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Analysis of the effectiveness of structural reinforcement in complex mechanical systems for ensuring reliability and structural integrity

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Abstract **- In modern construction, mechanical systems and machinery are crucial for projects like urban planning, road and railway construction, and utility installation. The designing of hydraulic excavators must address a variety of challenges, including working under extreme conditions, ensuring reliability and durability, and managing the weight and cost of the machinery. It is essential to balance these factors to design machines that are not only strong but also efficient and cost-effective. For assessing the strength and behavior of complex mechanical structures, such as hydraulic excavators, under stress, in this paper finite element analysis is implemented. Welded joints, while essential for providing structural integrity, can introduce weaknesses due to potential imperfections in the welding process. As a result, structural reinforcement is considered in the analysis, to improve durability and prevent failure. Through simulation, the analysis helps understand how different parts of the machine respond to forces, including those acting on welded joints. Since it takes into account factors such as material properties, welding quality, reinforcement placement, and stress distribution, the paper contributes towards ensuring that the mechanical system and structures are both efficient and durable.**

Keywords**- Mechanical Systems, Machinery, Hydraulic Excavator, Structural Integrity, FEA**

I. INTRODUCTION

In the existing construction sector, the integration of machinery is essential, even for the most basic projects. Modern urban development, infrastructure construction such as roads, railways, and utilities like water, sewage, and electricity networks, and the extraction of mineral resources are all heavily dependent on the use of various machines. To assess the level of mechanization in building construction projects, a computer-based tool can help assess mechanization levels, and also to gather expert opinions to improve and guide the process [1]. Consequently, a comprehensive understanding of the operation and functionality of these machines has become increasingly crucial. Among these, hydraulic excavators are essential in modern engineering applications. A thorough understanding of their mechanical systems, performance characteristics, and operational behavior is essential to ensure their efficient and effective utilization. The transmission mechanism in hydraulic excavators converts the mechanical energy from the drive unit, typically the engine's torque, into kinetic or potential energy within the hydraulic fluid system. This energy is subsequently transmitted to the machine’s actuators, such as hydraulic motors and cylinders, via safety devices, control systems, and transmission lines. These actuators then convert the fluid's energy into mechanical work, either in the form of rotational or linear motion, depending on the operational requirements. This energy conversion is critical for performing tasks such as digging, lifting, and material handling [2], [3]. Equally important is the mechanism of hydraulic excavators, which enables the transfer of the machine's load to the ground, thereby ensuring stability during both operation and relocation. This mechanism also enables the excavator to move between various work sites, enhancing its versatility in multi-area operations. The stability provided by this mechanical system is essential for not only the safety of the operation but also the efficiency and accuracy of the excavator’s tasks.

Mechanical systems and construction machinery must meet several critical requirements to ensure efficient and reliable performance in demanding environments. These machines must operate under a variety of temperature and atmospheric conditions, including humid and dusty environments, often at remote locations without direct access, and with frequent relocation between work sites. They must also exhibit high reliability and durability of all components throughout the inter-repair period, ensuring continuous operation without failure, while maintaining the longevity and dependability of primary machine components during the asset's depreciation period. Adaptability to diverse operational conditions is essential, including mobility, maneuverability, ease of transportation, and straightforward assembly and disassembly. Additionally, these systems must demonstrate resistance to various weather conditions to remain functional under extreme environmental influences. High work utilization is equally important, ensuring that machine productivity aligns with other equipment in the same operational complex, which facilitates maximum use of all machinery with minimal downtime and without operational bottlenecks. To reduce damage, 4.0 digital technologies for predict maintenance in heavy machinery can be applied [4], [5]. Remaining useful life (RUL) is an important but uncertain measurement that helps to predict the lifespan and

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to guide maintenance decisions, and estimating it relies on real-time data collected from monitoring systems to assess the current state of the mechanical system [6].The integration of complex mechanization systems accelerates the work pace and ensures an uninterrupted workflow, with machinery selection typically focused on identifying the key machine within the mechanized system. To reduce the physical labor demands on workers and mitigate exposure to adverse working conditions, the increasing use of mechanized and automated control systems in construction machinery enhances efficiency and worker safety.

II. MODELING OF MECHANICAL STRUCTURES

In following is presented plate element, considering the plate structures are similar to plain stress problem. In Figure 1 the plate is represented by its middle plane, and the deformation is captured by the deflection and rotation of normals, which depend only on the in-plane coordinates x and y and not the out-of-plane direction z [7].

