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FINITE ELEMENT ANALYSIS OF EXCAVATOR BUCKET DESIGN WITH BIOMIMETIC APPROACH WITH DIFFERENT STEELS

FARKLI ÇELİKLERLE BİYOMİMETİK YAKLAŞIMLA EKSKAVATÖR KEPÇE TASARIMININ SONLU ELEMANLAR ANALİZİ

Berkay KARAÇOR[1*] *(ORCID: 0000-0001-5208-366X)*
Kaan KOÇ[1] *(ORCID: 0009-0000-2096-4059)*
Mustafa ÖZCANLI[1] *(ORCID: 0000-0001-6088-2912)*

[1]Çukurova University, Faculty of Engineering, Department of Automotive Engineering

*Sorumlu Yazar / Corresponding Author: Berkay KARAÇOR, bkaracor@cu.edu.tr

ABSTRACT

One of the biggest problems of construction machines that make people's lives easier is digging efficiency. In this study, a new excavator teeth model with a biomimetic approach was developed to solve the problem of digging efficiency. This biomimetic digging teeth model is inspired by the front claw of the armadillo, which is naturally a successful digging animal. In the bucket, only the teeth are biomimetic and in the armadillo teeth model, the 5 mm deep thinned parts on the sides of the standard bucket are determined as 25 mm deep in the armadillo teeth model for extra lightness. In addition, a standard digging tooth was designed and finite element analysis of this standard design and the armadillo design was carried out using different steels. The designs were created using the CATIA V5 R21 program. The analyzes were carried out using the Ansys Workbench 18.1 program. Three different steel groups were used for the analysis results. These were St-37, S690QL, and Weldox900 E steels. Total deformation, safety factor, equivalent stress, and cost analysis were carried out. The average stress values were 228.85 MPa for the standard teeth and 162.01 MPa for the armadillo teeth.

Keywords: Excavator bucket, finite element method, biomimetic, armadillo

ÖZET

İnsanların hayatını kolaylaştıran iş makinelerinin en büyük problemlerinden biri kazma verimliliğidir. Bu çalışmada kazma verimliliği problemini çözmek için biyomimetik yaklaşımla yeni bir ekskavatör diş modeli geliştirilmiştir. Bu biyomimetik kazma dişi modeli, doğası gereği başarılı bir kazma hayvanı olan armadillonun ön pençesinden esinlenerek tasarlanmıştır. Kovada sadece dişler biyomimetik olup, armadillo diş modelinde standart kovanın yanlarında bulunan 5 mm derinliğindeki inceltilmiş parçalar ekstra hafiflik için armadillo diş modelinde 25 mm derinlikte belirlenmiştir. Ayrıca standart bir kazma dişi tasarlanmış ve bu standart tasarım ile armadillo tasarımının sonlu elemanlar analizi farklı çelikler kullanılarak yapılmıştır. Tasarımlar CATIA V5 R21 programı kullanılarak oluşturulmuştur. Analizler Ansys Workbench 18.1 programı kullanılarak gerçekleştirilmiştir. Analiz sonuçlarında üç farklı çelik grubu kullanılmıştır. Bunlar St-37, S690QL ve Weldox900 E çelikleridir. Toplam deformasyon, güvenlik faktörü, eşdeğer stres ve maliyet analizi yapıldı. Standart dişler için ortalama stres değerleri 228,85 MPa ve armadillo dişleri için 162,01 MPa olarak bulunmuştur.

Anahtar Kelimeler: Ekskavatör kovanı, sonlu elemanlar metodu, biyomimetik, armadillo

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INTRODUCTION

The development of construction machinery accelerated from the 16th century onwards. Until the 16th century, infrastructural activities were carried out using non-technical work equipment. Construction machinery was used in building work to create modern and orderly cities. In particular, they were often favored in the clean-up and reconstruction of regions that had been destroyed after the Second World War, which is why their importance increased. After that time, the production of construction machinery has gained considerable momentum (Onat, 2013). Construction machines are generally large, powerful machines used in industry or construction. Construction machinery used by government institutions such as agriculture, industry, national defense, and private industry are machines that are equipped with various devices depending on their purpose.

Excavators are construction machines that carry out channel-shaped excavation and loading work. They are often used in the construction of dams and mines. There are two different types: Crawler excavators and wheeled excavators. In general, they replace human power when excavating soil and transporting building materials and do the work more efficiently and quickly (Akpınar, 2010). The concept of biomimetics was first used by Otto H. Schmitt in 1969. The word is of Greek origin and is made up of the words ‘bios', meaning life, and ‘mimesis’, meaning imitation. For designers, it is both difficult to incorporate only biological information into the design process and insufficient if the results in the design are inadequate. Physically, the shape can be mimicked, but to understand the system chemically, scientific work is required. Determining the problem that the designer needs and then implementing the design that results from the scientific work of that problem leads to more efficient results. The abilities of living things in nature, such as digging, swimming, running, and flying, are a source of inspiration for technology, vehicles, mechanisms, and structures. Although the concept of biomimetics was not introduced until 1969, biomimetic studies go back much further. Leonardo Da Vinci, a painter who defined his time with his paintings, designed flying machines by working the structures of flying creatures in nature as they flew. The Crystal Palace in London and the Eiffel Tower in Paris are also examples of biomimetic designs (Yıldız, 2012). Since it is expensive to work on the parts of the excavator, most of the time the work is done in a computer environment. This is because these parts need to be developed.

In this research, Rao et al. studied in detail the effects of vertical cuts of excavator bucket teeth on the tooth. In this instruction, the researchers used 4 different materials (steel, grey cast iron, titanium boride, and titanium carbide) and 3 different cross-sections (round, triangular, and rectangular). Various analyses were carried out on the CAD model they created. These were examined in 4 different analyses, namely static analysis, vibration analysis, fatigue analysis, and impact analysis. The results of the education showed that excavator teeth made of grey cast iron and teeth with a square cross-section were more efficient in static and vibration analyses compared to other materials and cross-sections. These results show that excavator teeth made of grey cast iron and with a square cross-section are more suitable in terms of durability and efficiency (Rao et al., 2016). Lomate et al. investigated the different effects that occur on the excavator’s teeth under the digging force with different types of excavators. In these investigations, they first performed the analyses from the Ansys application and also performed mathematical calculations. As a result of the analysis, they determined values such as von Mises stresses, deformation amounts, and shear stresses. They compared the different types of excavators with each other (Lomate et al., 2016). Khedkar et al. investigated the resistance exerted by the excavator bucket on the soil. In the study, various calculations were carried out and the digging force was calculated according to SAE standards.

