



Structural Characterization of Excavator Working Device Based on Measured Digging Trajectories and Different Working Loads

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Abstract: This study investigates the effects of different load characterization methods on the structural response of a 20-ton backhoe excavator working device under compound digging conditions. Based on field measured data, four typical compound digging trajectories were adopted, and the critical postures with peak cutting-loading resistance were selected for high-load analysis. A dynamic model of the working device was established via D’Alembert’s principle. Under identical postures and boundary conditions, three load schemes, namely measured excavation resistance, conventional compound digging force, and limit compound digging force, were applied to calculate structural loads on the boom and stick. Corresponding parametric finite element models were developed to compare structural equivalent stress and deformation. The results demonstrate that different load representations yield similar high-stress distributions and overall deformation modes for both components. The limit compound digging force produces higher maximum equivalent stress than the other two load schemes, providing a conservative evaluation for structural strength. Under the limiting load condition, the boom exhibits significantly increased deformation, while stick deformation presents non-monotonic variation due to the combined effects of load direction and working posture. This work can support design load selection and structural optimization for excavator working devices under compound digging operations.

Key words: Hydraulic Excavator; Measured Digging Trajectory; Limit Compound Digging Force; Working Load; Structural Analysis

1. Introduction

Hydraulic excavators are core construction machinery used in earthwork and mining operations. As the key components directly responsible for excavation tasks, the working mechanisms are subjected to complex and variable loads over extended periods, and their structural performance directly affects the operational reliability and service life of the entire machine (Liu et al., 2021). Conducting structural characteristic analyses of working mechanisms under real-world operating conditions holds significant engineering importance for the structural optimization and performance enhancement of excavators.

Scholars both domestically and internationally have conducted extensive research on the acquisition of excavator working loads and the analysis of structural performance. Regarding the determination of excavation loads and resistance, a combination of numerical simulation and field testing has become the mainstream technical approach: Liu et al. (2015) constructed a virtual excavator model to simulate the force-displacement curves at key hinge points and determine the maximum excavation force; Wang et al. (2022) and Bi et al. (2019) respectively employed RecurDyn-EDEM and DEM-MBD co-simulation methods to simulate and experimentally validate excavation resistance under actual operating conditions; Liu et al. (2024) further analyzed the effects of complex material environments and different bucket trajectories on excavation performance through MBD-DEM co-simulation. Addressing the difficulty of directly measuring excavation resistance, Li et al. (2024a) proposed a resistance prediction method that integrates kinematic modeling with machine learning; Sun et al. (2022) calculated actual trajectory loads based on a limit excavation force model and optimized the bucket structure. The aforementioned studies have enriched the methods for determining excavation loads, but most focus



on the resistance characteristics of individual excavation conditions, with relatively little attention paid to the load patterns of composite excavation operations.

In the field of structural performance analysis of working mechanisms, the finite element method and load inversion techniques are widely applied. Yu et al. (2021) established a finite element model of the entire excavator, applied boundary constraints based on actual operating conditions, and systematically analyzed the mechanical performance of the entire machine; Liu et al. (2022) proposed an external load inversion method that fuses simulation and experimental data, enabling precise identification of loads at the boom hinge; Chen et al. (2025) constructed a multi-software joint simulation platform to obtain hinge loads and, by combining surrogate models with intelligent algorithms, completed the structural optimization of the bucket (Li et al., 2023). Meanwhile, regarding the lightweight design of working mechanisms, research findings have emerged, such as high-strength lightweight bucket design under uncertain loads (Yu et al., 2019) and methods for lightweighting working equipment based on adaptive approximation models (Zhang et al., 2023). The authors' team previously conducted research on theoretical modeling of excavation force and excavation resistance characteristics, establishing a limit excavation force model that accounts for normal force and resistance torque (Ren et al., 2022). Furthermore, based on the principal value intervals of the resistance angle and the difference angle, they proposed a limit composite excavation force model that incorporates resistance torque and the directional angle of the composite excavation force (Li et al., 2024b), providing a theoretical foundation for load calculations under composite excavation conditions. Excavation resistance plays a vital role in optimizing the working device and power system of hydraulic excavators. (Yuan et al., 2026) However, existing research still has significant shortcomings: most structural analyses rely on theoretical calculations or simulated loads, resulting in discrepancies with the load characteristics of actual composite excavation conditions measured in the field; simultaneously, there is a lack of systematic comparison of structural responses under different load models, and the patterns of how composite excavation methods affect the structural performance of the working equipment remain unclear.

To address these issues, this paper takes a 20-metric-ton backhoe hydraulic excavator as the research subject. Based on four types of measured composite excavation trajectories, hazardous excavation postures are selected, and the structural loads on the boom and dipper are calculated using the excavation resistance model, the composite excavation force model, and the ultimate composite excavation force model, respectively; A parametric finite element model was established to compare and analyze structural stress and deformation patterns under different operating loads, thereby verifying the safety and reliability of the ultimate combined excavation force model and providing a reference for the structural optimization design of the working mechanism.

2. Selection of Typical High-Load Operating Conditions

2.1 Selection of Actual Excavation Conditions for Testing

The common digging motions of a hydraulic excavator are achieved through the combined movements of the boom, dipper arm, and bucket. The test subject was a 20-metric-ton backhoe hydraulic excavator. Dynamic testing employed a composite excavation method and covered actual operating trajectories across the surface layer and at various excavation depths. Given that the original test records did not provide uniform soil mechanical parameters for each soil layer, this paper does not quantitatively classify operating conditions based on strict soil categories. Instead, selected trajectories are distinguished based on excavation location, depth, and measured load characteristics to ensure that subsequent comparisons are grounded in actual test data.

Excavation trajectories reflect the movement paths of the bucket teeth during actual operation. By processing hydraulic pressure and displacement test data, continuous excavation trajectories can be discretized into several excavation points at a specific step size, with each excavation point corresponding to a specific working mechanism posture. Figure 1 shows the four typical composite excavation trajectories selected in this paper and their corresponding working equipment attitudes. To maintain consistency with the original test records, these are uniformly designated as Operating Condition 1 (conventional surface excavation), Operating Condition 2 (high-resistance surface excavation), Operating Condition 3



87 (excavation at a depth of approximately 1 m), and Operating Condition 4 (excavation at a depth of approximately 2 m). It
 88 should be noted that a higher density of trajectory points in a local area merely indicates that the movement speed of the
 89 bucket teeth tips has relatively decreased during that phase. This may be attributed to a combination of external excavation
 90 resistance, hydraulic system output, and operational control; therefore, this paper makes judgments based on the measured
 91 loads at the corresponding time points, rather than directly equating the density of the trajectory with the magnitude of
 92 excavation resistance.

