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Numerical Investigation of Equivalent Elastic Strain and Shear Stress (XY) in an Excavator Arm under Variable Excavation Conditions

Ashish Makdey[1], Dr Sachin K Kamble[2], Dr. Usha C. Pawar[3]

[1]Student (Master of Engineering) Datta Meghe College of Engineering Airoli, Navi Mumbai, Maharashtra 400708.
[2]Professor and Head Design Department Terna Engineering college, Nerul, Navi Mumbai, Maharashtra 400706
[3]Professor & HOD Mechanical Engineering Department Datta Meghe College of Engineering Airoli, Navi Mumbai, Maharashtra 400708

Email- ashishmakdey@gmail.com

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Abstract – *Strain-based response parameters and directional stress components provide valuable insight into localized material behavior and potential damage initiation in structural components subjected to complex excavation loads. In the present study, a numerical investigation is carried out to evaluate the equivalent elastic strain and shear stress (XY) behavior of an excavator arm under variable excavation conditions. A three-dimensional finite element model of the excavator arm–bucket assembly is developed using ANSYS Workbench 18.2. To represent a conservative operating condition, the stick end of the arm is fully constrained. Excavation loads are simulated through distributed pressure applied on the bucket surface, with pressure magnitude varied from 100 kPa to 500 kPa to represent different levels of soil resistance. The effect of excavation posture is incorporated by varying the bucket inclination angle from 0° to 60°. The structural response is analyzed in terms of equivalent elastic strain to capture material-level deformation and shear stress (XY) to assess directional shear behavior. The results indicate that equivalent elastic strain increases progressively with digging pressure for all inclination angles, confirming elastic strain accumulation under increasing load severity. At the lowest pressure of 100 kPa, strain values range from approximately 1.96×10^{-3} to 2.65×10^{-3}, while at the highest pressure of 500 kPa, strain increases to values between 9.80×10^{-3} and 1.32×10^{-2}. Across all pressure levels, the maximum equivalent elastic strain consistently occurs at a bucket inclination of 30°, identifying this posture as critical from a strain localization perspective. In contrast, the shear stress (XY) response exhibits a different dependence on excavation posture. While shear stress (XY) increases significantly with pressure, reaching a maximum value of approximately 1.07×10^{9} Pa at 500 kPa, the highest stress levels are observed at higher inclination angles, particularly at 60°. This contrasting behavior highlights the importance of evaluating directional stress components alongside strain measures. The findings provide a complementary understanding of excavator arm behavior and contribute to improved assessment of damage-prone excavation conditions.*

Keywords- *Excavator arm; Equivalent elastic strain; Shear stress (XY); Finite element analysis; Excavation posture; Digging pressure*

INTRODUCTION

Excavator arms are critical structural components in earthmoving machinery, continuously subjected to complex loading during excavation operations. These loads arise from soil resistance, bucket orientation, and operational posture, resulting in combined bending, shear, and torsional effects. While the global structural response of excavator arms is commonly evaluated using deformation and strength-based stress parameters, such approaches may not fully capture the localized material behavior that governs damage initiation and long-term durability[1], [2].

Strain-based parameters provide a more detailed description of material-level deformation and are particularly useful for identifying regions susceptible to local yielding, crack initiation, and fatigue damage. Equivalent elastic strain, in particular, reflects the intensity of elastic deformation accumulated within the material and offers insight into strain localization under complex loading. Similarly, directional shear stress components, such as shear stress in the XY plane, enable assessment of stress redistribution along specific coordinate directions, which is not possible using scalar stress measures alone[3], [4].

During excavation, variations in digging pressure and bucket inclination significantly influence the direction and magnitude of load transfer through the arm–bucket assembly. Changes in excavation posture can alter the orientation of internal stress components and strain concentration zones, potentially leading to different damage mechanisms even under similar load magnitudes. Therefore, analyzing equivalent elastic strain and directional shear stress under variable excavation conditions is essential for developing a comprehensive understanding of excavator arm behavior[5].

In this context, the present study performs a numerical investigation of equivalent elastic strain and shear stress (XY) in an excavator arm under varying digging pressure and bucket inclination conditions using finite element analysis. The study aims to provide insight into material-level deformation patterns and directional stress behavior that are not evident from global deformation or scalar stress analysis[6], [7].

