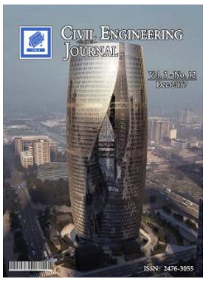
Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 3, No. 12, December, 2017



Analysis of Rake Angle Effect to Stress Distribution on Excavator Bucket Teeth Using Finite Element Method

S. Hadi Suryo [a*], A. P. Bayuseno [a], J. Jamari [a], A. Imam Wahyudi [a]

[a] *Department of Mechanical Engineering, University of Diponegoro, Semarang, Indonesia.*

Received 19 November 2017; Accepted 30 December 2017

Abstract

Excavator is mostly used for mining and construction. This heavy equipment, widely known as a backhoe, is a digging machine commonly used for dredging the mining materials, digging and leveling the soil, dredging the river, removing the road and demolition. Excavator has bucket teeth, component that frequently undergoes a change. The replacement of bucket teeth is performed due to its low usage time and many failure experiences such as wear, bend, crack and facture during the use. To prevent the occurrence of the failures, a structural analysis on bucket teeth is necessarily conducted. The analysis was conducted to find the stress distribution on bucket teeth from the rake angle effect during the excavation. The analysis was performed using finite element method by static loading and two-dimensional modeling to determine digging and resistive force in bucket teeth. Based on the analysis, it was obtained the stress distribution and maximum value of von misses occurring in the bucket teeth from the rake angle effect. The maximum stress, obtained from the analysis results, was then compared to the allowable stress of the bucket teeth material. The results showed that the materials used were in safe limits and had small potential for experiencing failure as well.

Keywords: Bucket Teeth; Excavator; Failure; Rake Angle.

1. Introduction

In mining industry, heavy equipment is familiar thing to hear and see. The equipment is used to support the mining process starting from opening a new mine, road construction, excavation and transporting the mining material to the next process. The types of heavy equipment are also variously based on its application, for example transporting and digging the mining materials and so on. Although this heavy equipment is mostly known in mining industry, however, it is not only used by mining industry. Construction, forestry, landscaping and some other applications also use this heavy equipment for daily activities. One type of heavy equipment that is mostly used for this activity is excavator. This heavy equipment, widely known as a backhoe, is a digging machine commonly used for dredging the mining materials, digging and leveling the soil, dredging the river, removing the road and demolition. Excavator has a part used as a tool for digging and loading the material that is called an excavator bucket. Excavator bucket is generally equipped protruding gear on its point that is called bucket teeth.

Bucket teeth (the gear or mostly called as the nail of the bucket) are parts of the bucket that easily experience failure when the excavator is being operated because this part will be in direct contact with the medium under work by the excavator. The bucket teeth must have appropriate geometrical design to the need so that the usage time can be prolonged and the cost can be reduced [1]. Excavator bucket teeth have several types, whose function is based on the shape. The examples are: Standard Long Teeth commonly used for the excavators working on various types of surfaces; Extra Teeth commonly used for rock and abrasive surface; Rock Chisel Teeth commonly used for rock or hard soil; Tiger Teeth

* Corresponding author: mr.sumarhadi@gmail.com

http://dx.doi.org/10.28991/cej-030952

commonly used on very hard surface; Twin Tiger Teeth commonly used on hard surface which requires more digging force, approximately it has the same use as Tiger Teeth; Rock Abrasion Teeth commonly used on surface with very high abrasive characteristic; SYL Teeth commonly used to dig on medium soil surface; Ribbed Teeth are commonly used on different types of surfaces.

The inappropriate shape and material composition of bucket teeth will lead to poor digging process. Moreover, it will cause high wear level to the bucket teeth, the loss in time and cost and productivity [2]. In its use, bucket teeth will experience direct contact with the soil so that it will experience high stress impact. Therefore, the material used to make the components of bucket teeth must have high enough characteristics of wear resistance, strength and ductility. Bucket teeth have two essential characteristics: maximum performance and wear durability. Maximum performance is affected by the design of bucket teeth and the wear life is affected by the strength of bucket teeth materials because digging on a very abrasive media needs good design and material. Commonly, the design of bucket teeth is made according to the use on soft or hard media. The power of bucket teeth comes from the combination of material composition and the treatment in the making process [3]. Bucket teeth are one part of excavator that is frequently replaced. The reason is that the bucket teeth have limited usage period and are often failed when the excavator bucket tries to make digging force to the soil. The example of failures frequently experienced by bucket teeth are wear, bent, crack and fracture from the abrasion on its point. The failures of the bucket teeth are commonly caused by some factors: soil type, digging speed, digging edge, and the material used for making the bucket teeth. To make the bucket teeth more efficient on its use, structure analysis needs to be performed when the excavator bucket digs the soil. One of the analyses is force distribution analysis of the bucket teeth. It is performed to prevent the failure on bucket teeth and to improve the usage period so that it will decrease the maintenance cost of the excavator.

Jin Chen et al. [4] conducted a research on a methodology characterizing the excavation performance of hydraulic excavator under the consideration of uncertainty during the excavation process. The natural variability of the terrain and the difference in operating forces are significant sources of the uncertainty. The most probable direction interval of excavation resistance that is obtained from the experimental data is used to measure the contribution of the uncertain medium to the variation in the direction of excavation resistance. By considering different operating styles at each excavation point, the excavation angle is discretized by certain steps and the inverse kinematic approach is taken to obtain the appropriate manipulator configuration to each incremental step from the excavation angle.

Zi-Qiang Fang et al. [5] conducted a research on contact force analysis of excavator bucket in the excavation process. By having DEM simulation, on the excavation process of the excavator bucket with different variations of excavation rates, pitch variations of the teeth and gear angle variations show that Fnmax and Ftmax of the teeth and cutting angles increase by the increase of the excavation rates, which can lead to the increase of wear probability to the teeth and cutting angle in the excavation process.

