculation of system simulation is faster, it is necessary to reduce the order of the finite element model to

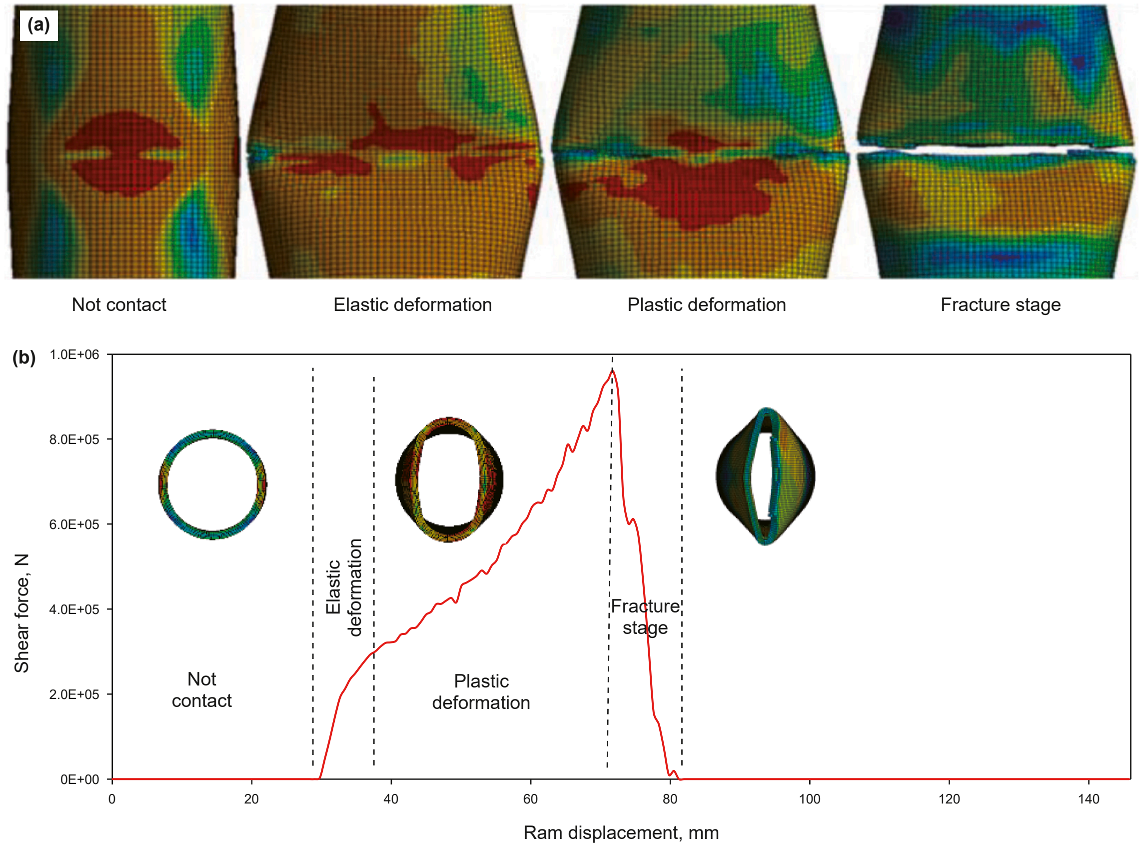

Fig. 9. (**a**) Crack changes pipe shear deformation process, (**b**) Shear force curve of ram BOP.

