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# Finite Element Analysis of Hydraulically Actuated Excavator's Attachment

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***Abstract*—The backhoe mechanism governs the productivity, weight, and reliability of earthmoving machines such as excavators and loaders. For this, the backhoe mechanism must provide the sufficient working range, digging forces, and stability, all of which are influenced by structural parameters such as component length and joint angles. The main goal of the proposed work is to perform the design calculation of excavator attachments and carry out finite element analysis of excavator attachment for validation. For the backhoe attachment with three degrees of freedom, a generalized model was created for calculation of forces and stresses. This model can be used to compute forces as well as simulate the digging process. The forces calculated with this model is used as the boundary conditions for finite element simulations. Static analysis is performed and used to determine the deformation and stresses created in the components. The results of static analysis is used to identify locations that required modification and weight optimization of the attachment. The results of simulation software is matching closely with the results obtain using design calculations.**

***Index Terms*— Backhoe attachment, Hydraulic excavator, Finite element analysis, Static force analysis.**

## I. INTRODUCTION

In this section brief introduction about excavator and its working principle is described below

### *A. Excavator Mechanism*

The high performance construction equipment with sophisticated industrial automation of construction activity ensure a rapid growth rate of the earth moving machine sector. Backhoe excavators are commonly used in engineering construction for the most difficult earth moving job, excavating below the ground level on which the machine is supported. The machine is operated by a hydraulic system when digging or moving the material. An excavator is made up of three planar implements (boom, arm, and bucket) joined by revolute joints, as well as one vertical revolute joint (swing joint). Backhoes are basically soil-digging machines. The Hydraulic Cylinders control the operating tools on the backhoe. The hydraulic cylinders are used to control the required motion for the digging operation. A hydraulic cylinder controls each component. The required motion of the components for digging is generated by a combination of hydraulic cylinder extensions and retractions. The hydraulic cylinder generates the digging forces at the bucket tip at the same time.

Backhoe mechanism consists four links like Bucket, Arm, Boom and Swing link. The backhoe is a four-degree-of-freedom mechanism since all of these linkages have a rotational degree of freedom. The backhoe mechanism is depicted in the diagram above, along with the linkages.

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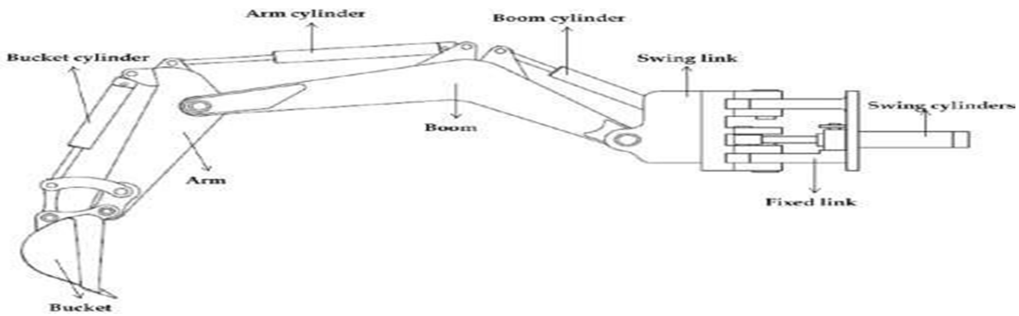



Figure 1 Backhoe Mechanism of Excavator [4]

*B. Objectives*

- Examine the current design of the excavator backhoe attachment, of a tracked excavation vehicle.
- Analyze static forces and simulate forces in order to do FEA for safe design while digging.
- To improve backhoe excavator attachment design.

