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Design and Static Analysis of Excavator Bucket

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Abstract

An excavator is a typical hydraulic heavy-duty machine used for versatile construction operations. During such operations, there is a possibility of wear and bending of bucket teeth. Therefore, the parts of the excavator must be strong enough to cope with caustic working condition. In the present work, FEM technique is used to simulate the operating conditions of mechanism. The aim of present study is to develop a three dimensional solid model of an excavator bucket by using SOLIDWORKS software and to conduct linear static stress analysis using ANSYS finite element software and to study the stresses and deformations using different types of materials for bucket teeth tips. Among the three types of joints used in this study, values of Von-misses stress and deformation is found to be less in rivet type of joint as compared to bolted joint used for fixing teeth caps to the bucket. In addition, a combination of teeth tips made of HARDOX 450 and remaining portion of bucket made of structural steel is found to be better than the bucket teeth tips made of HARDOX 500 and bucket body made of structural steel.

Keywords: Excavator, optimization, bucket volume calculation, maximum breakout force and stress analysis.

Introduction:

A backhoe excavator is equipment which consists of backhoe and also a cab that tends to be mounted to the back pivot near the undercarriage. For successful operation of such equipment, it is important to have sufficient knowledge about the structural and strength characteristics of the key parts of the excavator like bucket teeth, boom rods etc. Due to the nature of their work these excavator parts are subjected to high loads. Foundation like construction of highway, digging of trenches, holes, requires rapid removal of soil. This is achieved by a Backhoe Loader. Backhoe loader which is used for digging known as backhoe excavators. Three pieces of construction equipment of a backhoe excavator are a tractor, a loader, and a backhoe combined in to one unit as shown in fig. 1.1. The third piece of equipment which is known as a backhoe excavator consist of mainly boom, arm, and a digging bucket on the end of articulated part boom and arm. Bucket of backhoe excavator is the main area of research reported in this paper.

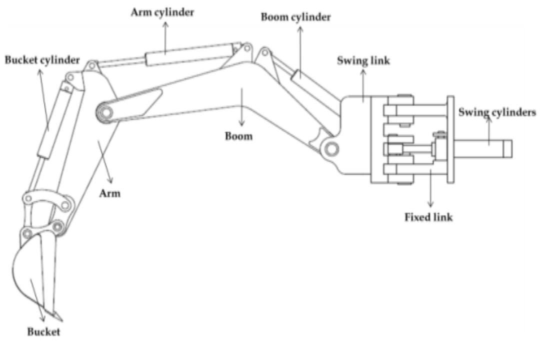

Figure 1.1 Major parts of a backhoe mechanism

Literature Review

Patel and Prajapati [1] conducted a detailed study on kinematics of hydraulic excavator's backhoe attachment. Researchers formulated an angle arrangement for safe working of excavator arm by using FEM approach. Due to severe working condition excavator parts are subjected to high loads. Thus it is very much necessary for the designers to provide not only an equipment of maximum reliability but also of minimum weight and cost, keeping design safe under all loading conditions. They also developed the formulae for calculating the arm crowd force and bucket curling force at an angle of 38.23° for the configuration of maximum breakout force condition. They also derived the formula for bucket capacity.

Bodur et al. [2] developed a model to include the kinematics of the excavator arm by controlling the cognitive force which controls and prevents the excessive ram forces by converting the control of the ram forces into the modification of the digging trajectory for the automation of the land excavation. The crawler and the rotational super structure bodies are stationary during digging at a certain point on the excavation trajectory, that's why the kinematic model is reduced to 3 degree of freedom.

Assenov et al. [3] studied kinematic and dynamic parameters of working mechanism of hydraulic excavator. They developed the 3D solid work model for dynamic study. The created dynamic model was simulated in the dynamic designer environment and shown the results of velocity of the mass center of the bucket, Piston force, and reaction force in the hinge between the arm and the jib.

Vadhe and Dave [4] developed a multi-body model of an excavator and simulated the prototype testing conditions. The stress results of particular gauge locations were also compared with experimental data. They concluded that the desktop prototype testing helps the designer to find out the worst operating condition, severe conditions and locate the trajectory of operation.

Bucket Design and Their Parts:

Primary aim of this study was to carry out a strength analysis of backhoe bucket used in an excavator for possible failures. This was achieved by creating a solid model of the bucket and then by carrying out a finite element analysis to assess the induced stresses in the bucket for different materials for teeth tips and different kind of joints provided to fix the teeth caps to the backhoe base.

