International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 3, October 2012

Research Paper

STATIC ANALYSIS OF MINI HYDRAULIC BACKHOE EXCAVATOR ATTACHMENT USING FEA APPROACH

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An excavator is a typical hydraulic heavy-duty human-operated machine used in general versatile construction operations, such as digging, ground leveling, carrying loads, dumping loads and straight traction. Normally backhoe excavators are working under worst working conditions. Due to severe working conditions, excavator parts are subjected to high loads and must work reliably under unpredictable working conditions. Thus, it is necessary for the designers to provide not only a equipment of maximum reliability but also of minimum weight and cost, keeping design safe under all loading conditions. The force analysis and strength analysis are important steps in the design of excavator parts. Finite Element Analysis (FEA) is the most powerful technique used to evaluate strength of the structures working under high loads. This paper focuses on the solid modeling of the mini hydraulic backhoe excavator intended for light duty excavation task and its FE analysis for strength evaluation. It also includes the effect of the welding on the developed stresses in backhoe excavator parts.

Keywords: Backhoe excavator, FEA

INTRODUCTION

Earth moving excavation represents a huge potential and a favourable approach for many earthmoving operations including construction, mining, agricultural, forestry, military applications and especially for cleaning up hazardous areas (Nareshkumar, 2006). Rapidly growing rate of industry of earth moving machines is assured through the high performance construction machineries with complex mechanism and automation of construction activity (Mehta, 2008). Hoes are used primarily to excavate below the natural surface of the ground on which the machine

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rests. A hoe is sometimes referred to by other names, such as backhoe or back shovels (Peurifoy and Schexnayder, 2006). Since the late 50's hydraulics have been the systems of choice where high force-to-weight ratios are required.

The skilled operator also cannot know about the terrain condition, soil parameters, and the soil-tool interaction forces exerted during excavation operation are required to find because these forces helpful for better design of the tool, backhoe parts and for trajectory planning. The design of all excavation machinery and the attachments are very as per their functional requirements and depends on their applications (Bhaveshkumar and Prajapati, 2011b).

An excavator is a typical hydraulic heavy-duty human-operated machine used in general versatile construction operations. In the toxic or hazardous environment, dirty places and worst working area it is very difficult to perform excavation task by human operator. To avoid this problem one of the best solution is automation of the excavation machine.

Herein the greatest opportunity to develop a backhoe excavator attachment, which can perform the digging operation in autonomous mode to fulfill the operational functionality with better strength, higher durability and reliability. Presented work emphasize on FEA of such a developed mini hydraulic backhoe excavator attachment for light duty construction work. The next section covers the problems concerned with the backhoe excavators used as earth moving machine.

PROBLEM FORMULATION

This digging task is repetitive in nature and during the operation the entire link mechanism working under the dynamical condition. Some time due to improper controlling of the dynamic forces the backhoe mechanism may failed. Higher damage rates lead to higher maintenance downtime (lower machine availability) which subtracts from the net capacity of the machine to produce (Andrew, 2002).

The excavator mechanism must work reliably under unpredictable working conditions. Poor strength properties of the excavator parts like boom, arm and bucket limit the life expectancy of the excavator. Therefore, excavator parts must be strong enough to cope with caustic working conditions of the excavator (Mehmet, 2005). Terrains are of different kind and exerted siol-tool interaction forces may very as per the terrain condition. Therefore it is challanging job to design such a excavator which can work under unpredictable working environment and also prolong all kind of forces without any kind of failure. For design engineer it is not enough to provide rubust design but also taking care of the weight of the attachmet for better controlling during excavation operation.

During the work cycle a backhoe must accelerate, move at constant speed, and decelerate. This time-varying position and orientation of the backhoe is termed as its dynamic behavior. Time-varying torques are applied at the joints (by the joint actuators) to balance out the internal and external forces. The internal forces are caused by motion (velocity and acceleration) of links. Inertial, Coriolis, and frictional forces are some of the internal forces. The external forces are the forces exerted by the environment. These include the “load” and gravitational forces. As a result, links and joints have to withstand stresses caused by force/torque balance across these (Mittal and Nagtath, 2008).

Earth moving process passages huge challenges to scientist and researchers due to the complexicity of the dynamical environment, in particular era of design, dynamics and controlling of the excavation process of an excavator (Bhaveshkumar and Prajapati, 2011b).

UTILITY OF FEA

The strength analysis is an important step in the design of excavator parts. Finite Element Analysis (FEA) is the most powerful technique in strength calculations of the structures working under known load and boundary conditions. One can determine the critical loading conditions of the excavator by performing static force analysis of the mechanism involved for different piston displacements. The boundary conditions for strength analysis will be determined according to the results of static force analysis. In general, Computer Aided Drawing (CAD) model of the parts to be analyzed must be prepared prior to the FEA. Preparation of the CAD model can be done either using a commercial FEA program or using a separate commercial program, which is specialized for CAD (Bhaveshkumar and Prajapati, 2011a).

The finite element method is an approximate numerical procedure for analyzing large structures and continua. In the finite element method, the finite element model is created by dividing the structure in to a number of finite elements. Each element is interconnected by nodes. The selection of elements for modelling the structure depends upon the behaviour and geometry of the structure being analyzed. The modelling pattern, which is generally called mesh for the finite element method, is a very important part of the modelling process. The results obtained from the analysis depend upon the selection of the finite elements and the mesh size. Although the finite element model does not behave exactly like the actual structure, it is possible to obtain sufficiently accurate results for most practical applications. Once the finite element model has been created, the equilibrium equations can easily be solved using digital computers without having to solve a large number of partial differential equations by hand. The deflections at each node of the finite element model are obtained by solving the equilibrium equations. The stresses and strains then can be obtained from the stress-strain and strain-displacement relations (Reena, 2005). Due to number of assumptions considered in design procedure, the design becomes idealized; hence the quality of the result is depend on the skill and expertise of the person (Bhaveshkumar *et al.*, 2011).