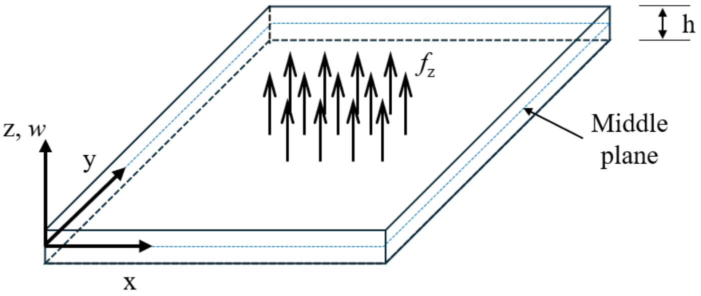

Fig. 1 A Plate with middle plane section

For the displacement component u and v which are parallel to the middle plane:

$$\begin{aligned} u(x,y,z) &= z\theta_y(x,y) \\ v(x,y,z) &= -z\theta_x(x,y) \end{aligned} \tag{1}$$

where, θ_x and θ_y are angles of rotation of vertical line of the plate in relation to x and y axes, respectively, and the in-plane strains is:

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} -\dfrac{\partial\theta_y}{\theta x} \\ \dfrac{\partial\theta x}{\partial y} \\ \dfrac{\partial\theta x}{\partial x} - \dfrac{\partial\theta}{\partial y} \end{bmatrix} \tag{2}$$

Strain energy U_e for this plate element is:

$$\begin{aligned} U_e = {} & \frac{1}{2}\int_{A_e}\int_{-h/2}^{h/2} \varepsilon^T\sigma \, dA \, dz \\ & + \frac{1}{2}\int_{A_e}\int_{-h/2}^{h/2} \tau^T\gamma \, dA \, dz \end{aligned} \tag{3}$$

where, τ is the average shear stresses in relation to the shear strain. The kinetic energy K_e of the plate is:

$$K_e = \frac{1}{2}\int_{V_e} \rho(\dot{u}^2 + \dot{v}^2 + \dot{w}^2) \, dV \tag{4}$$

$$K_e = \frac{1}{2}\int_{A_e} (\dot{\mathrm{d}}^T \mathrm{I} \, \dot{\mathrm{d}}) \, dA \tag{5}$$

For

$$\dot{\mathrm{d}} = \begin{bmatrix} \dot{w} \\ \dot{\theta}_x \\ \dot{\theta}_y \end{bmatrix}; \mathrm{I} = \begin{bmatrix} \rho h & 0 & 0 \\ 0 & \frac{\rho h^3}{12} & 0 \\ 0 & 0 & \frac{\rho h^3}{12} \end{bmatrix} \tag{6}$$

III. REINFORCEMENT SIMULATION

In the modeling process, several simplifying assumptions and hypotheses are often made to reduce computational complexity and improve calculation efficiency. These include, assuming that the material of the work equipment is uniform and continuous, ignoring errors due to tolerances, mechanical inaccuracies, and manufacturing defects, modeling all dimensions of the work equipment based on the basic, nominal size and treating the connections between components, which are typically welded, as rigid connections. While these assumptions help simplify the modeling process, they can also affect the accuracy of the calculation results. Therefore, it is important to define material properties accurately before starting the analysis of 3D models in the simulation environment.

Hydraulic excavators typically operate under harsh and challenging conditions. Due to these tough operating environments, individual parts of the excavator are subjected to high loads and must operate reliably under unpredictable conditions. Therefore, designers must create equipment that not only ensures maximum reliability but also minimizes weight and cost, all while maintaining safety across all operating conditions. Force analysis and strength calculations are critical steps in designing the components of hydraulic excavators. Finite element analysis (FEA) is one of the most powerful techniques used to assess the strength of structures that operate under high loads.

The boom viewed from the side has curved shape [8]. This shape is designed to provide the necessary reach and lifting capabilities. The main part of the boom consists of a bracket through which it is hingedly attached to the rotating platform of the excavator, a bracket for the hydraulic cylinders, and a hinged eye for attaching the tool holder. These parts are interconnected and assembled with metal plates, forming a welded structure that takes the shape of a hollow rectangular box. Inside the hollow boom, reinforcements are placed parallel to the cross-section, significantly increasing the rigidity of the structure against torsional loads and preventing the side plates from bending. Figure 2 shows the effect of the reinforcement of the cross-section during deformation. The attachment of reinforcement materials in welded structures presents significant challenges, as the quality of welded joints can vary based on production capabilities and the skill level of the operators performing the welding. Consequently, welding standards often prescribe lower allowable stresses to enhance long-term fatigue resistance, accounting for potential weaknesses in the welds. While this approach improves safety, it also leads to an increase in the overall weight of the structure. Furthermore, the addition of reinforcement materials themselves contributes to the overall weight of the design.