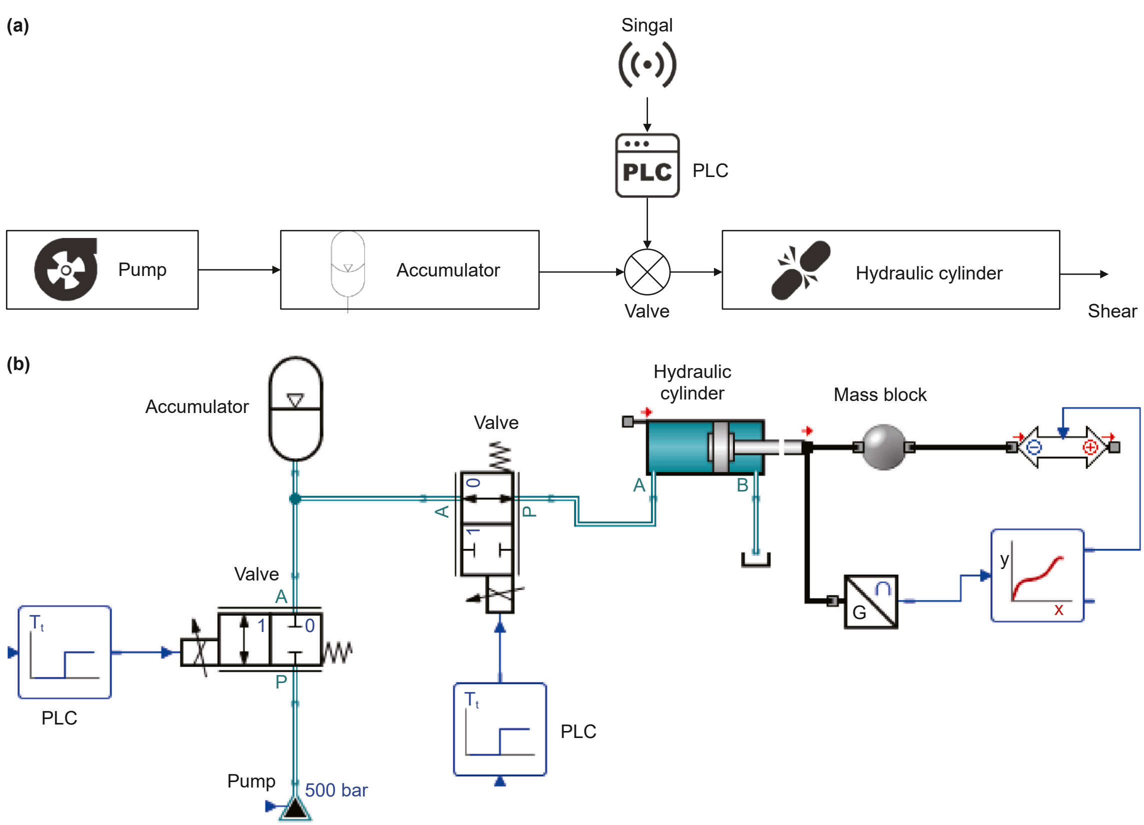

Fig. 10. (**a**) The flowchart of the control device, (**b**) ram BOP hydraulic control model.

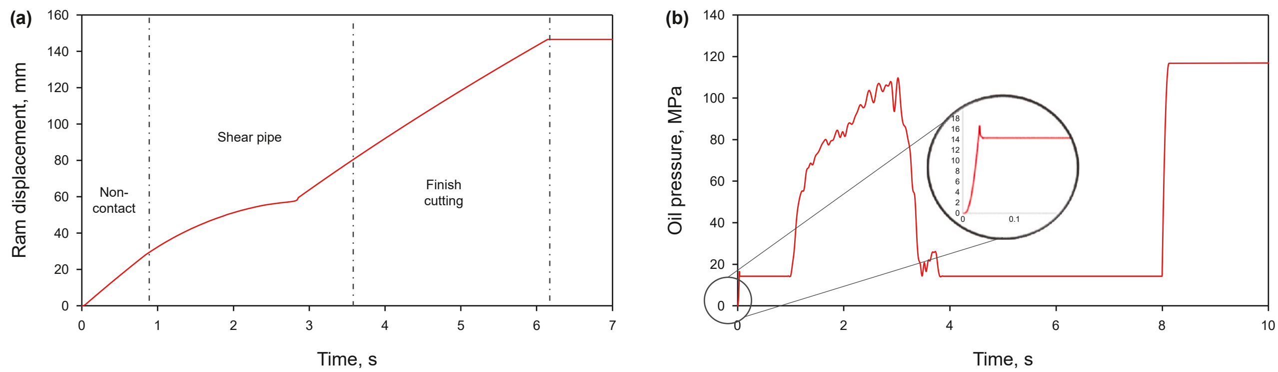

Fig. 11. Curves of **(a)** ram displacement and **(b)** oil pressure in the shear process.

accelerate the speed of the overall twin model. In this paper, the response surface method is employed to fit the finite element simulation results, yielding a fitted calculation model for the shear force of the ram BOP, thus simplifying its calculation. Ultimately, a real-time digital twin model of the ram BOP is constructed.

The finite element analysis of the shear process of the ram BOP is first conducted in conjunction with the actual drilling configuration in an oilfield, encompassing various pipe diameters, pipe wall thicknesses, ram models, and shut-in well pressures. The working parameters are presented in Table 1.

The ram ID represents two kinds of integrated double V-ram BOP produced by the North China Rongsheng Company. The ram model represents the two types of rams. Their geometric parameters are presented in Table 2.

Combined with Eq. (10), it is only necessary to add well pressure on the basis of fitted shear force data for shut-in well pressure, instead of fitting as a single variable. The variation of the well pressure is shown in Fig. 12.

Taking the ram model, the pipe outer diameter and the pipe thickness as independent variables, and the shear force at each node as a response, response surface analysis is carried out at each point on the shear force curve. Taking the node with the ram displacement of 50 mm as an example, its shear force is presented in Table 3.

Through second-order response surface analysis, the shear force model equation of this node is as follows:

$$F = 55148a^2 + 1685b^2 + 25c^2 + 15352ab + 689bc - 1589ac - 29583b - 6493c + 358188 \tag{12}$$

The simulation values and predicted values of the shear force obtained are shown in Fig. 13. It can be seen that the response surface values fit well with the simulation data.