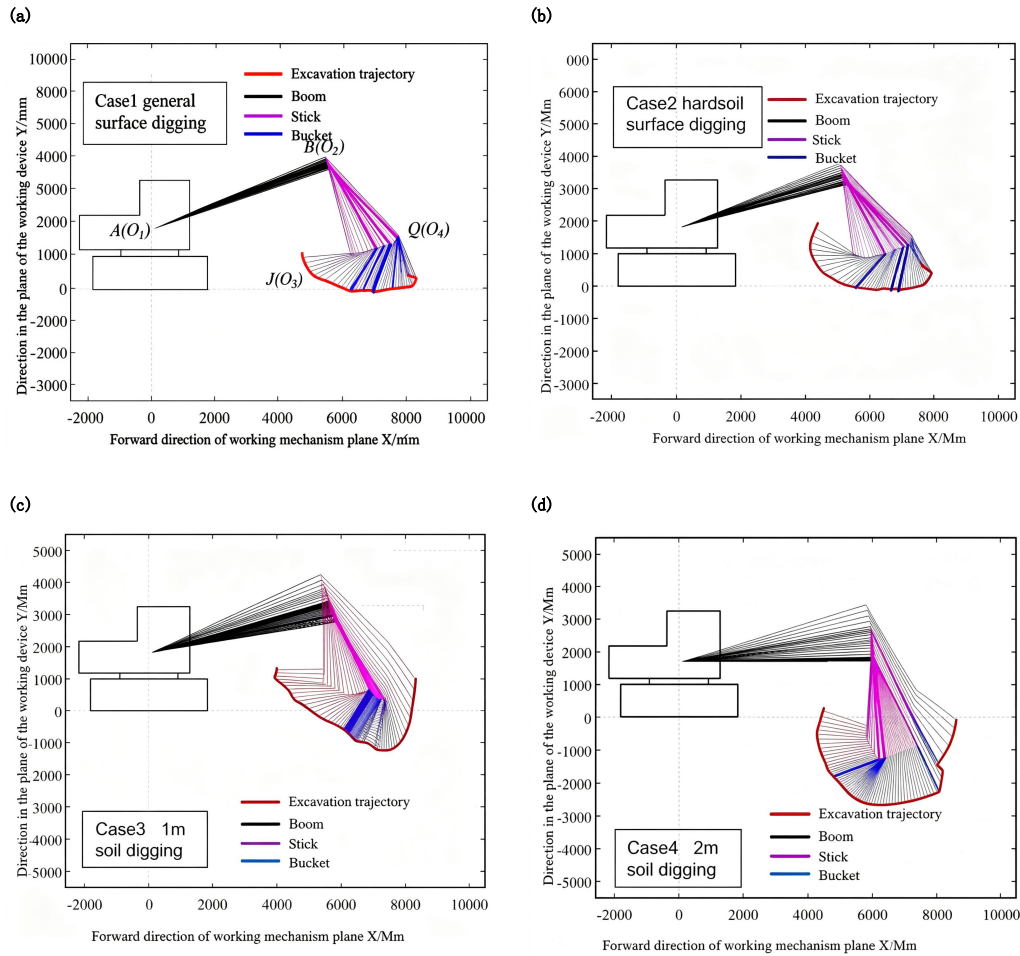


Figure 1. Selection of normal compound digging conditions: (a) Case 1 general surface digging; (b) Case 2 hardsoil surface digging;
 (c) Case 3 1m Soil digging; (d) Case 4 2m Soil digging

2.2 Solving for Excavation Resistance

During longitudinal excavation—excluding rotation while on the vehicle—the boom, dipper arm, and bucket can be approximated as moving within the same longitudinal plane, with the motion of each component consisting of both translational motion of the center of mass and rotation about the center of mass. When

establishing the dynamic equilibrium relationships for the various components of the working mechanism, the primary considerations include the components' own weight, the forces exerted by hydraulic cylinders, the constraints at pivot points, the excavation resistance experienced by the bucket, and the inertial terms resulting from the components' translational and



103 rotational motion. Given that the rockers and linkages have relatively small masses, their self-weight is neglected in the
 104 force analysis. The primary force relationships of the working mechanism are shown in Figure 2. This paper adopts the
 105 active-side calculation method for normal, incomplete excavation resistance developed by our team (Chen et al., 2015),
 106 which uses measured working mechanism motion parameters and hydraulic cylinder pressure data to calculate the
 107 excavation resistance, thereby avoiding direct reliance on soil parameters and soil-cutting tool contact models.

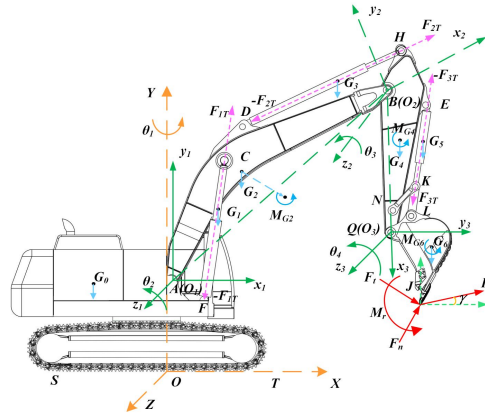


Figure 2. Backhoe hydraulic excavator force schematic diagram

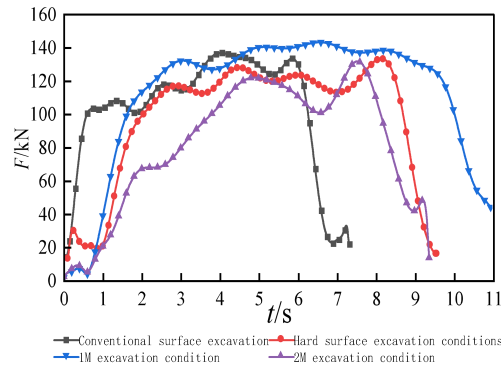


Figure 3. Resistance variation diagram of measured digging trajectory

112 Figure 3. shows the changes in excavation resistance under four measured operating conditions. The analysis excludes
 113 the initial phase—when the boom is lowered and before the bucket enters the soil—as well as the swing-and-lift phase
 114 following the completion of cutting and loading, focusing instead on the bucket’s cutting and loading phase. The measured
 115 curves indicate that the operation time is approximately 7 seconds for Operating Condition 1, approximately 9 seconds for
 116 Operating Conditions 2 and 4, and approximately 11 seconds for Operating Condition 3. The resistance curves for all four
 117 trajectories generally exhibit a common pattern: “rising after penetration—maintaining a high level during the cutting and
 118 loading phase—declining after cutting is complete”; however, the peak values and the timing of their occurrence vary across
 119 different operating conditions. Based on the test samples in this study, deeper excavation operating conditions exhibited
 120 higher resistance during certain phases; however, the resistance in the initial segment of the Operating Condition 4 trajectory
 121 remained lower than that of some shallow-layer operating conditions. This indicates that excavation resistance cannot be
 122 determined solely by excavation depth but is also influenced by factors such as local soil conditions, the attitude of the
 123 working equipment, the cutting process, and operational control. Therefore, this paper does not establish a single, definitive
 124 relationship between digging depth and resistance magnitude; instead, it uses the peak loads of each measured trajectory and
 125 their corresponding attitudes as the basis for subsequent structural analysis. The fact that the calculated resistance is not



entirely zero after the cutting and loading phases of each trajectory is due to the resistance being derived from the relationship between hydraulic cylinder pressure and dynamic equilibrium, which includes the effects of the working mechanism's weight and inertia.

