# Modelling, FE Analysis and Optimization of the components of Backhoe: A Review Study

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***Abstract* - In India, the Construction industry is undoubtedly the backbone and propelling force behind our progress towards the goal of becoming a developed nation. In response to booming construction industry, the utilization of Earth Moving Equipment has increased considerably, which lead to high rate of Machine Failure in such working environment. From all the classified earth moving equipment's the backhoe-loader (Backhoe-Loader) machine is the most popular one in the urban area development. The backhoe loader mechanism must work reliably under unpredictable working conditions. 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. So, for fulfilling this need, the Finite element approach (FEA) comes into play, which consists of a computer generated 3D-CAD model or design of a component/ machine is stressed and analysed for specific results. In this work, a Chronological review study of all the literature available is compiled and concluded for further reference of the users, who wants to carry out the future work in the relevant field, whereas this work will help the users to know the exact behaviour of the connections between the components of the machine in sustaining the forces/ stresses generated in carry out the required activity with enough strength under unpredictable working conditions, which results in better design optimization of the backhoe-loader machine.**

***keywords* - Construction Industry, Earth Moving Equipment, Machine Failure, Backhoe-Loader, Finite Element Approach (FEA), 3D-CAD model.**

## I. Introduction and Brief description of backhoe-loader

### A. Introduction

Construction industry is the backbone and a propelling force behind India's progress. The construction industry includes construction of dams, sky scrapers, bridges, roads & even mining work. This has increased the demand of 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 earth moving wor k are of the prime importance. Also there are numerous classes of earth moving equipment available, each aimed at specific purposes. Earth-moving machines are used for engineering projects such as roads, dams, open pit excavation, quarries, trenching, recycling, landscaping and building sites [1].

### B. Brief description of Backhoe-Loader

Backhoe-Loader is most preferred for excavation and earth moving due its versatility. Many construction companies 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 is a combination of 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.Backhoe loaders are powered by diesel engines. 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 rear of the equipment.

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 in order to switch from digging a hole to filling it back in again using the front-end loader.

On today's crowded construction sites, a four-wheeled steering backhoe, also called a skid steer, offers greatly improved manoeuvrability (Fig.3: The tractor). On these skid steer backhoes, operators can turn the front and rear wheels independently, offering the needed manoeuvrability 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

C.WORKING OF BACKHOE

The Backhoe is essentially, soil digging machine. The working tools off the Backhoe are actuated by the Hydraulic Cylinders. The required motion for digging operation is controlled by controlling the hydraulic cylinders. Each component is actuated by a hydraulic cylinder.

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

Fig.4 Working Volume of Backhoe

D.MOTIVATION OF THE STUDY

In response to booming construction industry utilization of Earth moving equipment has increased considerably. Backhoe-loader is often the only piece of earth moving 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. 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 in addition to the influx of variety of new types of Backhoe-Loaders and other earth moving equipment's.

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 analysed with respect to following parameters.

a) Strength
b) Safety
c) Cost

So, for the reference of the user which are interested in working in the relevant area, this study of literature below will provide the overall knowledge of all the work took place in this context till now, which are arranged in chronological order.

II.LITERATURE REVIEW

Excavation of soil and rock is a high volume and repetitive construction operation. Research in robotic excavation has been focusing mainly on path planning and path control. Very little is known about how to detect and handle underground obstacles such as rocks or utility lines robotically. X. D. Huang and L. E. Bernold introduces a research facility to study robotic backhoe excavation using a heavy-duty hydraulically powered and computer controlled manipulator in his paper [2]. Conventional excavation methods and an existing tele robotic excavator are introduced. The control system for this robotic backhoe excavator is based on multiple sensors for force, acceleration and position measurements. The same set of sensors are also used for obstacle detection, recognition and mapping. An approach for the detection and recognition of removable obstacle is discussed. Contour mapping procedures have been developed to provide a partial surface map of a buried obstacle.