Patel et al. [6] considered backhoe kinematics, differential motion, static and dynamic model of backhoe mechanism to develop the generalized breakout and digging force model. It is not necessary to analyze every position and orientation (better known as the configuration) of the mechanism from the available breakout and digging forces. In static analysis, one configuration of the mechanism has to be decided first for which the analysis will be performed. From all configurations, the maximum breakout force condition is the most critical one since it produces the highest breakout force. Thus, for this condition, force analysis is performed and will be used as a boundary condition for FEA static [6].

This research uses finite element method. Finite Element Method (FEM) is the numerical procedure that can be used to solve problems in engineering, as well as the analysis of stress on structure, natural frequency, and its shape mode, heat transfer, electromagnetic and fluid flow. This method is used for engineering problems when exact solution or analytical solution cannot solve them. The point of this finite element method is to divide the object that will be analysed to be some parts in the finite total. These parts are called elements in which every element is connected with the node. Then, mathematical equation is formulated to represent the object [7].

2. Mathematical Model

Research conducted by Patel et al. [8] used McKyes and Zeng models as the comparison. From the two calculation procedures, any of the two can be applied to the soil and tool parameters to accurately predict the excavation or resistive force. Based on the type of the soil to be cut, any of the two models can be utilized. For instance, if the operating depth (d) of the excavation tool is so high, compared to McKyes model, Zeng model will give a higher value of the force, which requires cutting the soil.

When the excavator bucket is working the digging process, the first process happens is digging process of the bucket teeth to the soil. This digging process will produce digging force which is affected by the amount of power released by the bucket and arm cylinders. The next process is the process of dredging where the bucket teeth will cut the soil that produces resistive force or soil cutting force. The resistive force is usually affected by the characteristic of the medium under excavation.

2.1. Fundamental Earthmoving Equation

Soil mechanics is concerned with the prediction of power that is required to produce failure in the soil mass. It relates to the limitation of balance and maximum force explained in soil power with no attention to the force strain. In the case of earthmoving, however, the soil is always brought to a state of failure and, therefore, the principles of soil mechanics be applied and there must be a development of the theory of earthmoving [9]. This Fundamental Earthmoving Equation (FEE) predicts soil-resistive force that is opposite to the blade (in this case the bucket teeth) that moves horizontally to the soil. As the blade moves forward, the soil will be cut off by the blade and create a wedge from the soil that slide along the surface of the failure. Fundamental earthmoving equation predicts the static force that is required to cut the soil based on all the forces on the wedge [10]. The basic equation of earthmoving was initially introduced by Reece in 1964 which is generally better known as Fundamentals Earthmoving Equation (FEE) (Equation 1).

$$F = cd^2N_c + \gamma d^3N_\gamma + qd^2N_q + c_a d^2 N_a \tag{1}$$

Where F is the resistive force or the force that is required to cut the soil in Newton (N), c is soil cohesion (N/m^2), d is the depth of the working blade (m), γ is the bulk density (N/m^3), q is the surface force (N/m^2), c_a is the soil adhesion with the blade, N_c, N_γ, N_q and N_a are the dimensionless factors illustrating the shape of soil surface failure based on internal friction angle (ø), soil-blade friction angle (δ), soil structure and soil mass [8].

2.2. Digging Force

Digging the bucket into the soil will produce the bucket curling force (Fb) and arm crowd force (Fs). The level of these forces has been established by SAE J1179 standard "Surface Vehicle Standards - Hydraulic Excavators and Backhoe Digging Forces" [11]. The forces are rated from the force given by the side part of excavator (bucket teeth). This rate can be counted by functioning hydraulic pressure of the cylinder on the digging process.

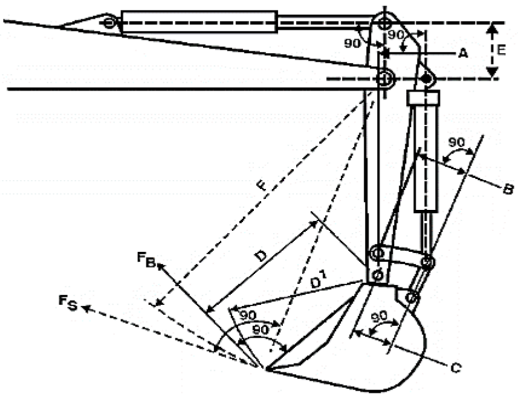


Figure 1. Digging force mechanism [9]

Maximum radial force of bucket teeth that is obtained from bucket curling force cylinder (F_b) is the digging force produced by the bucket cylinder and tangent radius $d_D{}^1$. The bucket must be positioned to obtain maximum moment output from the bucket cylinder and the connectors. F_b reaches the maximum when d_A range reaches the maximum as well, because other ranges in Equation 2 are constant.

$$F_b = \frac{p \times \left(\frac{\pi}{4}\right) D_B{}^2}{d_D}\left(\frac{d_A \times d_C}{d_B}\right) \tag{2}$$

Where *p* is the working force (MPa) and D_B is the piston diameter of the bucket cylinder (mm). Arm crowd force (Fs) is the digging force produced by arm cylinder and tangent radius dF. The arm should be positioned to get maximum moment from the arm cylinder and bucket. In calculating the maximum value of F_S, the arm cylinder axis is at the angle that is parallel to the connector line of pin arm cylinder and boom nose pin (Equation 3).

$$F_s = \frac{p \times \left(\frac{\pi}{4}\right) {D_A}^2 \times d_E}{d_F} \tag{3}$$

Where d_F is the radius of the bucket teeth (dD) plus the length of the arm connector, D_A is the piston diameter of the arm cylinder [1]. Good digging force ability will better effect on the bucket; easy to load. In addition, high digging force allows the excavator to process materials with higher hardness rates such as rock chips and limestone.

2.3. Resistive Force

When the bucket is digging the soil, the next process is dredging or cutting. This process will produce resistive force or soil cutting force. Resistive force is the force required by the bucket teeth when cutting or splitting the soil during the digging process.