ASSUMPTIONS

The following are the assumptions made in the analysis of the mini hydraulic backhoe excavator.

- The stress analysis that ANSYS simulations provides is appropriate only for linear material properties. These properties are where the stress is directly proportional to the strain in the material (no permanent yielding of the material). Linear behaviour results when the slope of the material stress-strain curve in the elastic region (measured as the Modulus of Elasticity) is constant.

- The total deformation is assumed to be small in comparison to the part thickness. As for an example, while studying the deflection of the beam, the calculated displacement must be less than the minimum cross-section of the beam.
- The results are temperature independent. The temperature is assumed not to affect the material properties.
- Inertia of the component is neglected as the acceleration of the parts is less than 0.05 m/sec^2 in the field.
- Minimum element size allows automatic refinement in small areas (Reena, 2005).

ANALYSIS OF BACKHOE EXCAVATOR PARTS

A backhoe excavator attachment having basically four links of bucket, arm, boom and swing link connected to each other in series. One more link namely fixed link connected with the structure of excavator on rear site. Here the static analysis is performed for all the parts of the mini hydraulic backhoe excavator attachment and stress analysis carried out based on FEA approach using ANSYS software.

Von Misses stress is used as a criterion in determining the onset of failure in ductile materials, and the materials in the presented study for the parts of the bucket, arm, boom and swing link are ductile materials, so the design of all parts should be on the basis of Von Misses stresses acting on the parts.

The failure criterion states that the Von Misses stress should be less than the yield stress of the material by taking appropriate safety factor into consideration. This indicates for the design of a part to be safe the following condition must be satisfied (Tirupathi and Ashok, 2005).

Design Stress (for ductile materials),

$$\sigma_{VM} \leq \frac{\sigma_y}{Safety\ Factor} \qquad ...(1)$$

Static force analysis is carried out based on the digging froce calculation according to SAE J1179 standards but entire calculations are not a part of this paper, it is taken from the reference (Bhaveshkumar and Prajapati, 2012). Stress analysis performed for bucket, arm, boom and swing link based on loading conditions obtained from the static froce analysis. The next section covers the stress analysis of the bucket.

Analysis of the Bucket

Here the static analysis is utilized to carry out the Finite Element Analysis for various parts of the backhoe attachment to know the developed stress level for known boundary and loading conditions.

Figure 1 shows static force analysis of bucket calculated for the maximum breakout force configuration. Figure 2 indicate the boundary and loading conditions applicated for the bucket. Figure 3 shows the mesh view of the bucket with 52219 nodes and 9636 elements.

Figure 4 shows the Von Misses stresses developed in the bucket and Figure 5 shows the enlarged view of the same. Maximum Von Misses stress acting on the bucket is 203.67

MPa, moreover; all parts of the bucket are made up of HARDOX 400 material except the bushes used in mounting lugs are made up of IS 2062 material.