There is growing interest in the automation of the production cycle of backhoe dredges. In order to realise an effective control mechanism for a non-rigid body it is necessary to acquire an adequate insight in not only the dynamic behaviour of the hydraulic system but also of the mechanical systems. This second factor is also influenced by the fact that bigger and bigger machines are being used. As there is no real reference material on this subject the first step has been the description of the kinematics of a backhoe. This was followed by determining of the Denavit-Hartenberg matrix to describe the mechanical motions of the system with respect to the position and orientation of the bucket. C.F. Hofstra1, A.J.M. van Hemmen, S.A. Miedema and J. van Hulsteyn described a dynamical model (using MATLAB and ADAMS) and show some of the simulation results with respect to the influences of the flexibility of the hydraulic fluid and the steel structure on the achievable accuracy in their paper [3].By the recent trend of high speed and efficiency, working condition of a hydraulic excavator tends to be more abominable, time varying and frequently with impact accompanying and the structure of it is prone to be more and more complex. Consequently, structural static and dynamic synthetic performances are desired to be higher. Furthermore, structural static and dynamic optimization included in entire performance optimization plays a significant role in complex mechanical system generalized optimization. XUE Caijun, QIU Qingying & FENG Peien put forward a new method in their paper [4], to realize the structural static and dynamic collaborative optimization of hydraulic excavator working equipment. The mathematical model of static and dynamical optimization is developed basing on finite element analysis and testing results of static and dynamical characters of hydraulic excavator working equipment. The paper introduces set-up of testing system and presents the experiment results that are used to validate the static finite element models and to update the dynamic finite element models. The optimum results prove the present method efficient and effective.

The excavator is treated as a system of appropriately inter-connected rigid solids, in which individual masses correspond to the basic component elements of the excavator. Zygmunt Towarek discussed the dynamics of a spatial model of a single-bucket excavator on a caterpillar chassis in his paper [5], the strain of the soil foundation being taken into consideration. It has been assumed that the excavator is resting on a soil foundation expressed as a Kelvin-Voight viscoelastic body carrying loads distributed on the surface of interaction of the caterpillar and the ground. For the dynamic description Lagrange second-order equations have been used. The generalized coordinates assumed enable one to make a dynamic analysis of working movements of the excavator during excavation for any position of the jib with respect to the chassis and any combination of movements of the bucket and the arm. The system of di8erential equations obtained has been solved numerically, for numerical data corresponding to a single-bucket excavator of its bucket capacity of 1:10 m3.

The automated structural optimization of an excavator boom was discussed by Uzer Cevdet Can in his thesis [6]. The need for this work arises due to the fact that the preparation of the CAD model, performing finite element analysis and model data evaluation are time consuming processes and require experienced man power. The previously developed software Opti-BOOM, which generates a CAD model using a finite set of parameters and then performs a finite element analysis by using a commercial program, has been modified. The model parameter generation, model creation, analysis data collection and data evaluation phases are done by the Python and Delphi based computer codes. A global heuristic search strategy such as genetic algorithm is chosen to search different boom models and select an optimum.To develop a dynamic model of the loader system of a backhoe-loader Boran Kiliç used physical modelling toolboxes inside the commercially available simulation software, MATLAB/Simulink in his thesis [7]. Rigid bodies and joints in the loader mechanism and loader hydraulic system components are modelled and analysed in the same environment using MATLAB. Interaction between the bodies and response of the hydraulic system are obtained by co-operating the mechanical and hydraulic analyses. System variables such as pressure, flow and displacement are measured on a physical machine and then compared with the simulation results. Simulation results are consistent with the measurement results. The main result of this work is the ability to determine the dynamic loads on the joints and attachments of the backhoe-loader. In addition to that, prototyping time and costs can be highly reduced by implementing this model in the design process.

Dongmok Kim et al. [8] prepared the operating algorithm has and verified it in many test cases. They have used CATIA Manikin extension to study the human behaviour and the stresses induced in human parts too while operating the excavator arm. They have also prepared a control system for the safety compared to all other standard model. The breakout force is calculated by SAEJ1179. The SAE provide the breakout and digging force. The optimization is done for various components of assembly and presented in the paper.

