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A Parametric FEA Study of Excavator Arm Deformation and Maximum Shear Stress during Excavation

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Abstract – *Excavator arms are subjected to severe mechanical loading during excavation, and their structural performance plays a critical role in operational safety and durability. In the present study, a parametric finite element analysis (FEA) is carried out to investigate the deformation and maximum shear stress behavior of an excavator arm under varying digging pressure and bucket inclination conditions. A three-dimensional numerical model of the excavator arm–bucket assembly is developed and analyzed using ANSYS Workbench 18.2. To represent conservative operating conditions, the stick end of the arm is fully constrained. Distributed pressure loads ranging from 100 kPa to 500 kPa are applied on the bucket surface to simulate soil resistance during excavation. Additionally, the arm–bucket assembly is rotated such that the bottom surface of the bucket is inclined at 0°, 15°, 30°, 45°, and 60° with respect to the global reference axis, representing different digging postures. The structural response is evaluated in terms of total deformation and maximum shear stress based on the Tresca failure criterion. Results indicate that total deformation increases consistently with increasing pressure for all inclination angles, reaching a maximum value of approximately 39 mm at the highest pressure level. The influence of inclination angle on deformation is moderate; however, a noticeable increase is observed around 30° inclination. In contrast, maximum shear stress exhibits strong sensitivity to bucket inclination, with peak values occurring consistently at 30° for all pressure levels. The maximum shear stress of 1.43×10^9 Pa is obtained at a pressure of 500 kPa and 30° inclination, identifying this configuration as the most critical digging condition. The findings provide valuable insight into the influence of digging posture and load severity on excavator arm structural behavior and can assist in safer design and operational planning.*

Keywords- *Excavator arm; Finite element analysis; Bucket inclination; Digging pressure; Total deformation; Maximum shear stress*

INTRODUCTION

Excavators are widely used in construction, mining, and earthmoving operations, where their performance and reliability are strongly influenced by the structural integrity of the arm–bucket assembly. During excavation, the excavator arm is subjected to complex loading conditions arising from soil resistance, payload, and varying digging postures[1], [2], [3]. These loads induce significant stresses and deformations, particularly near critical regions such as the stick end, pin joints, and bucket connection points. Excessive deformation may lead to poor operational accuracy, while high stress concentrations can cause premature failure, thereby affecting safety and service life[4].

With the increasing demand for higher productivity and durability, structural analysis has become an essential step in excavator design and evaluation. Experimental investigation of excavator arms under real digging conditions is often expensive, time-consuming, and difficult to control. As a result, finite element analysis (FEA) has emerged as an effective and widely adopted tool for assessing the structural behaviour of excavator

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components under various loading scenarios. FEA allows designers and researchers to evaluate stress distribution, deformation patterns, and critical failure zones under controlled and repeatable conditions[5].

Among the various operational parameters, digging force magnitude and bucket inclination angle play a crucial role in determining the load transfer path and bending characteristics of the excavator arm [6]. Different digging postures can significantly alter the direction and intensity of forces acting on the arm, leading to variations in structural response. Therefore, a systematic parametric investigation considering both load severity and bucket inclination is necessary to identify critical operating conditions and ensure safe and efficient excavator operation[7].

Several researchers have investigated the structural behaviour of excavator arms using numerical and analytical approaches. Finite element methods have been extensively employed to study stress distribution and deformation characteristics of excavator booms, sticks, and buckets under static and dynamic loading conditions[8]. Previous studies have primarily focused on evaluating von Mises stress, deformation patterns, and factor of safety under rated digging forces or manufacturer-specified load cases. These investigations have demonstrated that maximum stresses typically occur near the boom–stick joint and bucket–arm connection regions due to high bending moments and load concentration[9].

Some researchers have incorporated hydraulic cylinder forces and joint constraints to simulate more realistic operating conditions, while others have adopted simplified boundary conditions to represent worst-case scenarios [10]. Studies have also explored the influence of material selection, geometric optimization, and weight reduction on excavator arm performance. However, many existing works consider a limited number of loading configurations or a single digging posture, which restricts the understanding of how different excavation angles affect structural response[11].

A few parametric studies have examined the effect of digging force variation on excavator components, reporting a near-linear relationship between applied load and resulting stress or deformation. Nevertheless, the combined influence of distributed soil pressure and bucket inclination angle has not been sufficiently explored [12]. In particular, limited attention has been given to maximum shear stress evaluation based on the Tresca failure criterion, despite its relevance for ductile steel structures subjected to combined bending and shear loads. This indicates a clear research gap in systematically analysing the structural response of excavator arms under varying digging postures and pressure-based loading conditions[13].

