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Modeling, FEA & Optimization of Backhoe Excavator attachment for max. Machine Life

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Abstract* — Excavators are primarily be used to excavate below the natural ground, on which the Machine also rests. Due to severe working conditions, excavator parts are subjected to high wear and tear. For better results, the excavator mechanism should work efficiently and effectively in unpredictable working conditions. In this work, the reference of a backhoe machine failure case has been taken for its analysis. At first, all the relevant data concerning the Machine has been collected and tabulated, further based on the data collection, a 3D-CAD model of the machine components is generated in the 3D mechanical design package software PRO-E wildfire V 5.0, which is further analyzed in the PRO-E Mechanica module of the same for static, kinematic and dynamic condition, to know the behavior of the connections between the components of the Machine in sustaining the forces/ stresses generated in carrying out the required activity with enough strength, which results in better design optimization. Further, the Finite Element Analysis (FEA) of the boom (Boom) has been carried out to evaluate the boom's stresses and deflection to qualify the same with the standards for the system's fatigue life. Hence based on optimum findings [Factor of Safety (FOS)] from the analysis, we can predict the approximate machine life in the considered working conditions as per the ASME standards.

Keywords — *3D-CAD model, Pro-E Wildfire V 5.0, Pro-E Mechanica, Static, Kinematic, Dynamic, Finite Element Analysis, FEA, Boom, Fatigue life, Factor of Safety, FOS, Machine life, ASME.*

I. INTRODUCTION OF BACKHOE-LOADER

A. Introduction

In all the machines used in the construction industry, Backhoe-Loader is the most preferred one for excavation and earthmoving due to its versatility. Many construction concerns consider the Backhoe to be the workhorse of earthmovers.

The most common and versatile piece of equipment on any construction site today is the backhoe loader. The backhoe loader combines two useful tools into one Machine, which put it at the top of the list on most construction sites and many farms. It's just that useful, and utility is the name of the game.

Diesel engines power backhoe loaders. Backhoes are four-wheeled tractor vehicles with the Backhoe on the rear and the loader on the front end. The operator sits in the middle, just like on a traditional tractor. The front-end loader is operated while facing forward; however, to use the Backhoe, the operator must turn around and face the equipment's rear.

The front-end loader is a wide bucket (Fig.2: The Loader), usually about the width of the equipment, with attachment arms on each side. These arms are used to lift and lower the bucket hydraulically, while another hydraulic actuator tilts the bucket up and down to pick up loose piles of materials and dirt. Additionally, the operator may place the loader's bucket on the ground and drive in reverse to level or grade a site.

On the rear end of the backhoe loader is the actual Backhoe (Fig.1: The Backhoe). The Backhoe is a hydraulic digging scoop powered by the tractor's hydraulics. The Backhoe is a three-jointed arm designed to dig into hard surfaces and remove rough rocks. The backhoe operator must turn around in his seat to switch from digging a hole to filling it back in again using the front-end loader.

A four-wheeled steering backhoe, also called a skid steer, greatly improved maneuverability (Fig.3: The tractor). On these skid steer backhoes, operators can independently turn the front and rear wheels, offering the needed maneuverability for these tight operating areas. This feature of four-wheel steering is gaining a great deal of popularity on construction sites and modern farms.

A backhoe-loader is an Off-highway vehicle and a very useful piece of construction equipment. It is a piece of excavating equipment made of three separate components

Fig.1: The Backhoe

Fig.2: The Loader

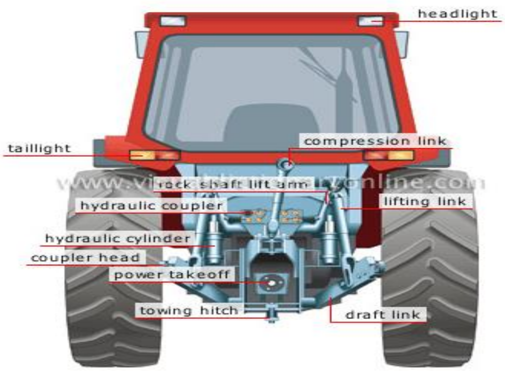

Fig.3: The Tractor

B. *Working of Backhoe*

As we know that the Backhoe is essentially a soil digging Machine, whose working tools of the Backhoe were actuated by the hydraulic cylinders, fitted for required motion and this motion for digging operation is controlled by controlling the hydraulic cylinders. In this Machine, each component is actuated by hydraulic cylinders.

A standard combination of extensions and retractions of the hydraulic cylinders generates the required motion of the components/ attachments for digging. The hydraulic cylinders simultaneously provide the digging forces to be generated at the bucket tip. The pressure to be developed is generated by the hydraulic pump, which is coupled to the engine. Fig. 4 describes the working volume of a backhoe

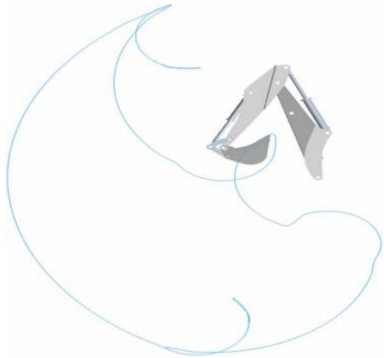

Fig.4 Working Volume of Backhoe

C. *The motivation of the study*

In response to the booming construction industry, a backhoe-loader is often the only piece of earthmoving equipment brought onto small to medium landscaping projects since a backhoe can duplicate the work of a bulldozer, front end loader, and excavator. Also, the working environment for Backhoe-Loader is quite diverse and sometimes extreme, which leads to:

1. The high rate of failure of Machine

2. Increased competition within OEM's (Original Equipment Manufacturers)

As a result of the above circumstances, the design of Backhoe-Loaders is continuously optimized and the influx of a variety of new types of Backhoe-Loaders and other earthmoving equipment.

