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ANALYSIS OF INTERACTIVE EFFECTS OF BULK MATERIAL ON EXCAVATOR BUCKET

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ABSTRACT: Hydraulic excavator is a heavy-duty machine that is generally employed in constructional and mining works for digging, carrying and sometimes leveling of bulk materials. It consists of several components such as the engine house, boom, arm, bucket, swing bearing, carriage, etc. Excavators are designed to handle bulk materials that can vary in shape and form, from large quarry rocks to cohesive soils, abrasive ores or free flowing granules. These materials and their interaction with the machine parts have a strong effect on the equipment performance. Understanding how bulk materials will behave with equipment is critical to ensure an optimal design that combines strength and durability, with performance efficiency. In this paper, research was conducted to understand the effect of bulk material interactions on the excavator bucket. The excavator was designed with Autodesk Inventor software and simulated in an EDEM bulk material simulation environment, the results of the total pressures and compressive forces acting on the bucket were investigated in Ansys Mechanical to check for deformations and available stresses. As a result of the analyses, the bucket suffered small deformation and stresses with maximum recordings of 0.55145mm and 138.75MPa respectively. It has been found that these stresses and deformations do not seriously damage the bucket.

Keywords: Autodesk Inventor, Ansys Mechanical, Bucket - Bulk Material Interactions, Bulk Materials, EDEM Simulation Software, Excavator.

DÖKME MALZEMENİN EKSKAVATÖR KEPÇESİ ÜZERİNDEKİ ETKİLEŞİMLİ ETKİLERİNİN ANALİZİ

ÖZ: Hidrolik ekskavatör, genellikle inşaat ve madencilik işlerinde, dökme malzemelerin kazılması, taşınması ve bazen tesviye edilmesi için kullanılan ağır hizmet tipi bir makinedir. Motor bölmesi, bom, kol, kepçe, döner yatak, araba vb. birkaç bileşenden oluşur. Ekskavatörler, büyük taş ocağı kayalarından yapışkan topraklara, aşındırıcı cevherlere veya akan granüller serbest malzemelere kadar şekil ve biçimde değişebilen dökme malzemeleri işlemek için tasarlanmıştır. Bu malzemeler ve bunların makine parçalarıyla etkileşimi, ekipman performansı üzerinde güçlü bir etkiye sahiptir. Dökme malzemelerin ekipmanla nasıl etkileşeceğini anlamak, güç ve dayanıklılığı performans verimliliği ile birleştiren optimum bir tasarım sağlamak için kritik öneme sahiptir. Bu makalede, dökme malzeme etkileşimlerinin ekskavatör kepçesi üzerindeki etkisini anlamak için bir araştırma yapılmıştır. Ekskavatör, Autodesk Inventor yazılımı ile tasarlanmış ve EDEM simülasyon ortamında dökme malzeme simüle edilmiş, kepçe üzerine etkiyen toplam basınçların ve sıkıştırma kuvvetleri, deformasyonları ve mevcut gerilmeleri kontrol etmek için Ansys Mekanik ile değerlendirilmiştir. Analizlerin bir sonucu olarak, kepçe sırasıyla 0,55145 mm ve 138,75 MPa maksimum kayıtlarla küçük deformasyon ve gerilmelere maruz kaldı. Bu gerilme ve deformasyonların kepçeye ciddi zarar vermediği görülmüştür.

Anahtar Kelimeler: Autodesk Inventor, Ansys Mechanical, Kepçe - Dökme Malzeme Etkileşimleri, Dökme Malzemeler, EDEM Simülasyon Yazılımı, Ekskavatör.

1. INTRODUCTION

Eugeniusz Rusiński ‘Material Handling and Mining Equipment - International Standards Recommendations for Design and Testing’ presented and matched theoretical assumptions proposed in various international design standards (DIM 22261, AS 4324 and ISO 5049). He also made assessment of real life applications and then compared the obtained results with that of the pre-stated theoretical standards. Design rules and guidelines with respect to static and dynamic loads which lead to strength and fatigue resistance were discussed in detail. He noticed that the AS 4324 standard had the highest requirements due to the failures that occurred in an Australian industry. The requirements however, improved safety and reliability of the equipment and also had substantial impact (of approximately up to 20% heavier than machines designed under the ISO or DIN standards) on the dead weights of machines. He also made it worth knowing that there has been a change in the fatigue calculation approach proposed long time ago by scientist, and that the cumulative damage criteria are up to date in the standardized calculations. He concluded however, that there is still adjustment in the standards that need to be taken care of to improve safety and quality of the designs [1].