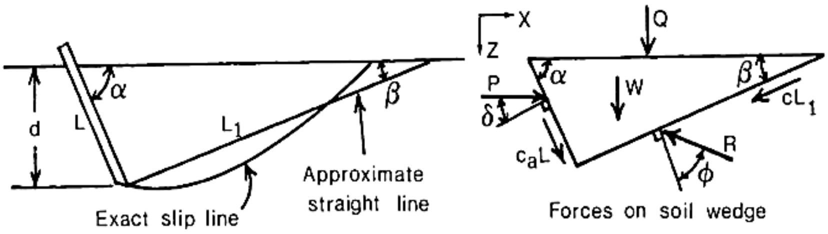


Figure 2. Resistive force modeling [12]

In which P is the resistive force (N), L is the length of bucket teeth (m), L1 is the length of failure surface (m), α is rake angle, ø is internal friction angle, W is heavy soil on length (N/m), q is soil surface force (N/m^2), δ is friction angle to bucket teeth, d is digging depth (m), γ is bulk density (kg/m^3), g is gravitation velocity (9,81 m/s^2), c is soil cohesion force (N/m^2), c_a is the magnitude of soil adhesion force to bucket teeth (N/m^2) and β is failure wedge angle. The total force on vertical and horizontal are assumed zero because of balance condition (Equation 4 and 5).

$$\sum F_x = P\sin(\alpha+\delta) + c_a L\cos\alpha - R\sin(\beta+\emptyset) - cL_1\cos\beta = 0 \tag{4}$$

$$\sum F_z = -P\cos(\alpha+\delta) + c_a L\sin\alpha - R\cos(\beta+\emptyset) + cL_1\sin\beta + W + Q = 0 \tag{5}$$

Based on Equation 3 and 4, it is obtained the magnitude of resistive force total (Equation 6).

$$P = \frac{W + Q + cd[1+\cot\beta\cot(\beta+\emptyset)] + c_a d[1-\cot\alpha\cot(\beta+\emptyset)]}{\cos(\alpha+\delta) + \sin(\alpha+\delta)\cot(\beta+\emptyset)} \tag{6}$$

For soil with uniform surface force (q), the magnitude of W and Q can be seen in Equation 7 and 8.

$$W = \gamma g \frac{d^2}{2}(\cot\alpha + \cot\beta) \tag{7}$$

$$Q = qd(cot\alpha + \cot\beta) \tag{8}$$

In which Q is the heaviness per length unit from failure wedge (N/m). When equation of resistive force is written to the equation of Fundamental Equation of Earthmoving, then the Equation 6 becomes Equation 9.

$$P = \left(\gamma g d^2 N_y + cdN_c + qdN_q + c_a dN_{ca}\right)w \tag{9}$$

Where w is the width of the bucket (m) and the N factor can be obtained from the following equations (Equation 10-13):

$$N_y = \frac{\cot\alpha + \cot\beta}{2[\cos(\alpha+\delta) + \sin(\alpha+\delta)\cot(\beta+\emptyset)]} \tag{10}$$

$$N_c = \frac{[1+\cot\beta\cot(\beta+\emptyset)]}{[\cos(\alpha+\delta) + \sin(\alpha+\delta)\cot(\beta+\emptyset)]} \tag{11}$$

$$N_q = 2N_y \tag{12}$$

$$N_{ca} = \frac{[1 - \cot\alpha \cot(\beta + \emptyset)]}{[\cos(\alpha + \delta) + \sin(\alpha + \delta)\cot(\beta + \emptyset)]} \tag{13}$$

Table 1 shows the description of the above equations.

Table 1. The description of the formula symbols

Description	Symbol
Rake angle	a
Angle of the internal shearing resistance	ø
Soil to metal friction angle	δ
Angle of the soil failure wedge	ß
Bulk density	γ
Acceleration due to the Earth gravity	g
Soil cohesion	c
Depth of the operating tool	d
Soil surcharge pressure	q
Soil to metal adhesion	c_a
Length of the tool	L
At rest Earth coefficient	K_o
Vertical acceleration	a_v
Horizontal acceleration	a_h
Weight of the tool	W_b
Width of the tool	w

To find the angle of soil failure wedge (β), it uses minimum value of β_{cr} value that is obtained from the amount of β angle from 0° to 90° which is inserted to Equation 10.

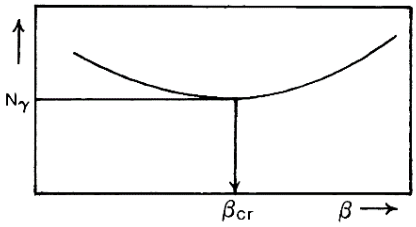


Figure 3. Minimum value of Ny as the function of β [12]

From the minimum N_y value, it obtains the value close to the amount of the β angle or β_{cr} which is then used to calculate the equations 11, 12 and 13. The result of calculating the amount of the N factor value in equations 10, 11, 12, and 13 is then inserted to equation 9, and then the value of the resistive force is obtained [12]. It will be used to analyze the force distribution and the bucket teeth using Abaqus software. When the excavator starts to dig the soil, it will trigger digging force and resistive force that occur due to the contact between the bucket and the soil. Initially, bucket teeth will dig into and cut the soil and fill the bucket to the full. The mechanism of soil cutting by bucket teeth is used to calculate the resistive force. This research uses two dimensional modeling during interaction between bucket teeth and soil. This two-dimensional modeling assumes that digging activities are conducted for wide bucket type. On the other hand, three-dimensional modeling is usually used for digging activities with a narrow cut [13].

In equation 12, the total resistive force of the bucket teeth can be estimated from the size of soil type, the soil cohesion, the surface force and the adhesion force between the bucket teeth and the soil. In this research, the amount of adhesion force between bucket teeth, soil, and soil surface force are ignored on calculation of resistive force. In the soil cutting process, it commonly has additional pressure that occurs due to the loading on the surface coming from the machine and the soil possibility that cannot be loaded completely by the bucket. Adhesion force is described as tug force between two different materials. In this research bucket teeth and soils are two different materials and do not have the tug force; so, it is assumed that the adhesion force is zero [10].