The optimization is mainly in the backhoe and loader components of the Machine. The first step towards optimization is analysis.

The Machine and its components are analyzed concerning the following parameters.

a) Strength
b) Safety
c) Cost

II. LITERATURE REVIEW

The construction industry is the backbone and a propelling force behind India's progress. The construction industry includes the construction of dams, skyscrapers, bridges, roads, and even mining work. This has increased the demand for much construction equipment, especially 'earth moving machines.' These machines have become an important aspect of human's day to day life, replacing the efforts of "thousands of human beings." In most construction work, excavation and earthmoving work are of prime importance. Also, there are numerous classes of earthmoving equipment available, each aimed at specific purposes. As we all know, the Earthmoving machines were used in engineering projects such as roads, dams, open pit excavation, quarries, trenching, recycling, landscaping, and building sites [1].

In the present demand for high speed and efficiency in machine work, a hydraulic excavator's working condition tends to be more abominable, and its structure is prone to be more and more complex. So, structural, static, and dynamic performances are desired to be higher. Furthermore, structural, static, and dynamic performance optimization plays a significant role in complex mechanical systems. In context to this, XUE Caijun, QIU Qingying & FENG Peien [2] discussed a new method in their paper to realize the structural, static, and dynamic, collaborative optimization of hydraulic excavator working equipment. A mathematical model of static and dynamic optimization is developed based on finite element analysis. Further work introduces the set-up of the testing system and evaluates the experiment results, which are used to validate the static F.E. models and update the dynamic F.E. models. Hence, in conclusion, the evaluated optimal results prove the presented method, efficient and effective.

After developing a mathematical model, researchers focused on the automated structural optimization of an excavator boom, which Uzer Cevdet Can [3] discussed in his dissertation work. This work's need is because the preparation of the CAD model, performing FEA, and data evaluation was time-consuming and require experience to work on. In this work, he discussed the software Opti-BOOM, which generates a CAD model using a definite set of parameters and then performs FEA by using a commercial program, which has been modified. Different parameters, such as the model parameter generation, model creation, analysis data collection, and data evaluation phases, can be done using the Python and Delphi-based computer codes. A global heuristic genetic algorithm was chosen to search different boom models, which helps us select an optimum one.

As the previous intellectuals discussed the optimization based on algorithms, so researcher Boran Kiliç [4] in his work thought of developing a dynamic model of the loader system of a backhoe-loader which he used physical modelling toolboxes inside the commercially available simulation software MATLAB/Simulink. He worked on the rigid bodies and joints in the loader mechanism, and loader hydraulic system components are modelled and analyzed in the same environment using MATLAB. Further, he showed the interaction between the hydraulic system's bodies and response, which were obtained by co-operating the mechanical and hydraulic analyses. The system variables such as pressure, flow, and displacement are measured on a physical machine and then compared with the simulation results, which are found consistent enough to determine the dynamic loads on the joints and attachments of the backhoe-loader. Above all, he suggested that the prototyping time and costs can be highly reduced by implementing this model in the future design process.

Since the time, optimization was focused on software only, so the gentlemen Luigi Solazzi [5] took a step forward in his work and analyzed the excavator, which is composed of three elements and assumed the load conditions to evaluate the Stress, where five. The aim of his work focuses on studying the boom and the arm of an excavator by replacing the conventional material (Aluminium Alloy-which they are usually made of) with the new one (Steel Alloy). The material change lightens the arm's components, which allows us to increase the load capacity of the bucket to 1.35m^3 from 1m^3, so it is justified that there is the possibility to increase the excavator productivity per hour by 35%.

Following remarkable work, Bhavsehkumar P. Patel & Dr J. M. Prajapati [6] focused on the work carried out by other researchers in the field of kinematic modelling which is helpful for understanding and improving the operating performance of the backhoe excavation machine. He concluded that there is much previous research work done by researchers in the same field. However, still, there is a scope to develop a kinematic model of backhoe attachment to predict the excavation trajectory as well as better control of backhoe attachment to carry out required excavation task at the desired location.

Juber Hussain Qureshi and Manish Sagar [7] concluded that force analysis and strength analysis are an important step in designing excavator parts. FEA is the most effective technique in strength calculations of the structures. In this paper, authors describe its basic structure, stress characteristics, and the engineering finite element modelling for analyzing testing, and validation of backhoe loader parts under high-stress zones. This study tells the Boom optimization for including the strength of welds where welds can be modelled with shell elements along with the boom to take moments that can be done to predict the failure stresses of the welds. Localization and stress linearization of the weld can be simulated for calculating the factor of safety for weld strength.

Juber Hussain Qureshi and Manish Sagar [8] performed the finite element analysis of the boom, which is followed by the results of the Dynamic study of the Boom of the Machine. This paper researcher described the platform to understand the Modelling and FEA of Boom of Backhoe Loader as Inertia plays a big effect while performing a dynamic analysis, which is completely dependent upon the time in this case, which can only be assumed for the cycle to complete. The effect of inertia was plotted on the graph, especially for new shapes of the boom, to get the safe results of stresses resulting in the safe life of the boom.

Anand Thorat and G.V.R Sheshagiri Rao [16] in their work, discussed the static analysis of the chassis, which shows the equivalent stress and deformation contour when Backhoe Loader is in working condition. As from static analysis, the high-stress area was found out when Backhoe Loader is considered to work in different load conditions and also suggested some design changes through which Stress can be minimized.