Numerical regression analysis results of the model under several different operating conditions are presented in Table 4. As can be seen, the determination coefficient of the obtained regression equation R^2-statistic is close to 1, the F-statistic is much larger than 1, and the P-value is smaller than α ($\alpha = 0.05$), indicating that the second-order regression equation is significant, and the second-order response surface model has a good degree of fitting, reliability, and prediction accuracy. Consequently, Eq. (12) can predict the shear force during the shear process of the ram BOP.

Although the above method greatly simplifies the calculation of the shear force using the finite element method, a large amount of calculation is still needed because of the large number of nodes on the shear force curve. To further simplify the calculation, the number of nodes should be decreased. To analyze the influence of shear force curves with different node numbers on the simulation results, the shear time in system simulation is taken as the output reference. The change curve of the shear time is obtained, as

Table 1
Operating parameters of the ram BOP.

Scenario	Ram ID	Pipe thickness, mm	Pipe material	Pipe diameter, mm	Well pressure, MPa
1	1	8.38	36CrNiMo4A	133.2	0
2	1	9.19	36CrNiMo4A	166.5	10
3	1	9.65	36CrNiMo4A	166.5	20
4	1	12.7	36CrNiMo4A	166.5	30
5	1	9.17	36CrNiMo4A	183.1	40
6	1	9.65	36CrNiMo4A	183.1	50
7	1	10.54	36CrNiMo4A	183.1	60
8	1	9.17	36CrNiMo4A	190.8	70
9	1	11.5	36CrNiMo4A	190.8	80
10	2	8.38	36CrNiMo4A	133.2	0
11	2	9.19	36CrNiMo4A	166.5	10
12	2	9.65	36CrNiMo4A	166.5	20
13	2	12.7	36CrNiMo4A	166.5	30
14	2	9.17	36CrNiMo4A	183.1	40
15	2	9.65	36CrNiMo4A	183.1	50
16	2	10.54	36CrNiMo4A	183.1	60
17	2	9.17	36CrNiMo4A	190.8	70
18	2	11.5	36CrNiMo4A	190.8	80

Table 2
Shear force of ram displacement of 50 mm node under different conditions.

Ram model	Ram ID	Ram dimensions, mm	V-shaped angle, °	Cutting edge angle, °	material
35-70	1	395 × 358 × 192	160	15	40CrNiMo
35-105	2	440 × 380 × 200	160	15	40CrNiMo

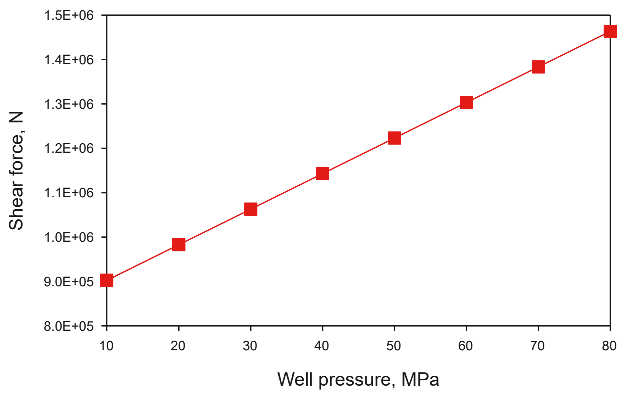

Fig. 12. Peak shear force variation under different shut-in well pressures.

Table 3
Shear force of ram displacement of 50 mm node under different conditions.

Scenario	Ram model *a*	Pipe thickness *b*, mm	Pipe diameter *c*, mm	Shear force *d*, kN
1	1	8.38	133.2	566.2
2	1	9.19	166.5	805.1
3	1	9.65	166.5	870.4
4	1	12.7	166.5	1,287.0
5	1	9.17	183.1	909.4
6	1	9.65	183.1	978.6
7	1	10.54	183.1	1,109.0
8	1	9.17	190.8	1,014.8
9	1	11.5	190.8	1,388.0
10	2	8.38	133.2	602.8
11	2	9.19	166.5	866.7
12	2	9.65	166.5	928.6
13	2	12.7	166.5	1,409.4
14	2	9.17	183.1	973.5
15	2	9.65	183.1	1,052.9
16	2	10.54	183.1	1,186.0
17	2	9.17	190.8	951.1
18	2	11.5	190.8	1,329.4

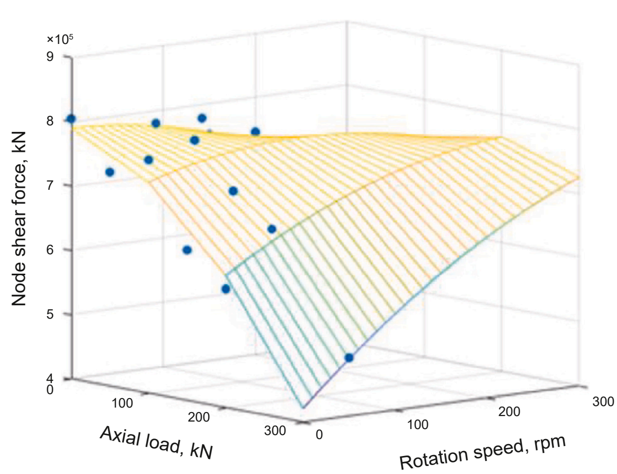

Fig. 13. Comparison of predicted node shear force and simulation results.