3. Research Methodology

This research started by collecting specification data of bucket teeth and soil specifications through testing. After getting the specification data, bucket teeth modeling process is conducted by using SolidWork software, digging force and resistive force calculation. Simulation of finite element method is performed by using Abaqus 6.12 software. After the simulation, from the results, it can be seen the distribution of force that occurs in bucket teeth due to the influence of rake angle during the digging process.

3.1. Bucket Teeth Material Specifications

Bucket teeth are made of steel material which has the elements of iron (Fe), carbon (C), manganese (Mn), silisium (Si) and other elements as mixed elements or residues. Mechanical properties of steel depend on the carbon content of the steel. The more carbon content contained in the steel, it will further increase the value of the hardness and wear resistance. Sometimes the steel for bucket teeth does not have enough hardness. Therefore, it is necessary to have hardening process. By having the hardening process, it will get higher hardness properties. The higher the hardness, the ductility will be low and the steel will become brittle. Such steel type is not good enough for various uses. Therefore, sometimes or often, after having the hardening process, it is then followed immediately by having the tempering process [15].

Tempering is a process when the hardened steel is reheated at a certain temperature and held for a certain time to remove or reduce residual force and restore some of its ductility and toughness. The resumption of some of this ductility or toughness is obtained by removing some of the ductility and toughness in the hardening process [16]. Thus, the bucket teeth product still has hardness, ductility and toughness values that is not easy to experience failure during the digging process.

The process of making bucket teeth is commonly carried out by Austempered Ductile Iron (ADI), Casting, and Forging. The Austempered Ductile Iron (ADI) process produces bucket teeth that have medium to high impact resistance. ADI teeth are essentially cast teeth with different chemical treatments. The steel, that gets heat treatment, is in a controlled condition (au tempering). The casting process produces bucket teeth with high strength and deep-hardening toughness and has excellent resistance to wear and abrasion. In the forging process, there is chrome-moly alloy steel with continuous fiber structure and grain flow from steel which gives power enhancement by keeping its hardness value. Bucket teeth from forging products have good tensile strength values and also have good ductility values [17].

This research uses bucket teeth of casting process whose material is AISI 1040 steel which is included in medium carbon steel category. The following is material specifications that are used to make the bucket teeth; as shown in Table 2.

Table 2. Material composition of bucket teeth

***Chemical Composition* (%)**									
C	**Si**	**Mn**	**P**	**S**	**Cu**	**Ni**	**Cr**	**Mo**	**Al**
0,37	0,25	1,34	0,017	0,006	0,007	0,022	0,32	0,16	0,011

The properties of steel materials used in this bucket teeth modeling are shown on Table 3. The properties of the materials are obtained from the testing result conducted in testing laboratory.

Table 3. Material properties of bucket teeth

Mechanical Properties				
Modulus of Elasticity (MPa)	**Poisson's Ratio**	**Yield Strength (MPa)**	**Tensile Strength (Mpa)**	**Density (ton/mm^3)**
205000	0,29	784	981	7,845 x 10^9

3.2. Soil Testing Specification

Bucket teeth are excavator components that have direct contact with the soil during the digging process. The soil has different types which are determined by its texture. The roughness and the softness of the soil are determined by the distribution of grains which is a simplification of the soil texture class; taking into account the soil fractions that are rougher than sand (2 mm larger), most grains for fractions are less than 2 mm including sandy loam, soft loam, rough dust, soft dust, soft clay, and very fine clay [18].

Each type of soil has physical properties including bulk density and soil shear power. Bulk density is the ratio of weight of dry soil to the unit of soil volume which stated in units of g/cm^3. The soil volume is the solid volume of bulk density including the pore space [19]. In addition, soil shear power is the ability of the soil against the shear power that occurs when it is overburden. In other words, soil shear power can be defined as measuring the ability of the soil to withstand the pressure without any soil friction. Generally, soil shear power may be affected by cohesion, internal shear angle, and avalanche power, sensitivity, and compression index and consolidation coefficients.

Cohesion and internal shear angle are basic parameters of soil mechanics determined by failure criteria of Mohr-

Coulomb that is applied to describe and check the stability in geotechnical engineering [20]. The shear angle is an angle formed by the relationship between normal stress and shear stress in soil material or rock [21]. Shear angle is fracture angle that is formed when a material is subjected to certain force that exceeds its shear stress. The larger the shear angle in a material, the material will be more resistant to receive the outside force.

Cohesion is a tug force between particles in soil or rock which is stated in units of weight per unit area. Cohesion gets bigger if shear power gets bigger. Cohesion is determined as a vertical intercept of the press field with surface failure [19]. Cohesion value (c) is obtained from laboratory testing of direct shear power test and tri-axial test. The aspects affecting the value of cohesion are the density and distance between molecules in an object. Cohesion is directly proportional to the density of an object, the greater the density is, the greater the cohesion.

Bucket teeth should have a good endurance capacity for materials such as wet soil and rock mixtures, as well as soils that have high abrasive values due to the nature of the soil properties. In this research, the soil specifications are obtained from the test results by using Tri-axial Unconsolidated Un-drained. The following is the testing of soil specification, as shown in Table 4.

Table 4. Soil specification

Soil Texture			Soil Physical Properties			
Sand	**Silt**	**Clay**	**Bulk Density (γ)**	**Cohesion (c)**	**Internal Friction Angle (ø)**	**Soil-Bucket Teeth Friction Angle (δ)**
64 %	19 %	17 %	1520 kg/m^3	23930 N/m^2	35.25^o	23.5^o

4. Modeling

The type of bucket teeth in this analysis is standard bucket teeth. This standard type is chosen because its ability of digging power and efficiency are quite good and balanced. The bucket teeth design is made as closely as possible to the design specifications that are described in the literature. Modeling is made by using SolidWork CAD software. The bucket teeth design in SolidWork is performed after receiving dimension data including length, width and height of bucket teeth which is obtained from the literature. The dimensions of the bucket teeth are outlined in Table 5 below:

Table 5. Dimension of standard bucket teeth

Model	Machine Capacity (ton)	Length (mm)	Width (mm)	Height (mm)	Surface Width (mm^2)	Volume (mm^3)
Standard Bucket Teeth	20 – 25	225,5	98,5	101,5	88498,29	593613,04

After knowing the geometry dimension of bucket teeth, the design process is performed by using SolidWork software. Figure 4 below presents the bucket teeth design.