Outcomes of research concluded that the designed bucket was usable because the digging force of the bucket was higher than the resistance force of the soil (Khedkar et al., 2017). Shaikh and Mulla applied forces and investigated the specific stress values of excavator teeth made of Hardox 400 and Hardox 500 sheets of steel according to SAE standards. In addition, excavator teeth for general purposes such as bolted standard teeth, heavy duty teeth, long teeth, tiger teeth, twin tiger teeth, and wear teeth for smallest batch sizes were analyzed and von Mises stress and total deformation values were observed and necessary optimizations were suggested and tested for reliability (Shaikh & Mulla, 2015). Demircioğlu et al. investigated the effects of bulk materials placed by excavators on the excavator bucket. They created the excavator design using Autodesk inventor software and simulated the bulk material in the EDEM simulation environment. They also used the Ansys mechanic program to investigate the wear, stress, and pressure values that would occur on the bucket. As a result of the analyses, they found that the bucket was subjected to deformation and stresses of 0.5514 mm and 138.75 MPa respectively. At the end of this study, they concluded that the stress and deformation values did not cause serious damage to the blade (Demircioğlu et al., 2021). Tasevski and Christine carried out studies to extend the life and increase the strength of excavator teeth, which are made of cast iron and do not have the same hardness values at every point. They designed 3 or 4 plates of Hardox steel, one of the most durable steels on the market, as excavator teeth. They tried to develop a design that offered better wear resistance in both the tooth structure and the material. They obtained the wear test values as a result of a DEM analysis. The result of the study was that the service life and wear resistance were at least twice as high as the adapter and teeth made of cast iron (Tasevski & Christine, 2016). Chang et al. designed a biomimetic handle inspired by the ability of the cryptotympana atrata nymph's front claws to cut and dig in the ground. Using reverse engineering and 3D printing, they designed two different corn cutting handles with different heights. They mentioned that the designed biomimetic stalks have lower cutting resistance compared to the stalks with traditional design and that the influence of cutting speed on cutting resistance is determined by the tooth height and digging angle of the cutting edge. They found that the cutting height was 2.5 mm cutting-edge digging angle was 40°, and the cutting resistance did not change significantly with the cutting speed. Results of the analysis, they found that the design of the tooth structure was the main factor in reducing the cutting resistance, and they concluded that the biomimetic design of the handle made by simulating the bottom cutting mechanism of the cryptotympana atrata nymph significantly increased the performance of the handle cutter (Chang et al., 2016). Zhi Jun et al. developed a biomimetic design that resembles a plowshare by modeling it on the nail structure of a field mouse, which has a strong digging ability. First, they studied the curvature and profile analysis of the inner contour line of the claw finger of a field mouse. They fitted the curve obtained to the cutting edge of the blade that first touches the ground. They explained that the part considered in the fit is the ratio of the horizontal length of the digging part in the ground to its vertical length (L/B). They examined the results of the digging process through a finite element analysis. As a result of the instruction, they found that those with an L/B ratio of 0.8 were subject to less soil resistance and less soil adhesion (ZhiJun et al., 2009).

Akter resorted to the biomimetic method to find a solution to one of the common problems of construction machinery, namely digging efficiency. In developing the design using this method, he was inspired by the claws of anteaters and badger excavators. The biomimetic excavator design variants created were compared with each other and with the standard excavators on the market by performing a static analysis in a computer environment. The analysis showed that the designed biomimetic excavator model was more efficient than the standard model in terms of the overall deformation of the excavator claw as well as the deformation and loading of the excavated soil (Akter, 2018). Qingyi et al. designed a biomimetic sawtooth structure on a standard rototiller blade, inspired by the claw structure of the oriental mole cricket, to improve the performance of the rototiller blade. They concluded that the design produced higher torque than standard blades in real and simulated tests and that the field quality was better after work (Qingyi et al., 2017). Hadi Suryo et al. have attempted to determine the stress and wear values to which excavator teeth are subjected. They performed the design, analysis, and maximum stress values using the Abaqus 6.10 Computer Aided Engineering (CAE) application. They determined the stress values of the analysis by applying a force of 8285.06 N at an angle of 32° to the horizontal under static conditions. The result of the analysis shows that the maximum stress to which the excavator's teeth are subjected is 209.3 MPa and this value is below the von Mises value. They therefore concluded that the design is safe (Hadi Suryo et al., 2018). Winter et al. have developed a device inspired by razor clams, sea creatures that dig by liquefying the soil. Using the device, called roboclam, they wanted to investigate how these clams work in different environments and conditions by mimicking their digging methods and transferring them to engineering applications. As a result of the research, they stated that the most efficient digging movements of roboclam mimic the razor clam shell structure and provide high efficiency in terms of energy to depth ratio. In line with these results, they concluded that this inspired design is efficient in terms of energy efficiency and frictional resistance and is therefore viable (Winter et al., 2009).

In this paper, the current standard excavator bucket and teeth were designed in the CATIA V5 R21 computer-aided design program, and a claw model resembling the claw structure of the armadillo, one of the most successful digging animals in nature, was designed using the biomimetic method and mounted on the standard excavator bucket however; to reduce weight in the armadillo bucket, the sides of the armadillo excavator bucket are slightly thinner than the standard bucket. The armadillo claw model was designed to be one piece without the need for an adapter, saving on parts and reducing labor. The resistance of these two different teeth models to the forces applied statically to the ground by 3 different steels was investigated. After the applied loads, the total deformation of the teeth, the values of the equivalent stresses, and the values of the safety factor were analyzed and, at the end of the work, the results of the armadillo-type teeth model created with the biomimetic method and the standard-type teeth model were compared.