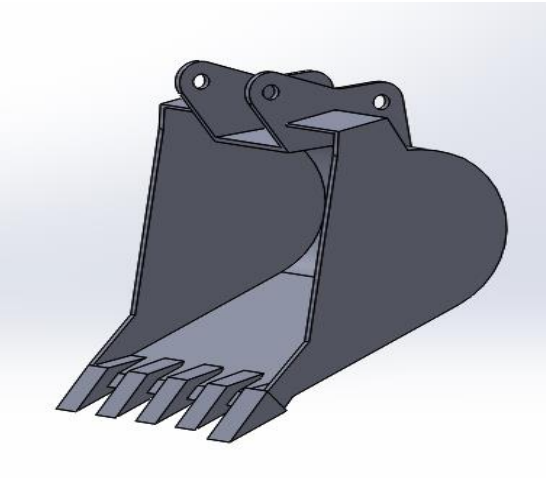

Figure 1.2 The 3-dimensional solid model backhoe bucket

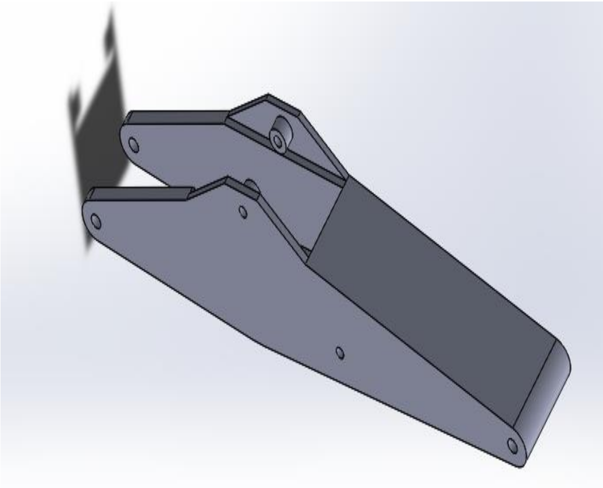

Figure. 1.3 Three dimensional view of the boom

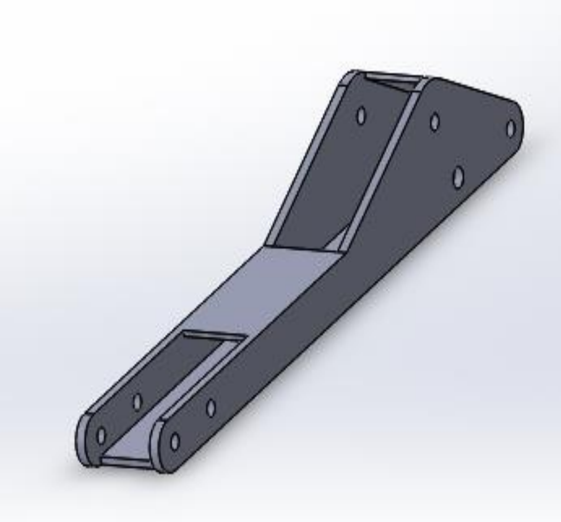

Figure 1.4 The three dimensional view of the arm

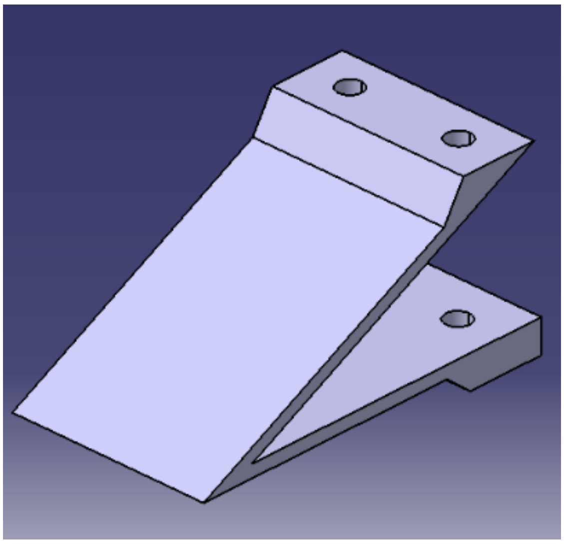

Figure 1.5 Solid model of cap

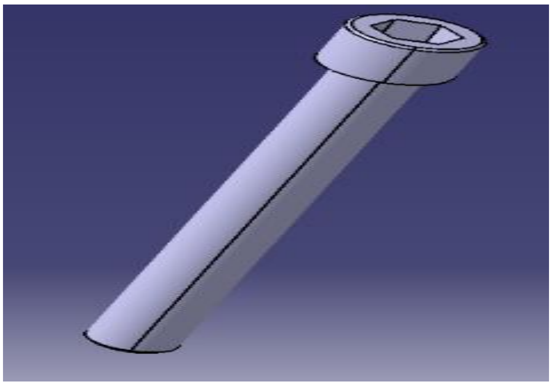

Figure 1.6 Solid model of the bolt

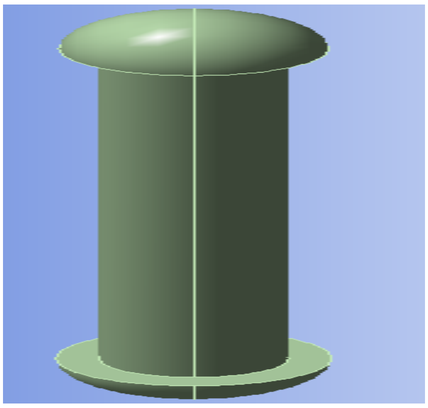

Figure 1.7 Solid model of the rivet

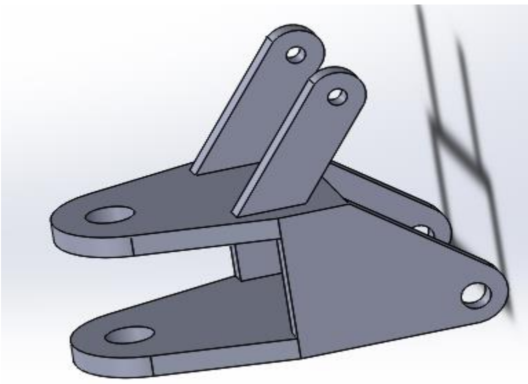

Figure 1.8 Three dimensional view of the base part

Research Gap / Research Problem

Wear resistance and life of the teeth can be increased by applying a coating of different materials on teeth and teeth cap. Moreover, the stress and deformation can be reduced by changing the design of the teeth and cap. The material for the bucket can also be varied to get the efficient work.

Research Objectives

The main objectives of the proposed research work are as follows:

- To design the backhoe bucket with different types of teeth joints for light duty construction work with optimum dimension for excavation task.
- To analyze the deformation, equivalent stress and strain, shear stress and safety factor of different types of teeth joints.

- To design a simple teeth cap with rivet and bolts type of joint to increase the life of bucket teeth because the maximum stress and wear occurred at the tip of tooth.