Table 4
Analysis of shear force fitting results.

Objective function	R^2-statistic	*F*-statistic	*P*-value	Error variance
Shear force	0.9877	90.3298	1.3e−7	1.3e+9
	0.9978	104.1148	1.2e−7	2.5e+9
	0.9731	85.7027	1.3e−7	9.4e+8

shown in Fig. 14. It can be seen that when the number of nodes exceeds 46, the calculated shear time is relatively stable. With the continuous reduction of the number of nodes, the shear time changes noticeably. Therefore, a fitting curve with 46 nodes is selected, as shown in Fig. 15.

The shear force fitting mathematical model of the ram BOP is also obtained. The simulation model of the hydraulic control system is directly packaged and output as a surrogate model. Python is selected as the unified programming language for the environment, where the FMU file is parsed and the shear force fitting data is uniformly processed as input to the system simulation model, the joint simulation model of the ram BOP is obtained. Then, real-time data (e.g., BOP model, hydraulic control parameters, ram-pipe combination data.) of a drilling site is connected to the system, and the on-site data stream is used as the input of the joint simulation model, that is, the construction of the digital twin model of the ram BOP is completed.

3.4. Practical experimental

In addition to theoretical analysis, this paper also builds a ram BOP pressure shear test rig, mainly including a hydraulic control device, a ram BOP, and pipes produced by the North China Rongsheng Company. The FK48-2 hydraulic control device mainly comprises an electric pump, a switch valve, a regulating valve, a set of accumulators, and a 36CrNiMo4A drill pipe, supplying oil power to the BOP. A stainless-steel shock-proof pressure gauge is installed on the console to respectively display the pressure change of the accumulators and the manifold during working time. The inside of the ram BOP is a double-V integral shear ram, consistent with the theoretical model. The specific material properties of 36CrNiMo4A are shown in Table 5.

Before the shear test, the lower end of the ram BOP is installed on a fixed base, and the upper end is sealed with an end cover. The BOP is connected to the hydraulic control device through the high-pressure manifold. The pipe is suspended vertically at the upper end and stabilized in the center. The BOP cavity is then subjected to high-pressure liquid injection through the fixed base at the bottom, thereby establishing a defined hydrostatic pressure environment. The test rig is shown in Fig. 16.

After the preparation is completed, the hydraulic control device is activated to perform the ram BOP shear test under different pressures, and test record is made. Through meticulous observation of the manifold pressure gauge, it is discerned that the pressure exhibits a tendency to decrease concomitant with the initiation of ram movement. The pressure rises and stabilizes when the pipe is touched and shearing is performed. The pressure drops sharply at the moment of the pipe breaks, followed by a rise until the rams are fully closed and remain stable within a certain

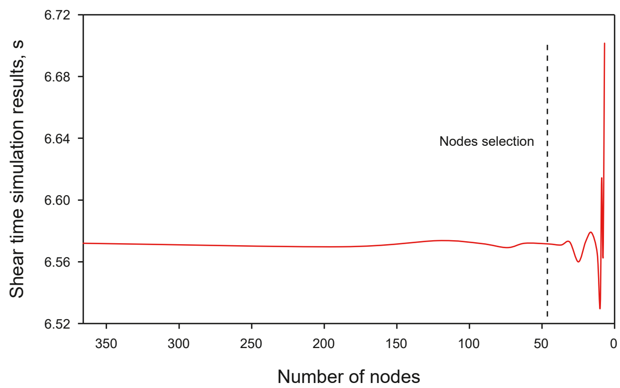

Fig. 14. Shear force curve node quantity sensitivity analysis.

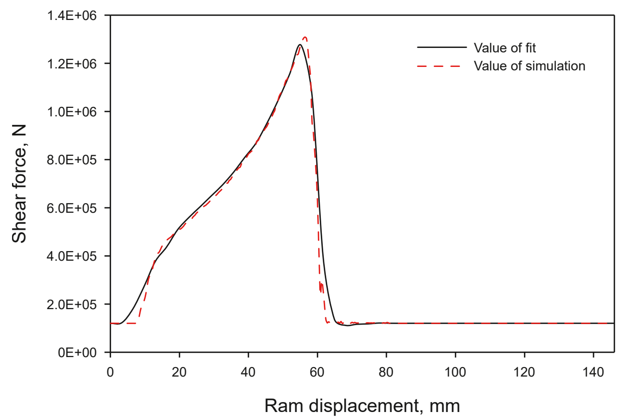

Fig. 15. Comparison of shear force curve fitting results and simulation results.