Finite element analysis has been widely employed to study the structural behavior of excavator components, including booms, sticks, and buckets. Numerous studies have focused on evaluating deformation, von Mises stress, and factor of safety under static and dynamic excavation loads. These investigations have contributed significantly to understanding global stiffness characteristics, stress concentration regions, and overall structural integrity of excavator arms under typical operating conditions[8], [9].

Several researchers have examined the influence of digging forces, hydraulic cylinder loads, and joint constraints on excavator arm performance. Results from these studies indicate that maximum stresses and deformations generally occur near the boom–stick joint, bucket–arm connection, and other highly constrained regions[10]. Parametric investigations involving variations in load magnitude or excavation posture have shown that operational conditions strongly affect structural response. However, most existing studies primarily rely on scalar stress measures and global deformation metrics[11].

Strain-based analysis of excavator structures has received comparatively limited attention. Equivalent elastic strain has been widely used in other mechanical and structural applications to identify strain localization, assess elastic energy distribution, and predict regions prone to damage initiation. In the context of heavy machinery, strain-based evaluation can offer enhanced insight into local material behavior, especially under repetitive or high-load excavation cycles[12].

Similarly, directional shear stress components have been used in structural mechanics to understand load transfer mechanisms and coordinate-dependent stress behavior. Shear stress components such as τ_{xy} are particularly relevant in structures subjected to non-uniform loading and complex geometries, where stress orientation plays a crucial role in failure mechanisms. Despite their importance, directional shear stresses have rarely been explored in excavator arm analysis, with most studies focusing on equivalent or maximum shear stress values[13].

The literature thus indicates a clear gap in systematic investigations that combine equivalent elastic strain and directional shear stress analysis for excavator arms under variable excavation conditions.

From the literature survey, it is evident that while the global structural response of excavator arms has been extensively studied, limited attention has been given to strain localization and directional stress behavior under realistic excavation conditions. Deformation- and strength-based assessments alone may not adequately capture the material-level response that governs damage initiation and long-term structural performance[14].

The primary motivation of the present work is to address this gap by focusing on equivalent elastic strain and shear stress (XY) as key response parameters for evaluating excavator arm behavior. By analyzing these parameters under varying digging pressure and bucket inclination angles, the study aims to reveal how excavation posture influences strain accumulation and directional stress redistribution within the arm structure.

The scope of this study includes a parametric finite element analysis of an excavator arm–bucket assembly

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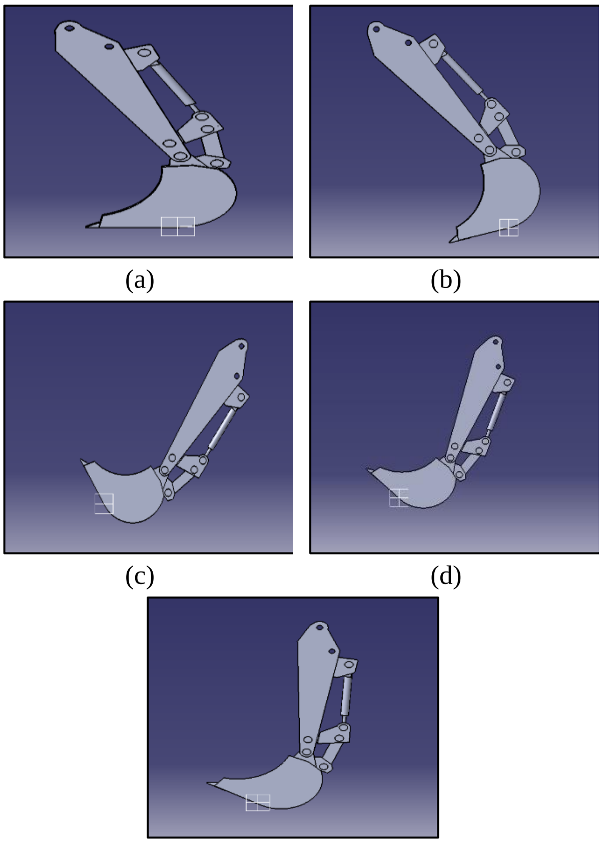
subjected to distributed excavation loads representing different soil resistance levels. The investigation systematically evaluates the influence of pressure magnitude and bucket inclination on strain localization patterns and shear stress (XY) distribution. The outcomes of this study are expected to complement conventional deformation- and stress-based analyses and provide deeper insight into damage-prone excavation conditions. Such understanding can support improved structural assessment, safer operation, and enhanced durability of excavator arm components.