Rahul Mishra and Vaibhav Dewangan [10] calculated the capacity of the bucket, according to SAEJ296. The bucket specification considered is the most superior one when compared to all the other standard models. SAEJ1179 calculates the breakout force. The SAE provides the breakout and digging force. The optimization is done for various components of the assembly and presented in the paper.

R M Dhawale and SR Wagh [11] reviewed the various analysis done in the past concerning the components of the excavator's arm and the effects of various forces on excavator arm components. This paper gives an overview of the work carried out in the modelling and F.E. analysis of an excavator. Various software's are used by researchers like PRO-ENGINEER, CATIA, ANSYS, according to their ease of user-friendliness and accuracy of results. The mini hydraulic backhoe excavator attachment was developed to perform excavation tasks for light-duty construction work. Further, the work carried out is based on static force analysis. Finite element analysis is carried out for individual parts and the whole assembly of the backhoe excavator with and without consideration of welding. The stresses produced in the backhoe excavator attachment, are within the safe limit of the material stresses for the case of with and without consideration of welding.

C.P. Motka and Ikbalahemad R Momin [12] presented the study, which covers the detailed design, modelling, and F.E. analysis of Backhoe Machine. The backhoe Loader is the rear part of the excavator machine. This Machine is incorporated in a wide variety of tasks such as construction, small demolitions, light transportation of building materials, powering building equipment, and digging holes/excavating, landscaping, breaking asphalt, and paving roads. Due to which various loads are applied at the bucket tip and to the boom and digger arm. So it is necessary to analyze the parts assembly to avoid failure while it is in working condition. According to the static analysis performed in this work, the high-stress area can be found when Backhoe Loader is considered to work in different load conditions. Also, some design changes have been suggested, which results in stress minimization in the area.

As the known fact that the main objective of structural design is to achieve the minimum mass structure, which will satisfy the stiffness, strength, and other requirements, in his work, Hemanth Kumar BL and Nagesh N [15] performed the static structural analysis of backhoe-loader arms with FEM. This research aims to stimulate and strengthen the back and front arms of the backhoe-loader concerning Stress under maximum loading conditions and different boundary conditions. According to findings, the back and front arms of the backhoe-loader are strengthened with reinforcements, which resulted in an increase of the strength of the components by 20%.

Following which R. Jaison and Ramesh Kumar [14] in their project work, designed and analyzed a detachable type backhoe components using ANSYS. This paper deals with the design of backhoe and loader components and special chassis for the tractor for a limited 2000N backhoe and 6000N loader load. The Machine has a hydraulic unit which is selected to run by the tractor engine power of 50Hp. In contrast, the original Backhoe has 60Hp, which is made of special replaceable attachment so that the load is limited when compared to the original Backhoe. The components are 3D modelled using CREO PARAMETRIC modelling software, and then the structural analysis is carried out using ANSYS.

III. RESEARCH METHODOLOGY

The Boom is the most effective part of the backhoe loader. The boom of L&T CASE 775 is made of fabricated plates bent and welded to make one side of the boom; the two opposite parallel sub-assembly are welded with stiffener plates inside. The drawing of the Boom with sectional width is shown in the Figure. All the plates welded of the boom area of 16 mm thickness. The fillet weld can be measured to be 8 to 10 mm strong.

The weld is stronger than the base metal is kept in mind, and thus the weld is not modelled in 3D software and is not considered for any Finite element analysis done in the project.

Few photographs of the original model are also displayed of the Machine of which the measurements are done (Fig.5-Fig.9).

Fig.5: Connection of Boom and Dipper

Fig.6: Dipper connection with Bucket

Fig.7: Hydraulic Block with hoses to control the cylinders and other operations

Fig.8: Weld Quality is shown in the snap

Fig.9: Cylinder connection & Weld connection shown

IV. MODELLING

The Major other components of the Machine as depicted above will be shown hereunder in a 3D model in the screen capture of the Pro-E window (Fig.11-Fig.14) along with the drawing for the Boom where the dimensions of all the kinematic points are maintained to the point measured from the Machine (Fig.10).

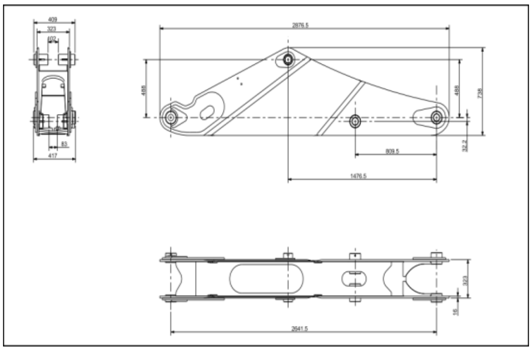

Fig.12: Showing the 3D model of the Dipper

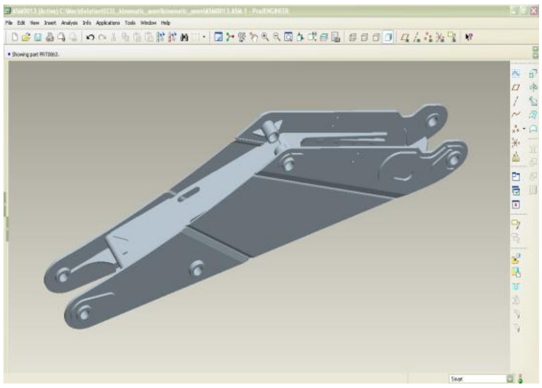

Fig.10: Drawing for the Boom where the dimensions of all the kinematic points are maintained to the point measured from the Machine