In 2015, Manisha P. Tupkar and Prof. S. R. Zaveri in their work, designed an excavator bucket employing CREO-parametric 2.0 software. By exporting the model in an IGES file format into Ansys mechanical and applying the necessary boundary conditions and forces at the tip of the bucket teeth, they carried out a static analysis. The results revealed the stresses that developed at the tip of the bucket teeth. They also performed analytical stress calculations and then went further to calculate the errors that existed between the analytical and simulated results. The analytical results showed a calculated stress of 96.39 MPa and 157.67 MPa at the tip of the excavator bucket teeth and due to shearing of the rivet respectively. However, the results from Ansys revealed slightly different results of 112.98 MPa at the tip of the teeth and 167.42 due to shearing of the rivet. The calculated errors were 14.69% for the teeth tip stress and 5.82% for the difference due to the shearing of the rivet. In accordance with the analysis made, they proposed that the bucket used for the excavation should be carefully examined for its application on the terrain. Moreover, considering the failure of the rivet and teeth due to the subjected load, changing the rivet would be more economical than changing the complete teeth assemblage [2].

Khedkar Y, Dey T and Padasalagi Y in their research work studied various forces that acted on an excavator bucket during digging operations. They analyzed the factors that contributed to the generation of the resistive force due to the bucket geometry and the resistive force offered by stiff soil to the bucket. Aside the resistive forces, they also calculated the digging forces in accordance with the SAE standard. Further discussions of the effects of different parameters on the resistive force were also made for horizontal and unbalanced digging conditions [3].

Young Bum Kim et al. wrote a paper in which they presented various procedures to determine the most optimal working path based on minimum torque or time to simulate digging works tracking on the designed working path. Aiming at minimizing the torques at the joints of the machine elements, they derived the optimal working path for the minimum torque situation. However, for the minimum time case, the most optimal path was determined to reduce required time duration for a single-cycle considering the hydraulic limitations such as pressure and oil flow rate and others. To verify the inverse dynamic code and optimized path used in the optimization, field measurements were made for the various parameters such as slew angles, cylinder lengths and pressures of a slew motor and hydraulic cylinders during excavation. The modified fundamental earthmoving equation is used to model the interaction between soil and tool in the excavation process, and the inverse dynamics with external forces, such as constant and reducing lifting weights, is used in the lifting and unloading process. In conclusion, all simulated data were compared with the measured data to investigate the genuineness of the proposed methods with respect to the development of the unmanned excavator [4].

Hadi, Priharyoto, and Ramadhan performed an analysis to determine the appropriate bucket teeth material that could be used on an abrasive field consisting of gravels, stones, soil etc. The design and analysis were performed with the Abaqus 6.10 Computer Aided Engineering (CAE) software to obtain the maximum stress as a result of the exerted loads on the teeth. They assigned steel mixture as the bucket teeth material. The analysis procedure to obtain the stress was performed by adding 8285.06 N load forces in the static state at an angle of 32° to the horizon. From the analysis, it was found that the maximum stress experienced by the excavator bucket tooth is 209.3 MPa and is still below the maximum equivalent von Mises stress, so the design can be considered safe [5].

As described above, a hydraulic excavator basically consists of boom, arm, bucket, undercarriage, link mechanisms, and three hydraulic cylinder sets, as shown in Figure 1 below. The first set has two cylinders that serve as supports and are also responsible for the up and down movement of the excavator boom. The second set has a single cylinder (also called the arm cylinder) that also engages the arm to obtain an appropriate radius to position the tray at a desired location for excavation. The last set also has a single cylinder (called the bucket cylinder) which is responsible for rotating the bucket for effective handling of the bulk material.