Figure 1: Static Force Analysis of Bucket

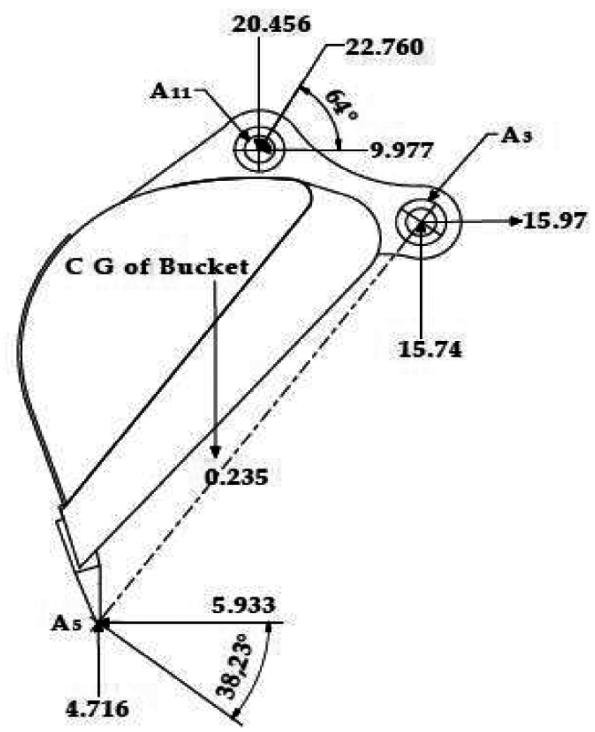


Figure 2: Boundary Conditions for Bucket

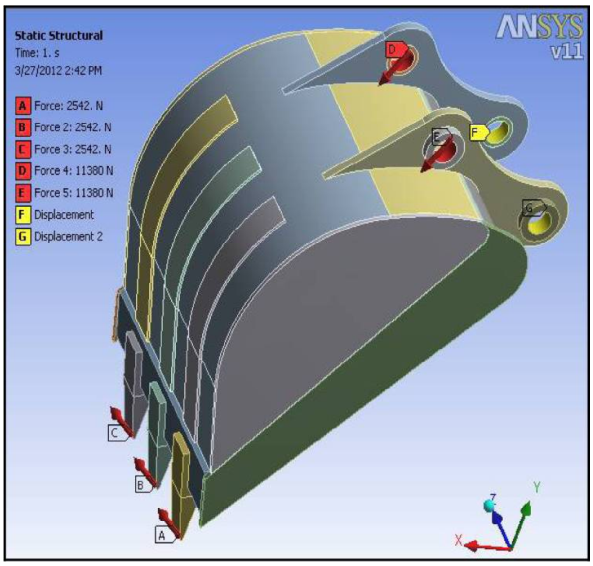


Figure 3: Mesh View of Bucket

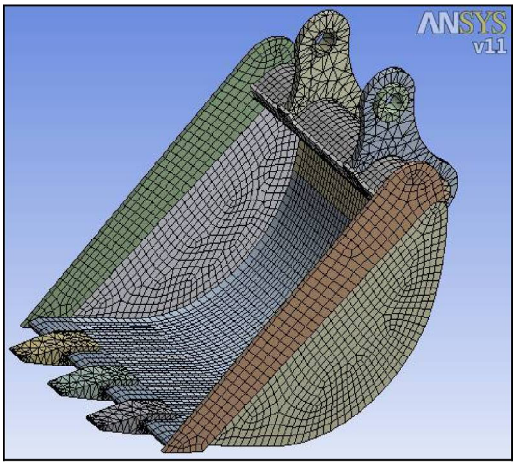


Figure 4: Von Misses Stresses of Bucket

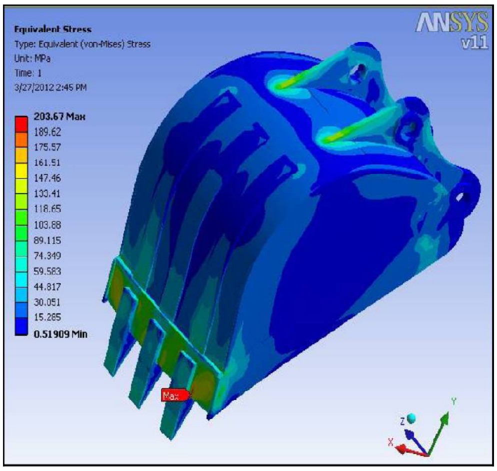
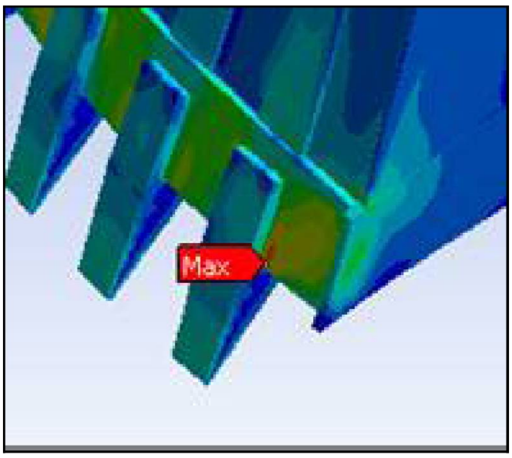


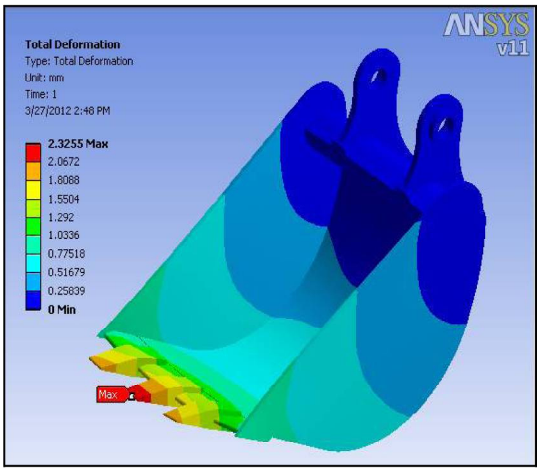
Figure 5: Enlarged View of Maximum Stresses of Bucket



The maximum Von Misses stress is acting at the leap plate near teeth as shown in Figure 4, which is made up of HARDOX 400 material with the yield strength of 1000 MPa, by taking safety factor as 2, Equation (1) yields = 203.67 MPa, $[\sigma_y] = (\sigma_y/\text{Safety factor}) = 500$ MPa, this clearly indicates $\sigma_{VM} < [\sigma_y]$, so the design of the bucket is safe.

Figure 6 shows the displacement of the bucket after application of known boundary and loading condition.

Figure 6: Displacement of Bucket



It clearly depicts that the maximum displacement occurs at the tip of the teeth as 2.3255 mm which is less than the minimum thickness of plate used in the bucket. It also indicate that the maximum displacement of the bucket is within the limit of acceptance, therefore the design of the bucket is safe for applied static load.

Analysis of the Arm

Figure 7 shows the static analysis of arm of the backhoe excavator. Figure 8 shows the boundary and loading conditions applied to the arm. Figure 9 shows the mesh view of the arm with 44126 nodes and 8670 elements.