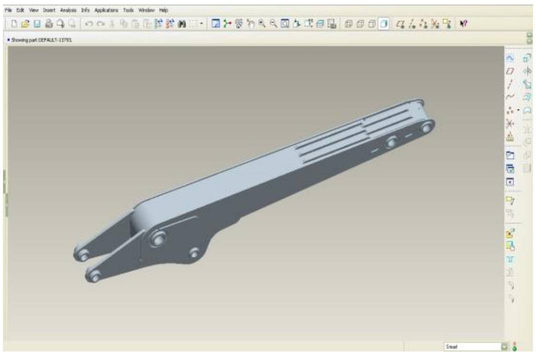

Fig.11: Cad model of Boom

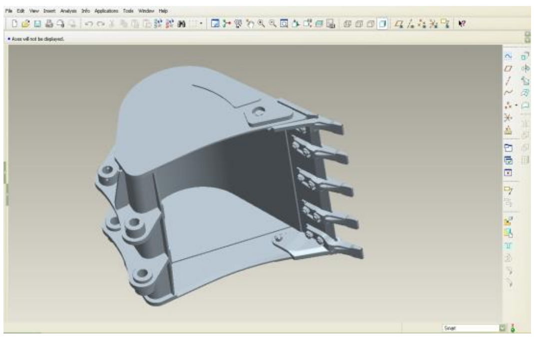

Fig.13: Showing the 3D model of the Bucket

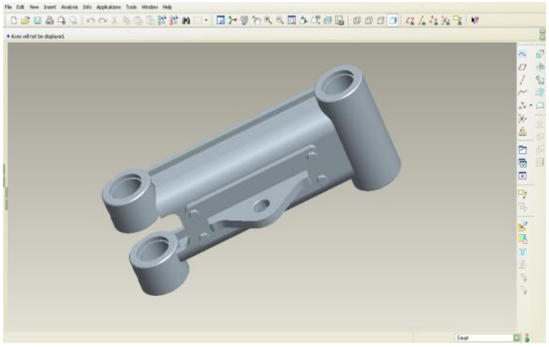

Fig.14: Showing the 3D model of the Linkages

V. KINEMATIC AND DYNAMIC ANALYSIS OF BACKHOE LOADER

A. Kinematic Analysis

To study the kinematic behaviour of the components connected, the assembly of all the components is done in Pro-E using connection joints in the assembly module of pro-e. The motion is then analyzed in the Pro-Mechanism module of Pro-E.

The Figure below shows the connections of Pin joint to different parts to facilitate the system's motion. At the same time, the linear motion of cylinders is performed via the use of slider mechanism constraint in the assembly mode of the Pro-engineer standard module. The closed setting for cylinders is done to exteriorize the dependencies of motion constraint to facilitate the regulation of motions.