METHODOLOGY

Finite Element Model Description

A three-dimensional finite element model of the excavator arm–bucket assembly was developed to investigate strain localization and directional shear stress behavior under excavation loading. The geometric model represents the structural configuration of the stick and bucket during excavation, with sufficient geometric detail retained in regions critical to load transfer, such as the stick end and bucket connection. Non-structural features that do not significantly influence strain or stress distribution were omitted to improve computational efficiency. The model was created and analyzed using ANSYS Workbench 18.2.



(a) (b) (c) (d) (e)

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 Modelling

The excavator arm and bucket were assumed to be manufactured from structural steel, which is widely used in heavy earthmoving equipment due to its ductility and load-carrying capability. The material was modelled as homogeneous, isotropic, and linearly elastic to enable clear interpretation of elastic strain behavior. The material properties considered in the analysis include a Young's modulus of 210 GPa and a Poisson's ratio of 0.3. Since the present investigation focuses on elastic strain accumulation and stress redistribution under static loading, plasticity and damage models were not included.

Boundary Conditions

To ensure conservative estimation of strain and stress response, 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 excavator arm and the boom. This assumption eliminates joint compliance and ensures that strain localization and stress concentration effects are not underestimated. The bucket–arm interface was left free to allow realistic transmission of excavation loads through the structure.

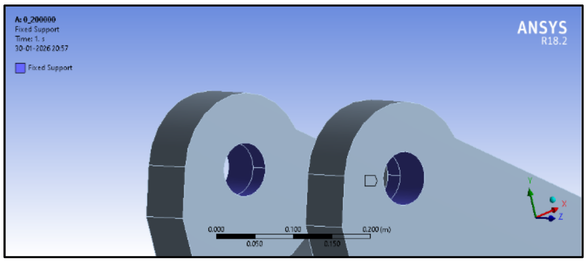


Fig. 2- Three-dimensional geometric model of the excavator arm–bucket assembly showing the fixed boundary condition applied at the stick end.

Loading and Excavation Conditions

Excavation loading was simulated by applying a distributed pressure on the bottom surface of the bucket to represent soil resistance encountered during digging. The pressure magnitude was varied from 100 kPa to 500 kPa in increments of 100 kPa, covering a wide range of excavation severity from light to heavy digging conditions. The use of pressure loading allows the load to

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be distributed over the contact surface, providing a realistic representation of soil–bucket interaction.

To investigate the effect of excavation posture, the bucket inclination angle was varied systematically. The arm–bucket assembly was oriented such that the bottom surface of the bucket made angles of 0°, 15°, 30°, 45°, and 60° with respect to the global X-axis. These inclination angles represent different excavation postures encountered during practical operation. For each pressure level, all five inclination angles were analyzed, resulting in a total of twenty-five load–posture combinations.

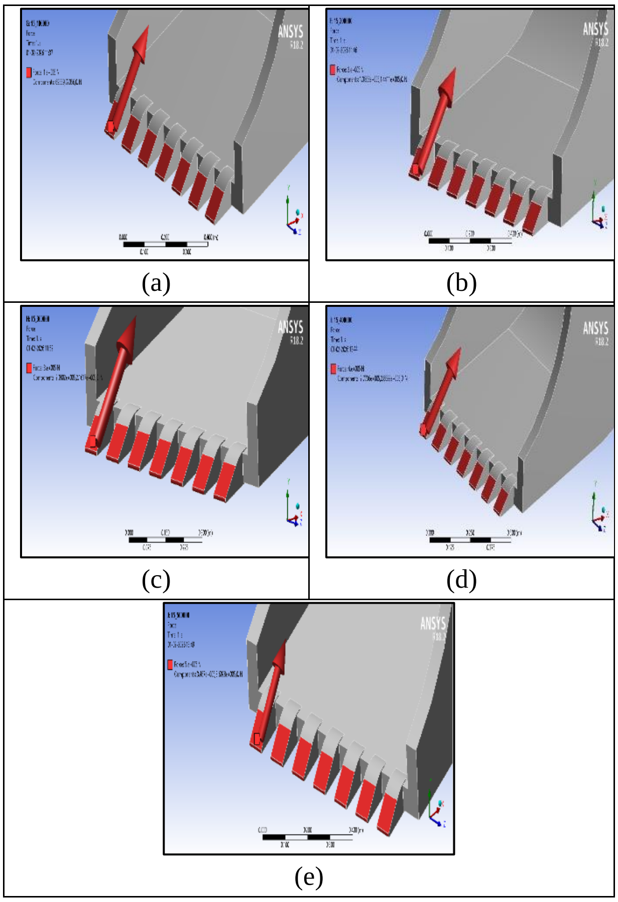


Fig. 3- Schematic representation of distributed pressure loading applied on the bucket bottom surface and the bucket inclination angles (a) 0^0 (b) 15^0 (c) 30^0 (d) 45^0 (b) 60^0 defined with respect to the global X-axis.