Table 5
Parameters of 36CrNiMo4A drill pipe material property.

Parameter	Value
Density, g/cm^3	7.83
Heat conductivity, W/(m·°C)	60.5
Specific heat constant pressure, J/(kg·°C)	477
Yield stress, MPa	1,031.1
Hardening constant, MPa	790.18
Hardening index	0.55
Melting temperature, °C	1,520
Shear modulus, MPa	77,692

range. The pressure change can help determine whether the shearing is completed.

The purpose of charging the BOP cavity is to analyze the influence of well pressure on ram shearing. On this basis, shearing tests are carried out under different working conditions with the well pressures of 20, 35, and 50 MPa respectively. Then, the peak shear oil pressure under each working condition is obtained according to the recorded data on the manifold pressure gauge, and the shear force in the compression shear process is derived to verify the theoretical formula under the same working conditions. The pipe deformation and the oil pressure curve are shown in Fig. 17.

West Engineering Services (Gauteng, 2004) has collected a series of field shear test data of specific size pipes, as shown in Table 6. A comparison of the data with the results obtained from the digital twin model is then made. It can be seen that the digital twin model of the ram BOP constructed based on the proposed method has an error of less than 10%. The relative deviation requirement of engineering data is met, thus verifying the engineering application value of the proposed model. It is concluded that the digital twin model conducts a better real-time and rapid evaluation of the shear capacity of the ram BOP. It provides a theoretical basis for on-site shear operation.

The shear force and shear time under the test conditions are compared with the simulation results of the twin model, as presented in Table 7.

Models lacking real-time inputs rely on fixed parameter initialization, which cannot accommodate dynamic operational variations. This limitation leads to significant cumulative errors. In contrast, real-time-enabled models continuously update critical inputs via joint simulation and recalibrates fitting coefficients (Eq. (12)), enabling transient condition responsiveness. For instance, Table 7 shows that real-time data reduces shear force error to 3.06% and shear time error to 2.6%. This dynamic adaptability overcomes the limitations of static assumptions and improves generalization performance in complex scenarios via data-physics fusion, demonstrating the pivotal role of real-time data in mitigating systematic errors.

3.5. Failure mode analysis

To enhance prognostic capabilities, a failure mode analysis framework is proposed based on the digital twin model. Integrated analysis of the digital twin model and historical failure data identifies three critical failure modes: 1) high well pressure; 2) pipe mismatch; and 3) hydraulic delay. Corresponding mitigation strategies include: 1) adjust pressure-regulating valve (Fig. 9(a)) to ensure $P \geq 0.9\ P_{min}$; 2) optimize ram geometry (Table 2, V-angle) for specific pipe diameters (validated by Table 7 errors < 10%); and 3) maintain accumulator efficiency using Eqs. (4)–(8) to control fluid discharge rate. Early warning mechanisms comprise: 1) real-time monitoring of oil pressure P and shear time t (Fig. 10). If $P < 0.9\ P_{min}$ or $t > 30$ s (API 16D), the system triggers alarms; and 2) simulation of failure boundaries under varying well pressures (Fig. 17) identifies risks (e.g., insufficient shear force due to high P_w). Regarding predictive maintenance, the digital twin enables offline validation of strategies (Figs. 2 and 3). Experimental comparisons (Tables 6 and 7) confirm model accuracy, forming a closed-loop framework from diagnosis to action.

3.6. Case study

To verify the real-time evaluation capability of the proposed digital twin model and its dynamic adjustment mechanism for shear predictions under blowout incidents, a synthetic case study of a simulated blowout incident was conducted. The case adopted parameters consistent with the actual drilling scenario and simulated the sudden increase in well pressure and pipe stress during a drilling, to demonstrate how the digital twin model updates shear force, shear time, and minimum shear oil pressure predictions in real time.

The scenario assumes an initial well pressure of 20 MPa. Two seconds after initiating the shear command, the well pressure begins to rise at a rate of 5 MPa/s due to a simulated blowout incident. The digital twin system continuously acquires this real-time well pressure data via its data interface. Based on Eqs. (9) and (10), it dynamically recalculates the minimum required shear oil pressure (P_{min}) and the actual required shear force (F).

As the well pressure increases dynamically from 20 to 45 MPa, the system's real-time calculated (P_{min}) correspondingly increases from 24.1 to 28.7 MPa. The digital twin model updates its parameters and reassesses the shear capacity within 1 s. It outputs an early warning if the current system oil pressure (P) falls below 0.9