- To study the bucket performance of different material using finite element analysis (FEA) with bucket made of structural steel while the cap, rivet, and bolts made of HARDOX 450 and HARDOX 500.

Bucket Capacity Calculation:

Bucket capacity is a measure of the maximum volume of the material that can be accommodated inside the bucket of the backhoe excavator. Bucket capacity can be either measured in struck capacity or heaped capacity. Globally two standards used to determine the heaped capacity, are: (i) SAE J296: “Mini excavator and backhoe bucket volumetric rating”, an American standard (ii) CECE (Committee of European Construction Equipment) section VI, a European standard. The struck capacity directly measured from the 3D model of the backhoe bucket excavator for our case as shown in Fig. 1.9 by following the SAE J296 standards [1].

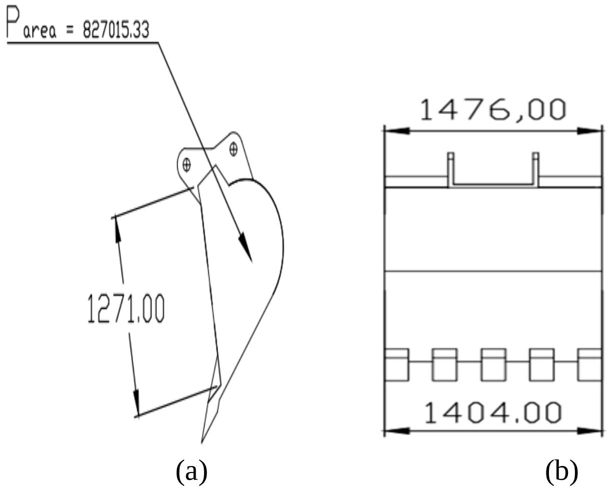

Figure 1.9 The different views of bucket, (a) side view, (b) top view

$$V_h = V_s + V_e$$

$$V_s = P_{Area}\left(\frac{W_f+W_r}{2}\right)$$

$$V_e = \left(\frac{L_B W_f^2}{4} - \frac{W_f^2}{12}\right)$$

Where $P_{Area} =$ 827015.33mm^2 (area bounded by the struck plane and side protector)
$W_r =$ 1404 mm (Width of the inside wall of the bucket)
$W_f =$ 1476 mm (Width of the outer wall of the bucket)
$L_B =$ 1271.05 mm (Length of the bucket)
$V_h = heaped\ capacity$
$V_s =$ Struck capacity
$V_e =$ Excess material capacity heaped

$$V_h = V_s + V_e \quad (1)$$

$$V_s = P_{Area}\left(\frac{W_f+W_r}{2}\right) = 1.1909\ m^3 \quad (2)$$

$$V_e = \left(\frac{L_B W_f^2}{4} - \frac{W_f^2}{12}\right) = 0.4243\ m^3 \quad (3)$$