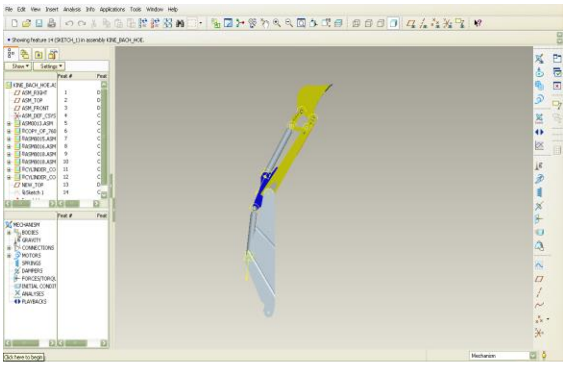

Fig.15: Connection of pin joint to different parts

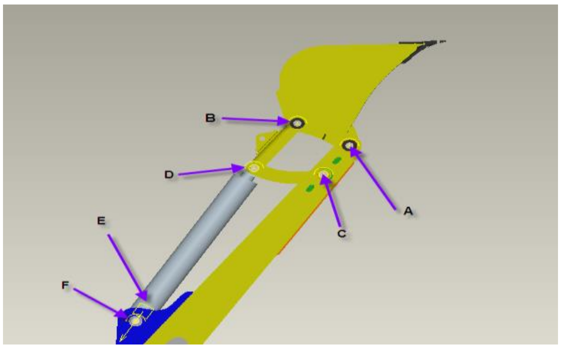

Fig.16: Connections used in the synthesis of the bucket

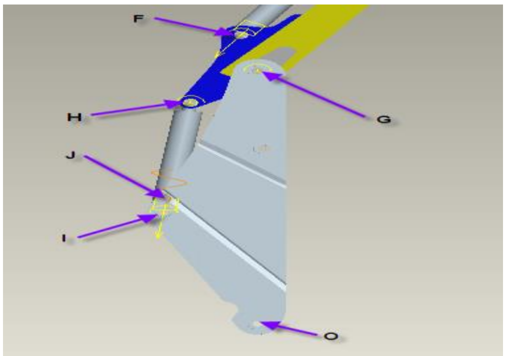

Fig.17: Joint connections in the boom

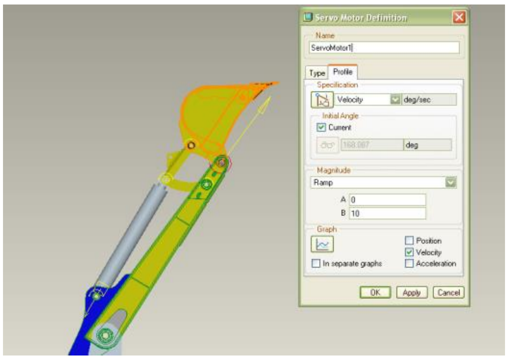

Fig.18: Showing the servo motor connection with velocity imparted

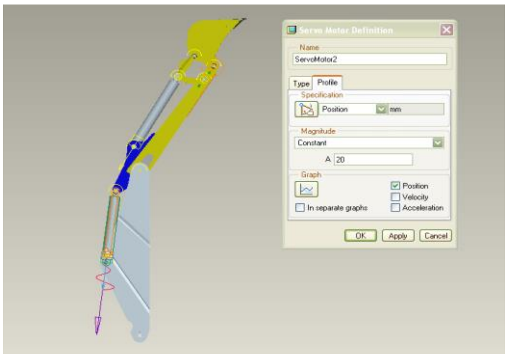

Fig.19: Inputs for the position in the mechanism module of Pro-E

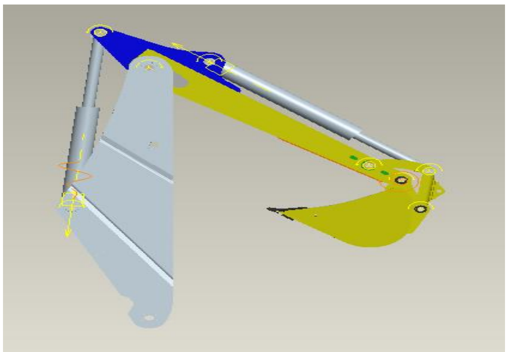

Fig.20: Constraint of overall workspace

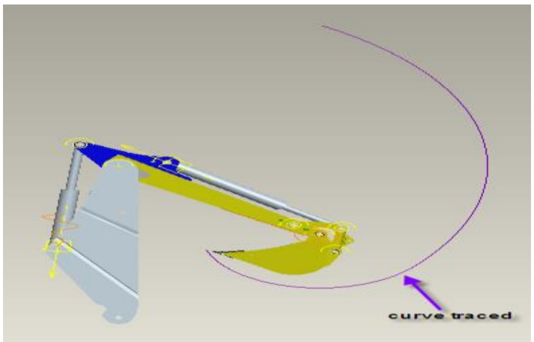

Fig.21: Curve traced by the toe of the bucket

B. Dynamic Analysis

Under the above section, covered is the kinematic part of the motion. Now digging into the dynamics part of the motion, we understand here that the total no. of connections allowed on the boom is two, as illustrated below:

A. Pin connection of the cylinder stated as "I" in Fig.17 above, which will be subjected to the reaction force produced by the cylinder.

B. The Rotational degree of freedom at joint "G" is subjected to the forces' reaction calculated when the bucket follows the trace path shown in Fig.21 above when the bucket is filled with the aggregate.

VI. EXPERIMENTAL WORK

Finite element modelling is one of the major subjects of Computer-Aided Engineering, where the importance of the Finite element method is subdivided into following rules of problem-solving methodologies.

1. Pre-processing
2. I am defining correct loads and correct Boundary conditions.
3. Solution and Post-processing

Each FEA program comes with an element library or can be constructed over time. Some sample elements are:

1. Rod elements
2. Beam elements
3. Plate/Shell/Composite elements
4. Shear panel
5. Solid elements
6. Spring elements
7. Mass elements
8. Rigid elements
9. Viscous damping elements

The basic decision to be taken by the F.E. analyst is to decide on the type of modelling to be done in an FEA package. Few types of modelling used are illustrated below:

1. Shell Modeling
2. Solid Modeling &
3. Beam Modeling

The Meshed model of the boom is shown in the Fig.22 below, along with the details of the mesh created by the Pro-Mechanica software, a meshed model of the boom is shown in the Fig.22 below:

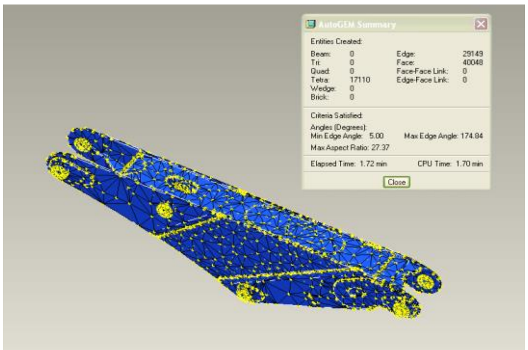

Fig.22: Showing the tetrahedral meshed model of boom

Fig.22 above shows the no. of elements created during the analysis. Each element will create an equation to be solved for displacement, which will be further used to make the assembly stiffness matrix combining the equation from all the elements. This assembly matrix will result in the values of displacements, which further be solved to result in Stresses.

The different parts of the boom which are connected in the assembly are also given a weld constraint in Pro-Mechanica to simulate the actual weld with 6 DOF fixed with each the two connected nodes to each other. Surface to surface weld known as perimeter weld and end weld commands are used in Pro-Mechanica.

The Resultant reaction loads from the Mechanism module is shown in the Figure below since this is a solid meshed model, the resultant point loads have to be assigned to surfaces to get the results from the FEA package.

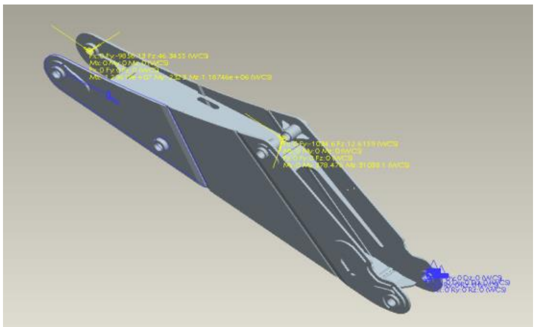

Fig.23: Reaction Loads from Pro-mechanism

VII. RESULTS AND DISCUSSION

A. Results

Since for dynamic analysis, the mass (Centre of Gravity) and the time play important two inputs required to solve any dynamic analysis. It is most difficult to predict the time of the motion. But by an average taken from viewing many cycles performed in-front of eyes by the driver driving the vehicle, we concluded the timing required to perform the operation shown in the complete video is performed in nearly 15-18 seconds.