From the literature survey, it is evident that while finite element analysis of excavator arms is well established, comprehensive parametric studies incorporating both digging pressure and bucket inclination angle remain limited[14]. Most existing studies focus on a single or nominal digging configuration, which may not represent the most critical operating condition encountered during actual excavation. Moreover, the majority of investigations rely on von Mises stress alone, whereas maximum shear stress can provide a more conservative and relevant failure assessment for ductile materials such as structural steel[15].

The motivation of the present work is to address these gaps by performing a systematic parametric FEA of an excavator arm under realistic excavation-related conditions. Distributed pressure loading is applied to represent soil resistance more accurately, and multiple bucket inclination angles are considered to simulate different digging postures. The study focuses on evaluating total deformation and maximum shear stress to identify critical load–angle combinations that govern structural performance[16].

The outcomes of this study are expected to provide valuable insights into the influence of digging posture and load severity on excavator arm behavior. The findings can assist designers in identifying critical operating conditions, improving structural safety, and supporting informed design and operational decisions for excavator systems.

METHOLOGY

Geometric Modelling of Excavator Arm

A three-dimensional geometric model of the excavator arm–bucket assembly was developed to represent the structural configuration during excavation. The model consists of the stick portion of the arm and the bucket, including the bucket teeth region where soil interaction occurs. Geometric features such as lug plates and connection regions were retained to ensure realistic stress transfer, while minor fillets and non-structural details were simplified to reduce computational complexity without affecting the global structural response. The geometric model was imported into ANSYS Workbench 18.2 for finite element analysis.

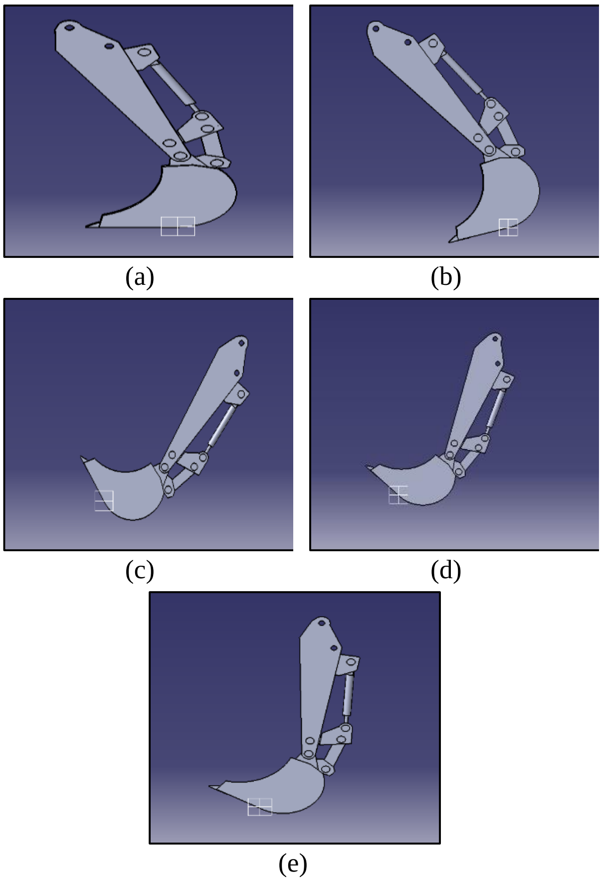


Fig. 1- Three-dimensional geometric model of the excavator arm bucket assembly with inclination angle (a) 0^0 (b) 15^0 (c) 30^0 (d) 45^0 (b) 60^0

Material Properties

The excavator arm and bucket were assumed to be manufactured from structural steel, which is commonly used in earthmoving equipment due to its high strength and ductility. The material was modelled as homogeneous, isotropic, and linearly elastic. The material properties used in the analysis include Young's modulus of 210 GPa, Poisson's ratio of 0.3, and density of 7850 kg/m³. Plastic deformation and material nonlinearity were neglected, as the present study focuses on elastic structural response under static loading conditions.

Boundary Conditions

To represent a conservative and worst-case loading scenario, the stick end of the excavator arm was fully constrained. All translational and rotational degrees of freedom at this location were restricted, simulating a rigid connection between the arm and the boom. This assumption eliminates joint compliance and results in higher stress and deformation levels, thereby providing a safe and conservative estimate of structural behaviour. The bucket–arm connection was left unconstrained to allow realistic load transfer from the bucket to the arm during excavation.