MATERIAL AND METHODS

Material

In this study, 3 different steels were preferred to be used in analyzing the excavator bucket in terms of cost, durability, manufacturability, in terms of market availability, performance, and strength. These were determined to be St-37, S690QL, and Weldox900E steel respectively**.**

St-37 is one of the most preferred steels in industrial organizations and is frequently used in general building materials. It is a type of steel formed as a result of re-processing the steel made by hot production and obtaining it by cold drawing. As a result of these processes, the steel becomes more durable than normal. It is one of the most commonly used steels in the industry due to its affordable cost and easy availability (Maraşlı et al., 2022). Since S690QL steels are tempered steels, they are used in heavy-duty machinery and the construction of high weight structures. Among the areas where the material is preferred are heavy-duty applications such as the truck industry, crane industry, and construction machinery (Efe et al., 2019). The last steel and the most expensive in terms of cost, is Weldox 900 E steel. These steels are known as high-strength and low-alloy steels. Although they are expensive, they are used for the manufacture of heavy objects such as construction and heavy machinery. Although it is structurally low in carbon, it contains elements such as titanium and vanadium. These elements ensure both good weldability and high strength properties. In addition to their high strength, they are steels with a flexible structure (Shi et al., 2022). The values of the material characteristics of the steel used required in the analysis are indicated in Table 1.

Table 1. Material Properties (Karaçor et al 2024; Shi et al 2022)

Material	Density (kg/m^3)	Elastic modulus (GPa)	Poisson ratio	Tensile strength (MPa)	Tensile ultimate strength (MPa)
St-37	7850	200	0.3	250	460
S690 QL	7860	210	0.29	770	810
Weldox 900 E	7800	206	0.3	947.48	1100

Methods

In this investigation, CATIA V5 R21, a Computer Aided Design (CAD) program, was used for the design and Ansys programs for the finite element analysis. While performing the analysis, static analysis was used in the finite element method. Computer Aided Design (CAD) is the use of computer systems that assist with creating and modifying designs. Currently, specific CAD programs also possess the capability to analyze these designs through the analytical modules they have developed. Examples of these analysis are deformation analysis of parts, dynamic analysis, and heat transfer calculations. With this analysis programs, the designer knows how her design will react mechanically and thermodynamically to the stresses to be applied and how to resolve possible errors by analyzing the design before production. This saves time and costs (Çınar, 2014). CATIA is a design program for creating and modifying objects. This design program has design and modeling functions. Designing means creating a new object or modifying an existing object. Drawing, on the other hand, means making the object visually understandable (Prasad et al., 2014). The design of the excavator housing was created in the CATIA V5 R21 program. The finite element method (FEM) is a calculation method used in engineering to obtain approximate solutions to boundary value problems. In short, a boundary value problem is the solution of differential equations that apply at each point of a region and whose boundaries must fulfill certain conditions. This method allows the design of complex shapes. The solution region can be divided into different regions and different finite elements can be used in the different regions (Yılmaz, 2023). The analysis was performed using the finite element method in the Ansys program. Ansys offers the possibility of obtaining analysis results with various characteristics in a computer environment without the need for physical production of the designs. Creating the design is both more costly and more time consuming than the analysis method.

In addition, Ansys increases the life and quality of the parts by identifying and improving the defective parts of the designs owing to the 3D simulations (Kibar & Öztürk, 2012).

While Figure 1a is the view of the excavator bucket designed in CATIA in the Ansys Workbench program; Figure 1b represents the designed armadillo claw excavator bucket. The view of the mesh distribution after the meshing is displayed in Figure 2a. Whilst, Figure 2b indicates which parts are fixed supported during the analysis; Figure 3a displays the view of the forces applied to the teeth and the value of the force. The points on the scale for poor quality are shown in Figure 3b.

While Figure 4 to Figure 6 reflect the analysis results of the standard excavator bucket, Figure 7 to Figure 9 show the analysis results of the armadillo excavator bucket.

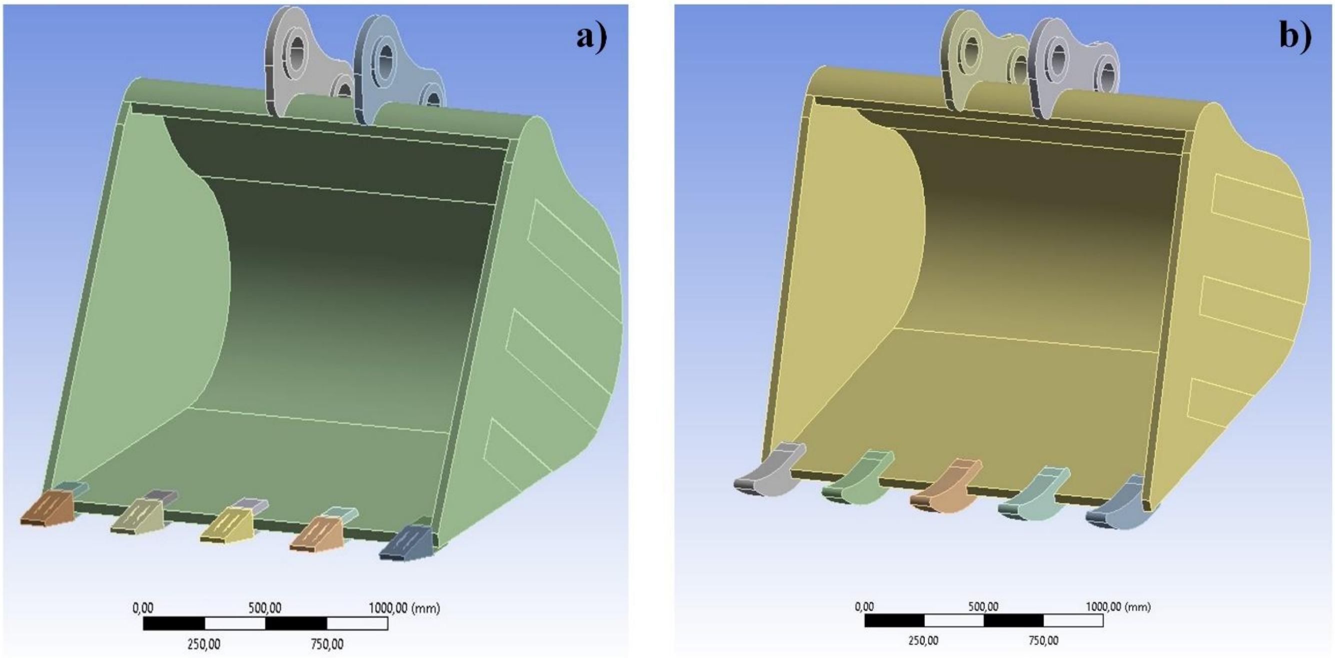

Figure 1. a) Standard Excavator Bucket General View b) General View of Armadillo Claw Design Excavator Bucket