Finite Element Discretization

The finite element model was discretized using three-dimensional solid elements. A tetrahedral meshing scheme was adopted due to the geometric complexity of the excavator arm–bucket assembly. Mesh refinement was applied in regions where strain localization and stress concentration were expected, particularly near the fixed stick end and the bucket–arm connection. Mesh convergence was ensured by verifying that further mesh refinement produced negligible variation in equivalent elastic strain and shear stress (XY) results.

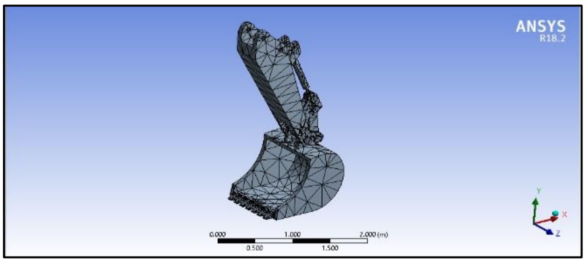


Fig. 4- Finite element discretization of the excavator arm–bucket assembly showing mesh refinement in critical regions such as the fixed stick end and the bucket–arm joint.

Solution Procedure and Output Parameters

A static structural analysis was performed for each loading and inclination case. The primary output parameters evaluated were equivalent elastic strain and shear stress (XY). Equivalent elastic strain was selected to assess material-level deformation and identify zones of strain concentration that may be prone to damage initiation. Shear stress in the XY plane was extracted to evaluate directional stress redistribution associated with excavation posture and load orientation.

For each simulation case, peak values of equivalent elastic strain and shear stress (XY) were extracted and analyzed. Contour plots were examined to identify strain localization zones and critical stress paths. The results were compared across different pressure levels and inclination angles to determine critical excavation conditions from a strain- and directional stress-based perspective.

RESULTS AND DISCUSSION

This section presents and discusses the numerical results obtained from the finite element analysis of the excavator arm under variable excavation conditions. The structural response is evaluated in terms of equivalent elastic strain and shear stress (XY), which provide insight into material-level deformation and directional stress redistribution within the excavator arm. Unlike global deformation or scalar stress measures, these parameters enable the identification of strain localization zones and orientation-dependent shear behavior that are critical for understanding damage initiation mechanisms.

The results are analyzed by systematically varying the digging pressure from 100 kPa to 500 kPa and the bucket inclination angle from 0° to 60°, representing a wide range of realistic excavation scenarios. For each load–posture combination, the distribution and magnitude of equivalent elastic strain and shear stress (XY) are examined to assess the influence of excavation severity and posture on localized structural response. The discussion focuses on identifying dominant trends, comparing the sensitivity of strain and directional shear stress to changes in pressure and inclination, and determining critical excavation conditions based on material-level response. The findings provide a complementary perspective to conventional strength- and deformation-based analyses and contribute to a more comprehensive assessment of excavator arm behavior during excavation operations.