By using equation (1), (2), and (3) the bucket capacity for the proposed 3D backhoe bucket model is

$$V_h = V_s + V_e = 1.6152\ m^3$$

Digging Forces:

Fig. 1.10 Shows the measurement of bucket curling force F_B, arm crowd force F_S, the other terms in the figure $d_A, d_B, d_c, d_D, d_D^1, d_E$and d_F shows the distances as shown in Fig. According to SAE J1179: Maximum radial tooth force due to bucket cylinder (bucket curling force) $F_B$is the digging force generated by the bucket cylinder and tangent to the arc of radius d_D^1. D_BIs the end diameter of the bucket cylinder in (mm) and the working pressure is p in MP_aor N/mm^2 and other distances are in mm and remains constant. $d_F is$ The sum of bucket tip radius (d_D) and the arm link length in mm, and $D_A$is the end diameter of the arm cylinder in mm.

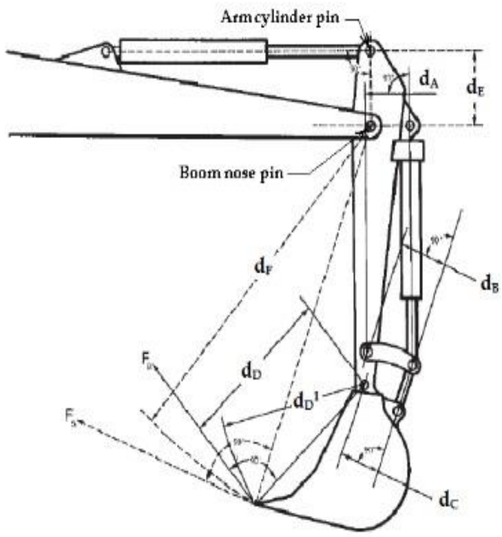

Fig. 1.10 Forces on bucket

The values of the parameters as: $d_A = 292\ mm, d_B = 826\ mm, d_C = 559\ mm, d_D = 1824\ mm, d_E = 560\ mm, and d_F = (1824 + 3031.4) = 4855.44\ mm.$

The working pressure p = 314 bar or 31.4 MP_a(this pressure taken from the manual of existing backhoe excavator model no. SK460 & SK480), $D_A = D_B = 80mm.$

$$F_B = \frac{p \times (\pi/4) D_B^2}{d_D} \left(\frac{d_A \times d_C}{d_B} \right) = 17100\ N$$

$$F_S = \frac{p \times (\pi/_4) D_A^2 \times d_E}{d_F} = 18204\ N$$

The calculated breakout force (F_B) = 17100 N

Calculated arm crowd force (F_S) = 18204 N

Consider the bucket have 5 no. of tooth, therefore total force applied on each tooth end is

$$F_B^{'} = \frac{F_B}{5} = \frac{17100}{5} = 3420\ N$$

The calculated breakout force on each tooth will act at the angle 38.23° for configuration of the maximum breakout force condition. By taking the reaction force at the tip of the tooth at an angle of 38.23° the applied force in x and y direction will be.

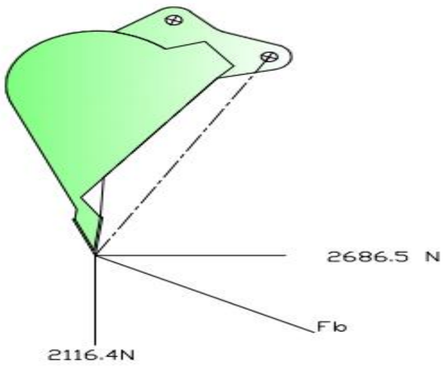

Fig. 1.11 Forces acting on the bucket teeth

$$F_{B_x} = F_B^{'} \cos 38.23° = 2686.52\ N$$

$$F_{B_y} = F_B^{'} \sin 38.23° = 2116.36\ N$$

So the breakout force acts on the each tooth in x and y direction is F_{B_x} and F_{B_y}.