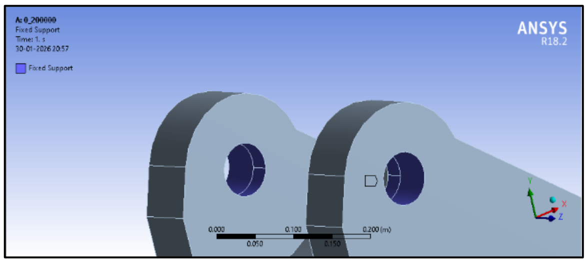
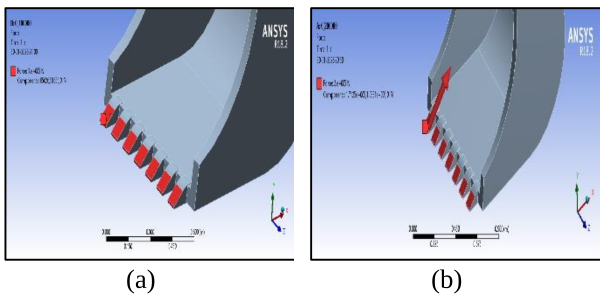


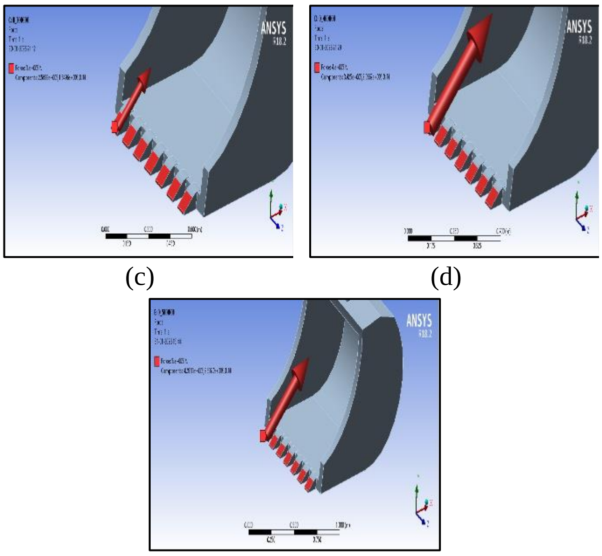
Fig. 2 - Three-dimensional geometric model of the excavator arm–bucket assembly showing the fixed boundary condition applied at the stick end.

Loading Conditions

The interaction between the bucket and soil during excavation was simulated using distributed pressure loading. Pressure loads of 100 kPa, 200 kPa, 300 kPa, 400 kPa, and 500 kPa were applied on the bottom surface of the bucket, representing increasing levels of soil resistance encountered during digging. The use of pressure loading instead of concentrated force provides a more realistic representation of soil–bucket interaction by distributing the load over the contact surface.

In addition to load variation, the effect of digging posture was investigated by varying the inclination angle of the bucket. The arm–bucket assembly was rotated such that the bottom surface of the bucket made inclination angles of 0°, 15°, 30°, 45°, and 60° with respect to the global X-axis. These angles represent different excavation postures ranging from near-horizontal cutting to deep penetration. For each inclination angle, all five pressure loading cases were analysed, resulting in a total of twenty-five load–angle combinations.





(c) (d) (e)

Fig. 3 - Schematic representation of distributed pressure loading applied on the bucket bottom surface and the bucket inclination angles (a) 0^0 (b) 15^0 (c) 30^0 (d) 45^0 (b) 60^0 defined with respect to the global X-axis.

Finite Element Discretization

The finite element model was discretized using three-dimensional solid elements. A tetrahedral mesh was employed due to the complex geometry of the arm–bucket assembly. Mesh refinement was applied in critical regions such as the fixed stick end, bucket–arm joint, and bucket tooth region, where high stress gradients were expected. A mesh convergence study was performed to ensure that further mesh refinement did not produce significant changes in deformation or stress results. The final mesh provided a balance between computational efficiency and solution accuracy.

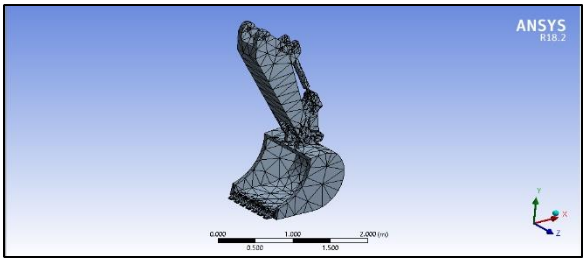


Fig. 4 - Finite element discretization of the excavator arm–bucket assembly showing mesh refinement in critical regions such as the fixed stick end and the bucket–arm joint.