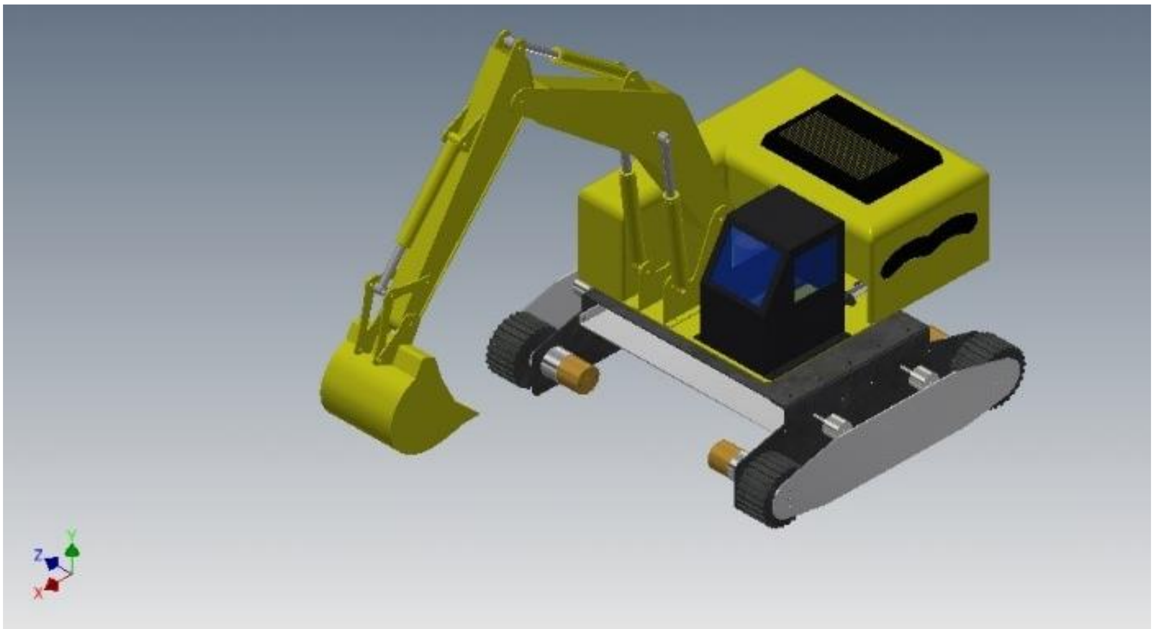

Figure 1. Mini Hydraulic Excavator.

The engine, hydraulic pump, together with some other essential components is mounted on the undercarriage. These components are joined to the undercarriage through the swing gear (bearing) which facilitates a 360-degree rotation of the upper part of the machine. An excavator has nine boom design variables, seven arm design variables, and seven design variables of the bucket and link mechanism. In addition, some other design parameters also relate to the performance of the excavator, including cylinder diameter, piston diameter of each cylinder, and maximum slew speed. The cylinder and rod diameters have a great influence on the digging force and the working speed, while the maximum rotational speed of the pivoting gear is relevant for the working cycle time.

During excavation, an element that continuously comes into direct contact with the bulk material is the bucket. For the bucket to be able to get it way into the park of bulk material, a force must be applied either by the arm or the bucket cylinder. While this force is being applied, the bulk material conversely tends to oppose the motion of the bucket into it by exerting a reaction force. This reaction force is called resistive force. The force applied to engage the bucket into the bulk material (ground) is also termed as digging force. These forces will be tackled in detail in the subsequent section [6] in his article, estimated bucket volume, and digging forces that acted on a bucket according to the SAE standard. He also established the comprehensive breakout force model and digging force. Using static analysis, he then also calculated the forces that acted at each joint of the bucket [6]. In his other article, discussed the approximation of resistive force calculations in relation to the earth moving equation using the principles of soil mechanics [7]. Also discussed about generated forces that existed between the bucket and the bulk material. (i.e. separation and penetration forces.) Their work has given detailed information on penetration resistance and separation resistance. They also modelled the bucket in a software and simulated it against the ground by defining the interaction between the ground and the tool and then determining the resistance forces.

The digging force is essentially the force required to dig into the bulk material. These forces act on the bucket tip. The digging forces are divided into bucket and arm curling force respectively. The bucket curling force is the force generated by the bucket cylinder at the tip of the bucket, while the force generated by the arm cylinder is the arm curling force. This force is also generated at the tip radius of the bucket and it is perpendicular to the distance D from the bucket tip to the arm-bucket joint. In general, the digging force is calculated at the maximum fracture state of the joints. The maximum fracture condition is when the excavator generates the maximum digging force. There are a total of three standards available for calculating the digging force, one of which is the SAE standard. As stated by SAE J1179 standard, excavation forces for maximum fracture state are shown in Figure 2 [3].

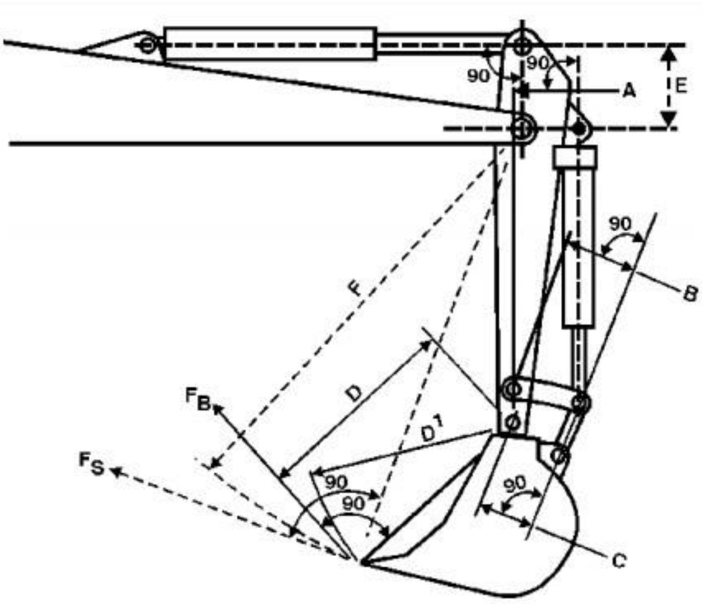

Figure 2. Digging Force.