8. Finite Element Analysis Of Excavator Bucket

The finite element method (FEM) rapidly grew as the most useful numerical analysis tool for engineers and applied mathematicians.

ANSYS is a finite element analysis tool for structural analysis, including linear, non linear and dynamic studies. It provides a cost effective way to explore the performance of product in virtual environment. The desired models were created in SOLIDWORKS modeling software as discussed in section 6 were imported in ANSYS workbench environment. The material properties were assigned for different parts of the bucket assembly and displacement and force boundary conditions were applied. The linear static analysis was carried out under following catagories:

1. Bucket material was taken as structural steel and bucket teeth and caps were assumed to be HARDOX 450 and HARDOX 500 is two analysis. The teeth and caps however in this study were assumed to be bolted, rivetted and welded to the base i.e. these are the integral part of the bucket.
2. Bucket, bucket teeth and caps material were taken as HARDOX 450 and HARDOX 500 is two analysis. The teeth and caps were assumed to be welded, bolted and rivetted to the base i.e. these are the integral part of the bucket.

Meshing of the Geometry

There are different mesh sizes were used and results using Von-mises stress in each case were compared to check the convergance of the final results. It was found that at about 20 mm mesh size the stresses values were converged. Therefore, meshing size of 20 mm was choosen for meshing of the bucket for each of the three cases. Each model was meshed using four noded tetrahedral elements. Figure 1.12 shows the meshed model of bucket having teeth riveted to the base.

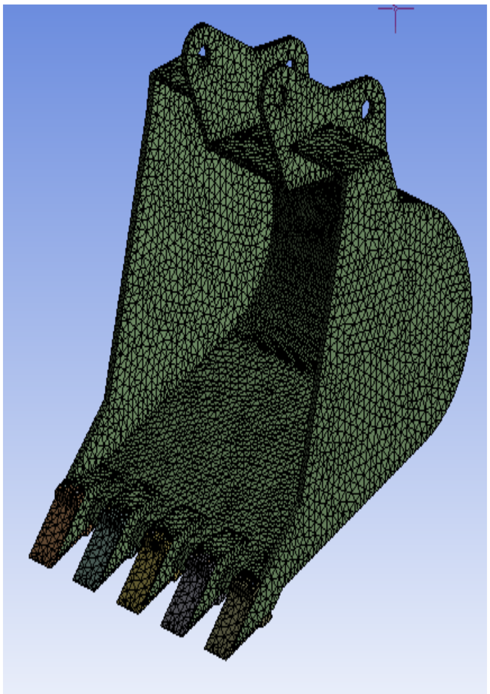

Fig. 1.12 Meshed bucket model with teeth caps riveted to the base

Table 1 nodes and elements formed in different type of joints

FE meshing attributes	Welded (cap is welded to the teeth)	Bolted (cap is attached to the teeth by bolt)	Riveted (cap is attached to the teeth by rivet)
Nodes	121603	163078	148158
Elements	68775	88280	79540

Table 1 shows the nodes and elements of the meshed model of the different type of joints. Where as in case of welded type of joint cap is welded to the teeth similarly in bolted and riveted type of joint cap is attached to the teeth by bolts and rivets.

Boundary Conditions:

Digging force, arm crowd force and displacements used as boundary condition in all the three type of joints to get the maximum stress and deformation formed on the bucket.

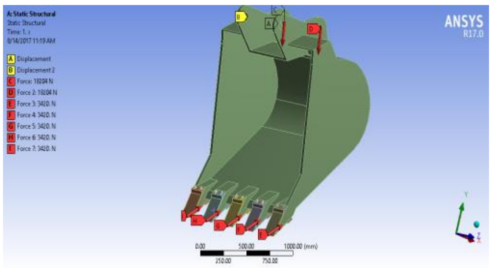

Fig. 1.13 Different forces and displacement boundary condition applied to the bucket, where A&B displacement, C&D arm crowd force and E,F,G,H digging forces at the tip of tooth

Displacement: displacement is taken as zero in all three directions at the pin joint of arm and bucket in all three type of joints i.e. welded, bolted and riveted type.
Arm crowd force: This force acts on the joint of arm cylinder to the bucket for excavation process. Arm crowd force is (F_S) = 18204 N calculated in section 7.