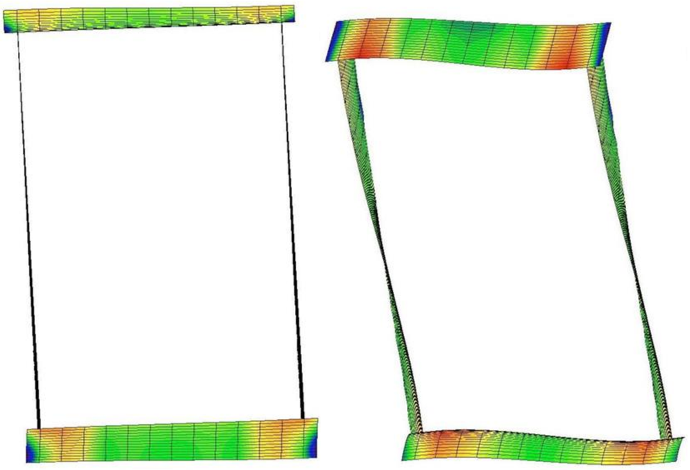

Fig. 2 Cross-section during deformation

Reducing the thickness of sheet metal while increasing the cross-sectional area of the box-shaped boom structure is a logical approach to achieving a lightweight design. However, as illustrated in Figure 2, reducing the thickness of each plate significantly compromises the structural rigidity, leading to increased deflection at the corners when exposed to torsional and lateral forces. In such cases, the use of reinforcing materials proves highly effective in mitigating deflection and preserving structural integrity. The design of work equipment, especially hydraulic excavators, can rely heavily on strong engineering intuition, but a thorough understanding of welding standards and effective application of FE load analysis techniques are mandatory.

IV. ANALYSIS AND RESULTS

In many finite element (FE) models of structures, the characteristics of welded joints are not explicitly modeled in detail, especially if the focus is on overall structural behavior rather than local stresses at welds. Instead, simplifying assumptions are often made, and the nominal load approximation is used to estimate the stress in areas near welded joints. As a result, a nominal load approximation is used to estimate the stresses around the welded region, which is consistent with standard welding codes. The nominal stress is calculated on the net cross-section of the structure, ignoring the local stress-concentration effects of joints and structural details but accounting for macro-geometric effects, which include larger geometric features of the structure. For N as the number of cycles, σ_{nAE} as constant-amplitude endurance limit related to N_E, where $N_E = 10^7$ and $N_E = 10^8$ for normal or shear stress, respectively, and slope k, it follows that σ_{nA} nominal stress amplitude is:

$$\sigma_{nA} = \left(\frac{N_E}{N}\right)^{1/k} \sigma_{nAE}, \qquad (N \le N_E) \tag{7}$$

Nominal stress can vary depending on cross-sectional geometry and loading conditions [9]. Therefore, macro-geometric effects must be considered when calculating nominal stresses. It is assumed that the nominal stress varies linearly if there are no external loads acting within the covered area. The approach for determining nominal stress involves extrapolating the linear stress distribution along the path of the structure to the welded area, assuming that the geometric stress components become negligible when the stress distribution is linear. This method helps in estimating the nominal stress from the FE model (Figure 3).

The extrapolation line must be perpendicular to the expected crack path, which means it should align with the direction of the applied load. This ensures that the stress distribution is accurately captured in relation to the loading conditions. The stress path must be sufficiently long to clearly reveal the behavior of the stress distribution along the structure. In cases where the loading is parallel to the weld path, the nominal stress can be directly obtained from the FE model (Figure 4), which provides detailed stress information along the model's geometry.