From Figure 2, parameters dA, dE, dF, dD, dC are the distances between the designated joints and F_B and F_S are the bucket curling force and arm curling force respectively. Note from the figure that bucket curling force is tangential to the tip radius of the bucket. This force is generated by the bucket cylinder and it's given by:

$$F_B = \frac{p \times \left(\frac{\pi}{4}\right) \times D_{B^2} \times d_A \times d_C}{d_D \times d_B} \tag{1}$$

Where, D_B is the bucket cylinder diameter, and p is the operating pump pressure. The arm curling force is also given by;

$$F_S = \frac{p \times \left(\frac{\pi}{4}\right) \times D_{A^2} \times d_E}{d_F} \tag{2}$$

Where D_A is the arm cylinder diameter.

It is of great importance to note that the digging force required for easy penetration of the bucket into the bulk material must be greater than the resistance forces generated by the bulk material. To fully understand the interaction between the blade and the bulk material, the resistance forces generated by the bulk material must be discussed in detail [3].

Resistive force is the force subjected by the bulk material to the bucket during digging operations. However, before discussing about the resistive force, it is very essential to understand the various digging phases encountered during digging operations. To make it easier, the excavator digging operation is split into three modes:

Digging phase I:
The digging operation begins with this phase. This is when the bucket teeth begin to penetrate the bulk material. During this phase, the two elements that come in contact with the material are the bucket teeth and toe plate. This phase is also called the penetration phase.

Digging phase II:
With the bucket teeth having penetrated the bulk material, the applied digging force from the hydraulic cylinder overcomes the material resistance and then forces the bucket to dig deep into the bulk material. This is what happens in the second phase (also called the separation phase). All other parts of the bucket are completely immersed in the terrain and separate a chunk of material from the whole.

Digging phase III:
In this phase a re-curling force is applied to bucket to rotate it to a position suitable enough to hold the material in place. This also termed as the escape phase, where the arm and boom are raised to remove the bucket from the terrain.

When operating the excavator, the preliminary part that interacts with the bulk material is the bucket. This causes the bucket to experience a certain resistance. This resistance can be classified into two types, namely, penetration resistance and separation resistance. Another study also says that the interaction of bulk material and bucket depends on the bulk material properties and bucket geometrical parameters.

In this study, instead of just simply applying forces and boundary conditions to the desired part of study for analysis, the designed excavator was simulated in a virtual environment (i.e. using EDEM) - carrying out the digging operation. This will enable acquiring approximate-realistic data (acting compressive forces and exerted pressures on bucket) just as it would have been in real life as the bucket interacts with the bulk material. The acquired data were then employed into the simulation environment for further structural analysis. Moreover, unlike in other work [2, 5] where the analysis prioritized the bucket teeth, this study is more focused on how the whole excavator bucket deals with resistive forces [3] and loads of the bulk material. It is therefore desired that the designed bucket should prove durable and strong enough to carry out operations without detrimental deformations wear or tear.

2. MATERIAL AND METHOD

2.1. Properties of Bulk Materials

Bulk material refers to a coarse or lumpy mixture which is in free-flowing state. Depending on the moisture content and magnitude of the cohesion and adhesion forces of the material however, it could be sticky in nature. This consequently renders the bulk material not to flow easily. The properties of a bulk material are determined by its grain size and particle size distribution, the angle of repose, its moisture content, cohesion, adhesion, temperature and as well as by its bulk density. Researches show that bulk materials are basically grouped into two:

- Cohesionless, free-flowing bulk solids
- Cohesive bulk solids

When bulk materials flow easily they are described as Cohesionless or free-flowing whereas, cohesive bulk solids are those whose particles are banded closely together with less or no flowing capability. In order to deeply understand the bulk material handling mechanism, intensive researches have been done to study storage and transportation conditions such as the angle of repose, bulk densities, discharge behaviour etc. For free-flowing bulk solids, when the particles are given sufficient initial velocities they tend to behave like fluids and begin to flow uniformly. This is however not the case with cohesive bulk materials. Bulk materials with wear-causing, cohesive, sticky and paste-like properties tend to be more demanding during dumping or discharging operations. Nonetheless, these kinds of materials can be discharged without encountering difficulties by using live bottom feeders. Some examples of daily used bulk materials are sand, gravel, rocks, raw materials such as iron ore and many more. Powdered materials such as pigments, granules and pellets can also be categorized as bulk materials.