Digging force: force acts on the tip of the tooth at an angle of 38.23° for maximum breakout force condition [8]. Digging force is (F_B) = 17100 N calculated in section 7.
There are 5 no. of teeth so the digging force acts on each tooth will be

$$F_B^{'} = \frac{F_B}{5} = \frac{17100}{5} = \quad 3420\ N$$

Analysis:
A linear static analysis was conducted for the backhoe in ANSYS software. Fig. 1.13 to Fig. 1.21 shows the contour plots of Von-misses stress and deformation when caps were fixed to teeth using rivets and during analysis, bucket material was taken as structural steel and cap and rivet material used as HARDOX 450 for the finite element analysis. Similarily observation for welded type of joint and bolted type of joint can be carried out in same manner for different type of material.

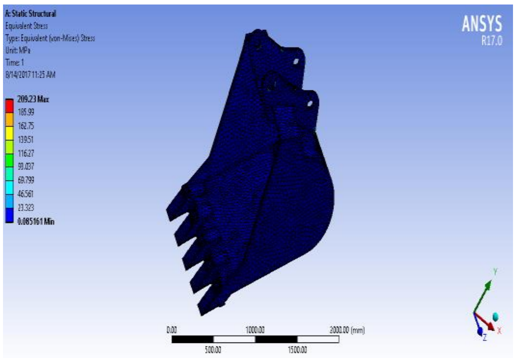

Fig. 1.13 Von-misses stress contour plot of bucket with cap and rivet

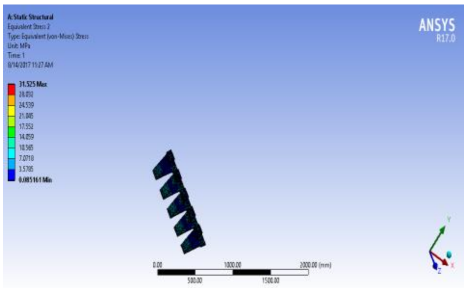

Fig. 1.14 Von-misses stress contour plot of cap

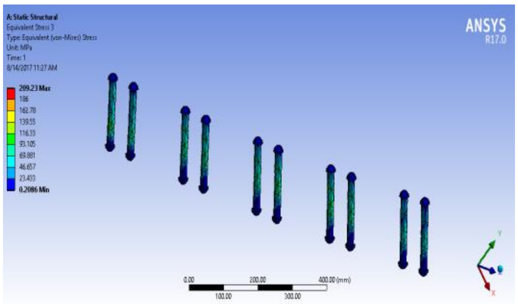

Fig. 1.15 Von-misses contour plot of rivet

From the contour plots of fig. 1.13 to fig. 1.15 it can observed that maximum von-misses stress formed in bucket was founded in riveted type joint. Similarily Von-misses stress distribution was also seen in bolted and welded type joints.

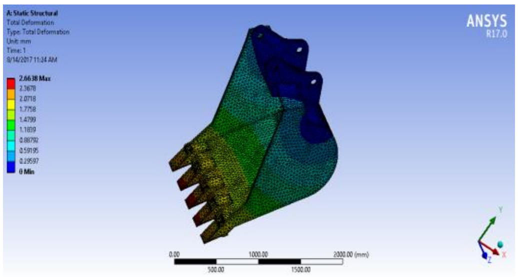

Fig. 1.16 Total deformation contour plot of bucket with cap and rivet

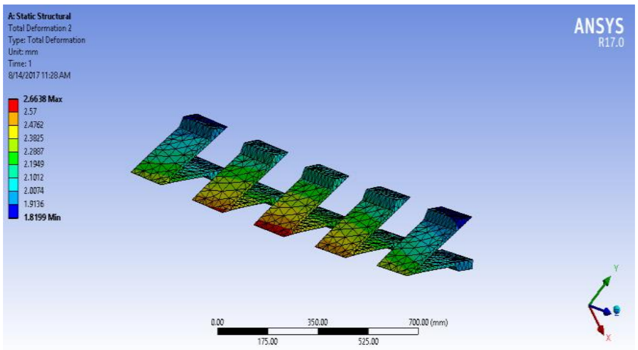

Fig. 1.17 Total deformation contour plot of cap

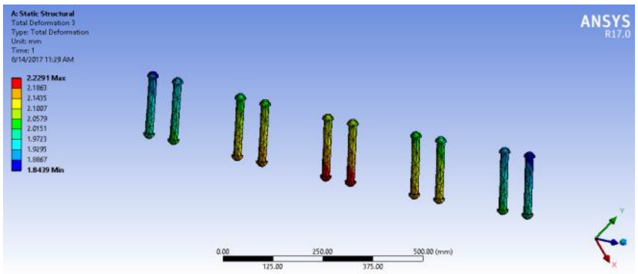

Fig. 1.18 Total deformation contour plot of rivet

Fig. 1.16 to Fig. 1.18 show the total deformation of bucket with cap attached to base with help of rivet joints. In rivet type of joint total 5 cap and rivets were used to join the cap with the bucket teeth. From the fig. 1.17 the maximum deformation 2.66 mm was found in cap which was least as compare to other type of joint further, it can be observed from fig.1.18 that maximum deformation occurred in the middle cap and the rivets that connected the middle cap with base. Deformation in remaining other caps and rivets were less as compared to centre rivet and cap.