Solution Procedure and Output Parameters

A static structural analysis was carried out for each loading and inclination condition using ANSYS Workbench 18.2. The solver computed the structural response assuming linear elastic behaviour. The primary output parameters evaluated were total deformation and maximum shear stress. Total deformation was used to assess the overall stiffness and serviceability of the excavator arm, while maximum shear stress was evaluated based on the Tresca failure criterion, which is suitable for ductile materials subjected to combined bending and shear loads.

For each simulation case, the maximum values of deformation and shear stress were extracted and tabulated. Stress and deformation contour plots were also recorded to identify critical regions and understand load transfer characteristics. The results were systematically compared to examine the influence of pressure magnitude and bucket inclination angle on the structural behaviour of the excavator arm.

RESULTS AND DISCUSSION

This section presents and discusses the structural response of the excavator arm under varying digging pressure and bucket inclination conditions obtained from finite element analysis. The results are analysed in terms of total deformation and maximum shear stress, which represent the serviceability and strength-related performance of the excavator arm, respectively. To clearly highlight parametric trends and critical operating conditions, the results are presented using graphical representations and contour plots rather than tabulated data.

The influence of digging pressure is investigated by varying the applied distributed load from 100 kPa to 500 kPa, while the effect of excavation posture is examined by changing the bucket inclination angle from 0° to 60°. These parameters are selected to simulate a wide range of realistic excavation scenarios encountered during field operation. For each load–angle combination, the resulting deformation and stress distributions are examined to understand the load transfer mechanism and identify regions susceptible to high structural demand.

The discussion focuses on identifying systematic trends, comparing the relative sensitivity of deformation and shear stress to changes in loading and inclination, and determining the most critical excavation condition. Special attention is given to the correlation between pressure magnitude and inclination angle, as their combined effect governs the severity of bending and shear in the excavator arm. The critical operating condition is identified based on the combined assessment of maximum deformation and maximum shear stress. The findings provide insight into the influence of digging posture and load severity on excavator arm behaviour and serve as a basis for safer design and operational guidelines.

Total Deformation Response of Excavator Arm

Total deformation is an important indicator of the structural stiffness and serviceability of the excavator arm during excavation. Excessive deformation can adversely affect digging accuracy, bucket control, and overall operational efficiency. In this study, the total deformation response of the excavator arm is evaluated to understand the influence of digging pressure and bucket inclination angle on global structural behaviour. The deformation patterns are analysed for different excavation conditions to identify trends, critical postures, and regions experiencing maximum displacement. The results provide insight into how variations in load severity and digging posture affect the overall flexibility of the excavator arm.

Effect of Digging Pressure on Total Deformation

The influence of digging pressure on the total deformation of the excavator arm is investigated by varying the applied distributed pressure from 100 kPa to 500 kPa for all bucket inclination angles considered in the study. This analysis aims to evaluate the serviceability response of the excavator arm under increasing soil resistance conditions and to identify deformation trends associated with load severity during excavation.

At the lowest pressure level of 100 kPa, the total deformation of the excavator arm remains relatively small for all inclination angles, with values ranging between approximately 7.68 mm and 7.79 mm. These low deformation values indicate adequate structural stiffness under light digging conditions, such as excavation in loose or soft soil. As the applied pressure increases to 200 kPa, deformation values rise to the range of 15.40 mm to 16.59 mm, showing a noticeable but proportional increase in displacement. This trend continues consistently for higher pressure levels.

For an applied pressure of 300 kPa, the total deformation increases further, reaching values between 23.03 mm and 23.38 mm across the different inclination angles. At 400 kPa, deformation values rise to the range of 30.71 mm to 31.17 mm, indicating increased bending of the excavator arm under higher soil resistance. Finally, at the maximum pressure of 500 kPa, the total deformation reaches its highest levels, varying between 38.39 mm and 38.97 mm, depending on the bucket inclination angle. The maximum deformation of approximately 38.97 mm is observed at this pressure level, confirming it as the most severe loading condition from a serviceability standpoint.