Figure 7: Static Force Analysis for Arm

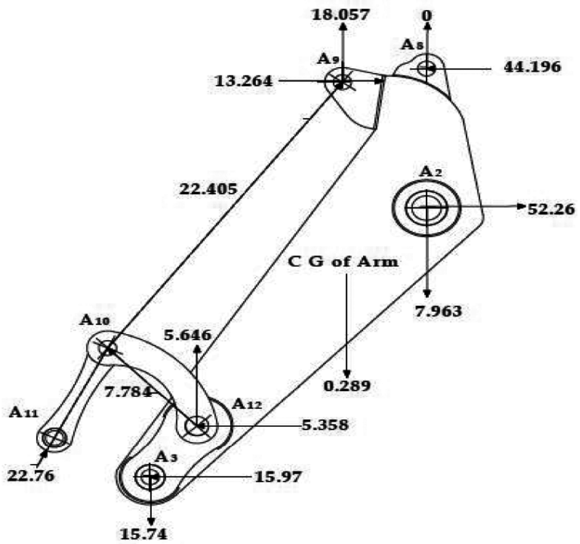


Figure 8: Boundary Conditions for Arm

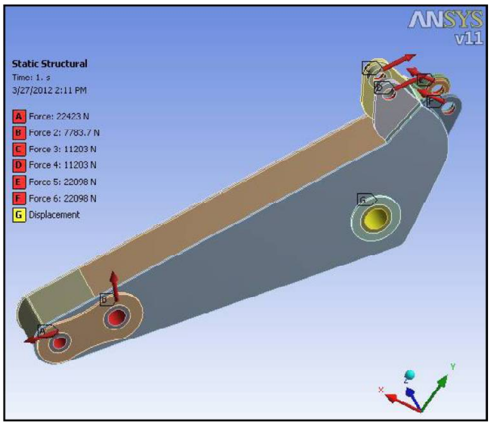


Figure 9: Mesh View of Arm

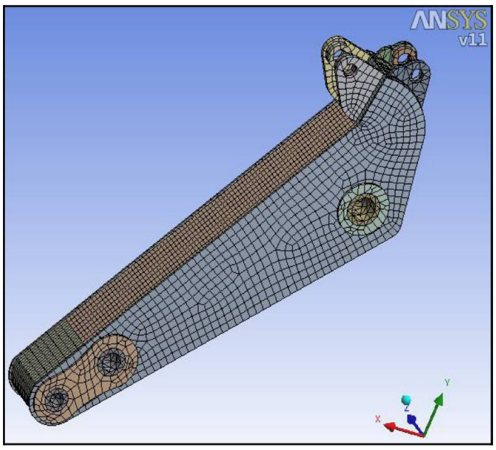


Figure 10 shows the results of the Von Misses stresses on arm assembly. As it can be seen from the Figure 10 that the maximum Von Misses stress is acting at the arm cylinder mounting lug and it is 239.39 MPa. Figure 11 shows enlarged view of the arm at which the maximum stress is produced.

Figure 10: Von Misses Stresses of Arm

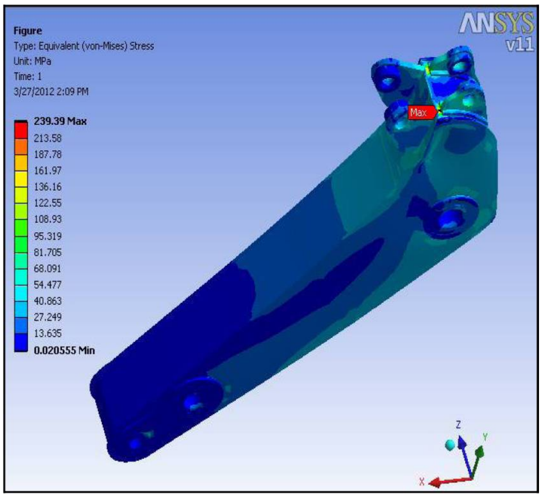
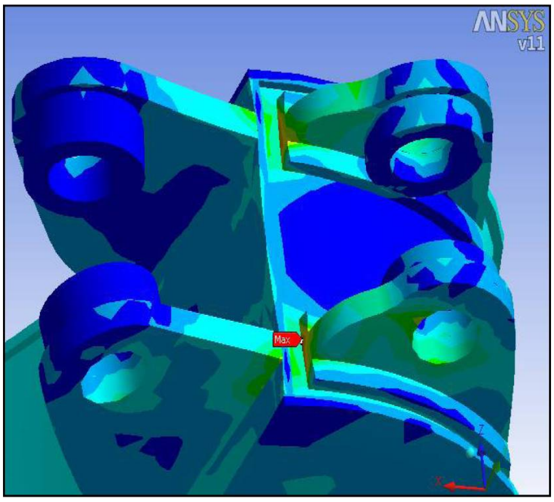
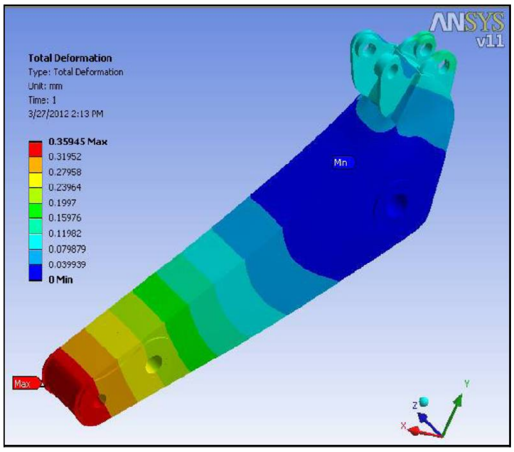


Figure 11: Enlarged View of Maximum Stresses of Arm



Now, yield strength of the material HARDOX 400 (because maximum Von Misses stress is acting at the mounting lug, made up of HARDOX 400) is 1000 MPa. Equation (1) yields $[\sigma_y]$ = 500 MPa (safety factor = 2), and σ_{VM} = 239.39 MPa (Figure 10), so $\sigma_{VM} < [\sigma_y]$ and this indicates that the design of the arm is safe. Figure 12 shows the maximum displacement of 0.35945 mm occurs at the free end of the arm (A_3 point) which is far less than the minimum plate thickness used in the arm therefore the design of the arm is safe for static condition.