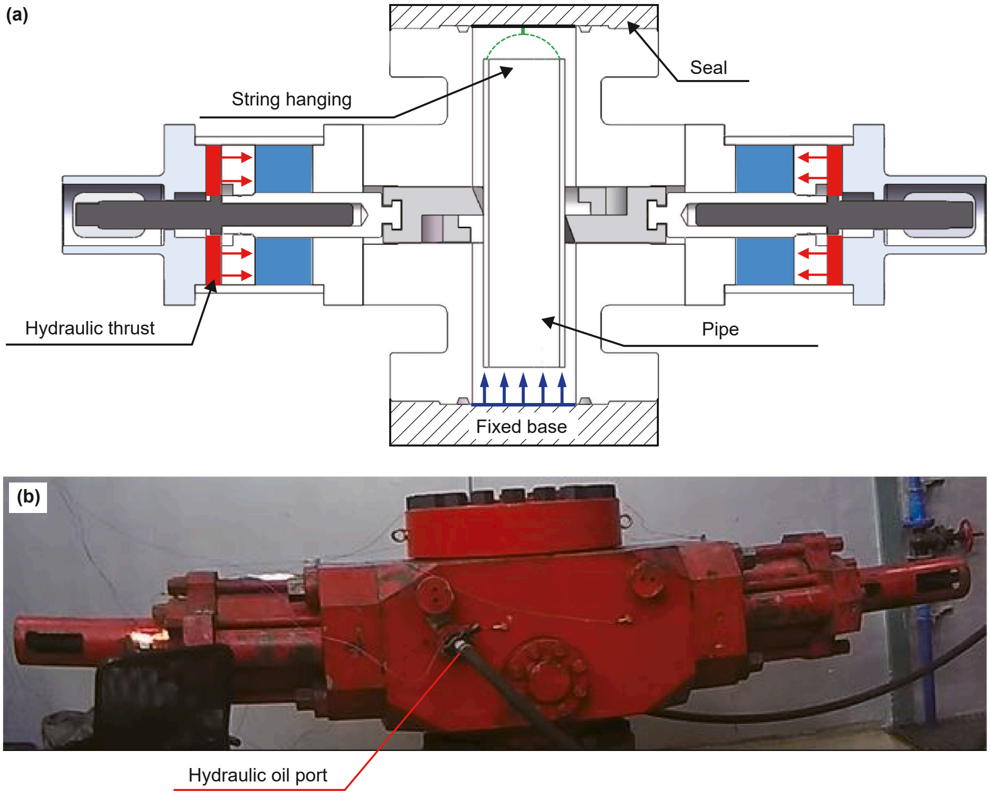

Fig. 16. BOP experimental setup, **(a)** schematic diagram, **(b)** experiment equipment.

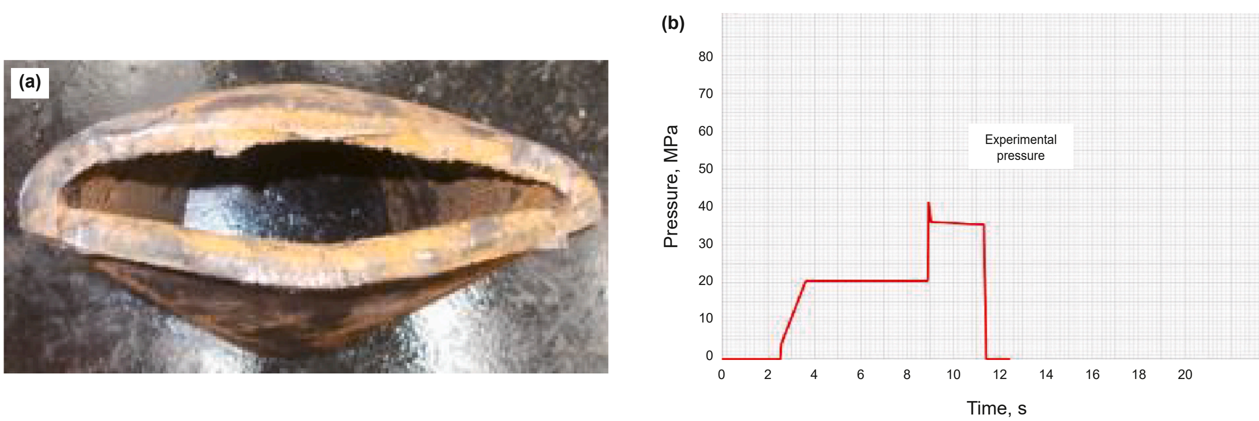

Fig. 17. The shear result: **(a)** pipe deformation, **(b)** oil pressure curve.

Table 6
Test data of shear force compared with the digital-twin data.

Diameter, mm	Wall thickness, mm	Well pressure, MPa	Shear force peak		
			Test value, kN	Digital-twin value, kN	Error
127	9.19	0	1,266	1,205	4.82%
139.7	9.17	0	1,424	1,283	9.89%
139.7	10.54	0	1,585	1,436	9.39%

Table 7
Test data of shear force and shear time compared with the digital-twin data.