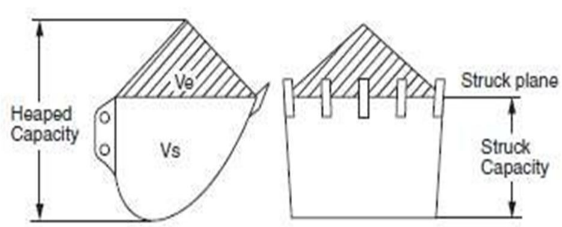
*C. Literature Review*

The basics of the foundation for the excavators' kinematics were defined by Kovio A. [5]. Using Newton-formula, Euler's Kovio A. et al. [6] created a dynamic model of an excavator excavating. They began by constructing kinematic formulas that represented component velocities and accelerations. Patel B. [4] developed a four-degree-of-freedom backhoe excavator kinematic model that may be used for any backhoe excavator autonomous operation. Backhoe kinematics and dynamics were described by Frankel J. [8] for use in the design of a robotic backhoe with haptic display. Chen J. et al. [9] devised a mathematical model for calculating tangential, normal, and bending moment resistive forces at the same time. To determine the operating ranges of the backhoe mechanism, Raju J. S. et al.[10] developed a forward kinematic model. For the FEA analysis and design of several types of teeth, Shaikh. et al. [12] employed the highest Bucket Cylinder force as the boundary condition. The bucket was studied using FEA and boundary conditions of maximum bucket curing force and arm curling force were calculated using the SAE J1179 standard by Lomate S. et al. [14]. Based on classical mechanic theory, Xiaoping P.et al. [15] suggested a structurally optimised excavator design. Structures' cross-sections were simplified to obtain maximum output stress under standard working conditions, which was included in self-developed structural analysis software (SASS). Zaman. The arm of a 125T shovel excavator was designed by M. F. [16] et al. They used a semi-elliptical cross section for the inner plates.

## II. Methodology

*A. Estimation of Bucket Capacity*

Bucket capacity is a measurement of the bucket's maximum filling capacity. There are two methods for determining bucket capacity Struck Capacity and Heaped Capacity.



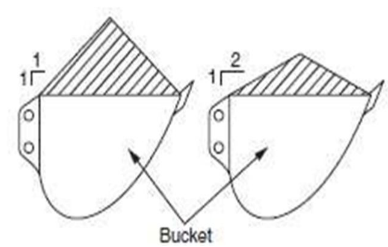




Figure 2 Bucket Capacity [2]

Figure 3 Bucket Capacity [2]

The struck capacity of a bucket is its capacity when the material is full to the struck plane, as shown in Figure 2. The striking capacity plus the volume of extra material filled above the struck plane is known as the heaped capacity. Two standards are used to determine bucket capacity. 1. SAE J296 that is for “Mini excavator and backhoe bucket volumetric rating" and 2. CECE "Mini excavator and backhoe bucket volumetric rating" (Committee of European Construction Equipment). The heaped capacity for the SAE standard can be calculated using a 1:1 angle of repose, but the CECE standard requires a 1:2 angle of repose. Figure 3 depicts the differences in finding the heaping capacity of both standards. For this model Vs = 0.613 $m^3$ and Ve = 0.193 $m^3$ for SAE standard and Ve = 0.055 $m^3$ CECE and Vh for SAE is 0.81 $m^3$ and Vh for CECE is 0.67 $m^3$.

*B. Digging Force Calculation as per SAE J1179 Standard*

The forces calculated at the tip of the bucket teeth are known as digging forces. Parameters of the bucket is shown in Figure 4 .Hydraulic pressure can be added to the cylinder exerting digging forces to apply these forces. SAE J1179 "Surface Vehicle Standards - Hydraulic Excavator and Backhoe Digging Forces" is used to compute these forces. As shown in Figure 5, $F_B$ is Bucket curling force and $F_S$ is Arm crowd force. As per SAE J1179, “maximum radial tooth force which occurs due to bucket cylinder (bucket curling force)$F_B$ is the digging force, which is developed by the bucket cylinder and tangent to the arc of radius $\mathbf{d_D}$.”

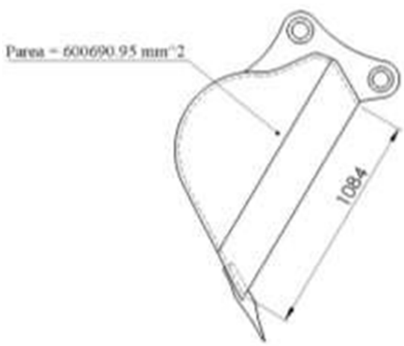



Figure 4 Parameters of 3D Model of the Bucket

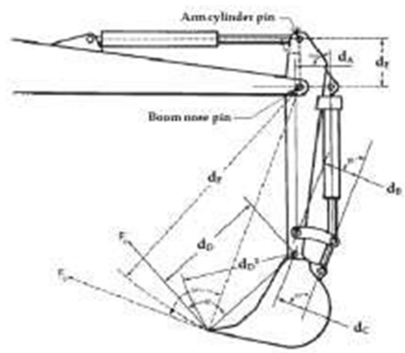



Figure 5 Digging force calculation using SAE J1179[3]

$$\mathbf{F_S} = \frac{\mathbf{P * D_A^2 * d_E * (\pi/4)}}{\mathbf{d_F}} \qquad [1]$$