To select representative high-load analysis postures, this paper first calculated the excavation resistance for four measured trajectories and then selected the working equipment postures corresponding to the peak excavation resistance during the cutting and loading phases of each trajectory as candidate high-load postures. The corresponding joint angles and peak excavation resistances are shown in Table 1, where θ_2 is the angle of the boom relative to the main frame, θ_3 is the angle of the stick relative to the boom, and θ_4 is the angle of the bucket relative to the stick. The excavation resistances in Table 1 represent the peak values for the corresponding measured trajectories during the analyzed phases, not the average values. The peak excavation resistances for the four operating conditions are 136.768 kN, 133.531 kN, 143.232 kN, and 131.959 kN, respectively. It should be noted that the maximum bucket excavation resistance does not necessarily correspond to the maximum structural stress in the boom or dipper arm; therefore, the subsequent analysis uses finite element results to further identify the high-response structural conditions for each component.

Table 1. The angle of each mechanism and excavation resistance for the selected digging postures

Excavation Conditions	$\theta_2/(^{\circ})$	$\theta_3/(^{\circ})$	$\theta_4/(^{\circ})$	F/kN
Case1	18.58	110.08	119.92	136.768
Case2	17.71	98.37	113.55	133.531
Case3	13.86	101.90	123.81	143.232
Case4	0.62	91.31	105.64	131.959

2.3 Solving for Composite Excavation Force

Theoretical digging force is used to characterize an excavator's ability to overcome external excavation resistance under a given posture. Considering that coordinated movements between the boom and bucket are common in actual operations, this paper employs a composite digging force model (Chen et al., 2015) to calculate the composite digging force for the postures specified in Table 1. It should be noted that the measured excavation resistance in Table 1 represents actual operational loads, whereas the composite digging force represents theoretical capacity loads under a given posture; the two have different physical origins. This paper converts these forces into structural loads under uniform attitudes and boundary conditions, with the aim of comparing the impact of different load characterization methods on structural evaluation results. Taking Operating Condition 2 as an example, the variation of the composite excavation force with the direction angle is shown in Figure 4, where the direction angle γ is defined as the angle between the composite excavation force reaction (i.e., the resultant force of the equivalent excavation resistance) and the horizontal direction.

As shown in Figure 4, under the same working mechanism orientation, the composite excavation force varies with the resistance direction angle. When the direction angle is 16° , the composite excavation force for Operating Condition 2 reaches its maximum value of 135.05 kN for that orientation. In this paper, the maximum theoretical combined digging force obtained within the direction angle search range is adopted as the combined digging force for the selected attitude; the results for the four operating conditions are shown in Table 2. Therefore, the values in Table 2 represent the theoretical maximum values for each selected attitude, rather than the time-history averages.

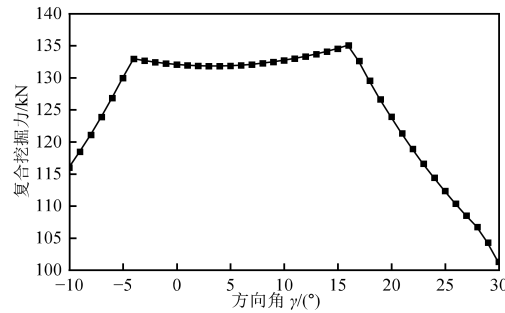


Figure 4. Change of the compound digging force with orientation angles

Table 2. The compound digging force of the selected digging postures in each working condition

Excavation Conditions	Azimuth / (°)	Combined Excavation Force/kN
Case1	6	129.768
Case2	16	135.051
Case3	-2	130.708
Case4	9	119.989

2.4 Solving for the Maximum Composite Excavation Force

The maximum composite digging force model is based on measured excavation resistance characteristics and comprehensively considers the combined effects of tangential resistance, normal resistance, and resistance torque. By defining a reasonable range for the direction angle of the composite digging force, the model determines the maximum digging capacity that an excavator can achieve under a given posture. The definition of the direction angle γ is consistent with that in the section on composite digging force.

Based on this model, the maximum composite digging force for selected digging postures under various operating conditions was calculated; the results are shown in Table 3.

Table 3. The limit compound digging force of selected digging postures in each working condition

Excavation Conditions	Azimuth / (°)	Maximum Combined Excavation Force/kN
Case1	17	154.849
Case2	14	153.817
Case3	12	156.817
Case4	27	150.483

A comparison shows that, under the same excavation conditions, the ultimate composite excavation force is 2.03% to 15.19% higher than the measured excavation resistance, and is also higher than the calculated value of the composite excavation force. This indicates that incorporating the resistance torque factor into the theoretical excavation force model is necessary and consistent with engineering practice—since the theoretical excavation force is used to characterize the excavator's maximum excavation capacity, its value should naturally be higher than the actual operating resistance. Therefore, conducting structural characteristic analyses using only measured excavation resistance or composite excavation force makes it difficult to comprehensively evaluate the structural safety margin of the working equipment.



3 Structural Load Calculations

3.1 Calculation of Pivot Point Loads

To determine the joint loads on each component of the working mechanism, this paper establishes dynamic models for the boom, dipper arm, and bucket based on D'Alembert's principle. For each component, this study accounts for its self-weight, forces exerted by hydraulic cylinders, hinge joint forces, external loads at the bucket tip, and inertial terms arising from translational and rotational motion. The inertial terms are incorporated into the equilibrium equations to ensure that each component satisfies instantaneous equilibrium in a dynamic sense. Figure 5 illustrates the force relationships among the components of the working mechanism. The horizontal principal vector is zero, that is.

$$\begin{cases} F_{Ax} + F_{Bx} + F_{Cx} + F_{Dx} + F_{G2x} = 0 \\ -F_{Bx} - F_{Dx} + F_{Ex} + F_{Nx} + F_{Qx} + F_{G4x} = 0 \\ -F_{Qx} + F_{Lx} + F_{Jx} + F_{G6x} = 0 \end{cases} \quad (1)$$

The principal vector in the vertical direction is 0, that is

$$\begin{cases} F_{Ay} + F_{By} + F_{Cy} + F_{Dy} + F_{G2y} = 0 \\ -F_{By} - F_{Dy} + F_{Ey} + F_{Ny} + F_{Qy} + F_{G4y} = 0 \\ -F_{Qy} + F_{Ly} + F_{Jy} + F_{G6y} = 0 \end{cases} \quad (2)$$

Calculate the moments about the centers of mass of each component; the principal moment is 0, that is.