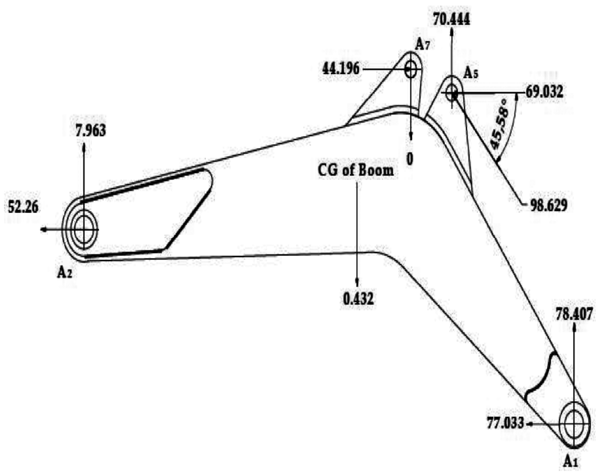
Figure 12: Displacement of Arm



Analysis of the Boom

Figure 13 shows the static force analysis of the boom to determine the boundary condition

Figure 13: Static Analysis of Boom



for performing stress analysis of the boom. Figure 14 shows the boundary conditions of the boom as calculated. Figure 15 shows the mesh view of the boom with 31855 nodes and 4647 elements.

Figure 14: Boundary Conditions for Boom

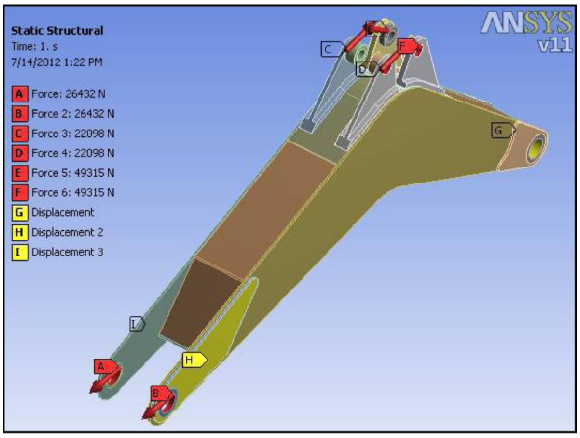


Figure 15: Mesh View of Boom

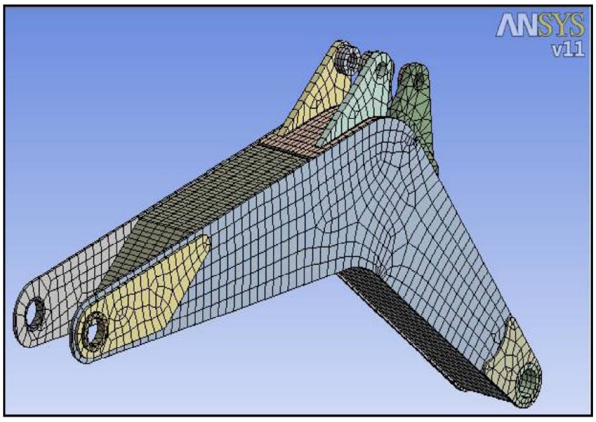


Figure 13 shows the static force analysis of the boom to determine the boundary condition for performing stress analysis of the boom. Figure 14 shows the boundary conditions of the boom as calculated. Figure 15 shows the mesh view of the boom with 31855 nodes and 4647 elements.

Figure 16 shows the results of the Von Misses stresses on boom assembly. As it can be seen from the Figure 16 that the maximum Von Misses stress is acting on the mounting lug and it is 246.71 MPa. Now, yield strength of the material HARDOX 400 (Because maximum Von Misses stress is acting on the mounting lug, made up of HARDOX 400) is 1000 MPa. Equation (1) yields $[\sigma_y] = 500$ MPa (safety factor = 2), and σ_{VM} = 246.71 MPa (Figure 16), so $\sigma_{VM} < [\sigma_y]$ and this indicates that the design of the boom is safe. Figure 17 shows the enlarged view of the boom at which the maximum stress developed. Figure 18 depict that the maximum displacement of