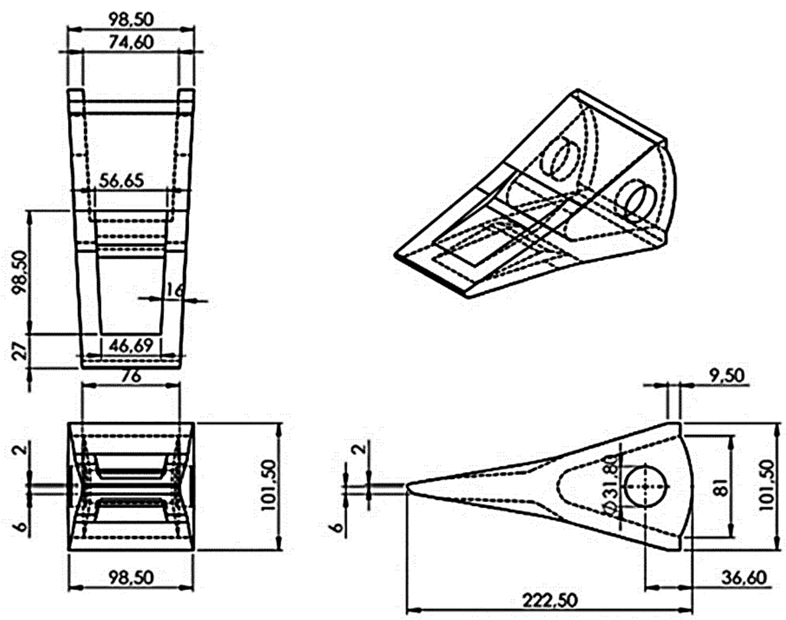


Figure 4. Bucket teeth 3D design

In this research, the type of excavator used is Komatsu PC200, which is commonly used for digging processes in construction work. The data of material specification are then inserted to the software analysis, so that the simulation data are close to the real condition, [23]. From the excavator specification, the data is used to calculate the digging force, as shown in the following table:

Table 6. Data of digging force calculation

d_A (mm)	d_B (mm)	d_C (mm)	d_D (mm)	d_E (mm)	d_f (mm)	D_A (mm)	D_B (mm)	P (Mpa)
594	631	453	1496	829	4415	95	80	37,3

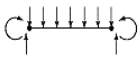
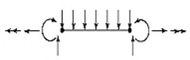
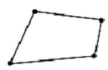
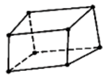
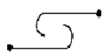
4.1. FEM (Finite Element Method)

Finite Element Method (FEM) is a numerical procedure that can be used to solve the problems in the field of engineering. This method is used on engineering problems when the exact solution or analytical solution cannot solve them. The essence of finite element method is to divide an object to be analyzed into several parts by the sum (finite). These sections are called elements. Each element from one to another are associated with nodal titles (nodes). Then, a mathematical equation can be made to represent the objects. The process of dividing objects into sections is called meshing [7].

4.1.1. Geometrical Element

Many geometric shapes of elements are used in finite element analysis for specific applications. The various elements used in commercial FEM software generally form a code deal as a reference, such as the element of code library. Elements can be placed in the following categories: line elements, surface elements, solid elements, and special purpose elements. Table 7 presents several types of elements along with the structural analysis.

Table 7. Some type of finite element in structural analysis

Element Type	Name	Shape	Nodal Number	Application
Line	Truss		2	The rod is withdrawn or pressed.
	Beam		2	Bend
	Frame		2	Axial, twist, bend, with or without the burden of stiffness
Surface	4-node quadrilateral		4	Tension / strain field, axisymetry, shear panel, bend on thin flat plate.
	8-node quadrilateral		8	Tension / strain field, bend on thin flat plate or shell.
	3-node quadrilateral		3	Tension / strain field, axisymetry, shear panel, bend on thin flat plate; the use of quad element is preferred for transition if possible.
	6-node triangular		6	Tension / strain field, axisymetry, shear panel, bend on thin flat plate; the use of quad element is preferred for transition if possible.
Solid	8-node hexagonal (brick)		8	Solid, thick plate
	3-node tetrahedron (tet)		3	Solid, thick plate for transition
Special Purpose	Gap		2	Free movement for the definition of pressure difference
	Hook		2	Free movement for the definition of pressure difference *(extension)*

5. Findings and Discussion

After getting the data result of measurement on excavator and soil testing data, the calculation of digging force and resistive force is complete. The following is the calculation result of digging force and resistive force that is caused by rake angle effect, as shown on Table 8, Table 9, and Figure 5.

Table 8. Digging force

Fb (N)	Fs (N)
8285,06	7695,97

Table 9. Resistive force based on rake angle differences

Rake Angle (°)	Failure Wedge Angle (°)	Depth (m)	Ny Density Factor	Nc Cohession Factor	Total of Resistive Force (N)	Resistive Force (N)	Total of Stress (MPa)	Normal Stress (MPa)
15	31	0,0589	2,5538	1,6394	2857,50	571,50	0,0299	0,0274
30	33	0,1138	1,7869	1,7633	6019,06	1203,81	0,0629	0,0577
45	31	0,1609	1,7169	2,2326	10830,91	2166,18	0,1131	0,1038
60	26	0,1970	1,9958	3,2278	19156,70	3831,34	0,2001	0,1835
75	21	0,2197	2,8001	5,3421	35226,47	7045,29	0,3680	0,3375
90	14	0,2275	5,1231	11,383	77133,00	15426,60	0,8058	0,7390