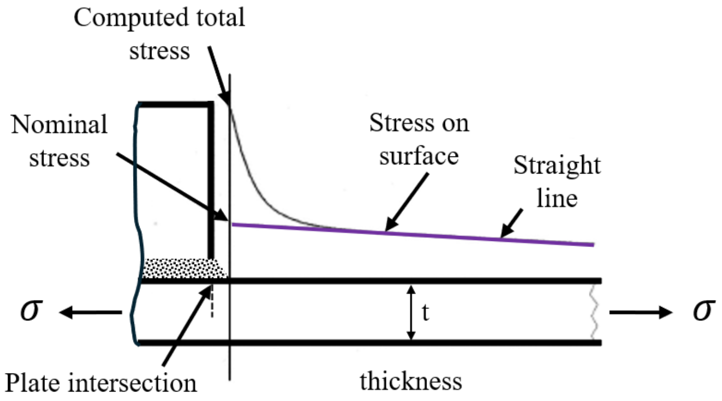

Fig. 3 Nominal stress analysis

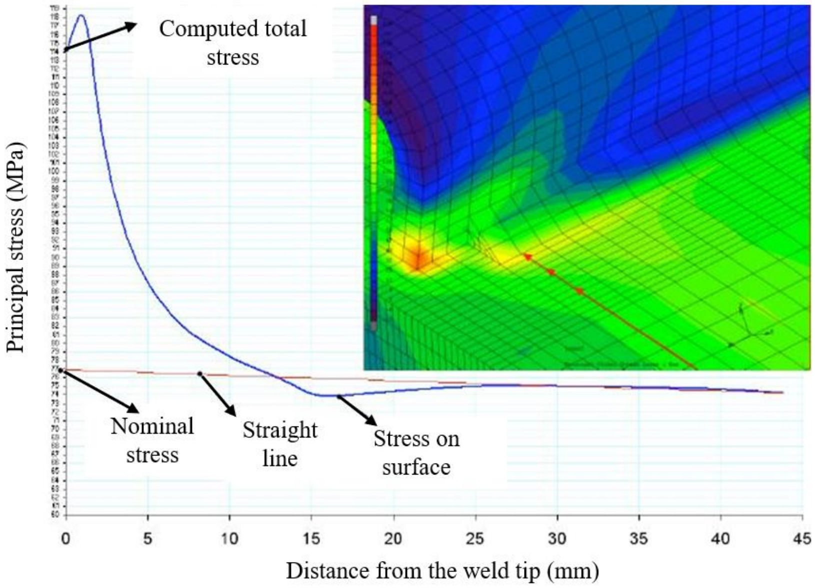

Fig. 4 Nominal stress and FE model

Using the nominal stress approach in a FE model enables stress concentrations and eccentric loading, as well as the effects of notches and residual tensile stresses caused by welding, not to be considered [10]. The nominal stress approach is established and widely used method for predicting fatigue life, but its application to complex, localized structures like spot-welded joints can be difficult. The method may not provide an accurate prediction of fatigue life in such cases because it doesn't account for the highly concentrated, localized stresses at the welds [11].

V. CONCLUSION

The construction of mechanical systems and machines must address a variety of challenges, including working under extreme conditions, ensuring reliability and durability, and managing the weight and cost of the machinery. It is essential to balance these factors to design machines that are not only strong but also efficient and cost-effective. Structural analysis, including FE analysis, plays a crucial role in understanding how individual parts of the excavator perform under high loads and varying conditions. However, macro-geometric effects must be considered to ensure an accurate representation of stress distribution across the structure.

Welded joints, while providing structural integrity, can be a source of weakness due to potential imperfections in the welding process. As a result, the nominal stress calculations in FE models often exclude the detailed analysis of these joints. Instead, the focus is on the overall structural behavior, with reinforcements added to prevent issues like bending or torsional deflection. In the case of high-load conditions, these reinforcements are essential for maintaining the rigidity and strength of the structure. The attachment of reinforcement materials and the quality of welded joints present additional challenges. Imperfections in the welding process may lead to weaknesses that can affect the long-term durability of the machine. Moreover, it is necessary to balance lightweight design with the strength provided by reinforcements to optimize performance without compromising safety or reliability.

In the traditional approach to designing the working equipment in hydraulic excavators, load distribution is typically determined using static calculations. Rigidity is then ensured by selecting an appropriate safety factor. However, this method does not fully account for dynamic stresses arising from shock, vibration, and other forces encountered during operation. As a result, it may not guarantee that the dynamic characteristics of the equipment are optimized for real-world conditions. To improve the design and extend the service life of the working equipment, it is essential to investigate its dynamic characteristics and incorporate dynamic analysis into the design process.

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