Consideration 1:- Since to get to the worst condition analysis, we performed the dynamic simulation in pro-e with the time consideration of 15 seconds to complete the cycle.

Consideration 2:- Since it is worthless to make one more model with the density of the aggregate filled in the bucket, the bucket is made the consideration for the additional weight of the aggregate inside, which is calculated via a part created. The welded material S.T. 42 is replaced by EN 9.

The analysis was run with calculated weight (in kgs) as the weight inside the bucket, which was distributed as per the bucket's shape. The C.G. of the complete Machine is shown in Fig.24 below.

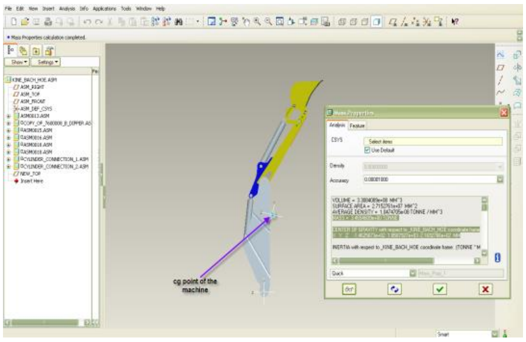

Fig.24: C.G. of complete Machine

The resulting window for the force analysis of the cylinder directly shifting the bucket is shown in Fig. 25 for the force graph for the complete range of time.

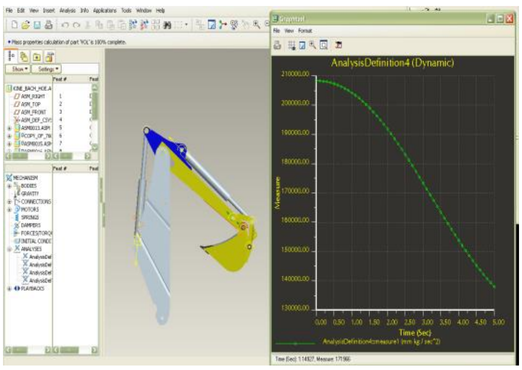

Fig.25: Result window for the force analysis of the cylinder

The force developed by the cylinder connected to the boom and the pin is given in Fig. 26 below.

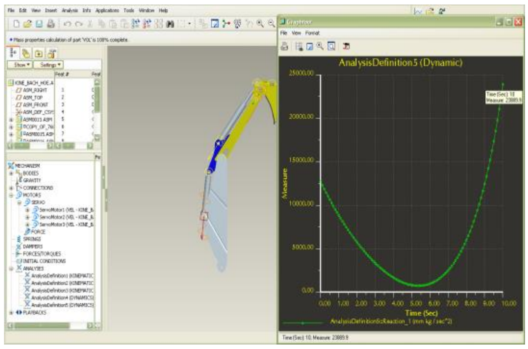

Fig. 26: Result of the force developed by the cylinder to the boom and pin

B. *Discussion*

i. *Discussion over the results of Stress produced as Result of Analysis:*

CASE 1: Mechanism Reaction Loads

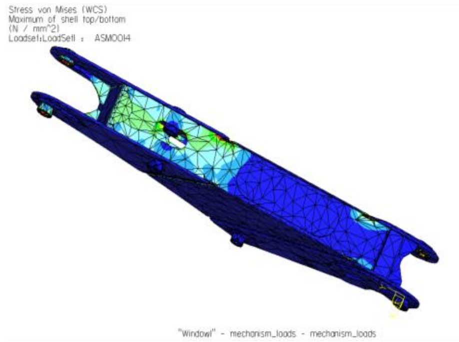

Fig. 27 (a): Results of Von-Mises Stresses for Mechanism Loads

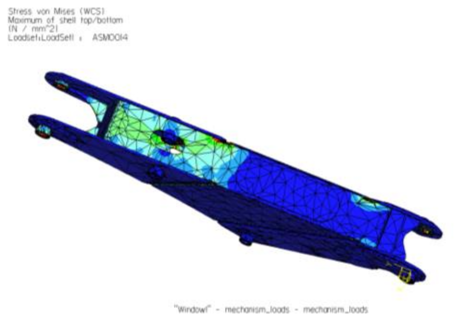

Fig. 27(b): Results of Von-Mises Stresses for Mechanism Loads

The green zone's stress level is 35 MPa limit while that is the red zone at the bushes are of the level of 55 MPa. This stress range is very much under the limit of stresses specified in the standards for the qualification of the material under the stress limit for fatigue loading.