The boom structure of the crane consists of welded sheet parts, of which one main unit is the stiffener (hoop), placed at the end of the boom. The function of this is to ensure anti-buckling while taking load. Another main part of the boom structure is the support, which is placed under the basic boom part. G. Fekete, N. H. Hoang, A. Varga discussed static structural analysis of the parts of telescopic boom of mobile crane and summarises the elastic analysis of different geometrical designs of boom-endings and supports by defining the so called ‘weak point’ of design in his paper [9]. The main goal of elastic calculations was to reduce the weight of bracing while guaranteeing the proper strength, and taking into account easy manufacturing. Elastic-plastic deformation would represent the overload of the structure, but plasticity is not acceptable in this construction. Finite Element Analyses were done according to the loads occur in practice and European standards.

The excavator which has been analysed by Luigi Solazzi in his paper [10] is composed of three elements and the load conditions assumed, in order to evaluate the stress, are five (lifting at the maximum and minimum distance from the axis of rotation, maximum load induced by hydraulic cylinders, spin of the arm of the excavator and collision with an obstacle, etc.). The aim of this work is to study the boom and the arm of an excavator in order to replace the material, which they are usuall y made of, with another material. In particular, the study wants to substitute the steel alloy for an aluminium alloy. This change lightens the components of the arm, allows to increase the load capacity of the bucket and so it is possible to increase the excavator productivity per hour. For this purpose many different load conditions have been studied numerically on the original excavator in order to estimate a safety factor and the deformability or flexibility of each component. These parameters have been used in order to design a new arm. As regards to the safety factor and deformability in order to maintain the original value the new geometry of the arm involves an increase of the dimension and so the lightness is not correlate only to the variation of the material density. The weight of the final geometry of the aluminium arm is 1080 kg whereas the one of the steel arm is 2050 kg and consequently it has been possible to increase the capacity of bucket from 1 m3 to the 1.35 m3. With reference to the manufacturing cycle of the aluminium arm with the new pins, the price increased about € 2.500-3.000 and this aspect could be justified if we consider that the productivity per hour increased about 35%.

The common design of the bucket wheel drive mechanism in some bucket wheel excavators (BWE) consists of a gearbox and a hollow shaft, while the bucket wheel is supported by the axle passing through the hollow shaft. Improper maintenance and inadequate elimination of axis misalignment of the hollow shaft and the bucket wheel axle are the main causes of excavator failure and axle fracture. Mile Savkovic, Milomir Gašic, Miodrag Arsic & Radovan Petrovic examines the causes of bucket wheel axle fractures in their paper [11]. Experimental testing of the chemical composition and mechanical properties of the material used to make the bucket wheel axle and metallographic inspections of the fracture surfaces in the bucket wheel axle by means of electronic and light microscope carried out in the first part of the paper have shown that there are no significant in homogeneities and errors in the material of the axle. The second part of the paper presents the FEM analysis of influences of disturbances on the manner of support of the bucket wheel axle on the fracture. It shows that the negative influences of support of the axle reflected through the increase in the stress concentration and occurrence of the initial crack are the main causes of the axle fracture.

Tomasz Geisler & Wojciech Sochacki discussed the modeling and researches regarding the vibrations of a truck crane are considered in their paper [12]. The finite element method, using a COSMOS/M package, was applied to build the model and an analytical method was used to build a discrete-continuous model of the crane. The research concerns changes in the frequency of vibrations for flexural vibrations in the telescopic extension arm in the lifting plane. Diagrams containing changes in the frequency of vibrations for chosen values of the geometrical parameters and the load are presented as the solution results to the vibration problem of the tested system. Conclusions are also drawn and their implications discussed.