Where, $d_F$ = tip radius of bucket ($d_D$) + link length of arm and $D_A$ = end diameter of the cylinder of arm. The assembly of the proposed model is placed in the position as shown in Fig. 6 it shows the values of the parameters such as: $d_A$ = 640 mm, $d_B$ = 575 mm, $d_C$ = 460 mm, $d_D$ = 1490 mm, $d_E$ = 835 mm, and $d_F$ = (2927 + 1490) = 4417 mm. The working pressure p = 37.3 MPa, $D_A$ = 135 mm and $D_B$ = 115 mm. Putting all these values forout model the equations lead to $F_B$ = 155.26 kN and $F_S$ = 96.72 kN.

*C. Force Calculations*

For each part of the backhoe mechanism, static forces acting at the highest breakout force condition were determined The arrangement in which the most forces are created is depicted in the figure 6 and figure 7.

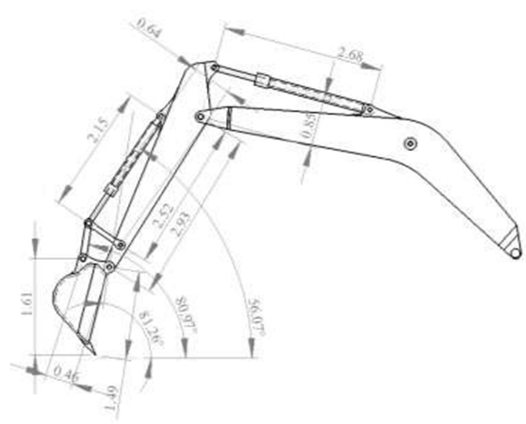



Figure 6 Configuration of Model for Maximum Breakout forces

*D. Finite Element Analysis of Parts*

Every part's 3D model was built in CATIA V5 and then imported into Hypermesh in STEP format. Geometry cleanup was carried out in order to eliminate any free edges and improve mesh quality. Distinct materials were assigned to different components of different parts based on their intended use. All of the sections were

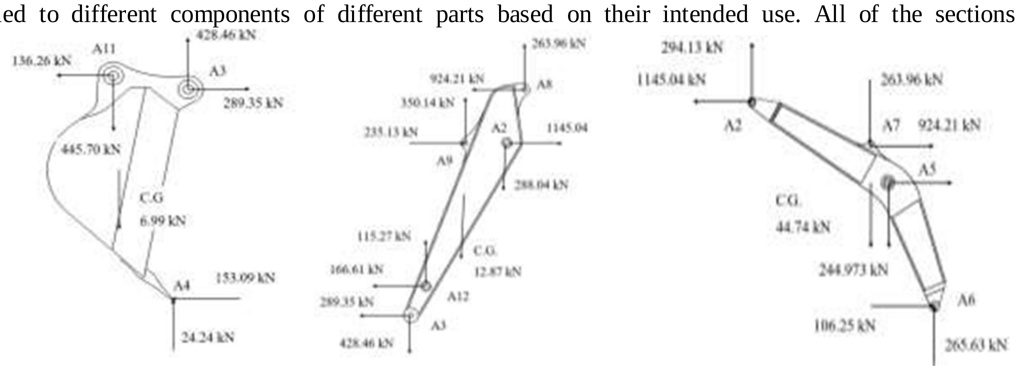



Figure 7 Static forces acting on the parts at maximum breakout force condition

sections were given boundary conditions, as indicated in Figure 8. The Hyperworks OptiStruct Solver was then used to analyze the pieces. Deformation and Von-mises stresses were computed and the results were calculated. The materials used are shown in the Table 1 and Table 2. The boundary conditions are as shown in Figure 8.