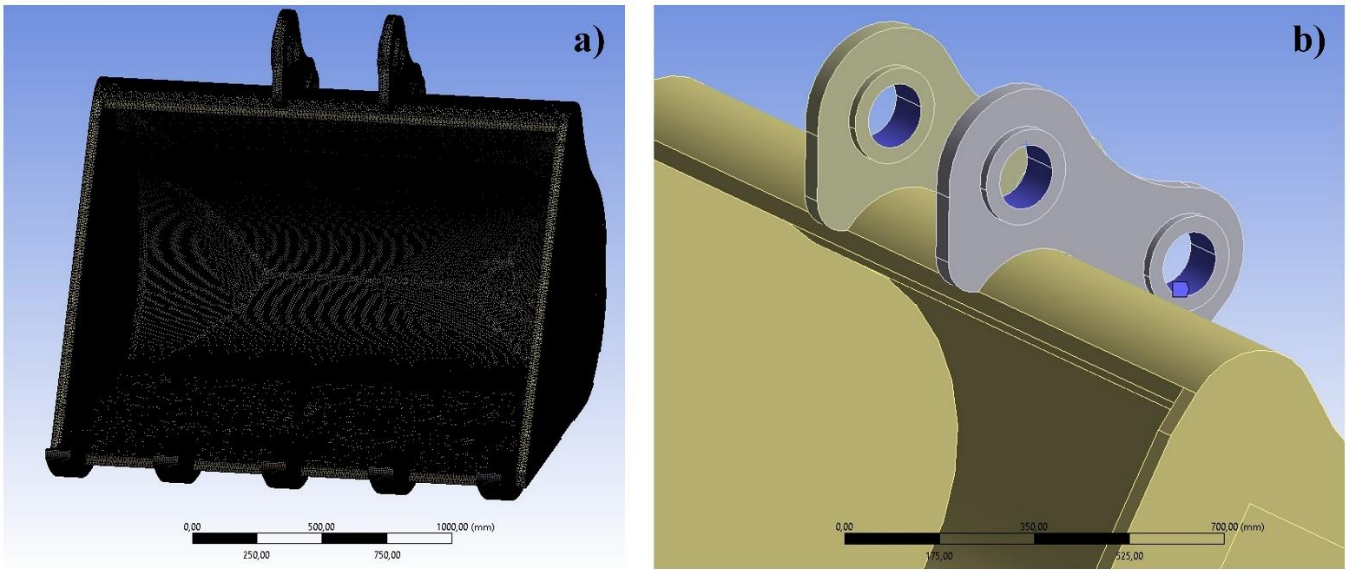

Figure 2. a) General Mesh View b) Fixed Support Section of the Excavator Bucket

During the analysis, not only generated mesh was used when creating the mesh. In terms of being more detailed and having fewer elements, a more efficient result was obtained with examinations such as face sizing, face meshing, and body sizing on the parts. As a result, mesh optimization was obtained.

A correct analysis can be solved by defining the number of meshes for each structure. This mesh number can vary according to the dimensions of the design. The bucket used in the study has a width of 1870 mm and therefore the number of meshes should be defined in a range close to the optimal values. The points we pay attention to in the mesh metrics are the skewness and element quality values. Skewness expresses the skewness value of the mesh group in a structure, and the closer this value is to 0, the lower the skewness in the mesh structure in that direction. The optimum skewness range for analysis is assumed to be 0.20-0 25. Element quality expresses the quality value of each element of the same mesh structure. This value is expected to be as close as possible to 1. The optimal range is 0.80-0.90. Considering these parameters, since the structure we analyzed consists of curved surfaces, the triangular mesh structure was preferred, and a mesh size of 4-8 mm was chosen for the nails. The triangular mesh structure provides a more consistent connection between points called nodes that form the corner joints of triangular structures on curved surfaces.

Face meshing is used in the automatic settings. When using the face sizing method, only the element size value was changed. Different element size values were used in different areas. The reason for this is that the accuracy margin at critical points is high. The values for the element size are as follows: Sides of the bucket: 10mm, top, back, and inside of the bucket: 20mm, bottom of the bucket: 15mm. In the method for determining body sizing method, only the values for the element size were changed. For the nails: 4 and 8 mm,for the bucket: 20 mm.

The excavator boom connection pin area was selected as the fixed support. Because the excavator can move thanks to that area while digging the soil. The connection point between the bucket and arm is supported by the pin slots on the arm and the hydraulic system on the arm, as can be seen in the picture. Since the movement of the bucket depends on the user's input, the hydraulic system restricts its movement in case of influences other than the user's input. For this reason, the support points have been chosen so that they are supported by both the hydraulic system and the pins.