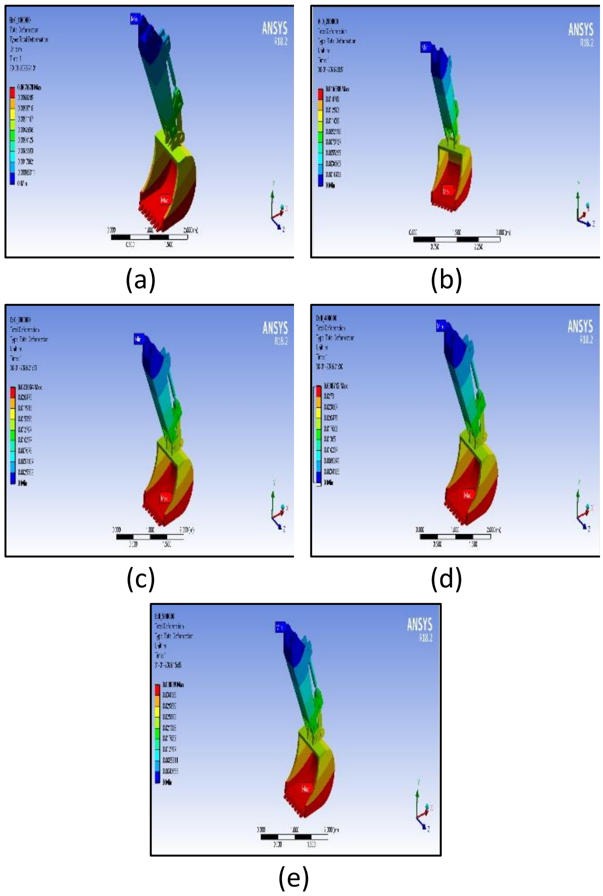


Fig. 5 - Total Deformation with varying load at inclination of 0^0 angle

The progressive increase in deformation with pressure demonstrates a near-linear relationship between applied load and structural response, which is characteristic of elastic behaviour in ductile steel structures. This linearity indicates that the excavator arm remains within the elastic range throughout the investigated loading spectrum and does not exhibit any sudden stiffness degradation or instability. The deformation contours further reveal that maximum displacement consistently occurs near the bucket tip, while minimal deformation is observed at the fixed stick end due to the applied boundary condition.

Although minor variations in deformation are observed between different inclination angles at a given pressure level, the overall trend clearly shows that digging pressure is the dominant parameter governing total deformation. The relatively narrow deformation spread at each pressure level suggests that global stiffness is primarily influenced

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by load magnitude rather than excavation posture when deformation alone is considered.

From an operational perspective, these results highlight that increasing soil resistance significantly affects the flexibility of the excavator arm, which may influence digging accuracy and bucket positioning. Therefore, evaluating deformation under different pressure levels is essential for ensuring acceptable serviceability performance and maintaining precise excavation control under demanding working conditions.

Effect of Bucket Inclination Angle on Total Deformation

The effect of bucket inclination angle on the total deformation of the excavator arm is analysed by varying the inclination from 0° to 60° for all applied digging pressure levels ranging from 100 kPa to 500 kPa. This analysis is carried out to understand how excavation posture influences the global deformation behaviour of the excavator arm under different load severities.

At a pressure level of 100 kPa, the total deformation varies marginally with inclination angle, ranging from 7.678 mm at 0° to 7.7936 mm at 30°, after which it slightly reduces to 7.7122 mm at 60°. This indicates that under light digging conditions, the effect of inclination angle on deformation is minimal, and the excavator arm maintains adequate stiffness across all postures.

A similar trend is observed at 200 kPa, where deformation values range between 15.402 mm and 16.588 mm. The maximum deformation at this pressure level occurs at 0° inclination (16.588 mm), while relatively lower deformation values are recorded at higher angles. Although the variation is small, it indicates a mild sensitivity of deformation to excavation posture as load increases.

For a pressure of 300 kPa, the total deformation increases to the range of 23.034 mm to 23.381 mm, with the maximum deformation again observed at 30° inclination (23.381 mm). At 400 kPa, deformation values vary from 30.712 mm to 31.174 mm, and at 500 kPa, they range from 38.39 mm to 38.968 mm. In both cases, the maximum deformation consistently occurs at 30° inclination, indicating that this posture produces the most severe bending condition in the excavator arm.

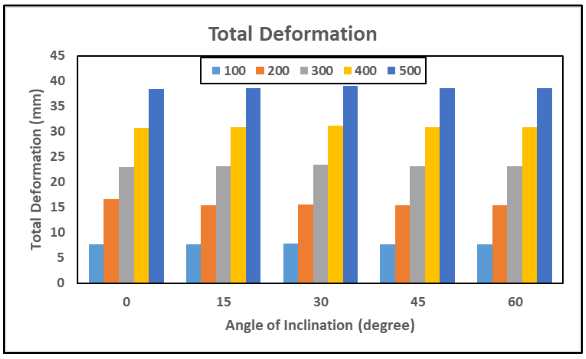


Fig. 6 - Effect of Angle of Inclination on Total Deformation

Across all pressure levels, the variation in deformation with inclination angle remains relatively small compared to the overall increase caused by pressure magnitude. However, the consistent occurrence of peak deformation around 30° inclination suggests that this angle aligns the digging force in a manner that maximizes bending moment in the arm. At higher inclination angles beyond 30°, a slight reduction in deformation is observed, which can be attributed to changes in the load transfer path and effective lever arm length.