$$\begin{aligned} & F_{Ax}(Y_{G2} - Y_A) + F_{By}(Y_{G2} - Y_B) + F_{Cx}(Y_{G2} - Y_C) + \\ & F_{Dx}(Y_{G2} - Y_D) - [F_{Ay}(X_{G2} - X_A) + F_{By}(X_{G2} - X_B) + \\ & F_{Cy}(X_{G2} - X_C) + F_{Dy}(X_{G2} - X_D)] + M_{G2} = 0 \\ & -F_{Bx}(Y_{G4} - Y_B) - F_{Dx}(Y_{G4} - Y_D) + F_{Ex}(Y_{G4} - Y_E) + \\ & F_{Nx}(Y_{G4} - Y_N) + F_{Qx}(Y_{G4} - Y_Q) - [-F_{By}(X_{G4} - X_B) - \\ & F_{Dy}(X_{G4} - X_D) + F_{Ey}(X_{G4} - X_E) + F_{Ny}(X_{G4} - X_N) + \\ & F_{Qy}(X_{G4} - X_Q)] + M_{G4} = 0 \\ & -F_{Qx}(Y_{G6} - Y_Q) + F_{Lx}(X_{G6} - Y_L) + F_{Jx}(Y_{G6} - Y_J) - \\ & [-F_{Qy}(X_{G6} - X_Q) + F_{Ly}(X_{G6} - X_L) + F_{Jy}(X_{G6} - X_J)] \\ & + M_{G6} + M_r = 0 \end{aligned} \quad (3)$$

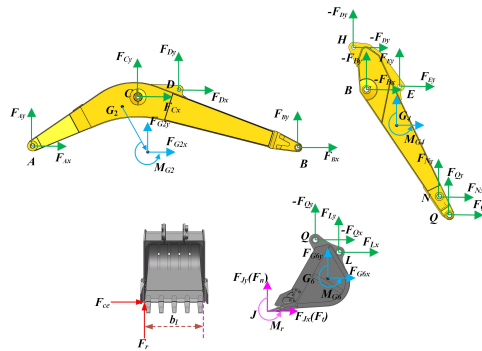


Figure 5. Analysis of the force on each member of the working device

In Equations (1)- (3): X_K , Y_K are the horizontal and vertical coordinates, respectively, of the hinge point (or center of mass) K in the global coordinate system; F_{Kx} and F_{Ky} are the forces acting on the hinge point (or center of mass) K in the horizontal and vertical directions, respectively; M_K is the moment acting on the corresponding member at the center of mass



194 K , F_{Jx} , F_{Jy} , and M_J represent, respectively, the horizontal resistance, vertical resistance, and resistance moment resulting
 195 from the projection of the digging resistance onto the center J of the cutting edge.
 196 The horizontal forces acting on the centers of mass G_i ($i = 2, 3, 4$) of the boom, dipper, and bucket are their respective
 197 horizontal inertial forces:

$$198 \quad F_{G_i x} = -m_i \cdot a_{G_i x} \quad (i = 2, 3, 4) \quad (4)$$

199 The force acting in the vertical direction is the sum of the vertical inertial force and the force of gravity:

$$200 \quad F_{G_i y} = -m_i \cdot (a_{G_i y} + g) \quad (i = 2, 3, 4) \quad (5)$$

201 The moments of inertia for each component are as follows:

$$202 \quad M_{G_i} = -J_i \cdot \alpha_{ii} \quad (i = 2, 3, 4) \quad (6)$$

203 In Equations (4) - (6), $i = 2, 3, 4$ represent the boom, dipper arm, and bucket, respectively; m_i is the mass of component i ;
 204 J_i is the moment of inertia; a_{G_i} is the absolute linear acceleration; α_{ii} is the absolute angular acceleration; and g is the
 205 acceleration due to gravity.

206 It follows that if the oil pressures in each hydraulic cylinder of the working mechanism and the motion parameters of
 207 each component relative to the coordinate system of the preceding component are known, the forces acting on each hinge
 208 can be determined by solving Equations (1) - (3) simultaneously.

209 3.2 Calculation of Lateral Forces and Off-Center Loads

210 As shown in Figure 8, the external load at the bucket tip can be decomposed into the tangential excavation resistance F_t ,
 211 the normal excavation resistance F_n , and the resistance moment M_r . In actual engineering applications, lateral loads and
 212 uneven loading conditions—such as loads applied to only one side of the bucket teeth—may also occur. To investigate the
 213 impact of these adverse factors on the structural response of the working mechanism, this paper introduces unilateral loading
 214 —specifically, the lateral force F_{ce} and the resultant force of excavation resistance F_r —as a conservative structural load
 215 condition for analysis. This unilateral loading condition is established for structural safety evaluation and does not imply
 216 that, during actual longitudinal excavation, the load is always applied to the side teeth of the bucket.

217 The magnitude of the lateral force depends on the braking torque M_T of the turret rotation motor and the radius of rotation
 218 J_{oy} , that is.

$$219 \quad F_{ce} = \frac{M_T}{J_{oy}} \quad (7)$$

220 To facilitate the application of lateral forces and off-center loads, these forces should be transformed into the coordinate
 221 system of each member, which results in additional torsional and bending moments. For the boom, when the lateral force is
 222 transformed into the $O_2-x_2y_2z_2$ coordinate system and translated to hinge point B, the additional torsional and bending
 223 moments are calculated using the following equations:

$$224 \quad \begin{cases} T_{x21} = r_{BJ-y2} \cdot F_{ce} \\ M_{y21} = r_{BJ-x2} \cdot F_{ce} \end{cases} \quad (8)$$

225 In the equation, T_{x21} and M_{y21} represent the additional bending moment and torque generated by the lateral force,
 226 respectively; r_{BJ-y2} and r_{BJ-x2} represent the components of the vector along the y_2 -axis and x_2 -axis, respectively. After
 227 applying the corresponding treatment to the resultant force of the excavation resistance under an off-center load, the
 228 resulting additional torque and bending moment are:

$$229 \quad \begin{cases} T_{x22} = F_{rx2} \cdot b_l / 2 \\ M_{y22} = F_{rx2} \cdot b_l / 2 \end{cases} \quad (9)$$



In the equation, T_{x22} and M_{y22} represent the additional bending moment and torque, respectively, caused by the off-center load of the resultant excavation resistance; F_{rx2} and F_{ry2} represent the components of the resultant excavation resistance F_r along the x_2 and y_2 axes, respectively. b_l is the bucket width.