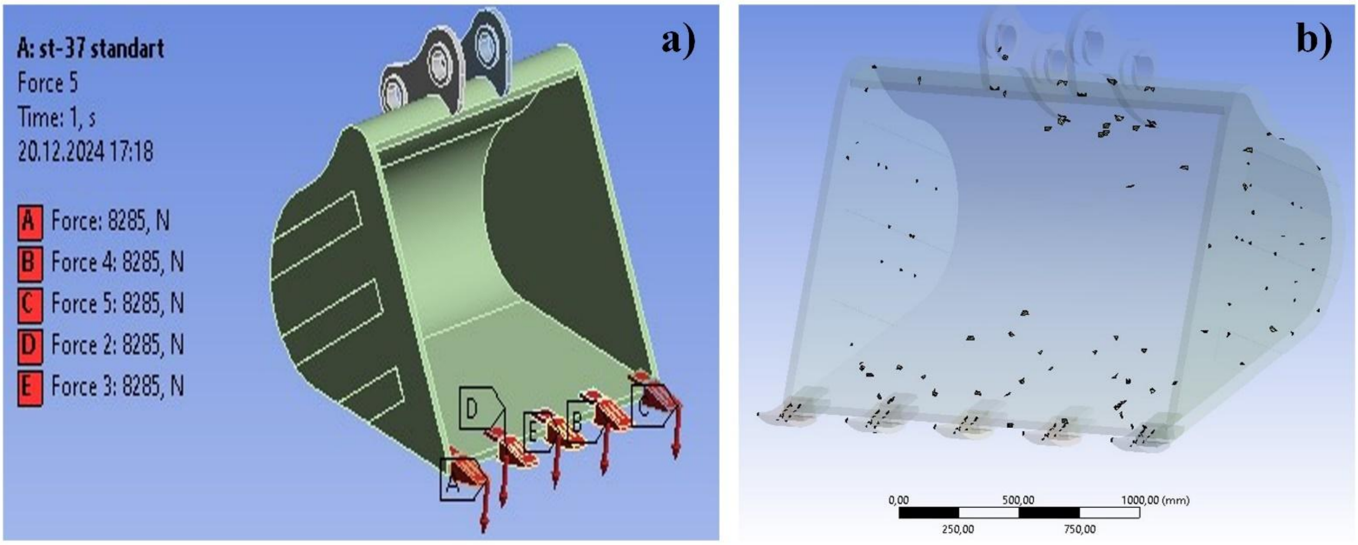

Figure 3. a) View of Forces Applied to Teeth b) Elements that can be counted in the Bad range

The force exerted on the teeth was taken from previous studies and determined to be 8285 N (Gurbet et al., 2021). The force was applied to each of the teeth in the negative Z direction. The reason why the force is given to the nails is that they are the most affected and most important part during excavation.

The qualities of the mesh values can be found in Table 2. There are 1001964 elements in the mesh process performed in the analysis. Only 124 of these elements are in the bad range. The closest value is in the bad and fair range. The

124 elements in the bad area are located on the sides of the bucket, which is in the area that is not damaged by the analysis.

Table 3 gives the result values for skewness and element quality that were applied to the other shell combinations using the same mesh methods.

Table 2 Optimum Mesh Properties (ANSYS, 2016)

Value of Skewness	Cell Quality
1	Degenerate
0.9-<1	Bad
0.75 — 0.9	Poor
0.5 — 0.75	Fair
0.25 — 0.5	Good
>0 — 0.25	Excellent
0	equilateral

Table 3. Mesh Values

	Maximum	Minimum	Average
Skewness	0.99951	1.3057e-010	0.26567
Element quality	0.99998	4.0974e-002	0.81329

The excavator bucket design was designed by taking the dimensions of the model of the company that produces the excavator bucket from previous studies as 1870mm in length and 1400mm in width (Akter, 2018).

RESULT AND DISCUSSION

Table 4 indicates the total deformation, equivalent stress, and safety factor values of the standard excavator bucket with different steels as a result of the analysis.

Table 4. Standard Excavator Bucket Results

	St-37	**S690QL**	**Weldox900 E**
Total deformation (mm) (Max)	6.8584	6.5166	6.6597
Equivalent stress (MPa) (Max)	180.44	245.26	260.86
Safety factor	1.3855	3.1024	3.6321

Table 5 displays the total deformation, equivalent stress, and safety factor values of the armadillo excavator bucket with different steels as a result of the analysis.

Table 5. Armadillo Excavator Bucket Results

	St-37	**S690QL**	**Weldox900 E**
Total deformation (mm) (Max)	7.3546	6.9957	7.1409
Equivalent stress (MPa) (Max)	156.6	164.85	164.6
Safety factor	1.5965	4.6157	5.7563

Table 4 and Table 5 values are given above, if these values are compared;

- The lowest value of total deformation was obtained with the standard S690QL design with a value of 6.5166 mm, while the highest value was obtained with the armadillo St-37 design with a value of 7.3546 mm.

- The lowest equivalent stress value was obtained in the armadillo S690QL design with a value of 156.6 MPa, while the highest value was obtained in the standard Weldox900 E design with a value of 260.86 MPa.

- While the lowest safety factor value was obtained in the Standard St-37 design with a value of 1.3855, the highest value was obtained in the armadillo Weldox900 E design with a value of 5.7563.

- Dontha applied values between 1000000 N and 1200000 N to the excavator bucket tooth in the education and as a result, found the highest equivalent stress value as 332.69 MPa (Dontha, 2017). In this paper, the highest equivalent stress value was found as 245.26 MPa.