Equivalent Elastic Strain Response

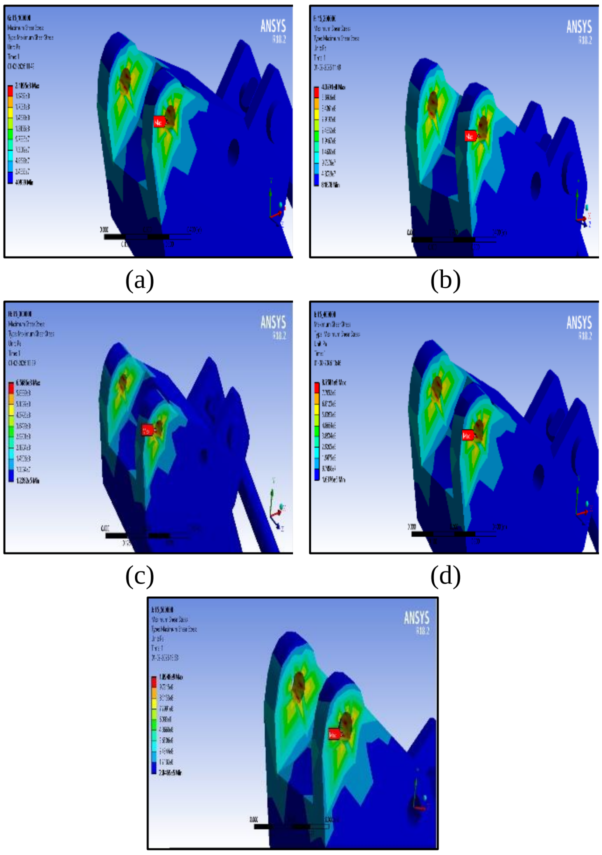
Equivalent elastic strain is evaluated to understand material-level deformation and strain localization in the excavator arm under variable excavation conditions. Unlike global deformation, equivalent elastic strain provides insight into how elastic deformation is distributed within the structure and helps identify regions where damage initiation may occur under repeated or severe loading. The strain response is analyzed by examining the effects of digging pressure and bucket inclination angle.

Effect of Digging Pressure on Equivalent Elastic Strain

The influence of digging pressure on equivalent elastic strain is investigated by increasing the applied distributed pressure from 100 kPa to 500 kPa for all bucket inclination angles considered in the study. The results show a clear and systematic increase in equivalent elastic strain with increasing pressure, indicating progressive elastic strain accumulation within the excavator arm as excavation severity increases.

At the lowest pressure level of 100 kPa, equivalent elastic strain values remain relatively low, ranging between approximately 1.96×10^{-3} and 2.65×10^{-3}, depending on the bucket inclination angle. These values suggest minimal elastic deformation at the material level under light digging conditions. When the pressure is increased to 200 kPa, strain values rise to the range of 3.92×10^{-3} to 5.30×10^{-3}, reflecting a noticeable increase in elastic strain due to higher soil resistance.

For an applied pressure of 300 kPa, equivalent elastic strain further increases, reaching values between 5.88×10^{-3} and 7.95×10^{-3}. This trend continues at 400 kPa, where strain values range from 7.84×10^{-3} to 1.06×10^{-2}, indicating substantial elastic strain development within the arm structure. At the maximum pressure level of 500 kPa, the highest strain values are observed, varying from 9.80×10^{-3} to 1.32×10^{-2}, confirming that severe excavation conditions significantly intensify material-level deformation.



(a) (b) (c) (d) (e)

Fig. 5- Equivalent Elastic Strain with varying load at inclination of 15^0 angle

The consistent and near-proportional increase in equivalent elastic strain with pressure across all inclination angles indicates elastic structural behaviour within the investigated loading range. No abrupt strain amplification or irregular trend is observed, suggesting numerical stability and absence of localised elastic instability. The strain contours reveal that strain concentration predominantly occurs near the fixed stick end and the bucket–arm connection region, where load transfer and constraint effects are most significant.

From a structural performance perspective, these results highlight that digging pressure is a primary factor governing elastic strain accumulation in the excavator arm. Increased soil resistance directly elevates material-level deformation, which may contribute to damage initiation under repeated loading cycles. Therefore, controlling excavation load severity is essential for limiting excessive strain accumulation and improving the long-term durability of excavator arm components.

Effect of Bucket Inclination Angle on Equivalent Elastic Strain

The effect of bucket inclination angle on equivalent elastic strain is analyzed by varying the inclination from 0° to 60° for all pressure levels. At a given pressure, the strain response shows a clear dependence on excavation posture, with intermediate inclination angles producing higher strain levels than extreme angles.

At 100 kPa, equivalent elastic strain increases from 2.01×10^{-3} at 0° to a maximum of 2.65×10^{-3} at 30°, after which it decreases to 1.96×10^{-3} at 60°. A similar trend is observed at 200 kPa, where strain values peak at 5.30×10^{-3} for 30° inclination, compared to lower values at 0° and 60°. As pressure increases to 300 kPa, 400 kPa, and 500 kPa, the same behavior persists, with maximum strain values of 7.95×10^{-3}, 1.06×10^{-2}, and 1.32×10^{-2}, respectively, consistently occurring at 30° inclination.