For the dipper arm, when the lateral force is transformed into the $O_3-x_3y_3z_3$ coordinate system and translated to the pivot point Q, the resulting additional torque and bending moment are calculated as follows:

$$\begin{cases} T_{x31} = r_{QJ-y3} \cdot F_{ce} \\ M_{y31} = r_{QJ-x3} \cdot F_{ce} \end{cases} \quad (10)$$

In the equation, T_{x31} and M_{y31} represent the additional bending moment and torque generated by the lateral force, respectively; r_{QJ-y3} and r_{QJ-x3} represent the components of the vector along the y_3 -axis and x_3 -axis, respectively. After applying the appropriate treatment to the resultant force of the excavation resistance under an off-center load, the resulting additional torque and bending moment are:

$$\begin{cases} T_{x32} = F_{ry3} \cdot b_l / 2 \\ M_{y32} = F_{rx3} \cdot b_l / 2 \end{cases} \quad (11)$$

In the equation, T_{x32} and M_{y32} represent the additional bending moment and torque, respectively, caused by the off-center loading of the resultant excavation resistance; F_{rx3} and F_{ry3} represent the components of the resultant excavation resistance F_r along the x_3 and y_3 axes, respectively.

Through the above load transformation, longitudinal excavation loads, lateral forces, and the additional bending moments and torques caused by off-center loading can be simultaneously accounted for in the respective local coordinate systems of the boom and dipper, providing a unified structural load input for subsequent finite element analysis.

4 Analysis of Structural Characteristics

4.1 Development of a Parametric Finite Element Model

The fully parametric finite element model of a hydraulic excavator's working mechanism includes parametric modeling of geometry, loading, and post-processing. To facilitate repeated use of the model and batch analysis under different load conditions, parametric finite element models of the boom and dipper were created using the APDL language. During structural modeling, details that do not significantly affect the overall stiffness or the primary load-bearing paths were appropriately simplified. This included not explicitly modeling inter-plate welds and omitting some minor chamfers and fillets, and the APDL command sequence was saved as a macro file. Figure 6 shows the parametric solid models of the boom and dipper arm. Since the weld geometry is not explicitly modeled in this paper, the finite element results presented below are primarily used to identify the transition zones between base materials and high-stress locations in the overall structure; they are not directly used for evaluating the local fatigue strength of the welds.

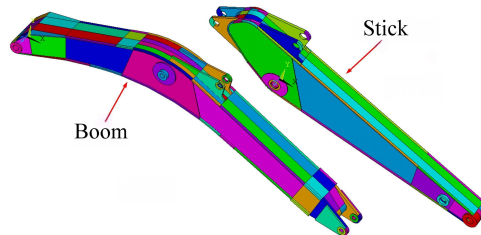


Figure 6. Parametric solid model of boom and stick

The material for the working mechanism is defined as Q345; its material parameters are shown in Table 4. After defining the material properties, and considering the complex structural geometry, SOLID187 elements were used to mesh the boom



and dipper. The boom model consists of 122,821 elements and 230,867 nodes; the dipper model consists of 94,088 elements and 180,160 nodes. The structural response comparisons in this paper follow the same modeling, meshing, and loading principles to minimize the impact of modeling discretization on cross-comparisons of different load scenarios.

Table 4. Performance parameters of the material

Materials	Modulus of elasticity, G/Pa	Density ρ (kg·m ⁻³)	Poisson's ratio ν
Q345	2.06×10^{11}	7850	0.3

4.2 Application of Boundary Conditions

Loads at each hinge point of an excavator's working mechanism are transmitted through cylindrical pins; the force is not concentrated at a single point but is distributed along the cylindrical surface of the hinge bore within a certain contact angle. To avoid false stress concentrations at the hinge holes, loads at all hinge locations are applied in the form of a **cosine-distributed surface load**—that is, the load density is distributed circumferentially around the hole according to a cosine function, with the maximum load at the center of contact and a gradual decrease toward both sides, consistent with the actual contact and force transmission characteristics between the pin and the hinge hole.

4.2.1 Constraint Settings

Separate finite element stress analyses were performed on the boom and the dipper stick; both were modeled as cantilever beams with constraints applied at their bases.

4.2.2 Load Application Methods

Loads are applied in three categories, covering the primary load conditions encountered during excavation. The application locations and methods for each load are as follows:

(1) Main Excavation Load (Pivot Force)

The radial forces at each pivot point, obtained from dynamic calculations, are applied to the load-bearing inner surfaces of the corresponding pivot holes according to a cosine distribution. The loading points on the boom include: the hinge hole in the hinge plate on the boom cylinder and the B hinge hole at the front end where the boom is hinged to the dipper arm; the loading points on the dipper arm include: the hinge hole in the hinge plate on the dipper arm cylinder and the H hinge hole at the front end where the dipper arm is hinged to the bucket.

(2) Lateral Force Load

The lateral force F_{ce} generated by the swing brake is perpendicular to the longitudinal plane of the work tool. It is applied as a uniformly distributed surface load to the lateral end faces of the hinge holes on the boom (B) and the stick (H), forming a surface load along the axial direction of the components to simulate the lateral force transmission effect during swing operations.

(3) Unilateral Loading

To simulate extreme torsional conditions in actual excavation operations where material resistance is concentrated on the teeth on one side of the bucket, the offset load method is employed. The implementation details are as follows:

The point of application of the resultant excavation resistance force F_r is shifted along the bucket's width from the bucket's center of symmetry to the midpoint of the cutting edge of the outermost bucket tooth, with an eccentricity of $1/2$ of the bucket's nominal width. According to the principle of equivalent force translation in statics, this offset load can be equated to a positive concentrated force acting at the bucket's hinge center J, superimposed with a torsional moment about the longitudinal axis of the member, corresponding to the additional torque and bending moment in Equations (9) and (11) above.

In the finite element model, the equivalent torsional moment on the boom side is transmitted through the front hinge bore B and converted into a tangential distributed load on the inner surface of the hinge bore. This load is superimposed on



the radially distributed cosine load, causing the boom to undergo a combined bending-torsion loading condition; The equivalent torsional moment on the dipper side is applied to the inner surface of the front H-pivot bore, creating a combined bending-torsion loading condition for the dipper. This loading method replicates the load transfer path during single-side excavation and accurately reflects the influence of the torsional component on the stress and strain distribution within the structure.

The boundary conditions for the boom and dipper arm are shown in Figure 7.