Standard Excavator Bucket

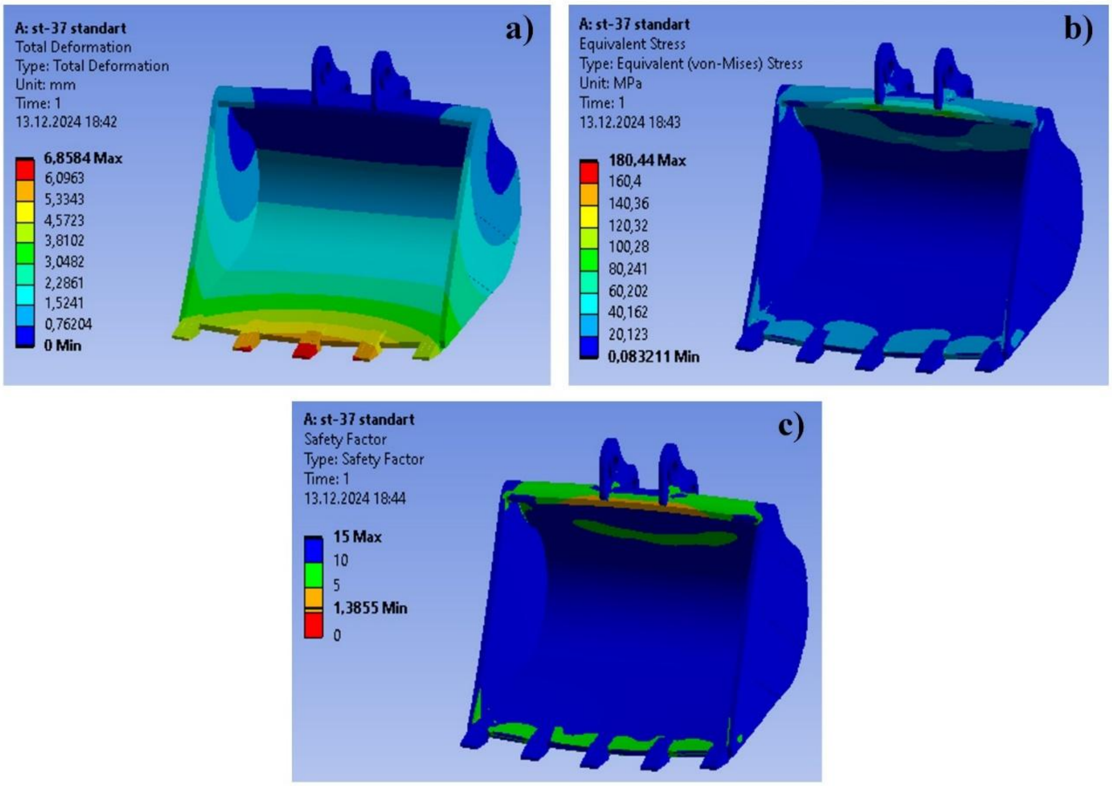

Figure 4. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Standard ST-37 Model

The maximum total deformation value with St-37 steel in the excavator bucket of the standard type was determined to be 6.8584 mm. It can be seen that the part that is deformed the most is the tooth at the middle point.

Since the efficiency of the bucket teeth during the lifting, tilting, and pulling motions of the bucket is important and inadequate performance in these areas directly affects the efficiency, Gurbet et al. attempted to determine the deformation, equivalent stress distribution, and safety factor values of the teeth at the front end of the bucket using the finite element method. They created the bucket design using the CATIA V5 design program and carried out the finite element analysis with different materials using the Ansys program. They determined the value applied to each claw as 8285 N. As a result of the research, they observed that the equivalent stress value of the excavator bucket made of St-37 steel was found to be 179.7 MPa (Gurbet et al., 2021). The equivalent stress value of the standard excavator bucket applied with St-37 steel was found to be 180.44 MPa and it was observed that the stress distribution was spread over a larger area.

The safety factor of the excavator bucket type Standard St-37 was determined with a minimum of 1.3855. It has been observed that the parts where the safety factor is minimum are generally the parts where the teeth and the adapter are connected.

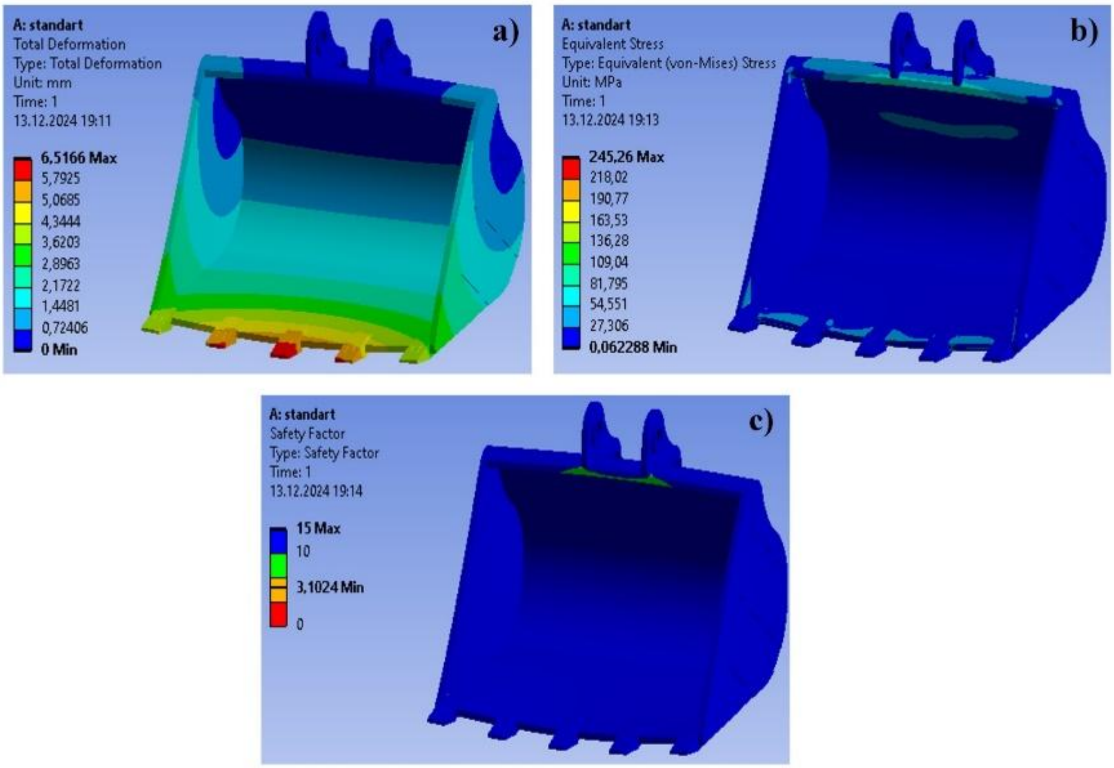

Figure 5. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Standard S690QL Model

The maximum total deformation value with S690QL steel in the excavator bucket of the standard type was determined to be 6.5166 mm. The equivalent stress of the excavator bucket type standard S690QL was determined with a maximum of 245.26 MPa. The safety factor of the excavator bucket type standard S690QL was determined with a minimum of 3.1024.