The deformation contours corresponding to different inclination angles reveal that maximum displacement consistently occurs at the bucket tip, while the fixed stick end remains largely undeformed. This confirms that changes in inclination primarily influence the bending behaviour of the arm rather than altering the deformation pattern itself.

From a practical standpoint, these results indicate that while bucket inclination has a secondary influence on total deformation compared to digging pressure, certain excavation postures particularly around 30° inclination can lead to slightly higher structural deflection. Identifying such critical postures is important for ensuring serviceability and maintaining precise bucket control during excavation operations.

Maximum Shear Stress Response of Excavator Arm

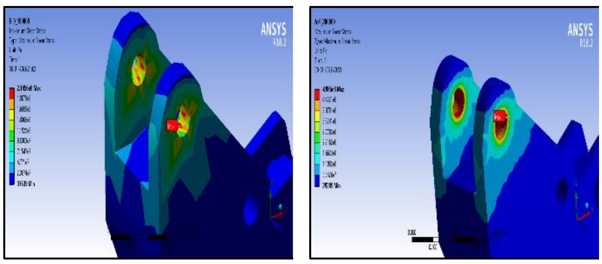
Maximum shear stress is a critical parameter for evaluating the strength and failure resistance of ductile structural components such as excavator arms, which are subjected to combined bending and shear during excavation. In the present study, maximum shear stress is evaluated based on the Tresca failure criterion to assess the structural safety of the excavator arm under varying digging pressure and bucket inclination conditions. The stress response is analysed to understand the influence of load severity and excavation posture on stress distribution and concentration. The results are used to identify critical loading configurations and regions susceptible to high shear demand, thereby providing insight into the structural integrity of the excavator arm during excavation operations.

Effect of Digging Pressure on Maximum Shear Stress

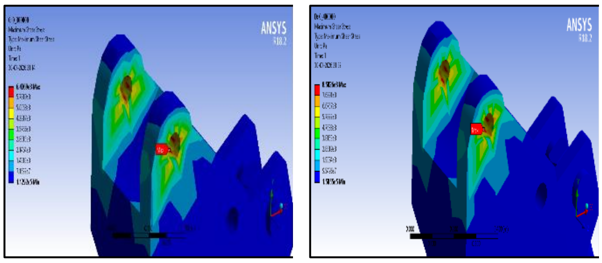
The effect of digging pressure on the maximum shear stress of the excavator arm is examined by increasing the applied distributed pressure from 100 kPa to 500 kPa for all bucket inclination angles considered in the study. This analysis aims to evaluate the strength-related structural response of the excavator arm under progressively severe excavation conditions and to identify stress trends associated with increasing soil resistance.

At the lowest pressure level of 100 kPa, the maximum shear stress values range from approximately 2.15×10^8 Pa to 2.87×10^8 Pa across different inclination angles. These relatively low stress levels indicate that the excavator arm experiences moderate shear demand under light digging conditions. As the applied pressure increases to 200 kPa, a significant rise in shear stress is observed, with values ranging between 4.38×10^8 Pa and 5.73×10^8 Pa, reflecting increased load transfer through the arm–bucket assembly.

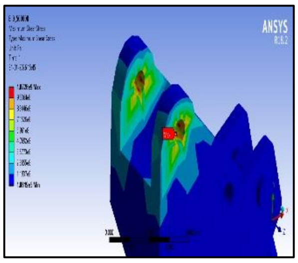
For a pressure of 300 kPa, the maximum shear stress further increases to values between 6.35×10^8 Pa and 8.60×10^8 Pa, indicating a substantial escalation in shear demand as excavation severity increases. At 400 kPa, the shear stress values rise to the range of 8.58×10^8 Pa to 1.15×10^9 Pa, demonstrating the strong sensitivity of shear stress to applied digging pressure. Finally, at the maximum pressure level of 500 kPa, the excavator arm experiences the highest shear stress levels, varying from 1.07×10^9 Pa to 1.43×10^9 Pa, depending on the bucket inclination angle. The maximum observed shear stress of approximately 1.43×10^9 Pa occurs at this pressure level, confirming it as the most critical loading condition from a strength perspective.