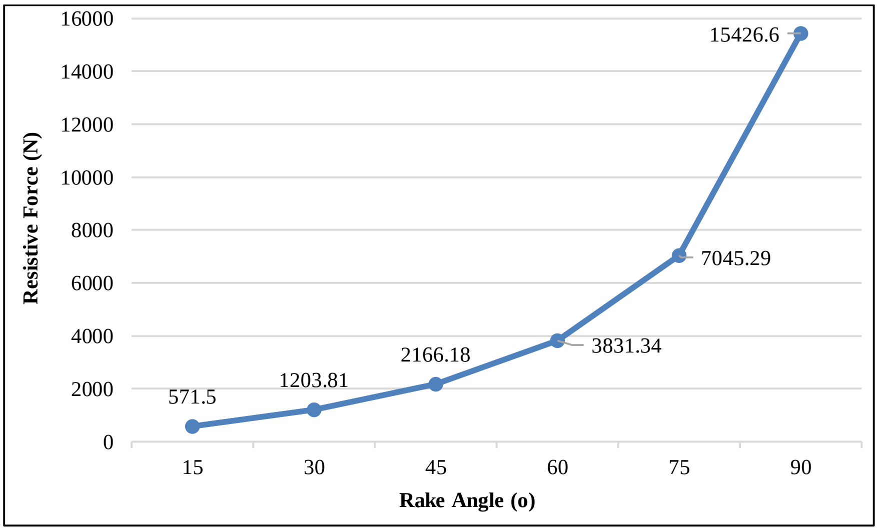


Figure 5. Resistive force based on rake angle differences

In the digging process, the highest amount of digging force is 8285.06 N which is obtained from bucket curling force. Meanwhile, in resistive force, the amount of force frequently increasing is equal to the increase of rake angle. The highest amount of resistive force is obtained from the rake angle of 90°; it is 15426.60 N for each bucket teeth.

5.1. Simulation Result

The simulation is performed by using 6 difference rake angles which become the main consideration in this research: 15°, 30°, 45°, 60°, 75° and 90°. The result of the simulation is presented in Figure 7 and Figure 8 for maximum stress value. The data presented below are in von misses stress on bucket teeth. After knowing the amount of maximum stress, then its result is compared to allowable stress from the material of the bucket teeth. The following is the calculation result of bucket teeth allowable stress:

$$Safe\ Stress = \frac{Strength\ of\ Material}{Safety\ Factor} = \frac{784}{2} = 392\ MPa$$

Based on simulation result, it can be seen the stress distribution is uneven on every bucket teeth caused by rake angle influence. While, the magnitude of maximum stress on bucket teeth from simulation result for digging force loading obtains maximum stress on both points of bucket teeth. This shows that when bucket teeth is used continuously, then it will fail on both points. The failure can be in wear, bent, crack and fracture. To minimize the failure, then hardening on bucket teeth's both points should be done.

In a research where finite element method is used, meshing step is very important step. Meshing is the step of dividing a part into small parts (elements). The size of the mesh is very important in viewing the accuracy of this research. Dense meshing is given on the bucket teeth so that the simulation results are more accurate. The shape of the element is tetrahedron. The meshing figure is presented in Figure 6 while the number and the type of meshing is presented in Table 10.

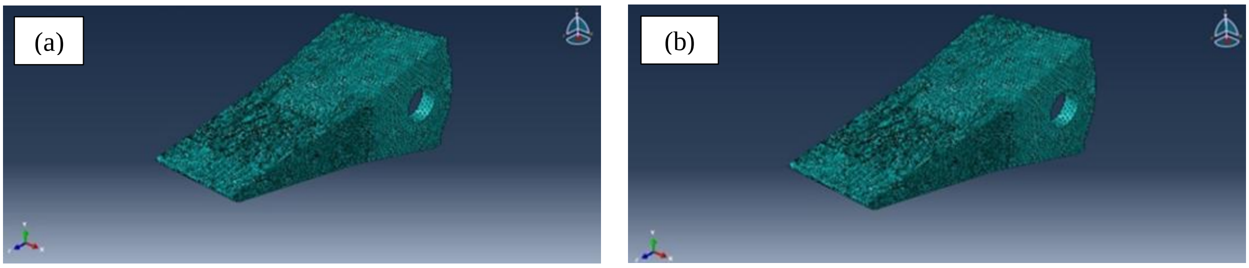


Figure 6. a) Provision of Mesh for Resistive Force Loading; b) Provision of Mesh for Digging Force Loading

Table 10. Description of Meshing of Bucket Teeth

Loading	Information
Penetration Force	Total number of nodes: 2.432.392 Total number of elements: 1.745.553 Quadratic tetrahedral elements of type C3D10
Resistive Force	Total number of nodes: 2.879.998 Total number of elements: 2,064,562 Quadratic tetrahedral elements of type C3D10

From the simulation result of resistive force loading, it presents the stress distribution on central point of bucket teeth. Meanwhile, the amount of maximum stress value is nearly small so that the risk to experience failure is small as well. However, it may experience failures if the bucket teeth are used continuously, it may experience wear, bent, crack and fracture on its center. Thus, to minimize the failure, hardening the bucket teeth' center should be conducted.