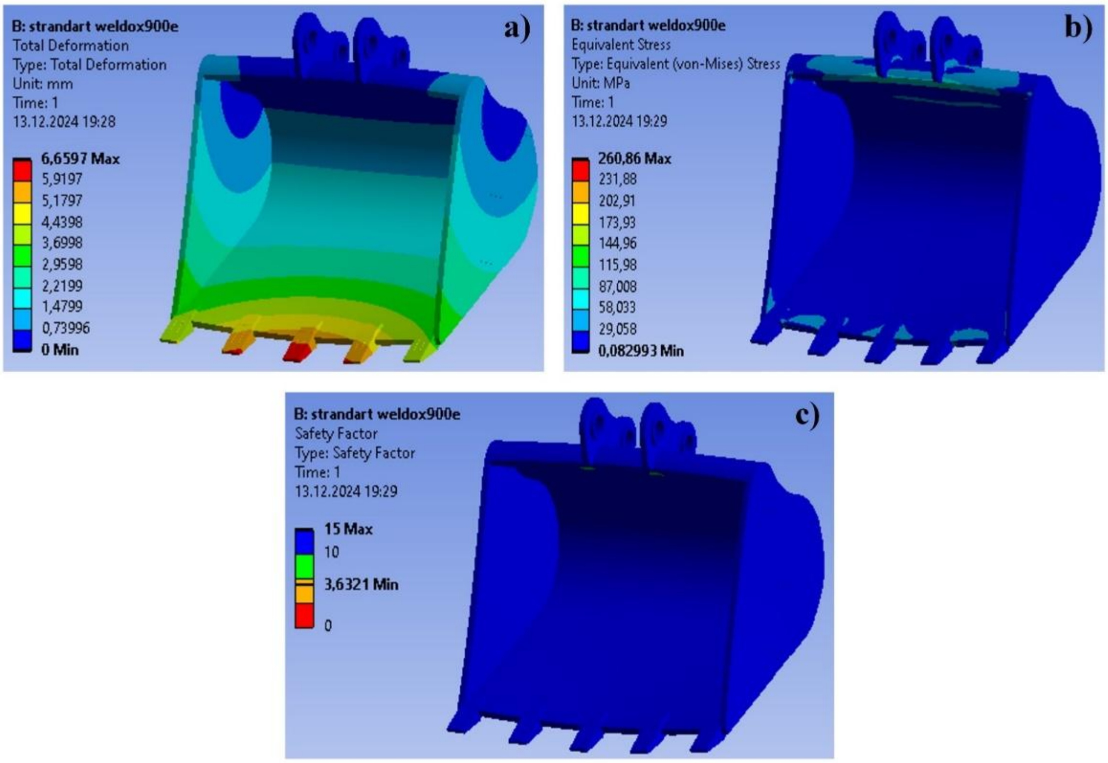

Figure 6. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Standard Weldox900 E Model

In their research, Sarkar et al. carried out a static analysis of the Tata JD 315SJ model excavator bucket made of Hardox 400 alloy, as the failures of the excavator bucket led to production losses. They designed the bucket with the CATIA V5 R18 design program using real dimensions. The material assignment and analysis were carried out using the Ansys Workbench 14.0 program. In the static analysis of the bucket, the bushing was considered a fixed component and the load was applied to the teeth. They determined the equivalent von Mises stress and deformation values formed in the blade using finite element analysis. It has been stated that the total deformation value is a maximum of 17.167 mm when the total force applied to the teeth is 53352 N (Sarkar et al., 2015). In this exploration, the total deformation value of the standard Weldox900 E excavator bucket was found as 6.6597 mm. In Sarkar's study with Hardox400 steel, a barrel with a digging depth of 4.42 m was used and a load of 53.352 kN was applied. In the study with Weldox900E steel, a load of 8.285 kN was applied to each tooth, for a total of 41.425 kN with five teeth. Although the Hardox400 structural steel is more brittle and has a higher yield strength than the Weldox900E steel, the main reason for the difference between the two studies is how the applied force is transferred to the buckets, the bucket design, and the dimensions of the bucket.
The equivalent stress of the excavator bucket type standard Weldox900 E was determined with a maximum of 260.86 MPa. The safety factor of the excavator bucket type standard Weldox900 E was determined with a minimum of 3.6321.

Armadillo Excavator Bucket

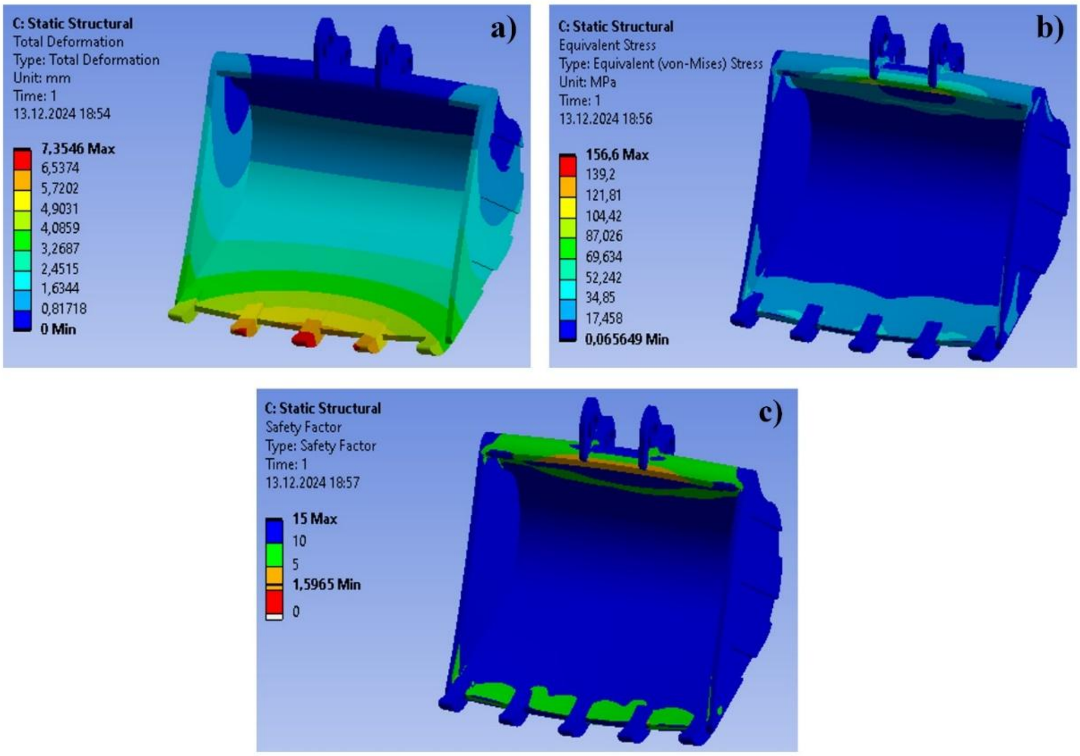

Figure 7. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Armadillo St-37 Model

The maximum total deformation value with St-37 steel in the excavator bucket of the armadillo type was determined to be 7.3546 mm. It can be seen that the part that is deformed the most is the tooth at the middle point. In this study, for comparison with Hadi Suryo's study, it was found that the value of the equivalent stress of the armadillo excavator bucket made of St-37 steel is 156.6 MPa and the stress is distributed over a larger area. The safety factor of the excavator bucket type armadillo St-37 was determined with a minimum of 1.5965.