Figure 16: Von Misses Stresses of Boom

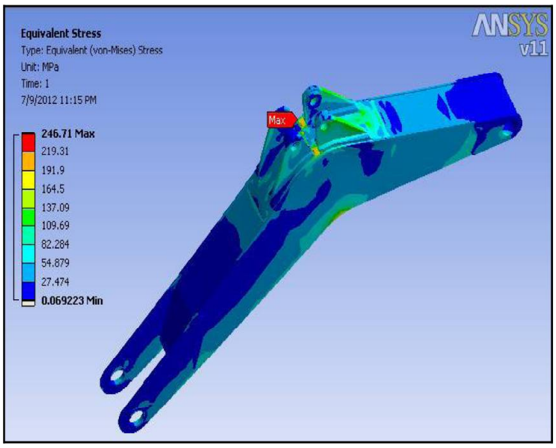


Figure 17: Enlarged View of Maximum Stresses of Boom

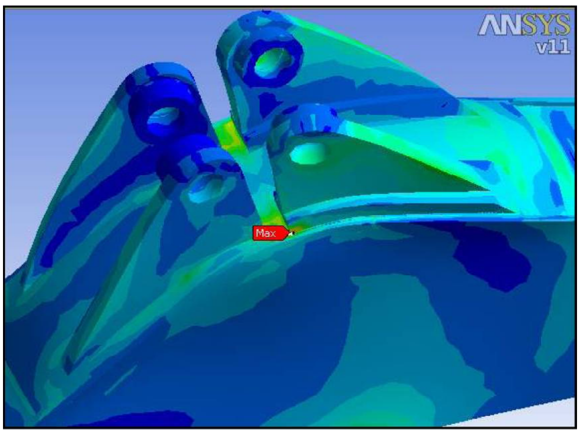
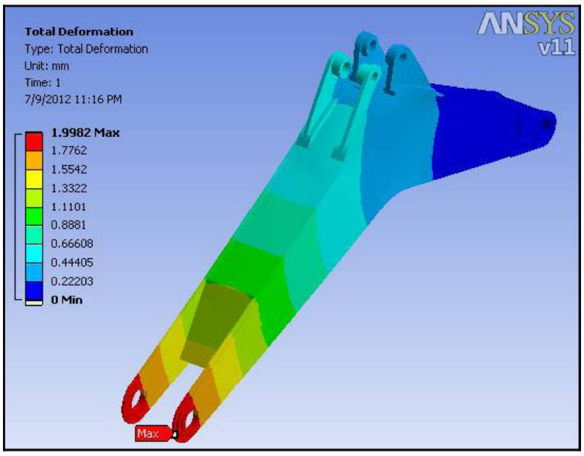


Figure 18: Displacements of Boom



1.9982 mm occurs at the free end of the boom (A_2 point) is very less than that of the minimum thickness of the plate used in the boom, therefore the boom is safe for the given static loading condition.

Analysis of the Swing Link

Figure 19 shows the static force analysis of the swing link. Figure 20 shows the boundary conditions of the swing link as calculated and Figure 21 shows the mesh view of the swing link with 47376 nodes and 25387elements.

Figure 19: Static Force Analysis of Swing Link

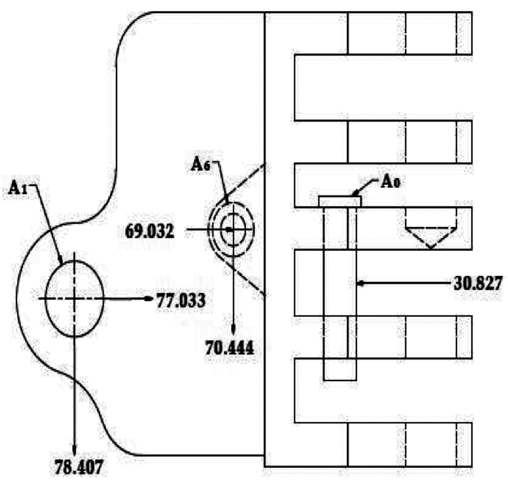


Figure 20: Boundary Conditions for Swing Link

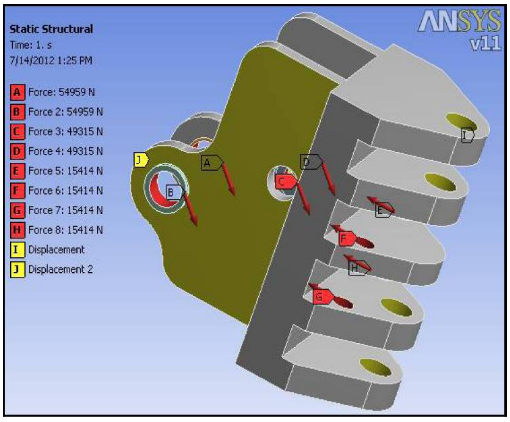


Figure 21: Mesh View of Swing Link

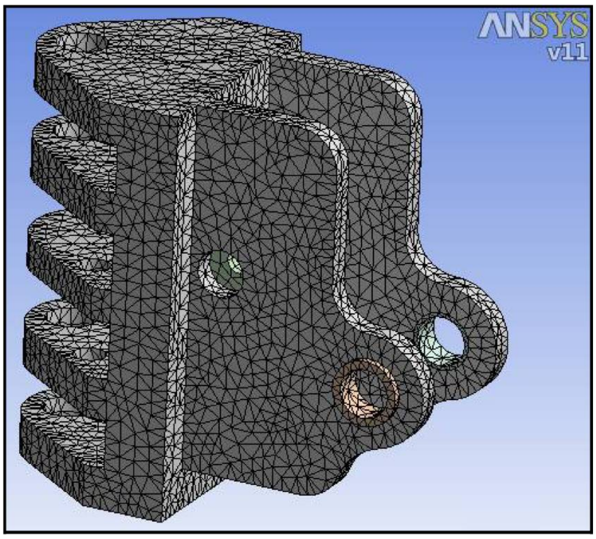


Figure 22 shows the results of the Von Misses stresses developed on swing link. As it can be seen from the Figure 22 that the maximum Von Misses stress is acting on the cylinder mounting lug and it is 119.83 MPa. Figure 23 shows the Enlarged view of maximum stress developed on the swing link.

Now, yield strength of the material HARDOX 400 (Because maximum Von Misses stress is acting at the cylinder mounting lug, made up of HARDOX 400) is 1000 MPa.