2.2. Geometry and 3D Model

Autodesk Inventor finite element analysis permits users to verify the design of the components by analyzing the performance of the parts under load. Optimization technologies and parametric studies in Inventor interface allow users to design parameters within assembly stress regions and compare design options. Then the 3D model is updated based on these optimized parameters. For this study, Autodesk Inventor was used to construct a mini-excavator, with all elements assigned to steel material. Figure 1 shows the designed mini excavator.

2.3. Finite Element Analysis

With Ansys Mechanical solutions, geometries of complex assemblies can be imported through their appropriate file formats, meshed optimally and apply realistic boundary conditions to them. By following the analysis criteria, detailed analysis can be performed to check for design strength, thermal response behaviour of systems, maximum von Misses stresses, vibrations, motions etc. The simulation solutions provide the user with comprehensive information through graphical and grid of coloured data, giving clues on how to optimize and make necessary modifications to designs. By doing so, industries are able to minimize costs and get to market quickly with high performance products.

Mechanical designs are expected to perform very well in all possible conditions. In this study, the simulation environment for the structural analysis was used to make faster design decisions. The data obtained from this study were used for structural analysis.

2.4. Discrete Element Method

The Discrete Element Method (DEM) simulation is gradually changing the industry of machine development and optimization for the control and processing of bulk materials. Once the software is used correctly, the DEM simulation provides you with important design information on the flow behavior of bulk particles, which is very difficult or impossible to obtain using standard assessment methods or other design simulation methods.

In order to cognize the interaction existing between the bulk material and the bucket, EDEM analyzes the resistive reactions subjected by the bulk material onto the bucket. The motion of the individual elements of the simulated model is defined kinematically. Fine soil and rocks are the selected bulk materials for the analysis. Physical properties of the generated materials are shown in the Table 1.

Table 1. Bulk Material Properties.

Properties	Soil	Rock
Poisson’s ratio (v)	0.25	0.25
Density (ρ)	2250 kg/m^3	3000 kg/m^3
Shear modulus (G)	1e+07 Pa	1e+07 Pa
Interaction	Rock	Rock
Coefficient of restitution	0.5	0.75
Coefficient of static friction	0.5	0.2
Coefficient of rolling friction	0.01	0.05

3. RESULTS AND DISCUSSION

3.1. Discrete Element Method Simulation Results

Simulations were carried out to observe the interactions between the bulk material and the bucket and to further analyze the effects of the interactions (i.e. Forces and pressures) on the bucket. Rock and soil were used as bulk materials with specified proportions in the simulation.

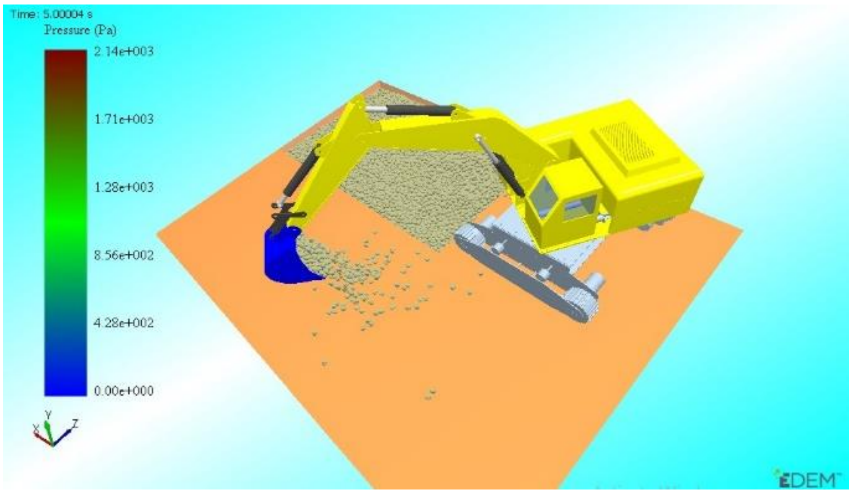

Figure 3. Pressures Acting on Bucket.

Figure 3 shows the minimum and maximum pressures that were subjected to the excavator bucket at time 5.00004s. From the figure, the maximum recorded pressure for bulk material – bucket interaction was 2.14 KPa with a minimum of 0 KPa.