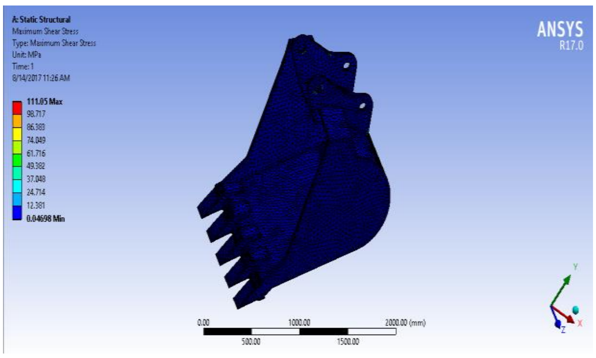

Fig. 1.19 Max. shear stress contour plot of bucket with cap and rivet

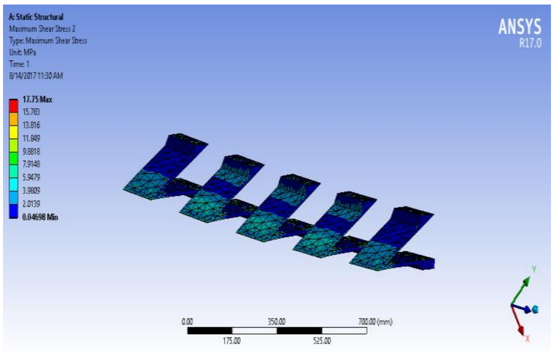

Fig. 1.20 Max. shear stress contour plot of cap

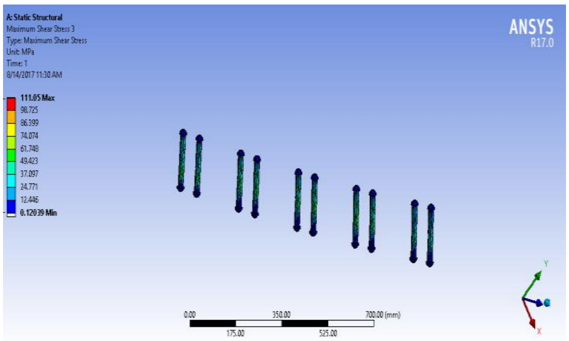

Fig. 1.21 Max. shear stress contour plot of cap

Fig. 1.19 to Fig. 1.21 display the contour plots for maximum shear stress in bucket, teeth and caps respectively. The maximum shear stress was found in bucket to rivet joint which was 111.05 MPa and it was equal at each of rivet which was less as compared to the bolted type of joint. Maximum shear stress of 17.75 MPa was observed at the centre of each cap, This shows that the shear stress because of the shearing of rivet to cap is equally distributed in each cap and rivet.

Results:

In the present study, HARDOX 450 and HARDOX 500 material were used for bucket tooth, cap, rivet, and bolt while the remaining parts of bucket designed of structural steel. Table no. 2 shows the different properties of excavator bucket with different conditions joint. It can be observed from the table that total deformation is maximum in case of welded type of joint and minimum in case of riveted. However, the other parameters like stress, strain, shear stress, maximum shear stress were found to be minimum in case of welded joint. Factor of safety was maximum for HARDOX500 and structural steel combination with riveted joints. Welded type of joint is not preferred because it displayed maximum deformation than others which is not good for excavation task. Also, because of high deformation bucket tooth can fail earlier and in such case the entire bucket needs to be replaced. In other type of joints, in case of failure, only cap, teeth, and rivet will require to be changed which can prove economical than changing the entire bucket. So selecting the bucket with riveted type of joint made of HARDOX 450 & Structural steel appears to be beneficial as per economical and strength point of view. Also HARDOX 450 & Structural steel has less deformation, stress and maximum life than HARDOX 500 & Structural steel.