An excavator is a typical hydraulic heavy-duty human-operated machine used in general versatile construction operations, such as digging, ground levelling, carrying loads, dumping loads and straight traction. These operations require coordinated movement of boom, arm and bucket in order to control the bucket tip position to follow a desired trajectory. Bhavsehkumar P. Patel & Dr. J. M. Prajapati focuses on review of a work carried out by researchers in the field of kinematic modelling of the backhoe attachment to understand relations between the position and orientation of the bucket and spatial positions of joint-links in their paper [13]. Kinematic modelling is helpful for understanding and improving the operating performance of the backhoe excavation machine. There are many research work done by researchers in the same field but still there is a scope to develop kinematic modelling of backhoe attachment to predict the digging trajectory as well as better controlling of backhoe attachment to carry out required digging task at desired location.

Excavators are used primarily to excavate below the natural surface of the ground on which the machine rests and load it into trucks or tractor. Due to severe working conditions, excavator parts are subjected to high loads. The excavator mechanism must work reliably under unpredictable working conditions. 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. It can be concluded that, force analysis and 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. In general, computer aided drawing model of the parts to be analysed must be prepared prior to the FEA. It is also possible to reduce the weight of the mechanism by performing optimization task in FEA. Bhaveshkumar P. Patel and J. M. Prajapati provides the platform to understand the Modeling, FEA and optimization of backhoe excavator attachment in their paper [14], which was already carried out by other researchers for their related applications and it can be helpful for development of new excavator attachment.

The bucket wheel boom tie-rods are vital structural parts of the bucket wheel excavators (BWE). Their failures inevitably cause BWE collapse and are followed, among other things, by a substantial financial loss (millions of €). Non-destructive testing revealed a flaw in the butt welded joint of the body and eye-plate of the bucket wheel tie-rod. Its size exceeds the level allowed by current technical regulations. An integrity assessment of the bucket wheel tie-rod has been carried out by Srd-an M. Bošnjak, Miodrag A. Arsic, Nenad D. Zrnic, Marko P. Rakin, Milorad P.

Pantelic in their paper [15], i.e. the remaining fatigue life has been determined based on the stress-state characteristics in the welded joint and defined by experimental research in real working conditions. The calculation results show that despite the excessive size of the internal flaw the welded joint integrity is not compromised. During periodical inspections of the welded joint in the past two years (BWE was put into operation in December 2007) changes that could compromise the structural integrity were not observed. In this way, by using a ‘‘fail-safe” philosophy design, a considerable financial saving (ca. 1,600,000 €) was achieved while at the same time there was no threat to the worker’s safety and life, the safety of the machine and the production process in the open pit mine.

Jakub Gottvald [16, 17] evaluated measuring of vibrations on a Bucket Wheel Excavator (BWE) during mining process. They have studied the dynamic behaviour of buckets during working under mines. The main aim of this study was on vibration caused and its effect on the arm assembly of the excavator. Natural frequencies and shapes are very significant characteristic of dynamical behaviour of structures. Their determination is mostly the first step in solving of various dynamical problems. Knowledge of natural frequencies and shapes gives us the possibility to assume how the structure will be sensitive to dynamical loads. Calculations of dynamical characteristics are very significant part in designing of structures in which various loadings are of utmost priority

Juber Hussain Qureshi and Manish Sagar [18] concluded that, force analysis and strength analysis is an important step in the design of excavator parts. FEA is the most powerful technique in strength calculations of the structures working under known load and boundary conditions. In this paper authors, describes its basic structure, stress characteristics and the engineering finite element modelling for analysing, testing and validation of backhoe loader parts under high stress zones. This study tells the optimization of the Boom for including the strength of welds where welds can be modelled with shell elements along with the boom to take moments 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 [19] performed thefinite element analysis of the boom which is followed by the results of Dynamic study of the Boom of the machine. In this paper researcher provides the platform to understand the Modelling and FEA of Boom of Backhoe Loader, which was already carried out by other researchers for their related applications and it can be helpful for the development of boom of backhoe loader.As Inertia plays a big effect while performing a dynamic analysis which is completely dependent upon the time in our case which can only be assumed for the cycle to complete. The max effect of inertia can be plotted on the graph especially for new shapes of boom, to get the safe results of stresses resulting in the safe life of the boom.