It is absolutely important to realize that the compressive forces that act on the bucket also have tremendous effects on the strength of the bucket for a long term usage. So in that regard, an analysis was made to determine the maximum compressive force that acted on the bucket from digging to dumping time. The graph in Figure 4 shows the compressive force data distribution with time. It is observed that the compressive force data recording started around time 1.26s. This means that the digging operation was initiated at that time. In other words, the bucket began to interact with the bulk material exactly around that time with a maximum total compressive force recording of 546.9N and a minimum of 0N. It is important to realize that these small recorded values, are as a result of the small size of the designed excavator (i.e. design limitations). These data will be exported to the simulation environment for the structural analysis.

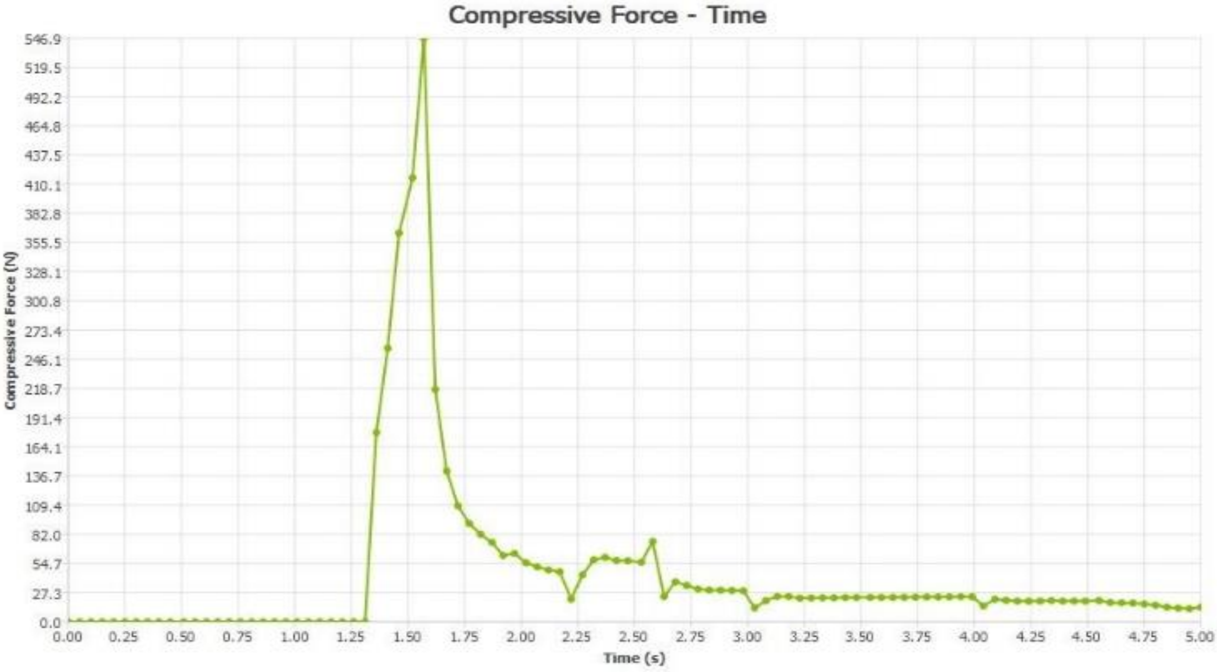

Figure 4. Compressive Force on the Bucket.

It is expected that the bucket is subjected to maximum pressure when it digs deep into the bulk material. This is because, during the digging operation, all surfaces of the bucket, both outside and inside together with the bucket teeth are engaged with the bulk material. Figure 4 shows exactly that. Figure 5 shows the maximum pressure distribution on the bucket throughout the simulation process. It is important to realize that the pressures and compressive forces mentioned here are what was referred to as resistive forces in study [3]. These data have thus been simply acquired without extra effort that would have been done through analytical calculations.

It is observed that pressure recordings ranges between times 1.26s to 2.5s, with a maximum pressure recording of 5.4625kPa. It can also be inferred that the bucket was completely immersed in the bulk material at time 2.5s. The magnitude of the forces and pressures subjected to the bucket at each time interval can be computed without difficulty. Doing this manually through hand calculations however, would have been very complicated. Having obtained these data, the next thing to do is to investigate how it affect the structural properties of the bucket.