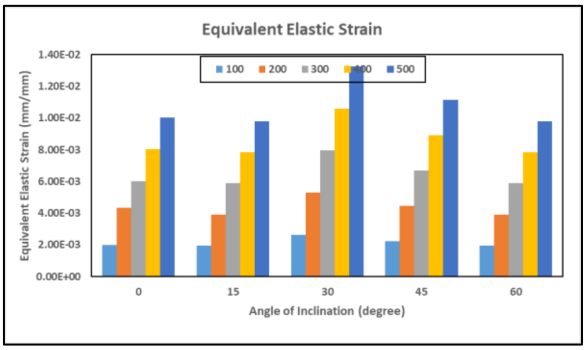


Fig. 6- Effect of Angle of Inclination on Equivalent Elastic Strain

The repeated occurrence of peak equivalent elastic strain at 30° indicates that this excavation posture induces the most severe strain localization within the excavator arm. At this inclination, the orientation of the digging load relative to the arm geometry promotes higher bending and shear interaction, leading to increased elastic strain concentration. At higher inclination angles beyond 30°, a reduction in strain is observed, which can be attributed to changes in load orientation and a reduction in effective bending contribution.

These results demonstrate that bucket inclination angle plays a significant role in governing strain localisation, even when the applied pressure remains constant. Identifying 30° inclination as the strain-critical posture is important from a damage initiation perspective, as repeated operation under this condition may accelerate material degradation. Consequently, strain-based assessment provides valuable insight into excavation postures that may not be identified as critical through global deformation or scalar stress analysis alone.

Shear Stress (XY) Response

Shear stress in the XY plane is evaluated to examine the directional stress behavior of the excavator arm under variable excavation conditions. Unlike scalar stress measures, shear stress (XY) provides insight into orientation-dependent stress redistribution arising from excavation posture and load direction. Analyzing this stress component is important for understanding how excavation conditions influence internal stress paths and identifying postures that may lead to elevated directional shear demand.

Effect of Digging Pressure on Shear Stress (XY)

The effect of digging pressure on shear stress (XY) is investigated by increasing the applied distributed pressure from 100 kPa to 500 kPa for all bucket inclination angles considered in the study. The results indicate a pronounced increase in shear stress (XY) with increasing pressure, highlighting the strong dependence of directional shear response on excavation load severity.

At the lowest pressure level of 100 kPa, shear stress (XY) values range between approximately 1.65×10^{8} Pa and 2.14×10^{8} Pa, depending on the bucket inclination angle. These values represent relatively low directional shear demand under light digging conditions. As the pressure increases to 200 kPa, shear stress (XY) increases significantly, with values ranging from 3.29×10^{8} Pa to 4.88×10^{8} Pa, indicating enhanced stress transfer within the excavator arm due to increased soil resistance.

For a pressure of 300 kPa, shear stress (XY) further increases to values between 4.94×10^{8} Pa and 6.43×10^{8} Pa. This trend continues at 400 kPa, where shear stress (XY) ranges from 6.58×10^{8} Pa to 8.58×10^{8} Pa, and reaches its highest levels at 500 kPa, varying between 8.23×10^{8} Pa and 1.07×10^{9} Pa. The maximum shear

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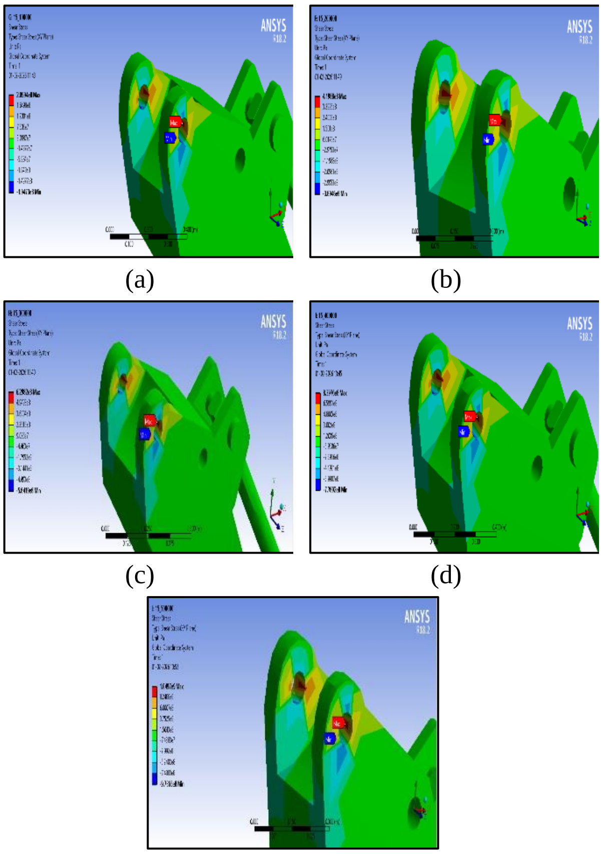
stress (XY) observed across all cases occurs at the highest pressure level, confirming that excavation load magnitude is a dominant factor governing directional shear response.