Anand Thorat and G.V.R Sheshagiri rao [20] presented the Static analysis of the chassis shows the equivalent stress and deformation contour when Backhoe Loader is in working condition. From static analysis, high stress area can be found out when Backhoe Loader is in different load condition. Also by providing some design changes, stress can be minimized.

Rahul Mishra and Vaibhav Dewangan [21] calculated the capacity of bucket according to SAEJ296. The bucket specification is the most superior when compared to all other standard model. The breakout force is calculated by SAEJ1179. The SAE provide the breakout and digging force. The optimization is done for various components of assembly and presented in the paper.

R M Dhawale and S R Wagh [22] carried out the review of the various analysis done in the past concerning the components of excavator arm and effects of various forces on the components of excavator arm. This paper gives the overview about the work carried out in the field of the modelling and FE 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 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.

C.P. Motka and Ikbalahemad R Momin [23], presented the study which covers the detailed design, modelling and FE analysis of Backhoe Machine. . Backhoe Loader is the rear part of the excavator machine. The backhoe loader is used for a wide variety of tasks: construction, small demolitions, light transportation of building materials, powering building equipment and digging holes/excavating, landscaping, breaking asphalt and paving roads. Various loads are applied at the bucket tip and to the boom and digger arm. So it is necessary to analyse the parts assembly to avoid failure while it is in working condition. From static analysis, high stress area can be found out when Backhoe Loader is in different load condition. Also by providing some design changes, stress can be minimized.

With the increased requirement of accuracy of pay loads, the stiffness characteristics of structure are increasingly influencing the design and performance of a backhoe loader. The main objective of structural design is to achieve the minimum mass structure, which will satisfy the stiffness, strength and other requirements. Hence optimum configuration and advanced technology have to be incorporated to achieve minimum mass. In this study Hemanth Kumar BL and Nagesh N [24], performed the static structural analysis of backhoe-loader arms with the finite element method (FEM). The aim of this study is to simulate and strengthen the back and front arms of the backhoe-loader concerning with stress under maximum loading condition and different boundary conditions. According to analysis result, back and front arms of the backhoe-loader are strengthened with the use of reinforcements. As a result of the study, strength of the arms has been increased by nearly 20%.

In their project R. Jaison and Ramesh Kumar [25] designed and analysed a detachable type backhoe components using ANSYS, so that it can be mounted over an agricultural tractor and can be used for trenching, digging etc. This design makes backhoe compact in size and shape so that it is fitted inside the tractor. This can be used as a special attachment to the tractor like other attachments like driller, slicer, truck etc. This paper deals with the design of backhoe components, loader components and special chassis for the tractor for a limited load of 2000N backhoe and 6000N loader. This has hydraulic unit which is selected to run by the tractor engine power of 50Hp whereas the original backhoe has 60Hp. It is made as a special detachable attachment so that the load is limited when compared to original backhoe. The design process is carried out from determining the component dimensions that are required to withstand the load by both analytical calculations and software modelling. The components are 3D modelled using CREO PARAMETRIC modelling software and then structural analysis is carried out over the components using ANSYS.

## III.CONCLUSIONS

This work has provided a comprehensive literature review of existing various research work carried out in terms of design, stress, fatigue, optimization analysis of the components of Backhoe-Loader machine. An effort has been made to comprise all the important contributions to this area and highlighting the most pertinent literature available for investigating the problems concerning the connections between the components of Backhoe-Loader along with their relevant solution. The concluding remarks from the current literature survey are as follows:

1. From the review of available literature on backhoe, it is apparent that nearly all the research conducted has been purely simulation based on finite element method but some researches also performed the static and kinematic analysis, which is an essential step in designing a new component/ modifying the existing one for the machine.
2. Most of the FEA of backhoe was done in different operating conditions by simulating actual working conditions in software. The studies shown that, most researchers stressed their work on the optimization of the backhoe's boom & bucket, which plays a vital role in excavation work. They tried to achieve it by changing the materials, acting forces and the shape.
3. Hence FEA is a useful tool since they provide accurate results to access strength and can predict it approximate fatigue life of the backhoe-loader in relevant working conditions.

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