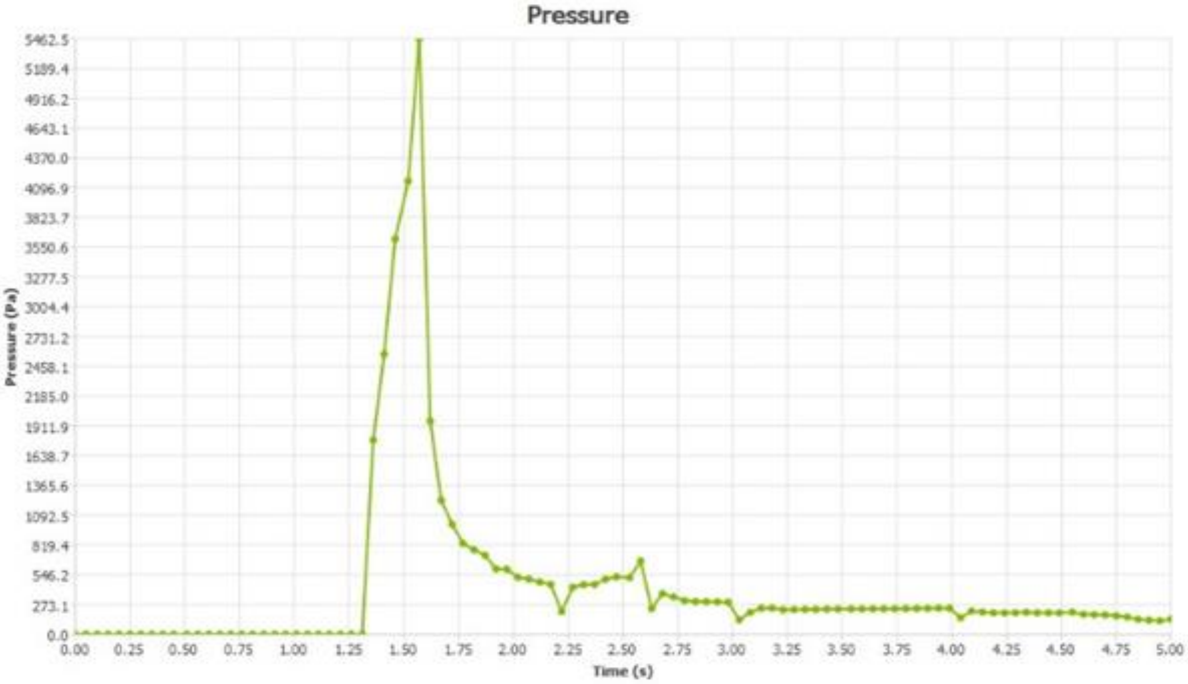

Figure 5. Pressure Distribution on Bucket.

3.2. Ansys Simulation Results

Digging, lifting and dumping operations have been simulated and the effects of the bulk material interaction on the bucket have been analysed. The data obtained from EDEM analysis are imported into Ansys mechanical for structural analysis. However, since the excavator bucket is the very crucial part, it has been thought to be wise to import a step file of only the bucket into the simulation environment for the structural analysis there by avoiding huge data and lengthy simulations times. The bucket was meshed with 23385 nodes and 11371 elements. Considering the total compressive force data obtained previously, the maximum recorded force was 546.9N. And so, any damage that would be done on the bucket cannot be caused by any other load other than the maximum subjected compressive force. Therefore, the bucket was subjected to a compressive force of 546.9N. Figures 6 and 7 show a meshed view and pre-processed view of the bucket respectively.

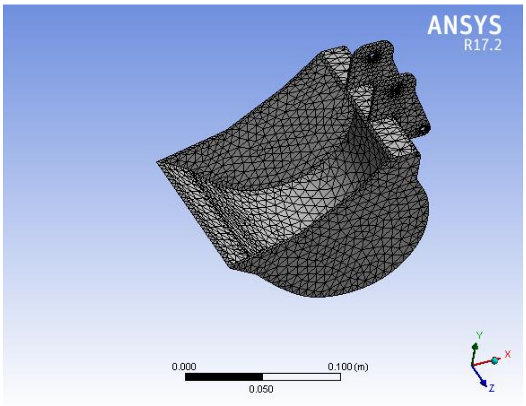

Figure 6. Meshed Bucket View.

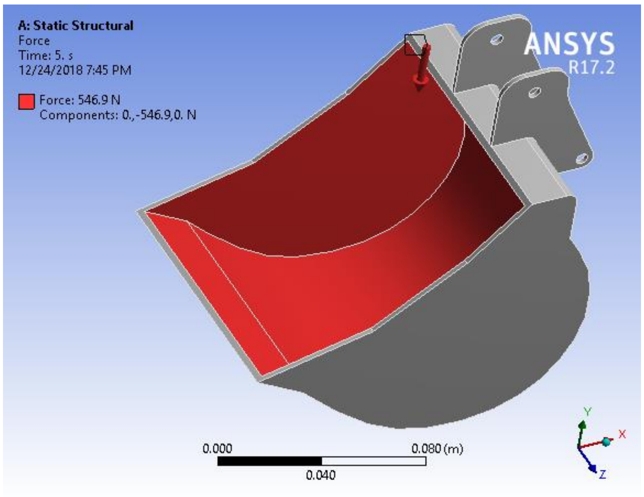

Figure 7. Bucket Pre-Processed View.