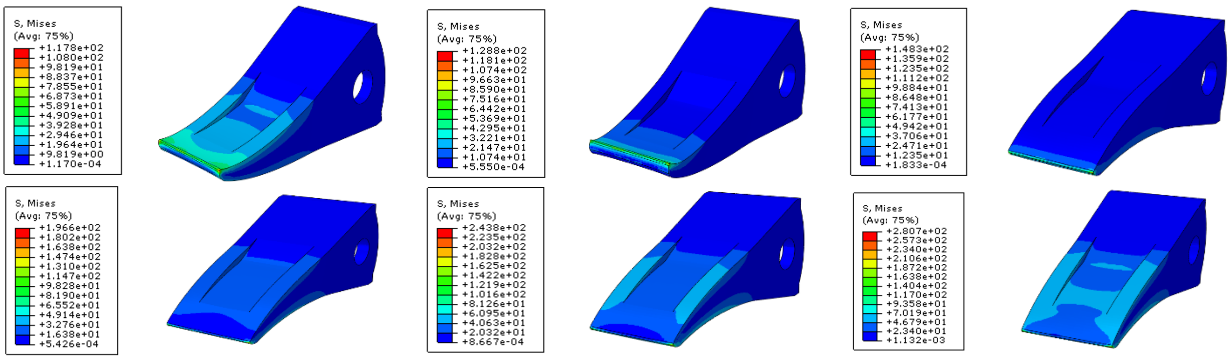


Figure 7. Stress distribution for digging force

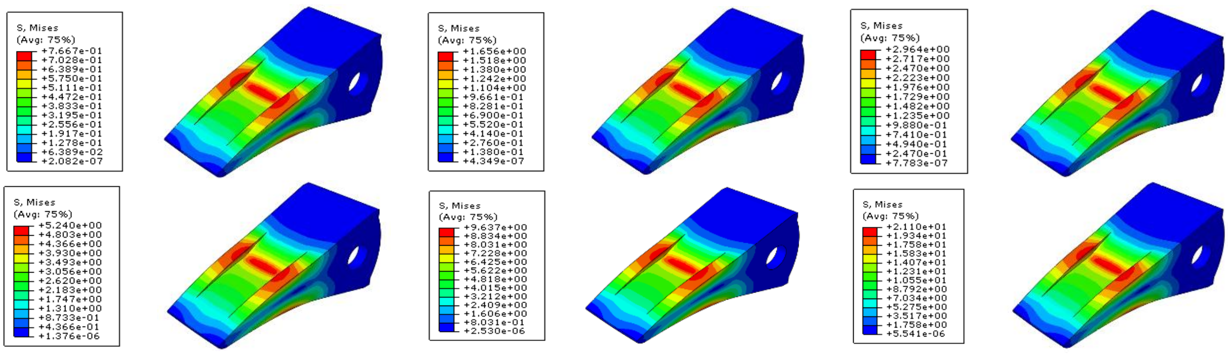


Figure 8. Stress distribution for resistive force loading

After obtaining the amount of allowable stress, then it is compared to the maximum stress result on bucket teeth that is caused by different rake angle effect. Table 9 presents the comparison ratio between the maximum stress and the allowable stress on bucket teeth for digging force loading. Meanwhile, Table 10 presents the comparison ratio between the maximum stress and the allowable stress for resistive force loading.

Table 11. Comparison ratio for digging force loading

Rake Angle (°)	Maximum Von Mises Stress (MPa)	Maximum Displacement (mm)	Ratio (%)	Safe/Unsafe
15	117,8	0,0128	30,05	Safe
30	128,8	0,0555	32,85	Safe
45	148,3	0,0320	37,83	Safe
60	196,6	0,0736	50,15	Safe
75	243,8	0,1104	62,19	Safe
90	280,7	0,1397	71,60	Safe

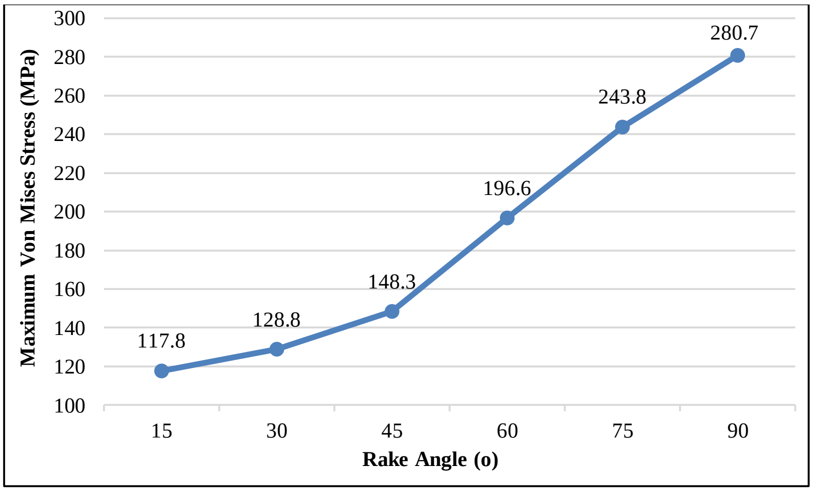


Figure 9. Comparison Ratio between Rake Angle and Von Misses Stress for Digging Force Loading

Table 12. Comparison ratio for resistive force loading

Rake Angle (°)	Maximum Von Mises Stress (MPa)	Maximum Displacement (mm)	Ratio (%)	Safe/Unsafe
15	0,767	0,0014	0,19	Safe
30	1,656	0,0031	0,42	Safe
45	2,964	0,0056	0,75	Safe
60	5,240	0,0100	1,33	Safe
75	9,637	0,0184	2,45	Safe
90	21,10	0,0402	5,38	Safe

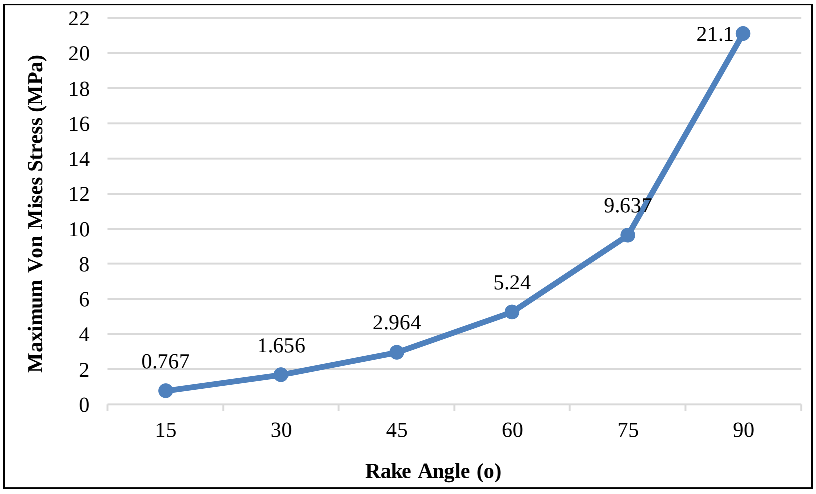


Figure 10. Comparison Ratio between Rake Angle and Von Misses Stress for Resistive Force Loading

Based on Table 11 and Table 12, it is known that the comparison ratio of maximum stress and allowable stress are under 100% so that the material or the model of bucket teeth is considered as safe to be used for digging process. The magnitude of stress value increase for every difference of rake angle. The digging force loading can obtain in the amount of 280,7 MPa. While, the resistive force loading obtains the highest stress value is in the amount of 21,1 MPa. The magnitude of maximum stress value from both loadings are still under allowable stress so that bucket teeth can be stated safe.