Figure 22: Von Misses Stresses of Swing Link

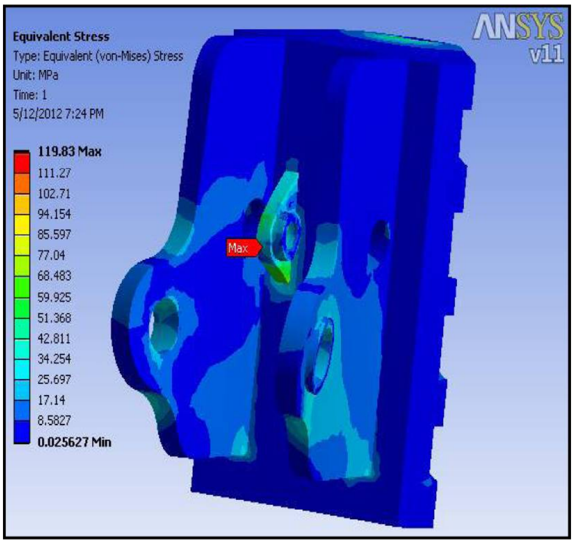
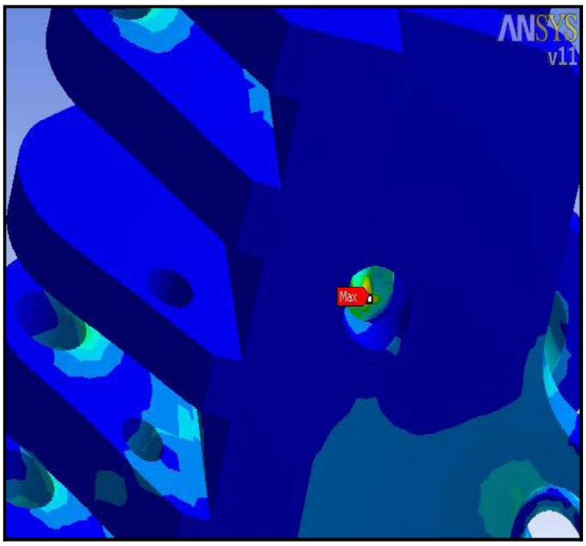


Figure 23: Enlarged View of Maximum Stresses of Swing Link



Equation (1) yields $[\sigma_y]$ = 500 MPa (safety factor = 2), σ_{VM} and = 119.83 MPa, so $\sigma_{VM} < [\sigma_y]$ and this indicates that the design of the swing link is safe.

Figure 24: Displacements of Swing Link

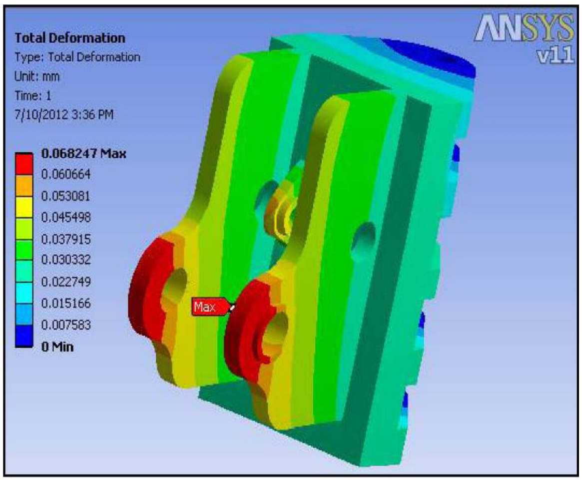


Figure 24 depict that the maximum displacement of 0.068247 mm occurs at hinge joint of the boom (A_2 point) is very less than that of the minimum thickness of the plate used in the swing link, therefore the swing link is safe for the given static loading condition.

Analysis of the Backhoe Excavator Attachment Assembly

Figure 25 shows the boundary conditions of the backhoe excavator attachment. Figure 26 shows the mesh view of the boom with 151910 nodes and 47749 elements.