(a) (b)



(c) (d)



(e)

Fig. 6 - Maximum Shear Stress with varying load at inclination of 0^0 angle

The progressive increase in maximum shear stress with applied pressure indicates a near-linear stress response characteristic of elastic behaviour in ductile steel structures. This proportional relationship suggests that the excavator arm remains structurally stable throughout the investigated pressure range, without exhibiting sudden stress amplification or numerical instability. The stress contours corresponding to higher pressure levels reveal pronounced stress concentration near the fixed stick end and the bucket–arm joint region, which are critical locations for structural integrity assessment.

Comparing shear stress variation due to pressure with that due to inclination angle, it is evident that digging pressure is the dominant parameter influencing maximum shear stress. While inclination angle affects stress magnitude at a given pressure level, the overall escalation in shear stress is primarily governed by the increase in applied pressure. This observation highlights the importance of controlling excavation load severity to limit excessive stress development in the excavator arm.

From an operational standpoint, these results emphasize that higher soil resistance conditions significantly increase shear demand in the excavator arm, which may accelerate material fatigue and structural degradation if repeatedly encountered. Therefore, understanding the relationship between digging pressure and shear stress is essential for ensuring structural safety and improving the durability of excavator arm components under demanding excavation conditions.

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Effect of Bucket Inclination Angle on Maximum Shear Stress

The influence of bucket inclination angle on the maximum shear stress of the excavator arm is analysed by varying the inclination from 0° to 60° for all applied digging pressure levels ranging from 100 kPa to 500 kPa. This investigation is essential for understanding how excavation posture affects stress distribution and identifying critical digging angles that may impose higher structural demand on the excavator arm.

At a digging pressure of 100 kPa, the maximum shear stress shows noticeable variation with inclination angle. The stress increases from 2.15×10^8 Pa at 0° to a peak value of 2.87×10^8 Pa at 30°, after which it decreases to 2.22×10^8 Pa at 60°. This trend indicates that even under light digging conditions, the bucket inclination angle influences shear stress development, with intermediate angles producing relatively higher stress levels.

A similar pattern is observed at a pressure of 200 kPa, where the maximum shear stress ranges between 4.38×10^8 Pa and 5.73×10^8 Pa. The highest stress at this pressure level occurs again at 30° inclination, confirming that this posture induces greater shear demand compared to lower and higher angles. At 300 kPa, the effect of inclination becomes more pronounced, with shear stress increasing from 6.35×10^8 Pa at 0° to 8.60×10^8 Pa at 30°, followed by a reduction to 6.67×10^8 Pa at 60°.

For higher pressure levels of 400 kPa and 500 kPa, the same trend persists. At 400 kPa, maximum shear stress reaches 1.15×10^9 Pa at 30°, compared to 8.58×10^8 Pa at 0° and 8.90×10^8 Pa at 60°. Similarly, at the maximum applied pressure of 500 kPa, the peak shear stress of 1.43×10^9 Pa is consistently observed at 30° inclination, while lower stress values of 1.07×10^9 Pa and 1.11×10^9 Pa are recorded at 0° and 60°, respectively. These results clearly identify 30° inclination as the most critical excavation posture across all loading conditions.

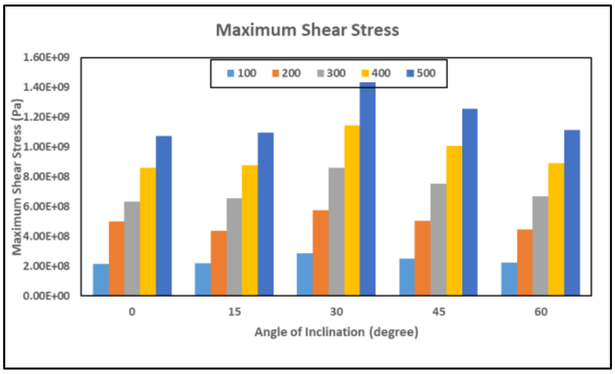

Fig. 7 - Effect of Angle of Inclination on Maximum shear Stress

The observed stress variation with inclination angle can be attributed to changes in the load transfer mechanism and bending shear interaction within the excavator arm. At intermediate inclination angles, particularly around 30°, the direction of the digging force aligns in a manner that maximizes bending moment and shear force simultaneously, leading to higher stress concentration. At higher inclination angles beyond 30°, a reduction in effective lever arm length and altered force orientation contribute to a decrease in shear stress.