Table 1: Von Mises Stresses Table for Case 1

S. No.	Von-Mises Stresses	Stresses Limit in Standard	Factor of Safety
1 (Green Zone)	35	110	3.14
2 (Red Zone)	55	110	2

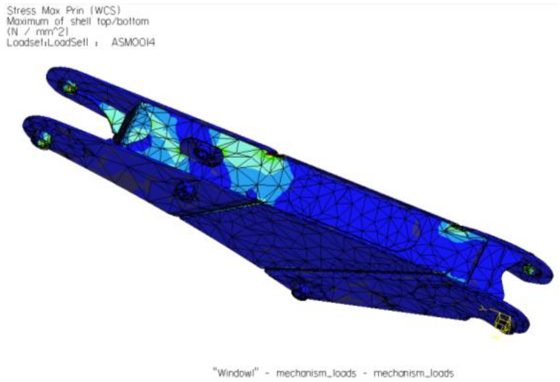

Fig. 28 (a): Results of Max Principal Stresses for Mechanism Load

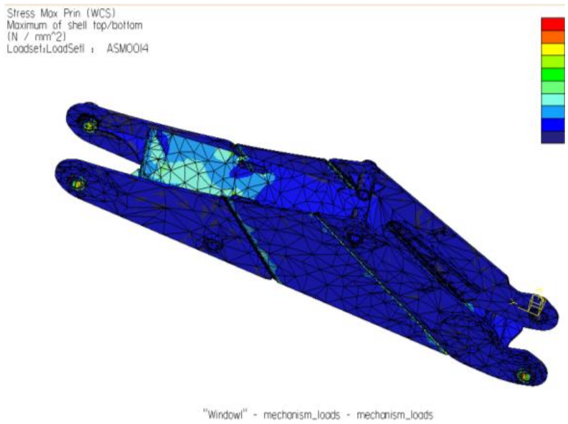

Fig. 28 (b): Max Principal Stresses for Mechanism Load

The Maximum Principal Stresses are shown in figures 28(a) & 28(b), where the stress limit in the green zone is 30-32 MPa while that in the red zone is 45-48 MPa.

Table 2: Maximum Principal Stresses Table for Case 1

S. No.	Max Principal Stresses	Stresses Limit in Standard	Factor of Safety
1 (Green Zone)	32	130	4.06
2 (Red Zone)	48	130	2.70

CASE-2: Total Force Applicable

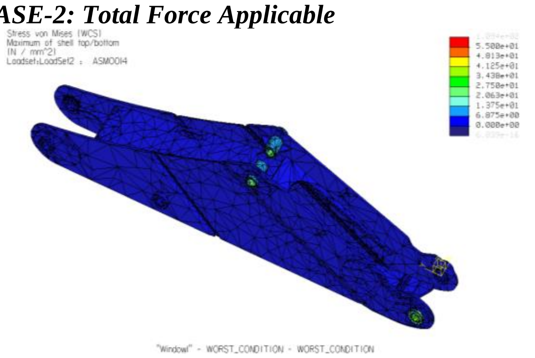

Fig. 29(a): Results of Von-Mises Stresses for Total Pressure Loads

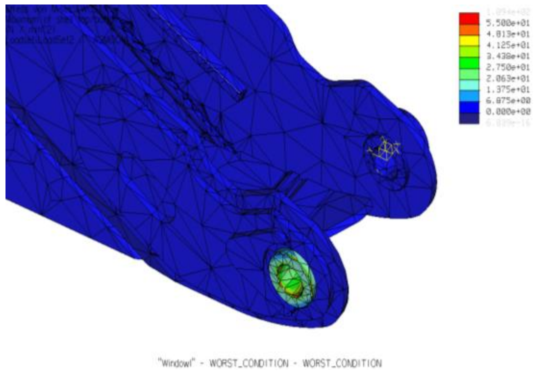

Fig. 29(b): Results of Von-Mises Stresses for Total Pressure Loads

Table 3: Von Mises Stresses Table for Case 2

S. No.	Von-Mises Stresses	Stresses Limit in Standard	Factor of Safety
1 (Light blue)	50	110	2.2
2 (Red Zone)	65	110	1.7

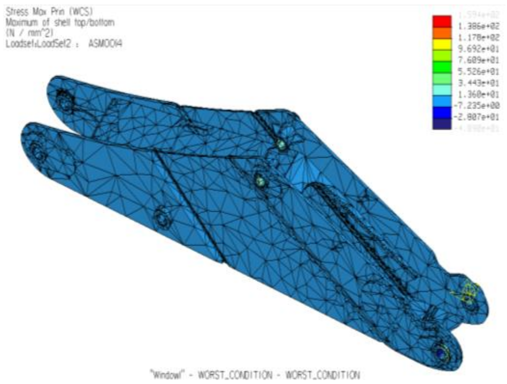

Fig. 30 (a): Results of Max Principal Stresses for Total Pressure Loads

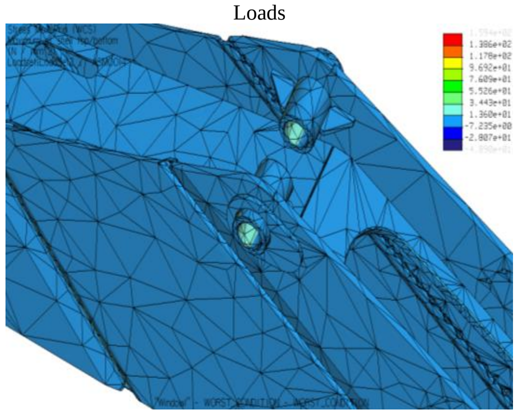

Fig. 30(b): Results of Max Principal Stresses for Total Pressure Loads

Table 4: Maximum Principal Stresses Table for Case 2

S. No.	Max Principal Stresses	Stresses Limit in Standard	Factor of Safety
1 (Light blue)	48	130	2.7
2 (Red Zone)	50	130	2.6

ii. Discussion over the results of Deflection plots produced as Result of Analysis

CASE 1: Mechanism Reaction Loads

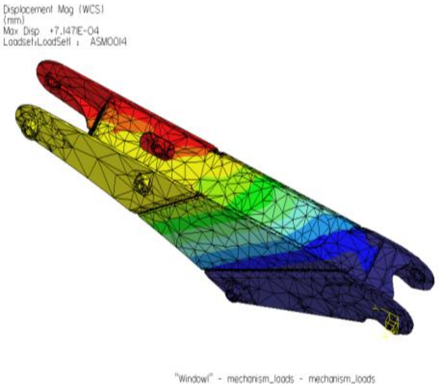

Fig. 31 (a): Results of Displacement for Mechanism Load

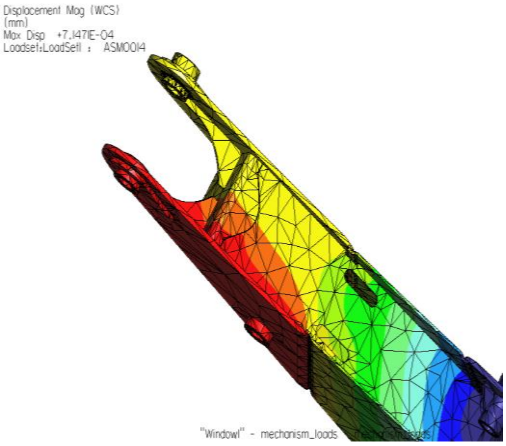

Fig. 31(b): Results of Displacement for Mechanism Load

The Maximum Displacement seen in the structure is only 7E-04. Thus the structure can be considered to be very stiff under this type of loading condition.