(a) (b) (c) (d) (e)

Fig. 7- Shear Stress (XY) with varying load at inclination of 0^0 angle

The near-monotonic increase in shear stress (XY) with pressure indicates stable elastic behavior and consistent stress scaling under increasing load severity. Stress contour plots reveal that higher pressure levels lead to more pronounced shear stress concentration near the fixed stick end and along the load transfer path between the bucket and arm. These regions are therefore critical from the perspective of directional stress accumulation under heavy excavation loads.

Effect of Bucket Inclination Angle on Shear Stress (XY)

The influence of bucket inclination angle on shear stress (XY) is analyzed by varying the inclination from 0° to 60° for each pressure level. Unlike equivalent elastic strain, which exhibits maximum values at intermediate angles, shear stress (XY) demonstrates a different sensitivity to excavation posture.

At 100 kPa, shear stress (XY) increases from 1.97 × 10^8 Pa at 0° to 2.14 × 10^8 Pa at 60°, with lower values observed at intermediate angles. A similar trend is observed at 200 kPa, where shear stress (XY) increases from 4.88 × 10^8 Pa at 0° to 4.29 × 10^8 Pa at 60°, while the minimum value of 3.29 × 10^8 Pa occurs at 30° inclination. This behavior persists at higher pressure levels.

At 300 kPa, shear stress (XY) reaches 6.43 × 10^8 Pa at 60°, compared to 4.94 × 10^8 Pa at 30°. At 400 kPa, the maximum shear stress (XY) of 8.58 × 10^8 Pa again occurs at 60° inclination, and at 500 kPa, the peak value of 1.07 × 10^9 Pa is recorded at 60°, clearly identifying this posture as critical from a directional shear stress perspective.

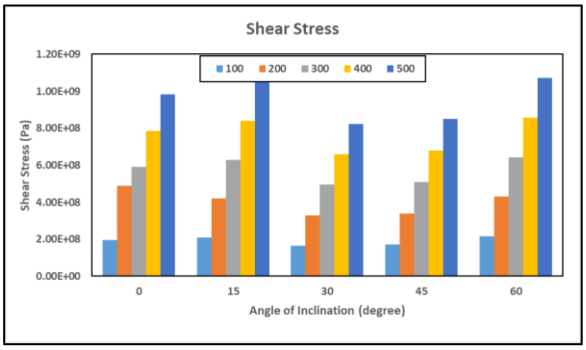


Fig. 8- Effect of Angle of Inclination on Shear Stress

The observed increase in shear stress (XY) at higher inclination angles can be attributed to the orientation of the excavation load relative to the global coordinate system. As the bucket inclination increases, the component of load contributing to shear in the XY plane becomes more significant, leading to higher directional shear stress. This behavior contrasts with equivalent elastic strain trends and demonstrates that different response parameters may identify different critical excavation postures.

From a structural assessment standpoint, these results highlight the importance of evaluating directional shear stress components alongside strain measures. While intermediate inclination angles may be critical for strain localization, higher inclination angles such as 60° can govern directional shear stress demand. Therefore, a combined strain- and directional stress-based evaluation provides a more comprehensive understanding of excavator arm behavior under excavation loading.

Strain–Stress Interaction and Identification of Critical Excavation Conditions

A combined evaluation of equivalent elastic strain and shear stress (XY) is essential for identifying critical excavation conditions, as these parameters represent different aspects of structural response at the material level. While equivalent elastic strain highlights zones of strain localization associated with damage initiation, shear stress (XY) reflects orientation-dependent stress redistribution influenced by excavation posture. Analyzing the interaction between these parameters provides a more comprehensive assessment of excavator arm behavior under variable excavation conditions.