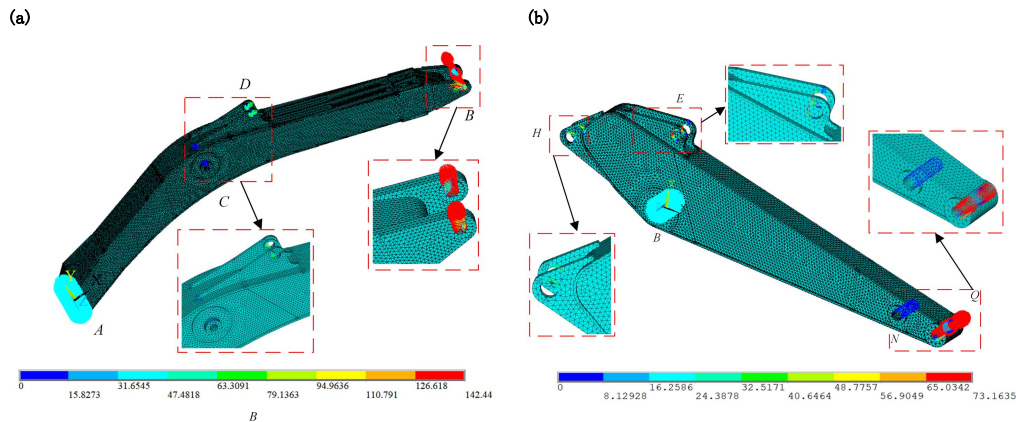


Figure 7. Impose boundary conditions:(a)Boom ;(b)Stick

4.3 Simulation Analysis

4.3.1 Applying Excavation Resistance Loads

First, the load at the hinge point was calculated using measured excavation resistance, and finite element boundary conditions were applied after superimposing lateral forces and off-center loading effects. Among the four measured operating postures, Operating Condition 4 resulted in the highest maximum stress and maximum deformation in the boom, as shown in Figure 8; Operating Condition 3 resulted in the highest maximum stress and maximum deformation in the stick, as shown in Figure 9. The term “maximum” here refers to the comparison results among the four selected positions under the respective load conditions.

As illustrated in Figure 8, high-stress regions of the boom are mainly distributed at the transition between the upper front flange and the side plate, around the upper ear plate, and at the boom-stick articulation. A peak equivalent stress of 197.341 MPa occurs at the transition between the upper ear plate and the upper front flange. Since welds are not explicitly modeled in the finite element analysis, this value reflects the base metal stress level in the transition zone and should not be taken as the local stress at the weld seam. The maximum displacement of the boom reaches 13.312 mm at hinge B.

As shown in Figure 9, high-stress regions of the stick are mainly distributed on the central side plate, at its junctions with the bottom plate and front/rear side plates, and near the stick hydraulic cylinder ear plate. The peak equivalent stress reaches 233.206 MPa at hinge H, while the stress on the central side plate adjacent to the bottom plate stays around 150 MPa. The maximum displacement of the stick is 12.888 mm at hinge Q.

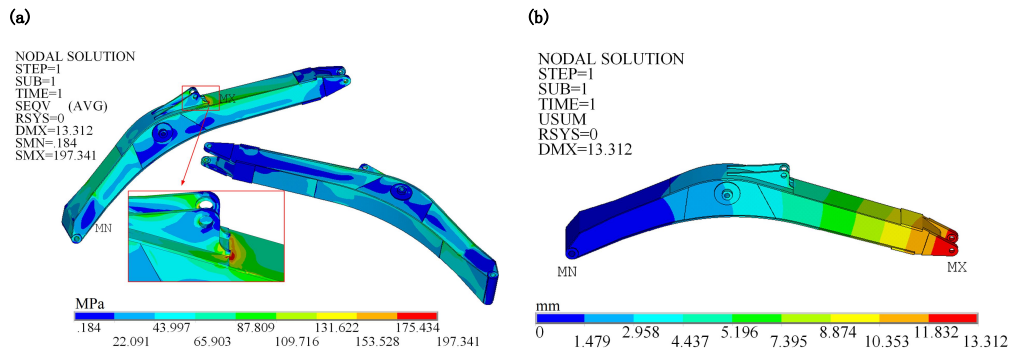


Figure 8. Maximum stress and deformation of the boom under resistance loading : (a) Stress Contour Map

; (b) Deformation Cloud Map

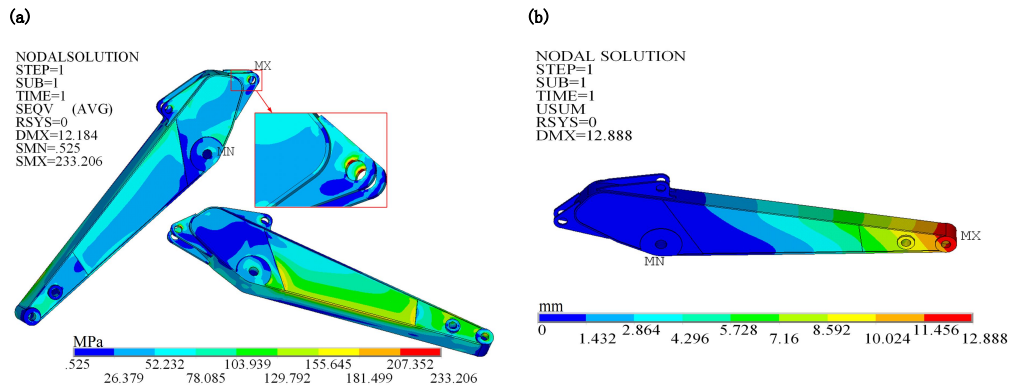


Figure 9. Maximum stress and deformation of the stick under resistance loading : (a) Stress Contour Map

; (b) Deformation Cloud Map

4.3.2 Application of a Composite Excavation Force Load

Next, a composite digging force model was used to calculate the structural loads, and the same finite element boundary conditions were applied. Among the four operating conditions, Operating Condition 2 corresponded to the highest equivalent stress in the boom, while Operating Condition 1 corresponded to the greatest deformation in the boom; the results are shown in Figure 10. Operating Condition 3 corresponded to the highest equivalent stress in the dipper arm, while Operating Condition 4 corresponded to the greatest deformation in the dipper arm; the results are shown in Figure 11.

As shown in Figure 10, the high-stress regions of the boom are still primarily distributed in the area where the front end plate connects to the side plate, near the upper ear plate, and around the boom-dish link hinge bore. The maximum equivalent stress of 221.988 MPa is located in the transition zone of the upper ear plate boss connection, which generally aligns with the high-stress locations identified under excavation resistance loads. The maximum displacement of the boom is 16.260 mm, occurring near hinge point B.

As shown in Figure 11, the high-stress regions of the dipper arm are primarily located in the central side plate and near the dipper arm hydraulic cylinder hinge bore. The maximum equivalent stress is 205.797 MPa, located near hinge point H, which aligns with the high-stress regions identified under excavation resistance loads. The stress in the area of the dipper arm base plate near the side plates is approximately 120 MPa. The maximum displacement of the dipper arm, 9.889 mm, occurred near hinge point Q.