CASE 2: Total Force Applicable

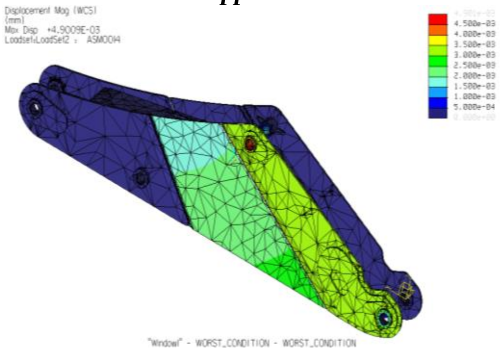

Fig. 32: Results of Displacement for Total force

The Maximum Displacement seen in the structure is only 4.9E-04. Thus the structure can be considered to be very stiff under this type of loading condition.

Validation of Results

Table 5: Comparison Chart for both the Cases

Particulars	Case 1	Case 2
Welded Material	S.T. 42	EN 9
Pressure	310 bar (Max.)	310 bar (Max.)
	240 bar	280 bar
Force	271416N	316652N

Table 6: Comparison Chart of Welded Material

Yield Strength (in MPa)	Rate (Rs. / kg)	Costing-16mm (Rs. / plate)	Costing-8mm (Rs. / plate)
420	86	1500	1250
410	74	1295	1073
380	61	1068	885

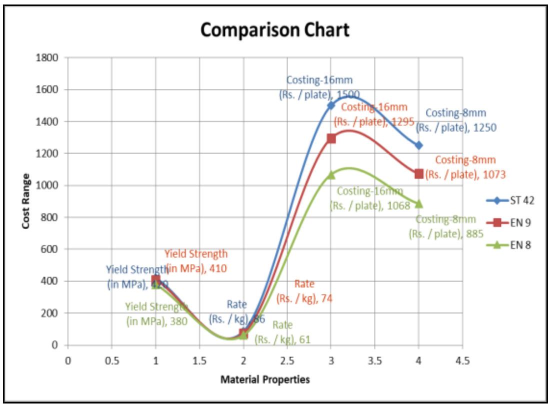

Fig. 33: Comparison graph/ chart between cost range versus material properties

VIII. CONCLUSION AND CONTRIBUTION

The stresses are nearly comparable in both cases, with high values in Case 2, where the total force applicable is used to calculate the safety factor for the system.

Assuming that the Machine runs at the direct working condition without any such disturbances of operating conditions, then the applicable case is case 1, where the **Factor of Safety** is **3.14** and **2** in the worst effect.

In heavy conditions where the Machine requires the full force for operation, say when the density of the material is very high, resulting in the more weight to volume ratio resulting in the Machine to operate at the highest possible pressure, **Case 2** plays its effect in the case. The results of case 2 result in the **Factor of Safety** of **2.2** and **1.7**. Thus the boom can be considered as safe for these analyzed conditions.

The results obtained from the **Finite Element Analysis** are very safe as per the stress values and the deflections.

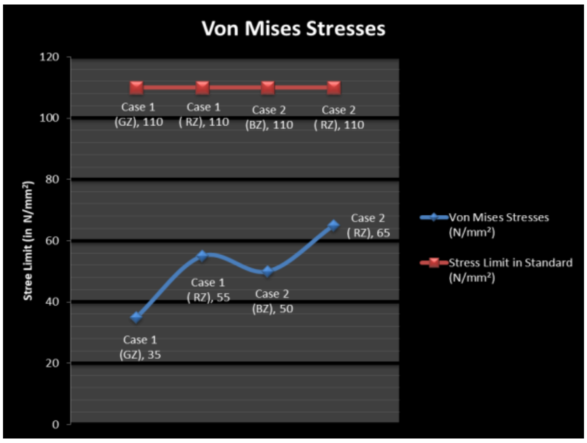

Fig. 6.1: Von Mises Stresses Comparative graph

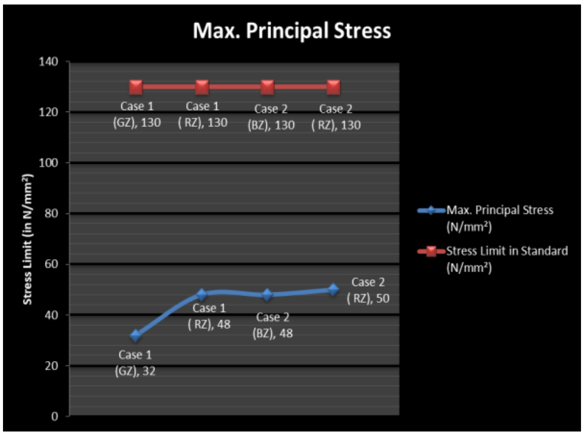

Fig. 6.2: Maximum Principal Stress Comparative Chart

Contribution

With such a factor of safety, we can predict that the working operation condition will result in the machine life of **10^6 cycles** as per the ASME standards.

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