TABLE I. MATERIAL PROPERTIES OF HARDOX [19]

| Sr. No | Parameter | Value |
|---|---|---|
| 1 | Material | HARDOX 400 |
| 2 | E | 210000 MPa |
| 3 | Mu | 0.29 |
| 4 | Density | 7.453 tonne/mm$^3$ |
| 5 | Yield Strength | 1000 MPa |
| 6 | Property Type | PSOLID |

TABLE II. MATERIAL PROPERTIES OF EN8 [21]

| Sr. No | Parameter | Value |
|---|---|---|
| 1 | Material | EN8 |
| 2 | E | 190000 MPa |
| 3 | Mu | 0.3 |
| 4 | Density | 7.80 tonne/mm$^3$ |
| 5 | Yield Strength | 450 MPa |
| 6 | Property Type | PSOLID |

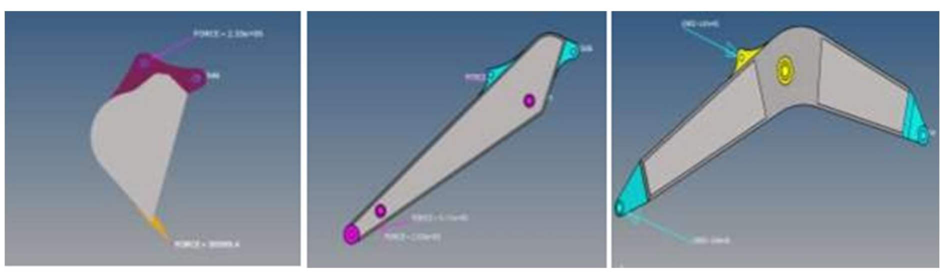


Figure 8 Boundary conditions given to the parts

## III. RESULTS AND DISCUSSIONS

The Figure 8, Figure 9 and Figure 10 show the deformation and stresses generated at various parts of the backhoe mechanism.

The bucket was subjected to a linear static analysis. As illustrated in the diagram below, the Von-Mises stresses in the hooks were 338.5 MPa, with a total deformation of 9.534 mm. The Von-Mises stresses were determined to be 329.8 MPa at the boom-arm junction, with a total deformation of 12.22 mm in the arm. This as depicted in the diagram below. The Von-Mises stresses found at the boom cylinder and boom, as well as the arm and boom joint, were 319.1 MPa. The overall deformation of the boom was found to be 16.03 mm. The Von-Mises Stresses generated VM should be less than the allowed stresses, according to the failure criteria.