6. Conclusion

From simulation result, it can be concluded that the maximum stress for digging force loading is on the two points of bucket teeth. It may cause failure on both points of the bucket teeth including wear, bent, crack and fracture. Meanwhile, from the resistive force loading, it is known that the maximum stress is on the center of bucket teeth but the maximum stress value is still far from the allowable stress. Thus, the risk of failure is smaller but it is possible to experience failure including wear, bent, crack and fracture on its center.

After the calculation process of digging force and bucket teeth modeling on SolidWorks software is complete, the bucket teeth model is imported to Abaqus software to be simulated. Stressing is performed by giving digging force on the point of the bucket teeth and resistive force to the bucket teeth which have direct contact to the soil in the digging process. This analysis aims to know the amount of maximum stress on bucket teeth in digging process and soil cutting. Thus, it will obtain the information of the part of bucket teeth that experience failures. The maximum stress outcome on bucket teeth is then compared to allowable stress from bucket teeth material. If the value of the maximum stress of analysis result is less than allowable stress from the bucket teeth material, then it can be concluded that the bucket teeth is safe.

7. Acknowledgment

The writer would like to thank to Faculty of Engineering of Diponegoro University for providing the scholarships.

8. References

[1] Tasevski, A. and Hedlund, C. Design of bucket teeth. Eskilstuna : Mälardalen University, 2016.

[2] Shaikh, Bilal Pirmahamad, and Abid M. Mulla. "Analysis of bucket teeth of backhoe excavator loader and its weight optimization." International Journal of Engineering Research & Technology 4 (5) (2015): 289-295.

[3] Deere, John. Bucket Tooth Catalogue. USA, 2002.

[4] Chen J, Zou Z, Pang X. Digging performance characterization for hydraulic excavator considering uncertainty during digging operation. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2017, https://doi.org/10.1177/0954406217692843.

[5] Fang ZQ, Hu GM, Gui WJ, Liu Y. Analysis of contact forces of particles with excavator bucket in digging process by using discrete element method. In Mechanics and Mechanical Engineering: Proceedings of the 2015 International Conference (MME2015) 2016 Jul 14 (pp. 30-38).

[6] Patel, Bhaveshkumar P. and Prajapati., J. M. "Evaluation of bucket capacity, digging force calculations and static force analysis of mini hydraulic backhoe." Jr. of Machine Design 4 (2012): 59-66.\

[7] Zienkiewicz, O. C., Taylor, R. L. and Zhu, J. Z. The Finite Element Method: Its Basis and Fundamentals 6th Edition. Amsterdam, 2005.

[8] Patel, B. P., Prajapati, J. M. and Gadhvi, B. J. "An excavation force calculation and applications: an analytical approach." International Jounal of Enggineering Science and Technology 3 (2011): 3831-3837.

[9] Reece, A. R. "The fundamental equation of earth-moving mechanics." Proc Instn Mech Engrs (1964): 16-22.

[10]Cannon, H. N. Extended Earthmoving with an Autonomous Excavator. Pittsburg: Carnegie Mellon University, 1999.

[11] SAE International. SAE J1179: Hydraulic Excavator and Backhoe Digging Force. Warrendale: SAE, 1990.

[12] McKyes, E. Developments in Agricultural Engineering 7 Soil Cutting and Tillage. Amsterdam: Elsevier Science Publishers, 1985.

[13] Blouin, Stéphane, Ahmad Hemami, and Mike Lipsett. "Review of resistive force models for earthmoving processes." Journal of Aerospace Engineering 14, no. 3 (2001): 102-111, https://doi.org/10.1061/(ASCE)0893-1321(2001)14:3(102).

[14] Golbasi, O. Investigation of Stress Distribution in a Dragline Bucket Teeth Using Finite Element Analisys. Turki : Midle East Technical University, 2011.

[15] Pollack, H. W. Materials Science and Metallurgy 2nd Edition. Singapore: McGraw-Hill, 1988.

[16] Callister, W. D. Materials Science and Engineering: An Introduction 7th Edition. New York: John Wiley & Sons Inc, 2007.

[17] National Soil Survey Center NRCS. Field Book for Describing and Sampling Soils. USA: U.S. Department of Agriculture, 2012.

[18] Sara, M. N. Site Assessment and Remediation Handbook 2nd Edition. USA: Lewis Publishers, 2003.

[19] Burland, J. B. "On the compressibility and shear strength of natural soils." Geotechnique 40 (1990): 329-378.

[20] Wu, X. Z. "Modelling dependence structures of soil shear strength data with bivariate copulas and applications to geotechnical reliability analysis." Soils and Foundations 55 (2015): 1243-1258, https://doi.org/10.1016/j.sandf.2015.09.023.

[21] Polovinko, V. A., and A. I. Fedulov. "Geometry of the working part of an excavator tooth." Journal of Mining Science 29, no. 2 (1993): 115-121, https://doi.org/10.1007/BF00733460.

[22] Lazić, V., A. Sedmak, R. R., Nikolić, M. Mutavdžić, S. Aleksandrović, B. Krstić, D.M. "Selection of the most appropriate welding technology for hardfacing of bucket teeth." Materials and Technologies/Materijali in Tehnologije, 49(2015): 165–172.

[23] Fernandez J. E., Vijande R., Tucho R., Rodriguez J., Martin A. "Materials selection to excavator teeth in mining industry." Elsevier, Wear 250 (2001): 11, https://doi.org/10.1016/S0043-1648(01)00624-X.