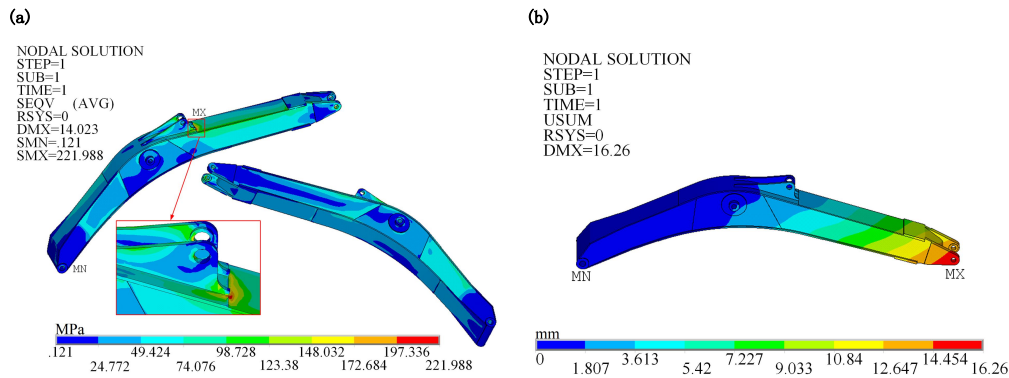


Figure 10. Maximum stress and deformation of boom under the composite digging force loading : (a) Stress Contour Map ; (b) Deformation Cloud Map

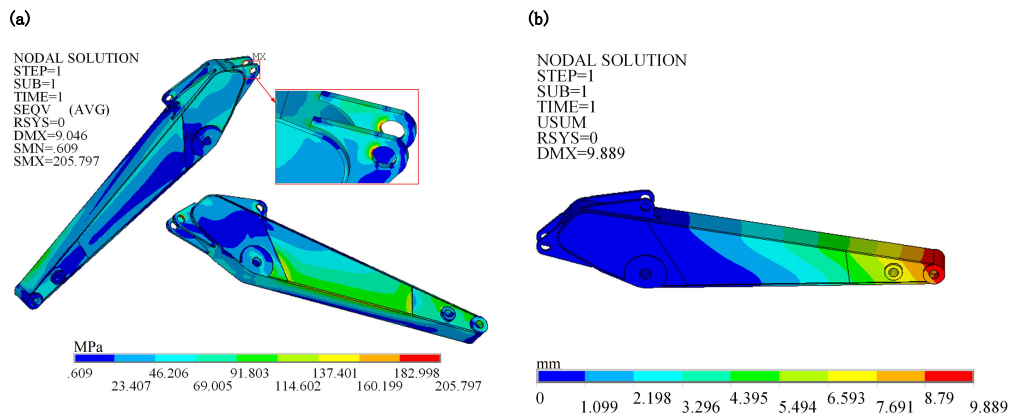


Figure 11. Maximum stress and deformation of stick under the composite digging force loading : (a) Stress Contour Map ; (b) Deformation Cloud Map

4.3.3 Application of the Ultimate Combined Excavation Force Load

Finally, finite element analysis under the ultimate composite digging force load was conducted with identical boundary conditions. For the boom, the maximum stress and deformation among all four operating conditions appear in Operating Condition 1 (Figure 12). For the stick, the peak equivalent stress occurs in Operating Condition 2 and the maximum deformation in Operating Condition 4 (Figure 13).

As shown in Figure 12, high-stress regions of the boom concentrate at the front cover plate-side plate junction, around the upper ear plate hinge hole, and at the boom-stick articulation hole. The peak equivalent stress of 235.892 MPa locates at the transition between the upper ear plate and front cover plate, consistent with the high-stress positions under the previous two load cases. The maximum boom displacement reaches 26.245 mm at hinge B.

As shown in Figure 13, high-stress regions of the stick lie on the central side plate, around the stick hydraulic cylinder hinge hole and the ear plate. The peak equivalent stress of 268.796 MPa occurs at hinge H, and the stress on the central side plate near the bottom plate is approximately 140 MPa. The maximum stick displacement is 9.208 mm at hinge Q.

Notably, although the peak stress of the stick rises markedly under the ultimate composite digging force, its maximum deformation does not rank highest among the three load cases. This indicates that stick deformation is also strongly affected by load direction and operating attitude.

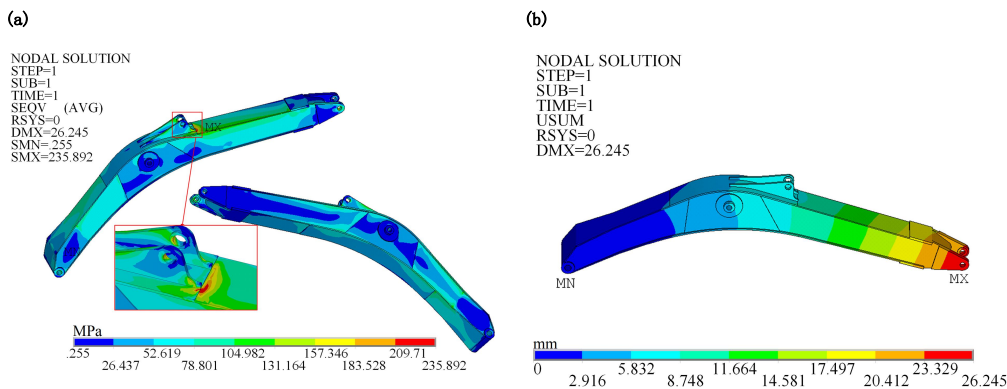


Figure 12. Maximum stress and deformation of boom under the limit composite digging force loading : (a)Stress Contour Map ; (b)Deformation Cloud Map

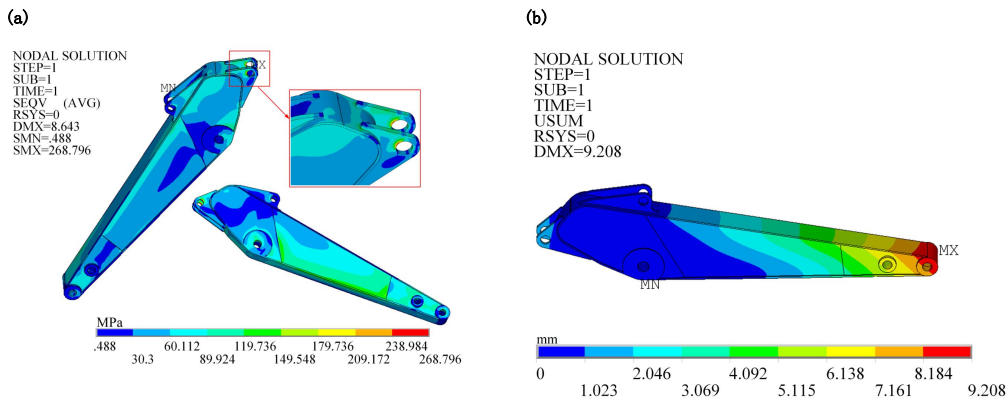


Figure 13. Maximum stress and deformation of stick under the limit composite digging force loading : (a)Stress Contour Map ; (b)Deformation Cloud Map

5 Comparative Analysis of Calculation Results for Different Work

Loads

A comparison of stress and strain contour plots under different operating conditions and loads reveals a strong consistency in the primary high-stress regions of the boom and dipper, as well as in the overall deformation patterns. This indicates that, under the operating configurations and boundary conditions selected in this study, the structural geometry, primary load paths, and constraint locations play a dominant role in determining the response distribution; different load models primarily alter the amplitude of local responses and, to a certain extent, change the ranking of different operating conditions. Therefore, the most critical structural operating condition for the boom or dipper arm cannot be directly determined based solely on the magnitude of the load at the bucket end; a comprehensive analysis must also consider the load direction, lever arm, and structural load transfer paths.