$$\sigma_{VM} \leq \frac{\sigma_y}{Factor\ of\ safety}$$

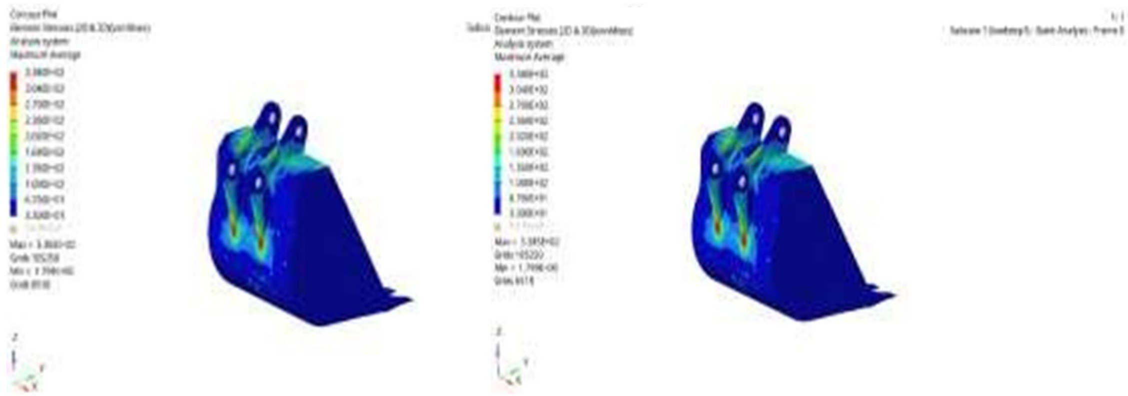


Figure 8 Stress and deformation in the bucket

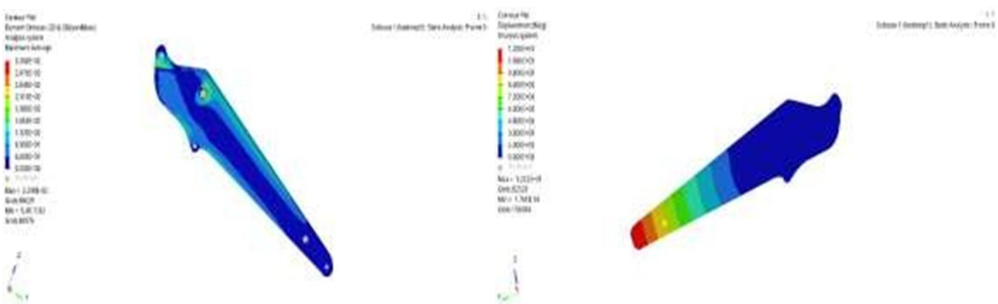


Figure 9 Stress and deformation in the arm

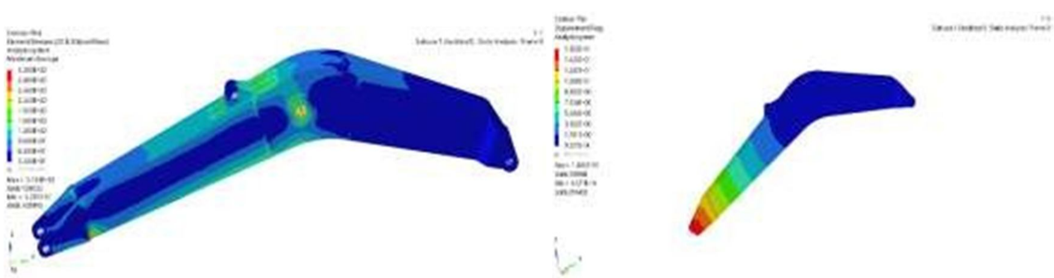


Figure 10 Stress and deformation in the bucket

Using 2[4] as the factor of safety and y = 1000 MPa as shown in table 2.1, we can see that the VM stresses are less than the permissible stress, indicating that the design is safe. The junction between the mounting lugs and the bucket rear plate generates the most stress. The strains created at the curved part of mounting lugs are likewise higher. This diagram depicts the locations where changes can be made. Also, because the side plates of the bucket are the least stressed parts, they can be modified. The deformation is greatest near the bucket's tip, which is acceptable because the force created by the bucket cylinder is greatest there. Using the factor of safety of 2[4] and y = 225 MPa from table 2.2, we can see that the VM stresses are higher than permissible at the joint where the boom is linked to the arm, but they are lower than yield stress, therefore the design can be improved to minimize the stresses on the plates. Similarly, the stresses at the junction between the boom cylinder and the boom, as well as the joint between the boom and the arm, are higher than permitted values, indicating that the boom has some potential for improvement. We can minimize the thickness of the arm and boom plates because they are comparably safer. In order to improve the design, we can also add some stiffeners to the plates.

## IV. CONCLUSIONS AND FUTURE SCOPE

From the present work, important conclusions drawn are as follows :

### *A. Conclusions*

A complete generalized model for force calculation is provided in the present work. The maximum forces acting in every backhoe attachment is calculated as $F_B$ = 155.26 kN which is highest during entire digging cycle. Indigenous MATLAB code is developed for design calculations. The forces and reaction obtained from MATLAB is very closed to those obtained from finite element simulations. For the SAE and CECE standards, the valuers obtained from MATLAB code is used to calculate bucket capacity and forces for the arm and boom. For all of the components, it provides the forces at their maximum breakout force state. The excavator's FEA was done with Hyperworks Linear Static Analysis for the Bucket, Arm, and Boom. Bucket, Arm, and Boom maximal von-mises stresses were measured to be 338, 329.8, and 319.1 MPa, respectively. The stresses generated in the bucket are below the permitted stresses for all the components. Hence the design is safe under maximum break out force. The developed MATLAB code can be used to calculate dynamic parameters and operate the backhoe excavator autonomously.

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