Figure 25: Boundary Conditions of Backhoe Excavator

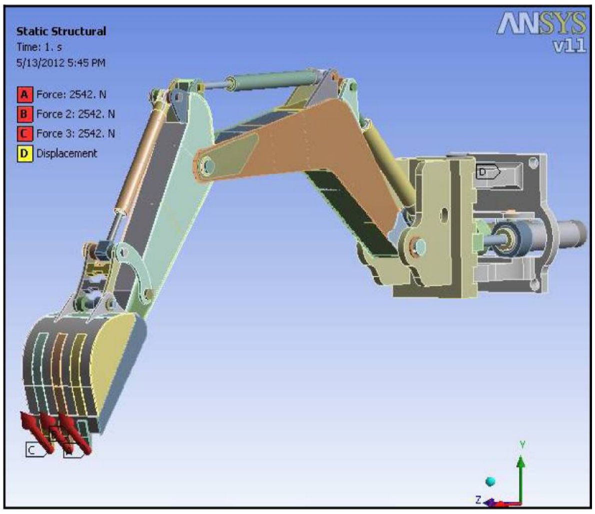


Figure 26: Mesh View of Backhoe Excavator

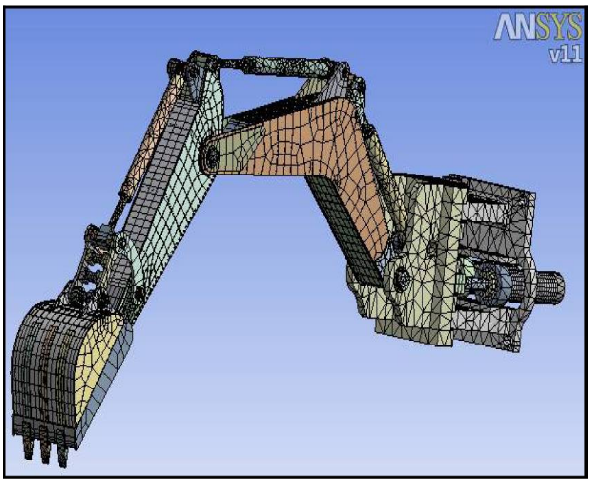


Figure 27 shows the maximum Von Misses stresses produced in the backhoe attachment assembly. Maximum Von Misses stress acting on the bucket is 252.3 MPa. The maximum Von Misses stress is acting at the intersection of mounting lug and top bucket plate as shown in Figure 27, which is made up of Hardox 400 material with the yield strength of 1000 MPa, by taking safety factor as 2, Equation (1) yields σ_{VM} = 252.3 MPa [σ_y] = 500 MPa, this clearly indicates $\sigma_{VM} < [\sigma_y]$, so the stresses produced

Figure 27: Von Misses Stresses of Backhoe Excavator

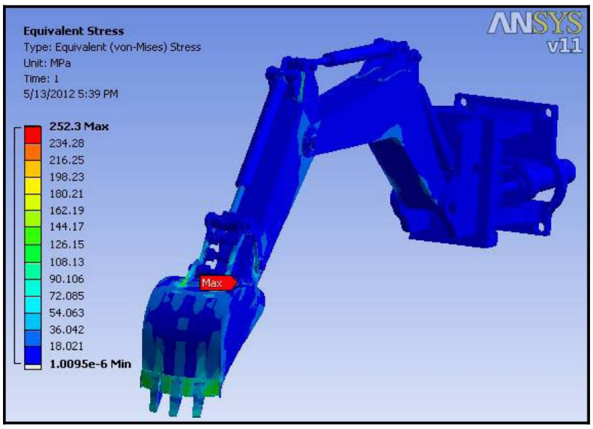
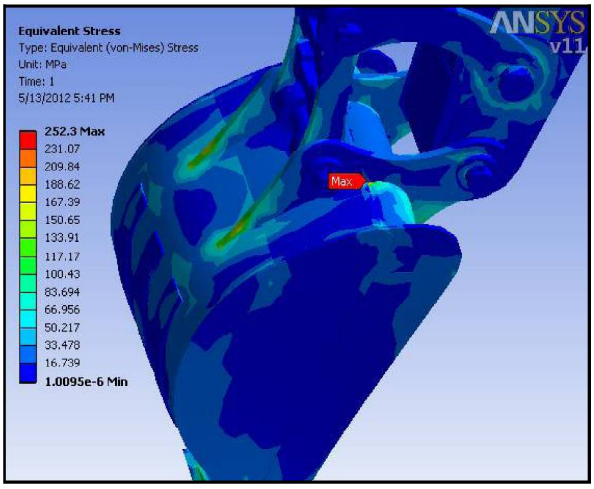


Figure 28: Enlarged View of Maximum Stresses of Backhoe Excavator



in the assembly of the backhoe are within the limits and the design is safe. Figure 28 shows the enlarged view of excavator assembly where maximum stress is produced.

Analysis of the Backhoe Excavator Attachment with Consideration of Welding

Now, welding is introducing to each part of the excavator with the help of WLDMENT tool of the Autodesk Inventor 2011. Then the parts with welding are analyzed with FEA approach using ANSYS and procedure for analysis remain same as discussed in above sections.

Strength of the material for the welding should be less than the strength of the base metal. A soft electrode is a filler material with yield strength less than parent material. These electrodes reduce the level of residual tension in the weld and hence the tendency of the material to develop cracks in cold state (Bhaveshkumar and Prajapati, 2011b). Therefore it is very important to carry out the stress analysis of backhoe excavator parts and its assembly with application of welding.

Based on this analysis we can know the effect of the welding on the stress produced in the parts of excavator.

The Table 1 shows the comparison of stresses produced in the parts with welding and without welding.

Table 1: Comparision of Stresses Produced in Backhoe Model with and Without Welding

S. No.	Part Name	Maximum Von Misses Stresses (MPa)	
		Backhoe Model Without Welding	Backhoe Model With Welding
1.	Bucket	203.67	178.33
2.	Arm	239.39	212.46
3.	Boom	246.71	242.41
4.	Swing link	119.83	119.29
5.	Backhoe Assembly	252.30	241.87

CONCLUSION

The mini hydraulic backhoe excavator attachment is developed to perform excavation task for light duty construction work. Based on static force analysis finite element analysis is carried out for individual parts as well as the whole assembly of the backhoe excavator with and without consideration of welding. It is clearly depicted that the stresses produced in the parts of the backhoe excavator attachment are within the safe limit of the material stresses for the case of with and without consideration of welding. The result shows the maximum stresses produced in the parts with welding is less than the parts without welding, it clearly depict that the welding strengthen the parts. Based on results also we can conclude that the maximum stresses produced in the parts are very less compare to limiting (safe) stress of the parts material, therefore there is a scope to perform the structural optimization of the excavator attachment for weight reduction. Optimization can help to reduce the initial cost of the attachment as well as to improve the functionality in context of controlling of the excavation operation.

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