The bucket structure was then solved for total deformation and equivalent stress. The results showed that the bucket suffered very small deformations. As can be seen from Figure 8, the maximum recorded deformation was 0.55145mm with a minimum of 0. It was also observed that the highest deformation occurred at the bucket tip where the teeth are attached. The equivalent (Von Mises) stress generated on the bucket on the other hand, showed a maximum recording of 138.75MPa with a minimum of 120.48KPa.

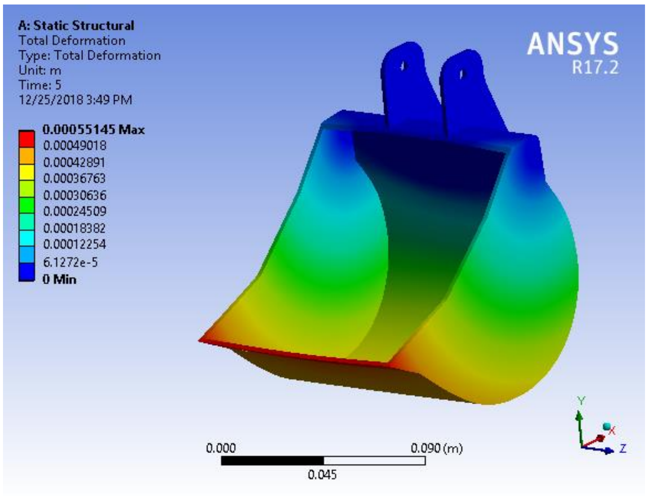

Figure 8. Total Deformation.

The results of the stress are shown in Figure 9. A close observation of the bucket shows that the maximum stress was generated at the bucket-arm joint and at two close points inside the bucket.

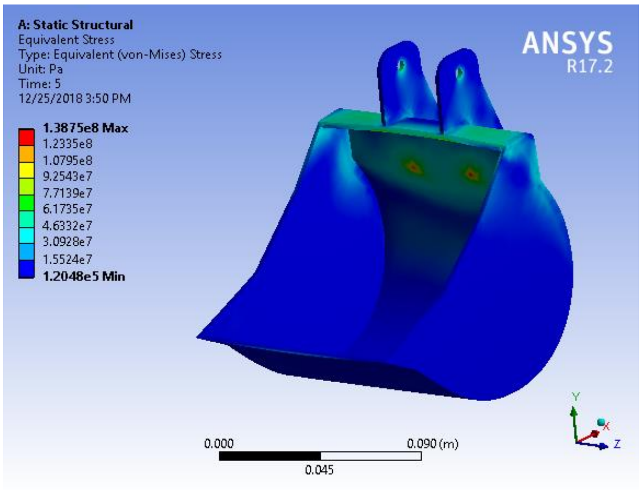

Figure 9. Von Mises Stresses.

4. CONCLUSIONS

All mechanical designs are expected to perform extremely well under any possible condition. With this analysis, a mini-sized hydraulic excavator was designed to analyze how well it would perform in real life during digging, lifting and dumping operations of bulk material on a terrain. Based on a standard excavator design, the dimensions of the designed excavator in this paper was scaled down to obtain a mini prototype. The simulation done in EDEM has simplified significantly, the process of quantifying the exerted loads on the excavator bucket. By simulation, all dynamic and static calculations which otherwise, would have been done manually by engineers, have been computed by the software. Moreover, the nature by which the bucket would have physically interact with the bulk material has been virtually demonstrated in EDEM virtual environment.

In this study, instead of just simply applying forces and boundary conditions to the desired part of study for analysis, the designed excavator was simulated in a virtual environment (i.e. using EDEM) - carrying out the digging operation. This will enable acquiring approximate-realistic data (acting compressive forces and exerted pressures on bucket) just as it would have been in real life as the bucket interacts with the bulk material. The acquired data were then employed into the simulation environment for further structural analysis. In the analysis, total deformation and stress generated on the bucket were analyzed. The bucket suffered small deformation and stresses with maximum recordings of 0.55145mm and 138.75MPa respectively. It is observed that the maximum recorded deformation occurred at the digging edge of the bucket. Despite the fact that the effects cannot cause serious damage to the bucket, design optimization such as the addition of teeth at the bucket tip could significantly erase the deformation and stresses.

In this study, which will be a reference for future studies, a research was conducted to understand the effect of bulk material interactions on excavator bucket. In this way, more accurate productions can be performed in the industry by considering parameters such as the correct bucket type, size and material density.

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