Tables 5 and 6 summarize the maximum equivalent stresses and maximum deformations of the boom and dipper under the four selected working postures for different working loads, and Figure 14 presents the corresponding comparative results. All comparisons below are based on the same finite element model, mesh, and boundary conditions; therefore, they primarily reflect the effects of load characterization methods and changes in working posture on structural response.



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Table 5. Maximum equivalent stress and deformation results of boom for each digging condition under different loads

Load Type	Case1		Case2		Case3		Case4	
	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm
Excavation Resistance Load	165.484	12.372	175.239	10.638	160.343	10.153	197.341	13.312
Combined Excavation Force Load	216.748	14.023	221.988	16.26	210.149	12.262	189.438	10.138
Maximum Combined Excavation Force Load	235.892	26.245	227.582	21.421	234.599	21.612	214.514	14.063

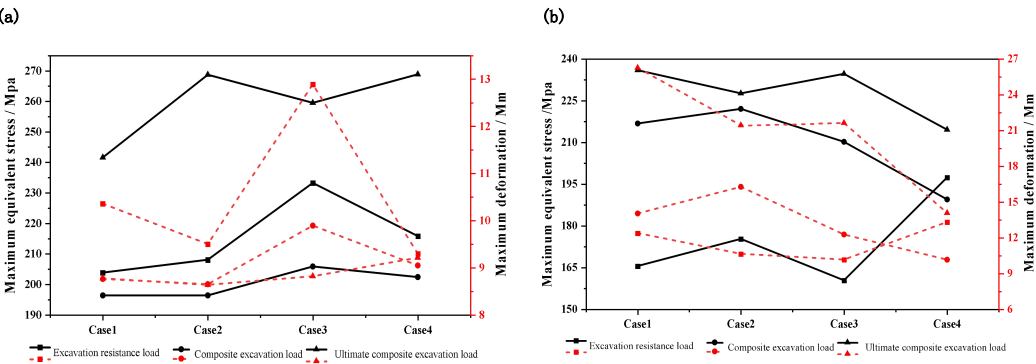
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Table 6. Maximum equivalent stress and deformation results of stick for each digging condition under different loads

Load Type	Case1		Case2		Case3		Case4	
	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm	Stress/MPa	Deformation/mm
Excavation Resistance Load	203.794	10.357	208.019	9.499	233.206	12.888	215.771	9.294
Combined Excavation Force Load	196.314	8.759	196.308	8.646	205.797	9.889	202.329	9.046
Maximum Combined Excavation Force Load	241.561	8.769	268.69	8.634	259.472	8.816	268.796	9.208

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Figure 14. Comparison of maximum stress and deformation of boom and stick under different loads:(a)Boom;(b)Stick

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As presented in Table 5 and Figure 17(a), under all four working conditions, the maximum equivalent stress and deformation of the boom under the ultimate combined excavation force are higher than those under the other two load cases. Specifically, under Working Condition 1, the boom achieves a maximum equivalent stress of 235.892 MPa and a maximum deformation of 26.245 mm under the ultimate combined excavation force. This peak stress is 142% of that under the measured excavation resistance load and 109% of that under the conventional combined digging force load, while the corresponding deformation values are 212% and 187% of the two reference loads, respectively. This indicates that the



ultimate combined excavation force significantly increases the load level for boom strength evaluation and induces a remarkable growth in boom deformation.

As illustrated in Table 6 and Figure 14(b), the stick exhibits inconsistent stress and deformation responses to different load models. The maximum equivalent stress of the stick under the ultimate combined digging force is consistently higher than that under the other two loads across all working conditions, with the maximum value of 268.690 MPa observed under Working Condition 2. This stress value is 125% and 133% of the results from the measured excavation resistance load and conventional combined digging force load, respectively. Nevertheless, stick deformation does not increase synchronously with the ultimate load magnitude. The maximum stick deformation of 12.888 mm occurs under Working Condition 3 with the measured excavation resistance load, whereas the maximum deformation under the ultimate combined digging force is only 9.208 mm under Working Condition 4. This reveals that stick deformation is jointly determined by load magnitude, load direction, lever arm and working posture.

In summary, the stick suffers more severe local stress concentration under measured and ultimate combined excavation loads, while the boom produces larger overall deformation in most working scenarios, which stems from the differences in structural dimensions, cross-sectional configurations, force transmission paths and load application positions. In structural design, the boom should be optimized for overall stiffness and transition zone stress performance, while the stick should prioritize the improvement of local high-stress regions such as hinge joints and middle side plates. The ultimate combined digging force model provides conservative stress evaluation results and is applicable as a reliable design load reference. Further structural tests and strain measurement data are required to fully validate its engineering reliability.

6 Conclusion

Based on measured composite excavation trajectories, this paper compares the structural responses of the boom and stick under three load types—measured excavation resistance, composite excavation force, and ultimate composite excavation force—with consistent operating postures and finite element boundary conditions. The main conclusions are drawn as follows:

(1) Taking the posture corresponding to the peak excavation resistance in the cutting-loading phase of each measured trajectory as the critical load analysis posture, the ultimate composite excavation force is consistently higher than the corresponding measured peak resistance and composite excavation force, with an increment of 2.03%–15.19% relative to the measured peak resistance. These results demonstrate that, by incorporating the principal value ranges of normal resistance, tangential resistance, resistance moment and direction angle, the ultimate composite excavation force can serve as a relatively conservative load for structural design.

(2) Across different load models and selected postures, the primary high-stress regions and overall deformation patterns of the boom and stick exhibit strong consistency. High stresses in the boom are mainly concentrated at the upper ear plate, the transition between the front cover plate and side plate, and the boom-stick articulation. High stresses in the stick are primarily located at the hydraulic cylinder articulation and the central side plate. The overall deformation of the boom is generally larger than that of the stick, indicating that the boom is more susceptible to structural deflection.

(3) Under identical operating conditions, the maximum equivalent stresses of both the boom and stick under the ultimate composite excavation force exceed those under the other two load types, verifying its higher load conservatism for structural strength assessment. However, the deformation of the stick does not vary monotonically with load magnitude, implying that structural deformation is also governed by load direction, force arm and operating posture. Therefore, design load selection for the working device should not rely solely on the magnitude of a single load; instead, combined motions, load directions and structural force transmission paths should be considered comprehensively. It should be noted that weld details are not included in this study, and the corresponding local fatigue performance and model reliability require further validation via measured strain data or structural tests.

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Cao: Investigation , Software , Writing – review& editing .Liang Lv:Writing – review& editing Xiaoping Pang:
 Investigation,Software, Writing – review& editing. Kaitao Ren: Supervision, Writing – review & editing, Formal analysis.
 Heng Zhang: Supervision, Writing – review & editing, Formal analysis.

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