Table 2: Results of different materials for different type of joints

Properties	Welded		Bolted		Riveted	
	HARDOX 450 & S.S	HARDOX 500 & S.S	HARDOX 450 & S.S	HARDOX 500 & S.S	HARDOX 450 & S.S	HARDOX 500 & S.S

Deformation (mm)	5.5146	5.7798	2.7129	2.7129	2.6638	2.682
Von-misses stress (MP_a)	198.52	205.17	399.08	399.08	209.23	286.93
Maximum shear stress (MP_a)	114.22	118.04	230.40	230.4	111.05	164.21

On comparing Table no. 2 and Table no. 3, it can be observed that the bucket made of HARDOX 450 and Structural Steel is more efficient, stronger and more durable than the entire bucket made of HARDOX 450 & HARDOX 500 material. The analysis clearly demonstrates that the bucket having of teeth and cap made of HARDOX 450 and bucket body made of structural steel offer a good option for the designer from strength point of view due to its lower deformations and stresses under loading conditions along with the higher factor of safety and service life.

Table 3: Results of different materials for different type of joints

Properties	Welded		Bolted		Riveted	
	HARDOX 450	HARDOX 500	HARDOX 450	HARDOX 500	HARDOX 450	HARDOX 500
Deformation (mm)	5.2366	5.2329	2.542	2.5442	2.542	2.5593
Von-misses stress (MP_a)	198.85	196.17	0.00237	422.49	214.47	295.13
Maximum shear stress (MP_a)	114.4	112.93	226.21	241.46	113.91	169.05

Analysis of Bolt, Rivet and Cap:

This section shows the finite element analysis of different properties such as deformation, Von-misses stress, strain, max. shear stress, factor of safety and life of bolt, rivet, and cap of bucket having different type of joints made of different materials (HARDOX 450 HARDOX 500)

Table 4 Results of different materials for different type of joint (cap)

Properties	Bolted cap		Riveted cap	
	HARDOX 450	HARDOX 500	HARDOX 450	HARDOX 500
Deformation (mm)	2.71	2.7129	2.663	2.682
Von-misses stress (MP_a)	168.56	168.56	31.525	33.70
Maximum shear stress (MP_a)	96.85	96.85	17.75	17.837

Table no. 4 shows results of analysis in which the deformation, von-misses stress, strain, maximum shear stress, shear stress in cap of bolted type of joint to the base is more as compared to riveted type of joint to the base either the cap is made of HARDOX 450 or made of HARDOX 500. it can also observed that the cap made of HARDOX 450 is more efficient and stronger than the cap made of HARDOX 500 in rivet type of joint to the base. Also the life and factor of safety is more as compared to bolted type of joint to the base. Table 5 shows the same conclusion as Table 4 that rivet made of HARDOX 450 is more efficient and safe as compared to bolt.

Table 5 Results of different materials for different type of joint (bolt and rivet)

Properties	Bolt		Rivet	
	HARDOX 450	HARDOX 500	HARDOX 450	HARDOX 500
Deformation (mm)	2.225	2.2254	2.229	2.230
Von-misses stress (MP_a)	399.08	399.08	209.23	86.93
Maximum shear stress (MP_a)	230.4	117.67	111.05	164.21

Discussion:

It can be observed from the above graphs and tables in chapter 4 that the welded type of joint has lesser stress than bolted and riveted type of joint but the deformation is more. Welded type of joint also has maximum life but from the economical prospectus welded type of joint will be costly because after so many excavation process the damaging chances of bucket teeth is more. In that case, the whole bucket required to be changed but in case of rivet or bolt type of joint, changing the bucket teeth will be economical than changing the whole bucket. Now the remaining two options are, rivet type and bolt type. There is no big difference in deformation but in case of stress and life there is large difference and also the cost of HARDOX 450 is less as compared to HARDOX 500.

Conclusion

For light duty construction work or excavation process, backhoe excavator is used. The digging forces acting on the each bucket teeth are obtained by the formula derived by the researchers and these forces are used as boundary conditions for finite element analysis. Finite element analysis technique is used to simulate the operating conditions of mechanism. A Cap has been designed to reduce the stress on teeth and chances of damaging the tooth. After performing finite element analysis, stresses in bucket, cap and rivet are found to be within allowable stress limit. By modeling and analysis of backhoe excavator bucket, it has been observed that, the values of von-misses stress and deformation is less in rivet type of joint as compared to bolted type of joint because of using cap and rivet made of HARDOX 450 and remaining portion of bucket made of Structural Steel is feasible than the bucket made of HARDOX 500 and Structural Steel. Analysis also includes the von-misses stress, deformation, maximum shear stress, life and other parameters for cap and rivet individually for different types of material and joints. In each case riveted type of joint made of HARDOX 450 and Structural Steel found efficient and durable as compared to other type of joints.

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