Diameter, mm	Wall thickness, mm	Well pressure, MPa	Shear force peak			Shear time		
			Test value, kN	Digital-twin value, kN	Error	Test value, s	Digital-twin value, s	Error
127	9.19	20	1,248	1,212	2.87%	4	3.99	0.25%
127	9.19	35	1,368	1,334	2.49%	4.4	4.33	1.60%
127	9.19	50	1,499	1,453	3.06%	4.93	4.8	2.60%

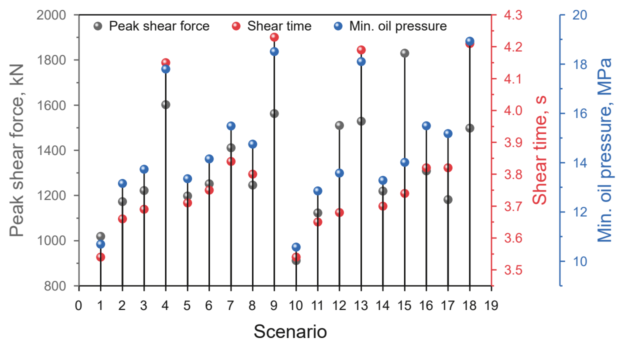

Fig. 18. Shear capacity characterization parameters of ram BOP under different working conditions.

$P_{\min}$, indicating a potential shear failure risk. Compared to a static evaluation based on the initial well pressure, the required shear force under dynamic blowout incident is approximately 18% higher, and the estimated shear time is extended by about 12%.

This case study illustrates that the proposed digital twin model can effectively respond to sudden changes in operating conditions, enabling real-time re-evaluation of shear capability. It provides immediate data-driven support for decision-making during well control emergencies.

4. Result analysis and discussion

Based on the constructed digital twin model of the ram BOP and combined with on-site drilling data, key shear performance characterization parameters—including peak shear force, shear time, and minimum shear oil pressure—are analyzed under different operating conditions, as shown in Fig. 18.

For rams of different sizes, a greater ram mass results in a more significant impact on the pipe, so that the required shear force is smaller, and the shear time is shorter. For pipes with different diameters, it is equivalent that the volume of the hollow part of the pipe changes. As the volume increases, the contact part between the rams and the pipe moves in the unconstrained direction subjected to the extrusion from the rams. The deformation of the pipe due to extrusion results in the imposition of additional force by the rams, thereby necessitating greater energy expenditure compared to a smaller diameter. Consequently, the shear force experiences an increase. Higher oil pressure and longer shear time are required to cut the pipe. For pipes with different wall thicknesses, the energy required to cut the pipe increases as the wall thickness (or cross-sectional area) increases, so that larger shear force and longer shear time are required.

Moreover, it usually takes 6–7 h to complete the simulation under the above working conditions in the finite element software, and based on the digital twin model described in this paper, the finite element simulation results of the shear force of the ram BOP can be obtained within a few seconds in the system, and then provide real-time and accurate data support for field shear operation. While this model focuses on V-type rams, the framework can be extended to non-V-type ram (e.g., shear blind rams) by adjusting geometric parameters (Table 2) and boundary conditions (Fig. 7). Additionally, the Johnson-Cook constitutive model supports alternative materials (e.g., titanium alloys) through recalibration of material constants in Table 5, validated by error margins below 10%