From a structural safety perspective, these findings highlight that bucket inclination angle has a significant influence on maximum shear stress, especially under high digging pressure conditions. Identifying 30° inclination as the most critical posture is valuable for both design evaluation and operational planning, as repeated excavation at this angle under high load conditions may accelerate structural degradation. Therefore, careful consideration of excavation posture is essential for minimizing excessive shear stress and enhancing the durability of excavator arm components.

Identification of Critical Excavation Condition

The identification of the most critical excavation condition is essential for evaluating the structural safety and serviceability of the excavator arm. In the present study, the critical condition is determined based on a combined assessment of total deformation and maximum shear stress obtained under varying digging pressure and bucket inclination angles. Considering both parameters together provides a comprehensive understanding of structural performance, as deformation reflects serviceability behaviour while shear stress represents strength-related response.

From the deformation analysis, it is observed that total deformation increases steadily with digging pressure for all inclination angles, reaching its maximum value of approximately 38.97 mm at the highest applied pressure of 500 kPa. Although the variation of deformation with inclination angle is moderate, the maximum deformation consistently occurs at a bucket inclination of 30°, indicating that this posture induces the most severe bending condition in the excavator arm.

Similarly, the maximum shear stress analysis reveals a strong dependence on both digging pressure and bucket inclination angle. Shear stress increases significantly with pressure, with the highest values recorded at 500 kPa for all inclination angles. Among the investigated postures, the 30° inclination consistently produces the maximum shear stress across all pressure levels. The peak shear stress of approximately 1.43×10^9 Pa is observed at 500 kPa and 30° inclination, clearly identifying this load–angle combination as the most critical condition from a strength perspective.

The consistent identification of 30° bucket inclination as the critical posture in both deformation and shear stress analyses highlights the importance of excavation posture in governing structural demand. At this inclination, the applied digging load aligns in a manner that maximizes bending moment and shear force simultaneously, resulting in increased structural response. In contrast, lower and higher inclination angles exhibit comparatively reduced deformation and shear stress due to changes in load orientation and effective lever arm.

Based on the combined results, the excavation condition corresponding to 500 kPa digging pressure and 30° bucket inclination is identified as the most critical operating scenario for the excavator arm. This condition represents the worst-case structural demand within the investigated range and should therefore be considered during design evaluation, safety assessment, and operational planning to ensure reliable and durable excavator performance.

CONCLUSIONS

In the present study, a parametric finite element analysis was carried out to investigate the structural behaviour of an excavator arm under varying digging pressure and bucket inclination conditions. The analysis focused on evaluating total deformation and maximum shear stress as key performance indicators representing serviceability and strength-related response, respectively. The excavator arm–bucket assembly was analysed using ANSYS Workbench 18.2 under distributed pressure loading ranging from 100 kPa to 500 kPa and bucket inclination angles varying from 0° to 60°, thereby simulating a wide range of realistic excavation scenarios.

The results demonstrate that digging pressure has a dominant influence on the total deformation of the excavator arm. For all inclination angles, deformation increases consistently with increasing pressure, indicating near-linear elastic behaviour within the investigated loading range. The maximum deformation increases from approximately 7.7 mm at 100 kPa to about 39 mm at 500 kPa, confirming that higher soil resistance significantly affects the serviceability performance of the excavator arm. Deformation contours reveal that maximum displacement consistently occurs at the bucket tip, while the fixed stick end remains largely undeformed, validating the assumed cantilever-type structural behaviour.

Bucket inclination angle exhibits a comparatively moderate but systematic influence on total deformation. Although the variation in deformation across different angles is relatively small at a given pressure level, a consistent peak deformation is observed at approximately 30° inclination for higher pressure levels. This indicates that certain excavation postures can induce more severe bending conditions, even when load magnitude remains unchanged.

In contrast to deformation behavior, maximum shear stress is found to be highly sensitive to both digging pressure and bucket inclination angle. Shear stress increases significantly with pressure, reaching a maximum value of approximately 1.43×10^9 Pa at the highest-pressure level. Among all the investigated excavation postures, the 30° bucket inclination consistently produces the highest shear stress across all pressure levels. This behaviour is attributed to the combined effect of bending and shear resulting from the alignment of the digging load with the arm geometry at intermediate inclination angles.

The combined assessment of deformation and shear stress clearly identifies the excavation condition corresponding to 500 kPa digging pressure and 30° bucket inclination as the most critical operating scenario. This condition represents the worst-case structural demand within the studied parameter range and should therefore be carefully considered during design evaluation and operational planning. The findings of this study provide valuable insight into the influence of digging posture and load severity on excavator arm structural behaviour and can support safer design, improved durability, and informed operational guidelines for excavator systems.

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