The results demonstrate that equivalent elastic strain and shear stress (XY) exhibit different sensitivities to bucket inclination angle, even under identical loading conditions. Equivalent elastic strain increases consistently with digging pressure and reaches its maximum value of approximately 1.32×10^{-2} at the highest pressure level of 500 kPa. Across all pressure levels, the maximum strain consistently occurs at a bucket inclination of 30°, indicating that this posture induces the most severe strain localization within the excavator arm. This behavior suggests that intermediate excavation postures promote a combination of bending and shear that intensifies elastic strain accumulation at critical regions such as the fixed stick end and bucket–arm joint.

In contrast, shear stress (XY) exhibits a different posture-dependent trend. Although shear stress (XY) also increases with digging pressure, its maximum values are observed at higher inclination angles. At the maximum pressure level of 500 kPa, shear stress (XY) reaches approximately 1.07×10^{9} Pa at a bucket inclination of 60°, which is significantly higher than the corresponding value at 30°. This indicates that higher inclination angles generate greater directional shear components in the XY plane due to changes in load orientation relative to the global coordinate system.

The contrasting critical postures identified by strain and directional shear stress highlight the importance of multi-parameter evaluation in excavator arm analysis. While 30° inclination is identified as critical from a strain localisation perspective and may govern damage initiation under repeated loading, 60° inclination emerges as critical from a directional shear stress standpoint and may govern stress redistribution and potential shear-driven failure mechanisms. These findings demonstrate that reliance on a single response parameter may lead to incomplete assessment of structural risk.

Based on the combined analysis, excavation conditions involving high digging pressure combined with intermediate inclination angles are most critical for strain-based performance, whereas high digging pressure combined with steep inclination angles governs directional shear stress demand. Therefore, excavation at 500 kPa pressure represents the most severe loading condition, with 30° inclination being strain-critical and 60° inclination being shear stress (XY)-critical. This distinction provides valuable insight for design evaluation and operational planning, emphasizing the need to consider both strain localization and directional stress behavior for comprehensive assessment of excavator arm performance under excavation loading.

CONCLUSIONS

In this study, a numerical investigation was carried out to evaluate the equivalent elastic strain and shear stress (XY) response of an excavator arm under variable excavation conditions. A three-dimensional finite element model of the arm–bucket assembly was analyzed using ANSYS Workbench 18.2, considering distributed excavation pressure and multiple bucket inclination angles to simulate realistic digging scenarios. The study emphasized strain-based and directional stress assessment to provide insight into material-level deformation and stress redistribution that cannot be fully captured through global deformation or scalar stress measures.

The results show that equivalent elastic strain increases progressively with digging pressure for all excavation postures, indicating systematic elastic strain accumulation as soil resistance increases. At the lowest pressure level of 100 kPa, strain values remain below 2.65×10^{-3}, while at the highest pressure of 500 kPa, equivalent elastic strain increases to a maximum value of approximately 1.32×10^{-2}. This behavior confirms stable elastic response within the investigated loading range and highlights the strong influence of pressure magnitude on material-level deformation of the excavator arm.

Bucket inclination angle is found to have a significant effect on strain localization. Across all pressure levels, the maximum equivalent elastic strain consistently occurs at a bucket inclination of 30°, identifying this posture as critical from a strain-based perspective. The elevated strain at intermediate inclination angles is attributed to the combined bending and shear effects arising from the alignment of excavation load with the arm geometry. This finding suggests that repeated excavation at this posture may accelerate damage initiation and material degradation.

The shear stress (XY) response exhibits a contrasting dependence on excavation posture. While shear stress (XY) increases substantially with digging pressure, its maximum values are consistently observed at higher inclination angles. At the maximum pressure of 500 kPa, the peak shear stress (XY) of approximately 1.07×10^9 Pa occurs at a bucket inclination of 60°, indicating that steep excavation postures generate higher directional shear demand. This behavior highlights the importance of evaluating directional stress components, as they may govern stress redistribution and shear-driven failure mechanisms.

The combined assessment of equivalent elastic strain and shear stress (XY) demonstrates that different excavation postures govern different aspects of structural response. Intermediate inclination angles are critical for strain localization, while higher inclination angles control directional shear stress demand. These findings underline the necessity of multi-parameter evaluation for comprehensive assessment of excavator arm performance. The outcomes of this study provide valuable insight for design evaluation, durability assessment, and operational planning, and contribute to a more complete understanding of excavator arm behaviour under excavation loading.

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