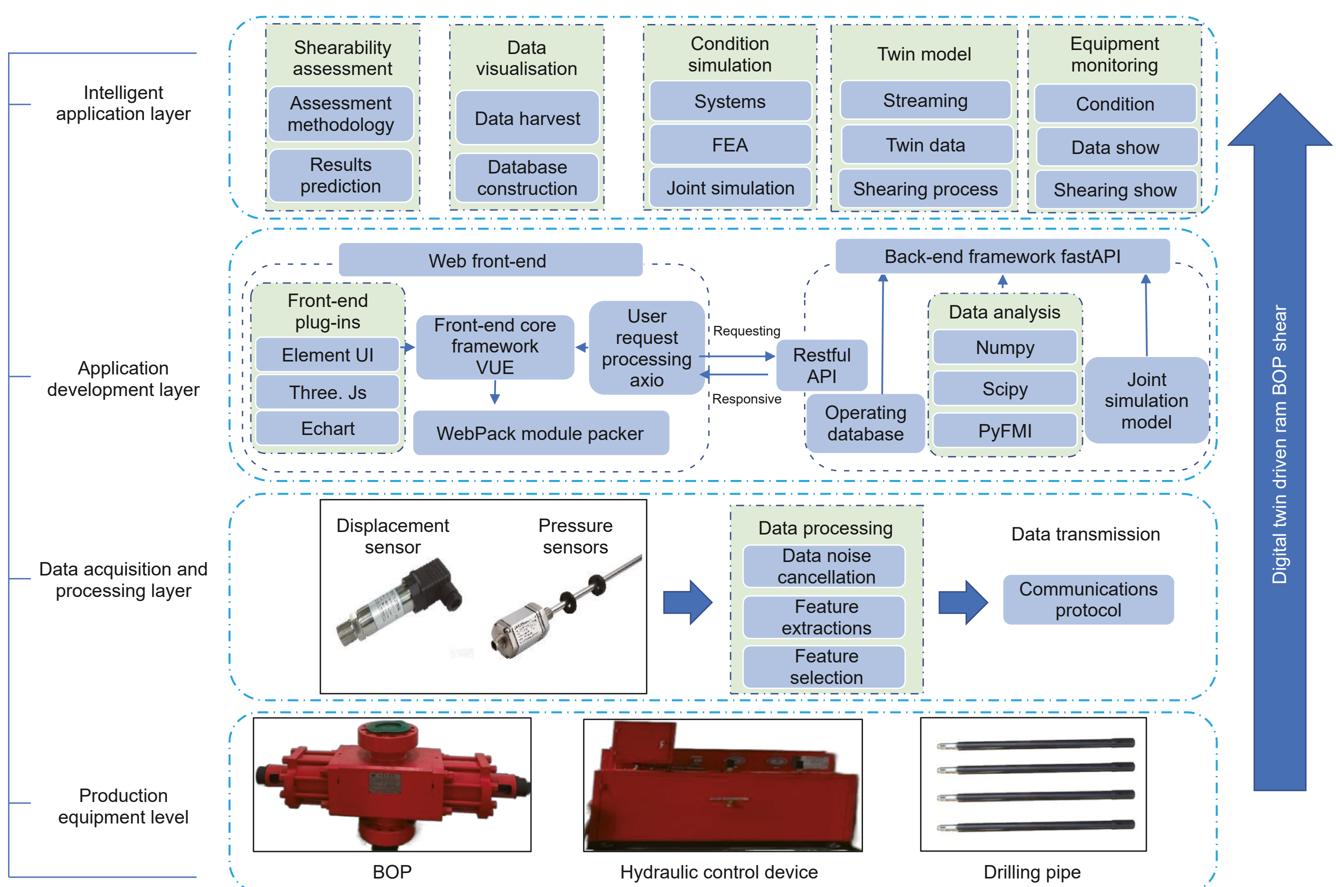

Fig. 19. BOP shear capacity digital twin interactive platform.

(Tables 6 and 7). The study demonstrates adaptability to diverse ram configurations and materials, as validated by parametric flexibility in simulations and experimental consistency.

This paper proposes a digital twin-driven ram blowout preventer (BOP) shear capacity assessment method, integrating joint simulation of the BOP digital twin model with real-time monitoring of critical parameters such as hydraulic pressure and shear duration under blowout scenarios. The framework delivers multi-dimensional data for the ram BOP shear capacity assessment under complex working conditions, so as to provide guidance for on-site shear operation.

Experimental validation employs North China Rongsheng 71/16-5000 shear BOPs paired with FK48-2 hydraulic control systems for N80-grade casings. A dedicated test bench is designed with dual fixation mechanisms for BOP stabilization and drill pipe immobilization. The digital twin platform simultaneously tracks ram displacement trajectories and hydraulic pressure transients during shear operations, coupled with post-test metallurgical analysis of shear blade wear patterns and drill pipe deformation/fracture characteristics, to evaluate BOP shear capacity. A distributed sensing architecture with real-time data acquisition is implemented to validate the assessment framework. Real-time synchronization of shear process parameters enables dynamic interaction between the physical test apparatus and its virtual counterpart, as shown in Fig. 19.

5. Conclusions

By analyzing the shearing process mechanism of ram BOPs, this study proposes a digital twin-driven shear capacity evaluation method, and finally draws the following conclusions:

(1) By constructing the digital twin model of the ram BOP based on joint simulation, the key performance characterization parameters such as shear force, shear time, and oil pressure during the shear process of the ram BOP are analyzed in real-time, and the shear capacity of the ram BOP is evaluated in multiple dimensions in real-time.
(2) The response surface method is used to fit the ram BOP shear force simulation data to reduce the order of the finite element simulation model, which not only maintains the accuracy of the shear force data, but also solves the problem of long calculation time of the digital twin model. The obtained results are acceptable.

This paper presents a real-time assessment method of the shear capacity of the BOP based on digital twin and joint simulation. There are still deficiencies in the current study, such as incomplete validation of the adaptability of the model to extreme operating conditions; unquantified delay effects in real-time data acquisition and model synchronization, both potentially impacting dynamic scenario predictions. Future work will focus on expanding experiments under high-pressure, high-temperature and multiphase flow conditions to validate model robustness and optimizing real-time data flow processing algorithms to minimize update delays and improve dynamic performance.

CRediT authorship contribution statement

Feng-Li Zhang: Writing – original draft, Supervision. **Jie Liu:** Writing – original draft. **Jin-Tao Ni:** Writing – original draft, Data curation. **Jin-Jiang Wang:** Methodology, Funding acquisition.

Consent to participate

The authors voluntarily agree to participate in this research study.

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

This study involves no human/animal subjects. All data are equipment operational parameters or simulation results, authorized by collaborative enterprises, and adhere to strict data privacy and security protocols.

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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