The maximum total deformation value with S690QL steel in the excavator bucket of the Armadillo type was determined to be 6.9957 mm. The equivalent stress of the excavator bucket type armadillo S690QL was determined with a maximum of 164.85 MPa. The safety factor of the excavator bucket type armadillo S690QL was determined with a minimum of 4.6157.

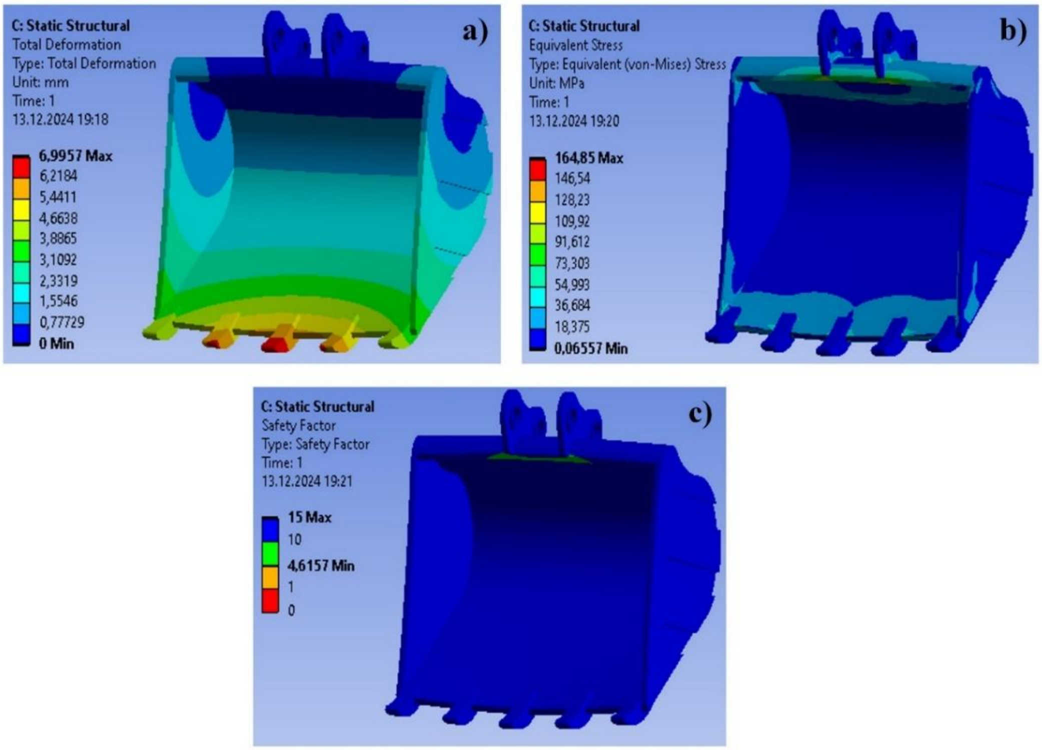

Figure 8. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Armadillo S690QL Model

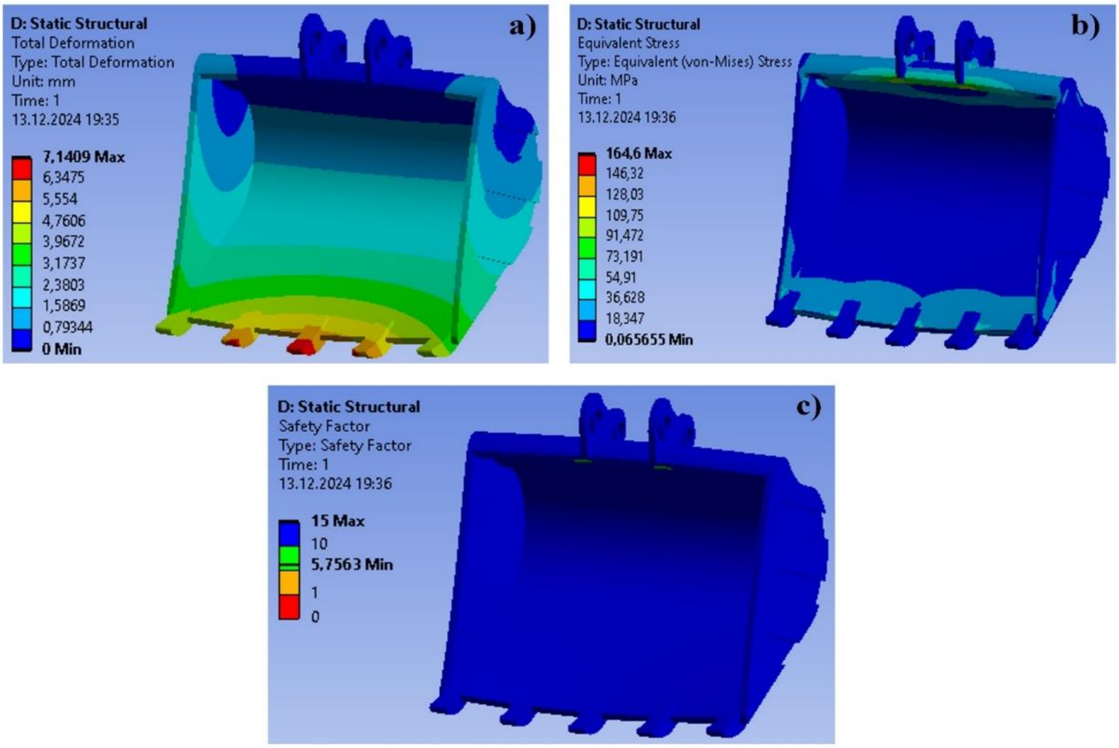

Figure 9. a) Total Deformation b) Equivalent Stress Analysis c) Safety Factor Analysis Result of Armadillo Weldox900 E Model

The maximum total deformation value with Weldox900 E steel in the excavator bucket of the armadillo type was determined to be 7.1409 mm. In this study, for comparison with Akter’s study, it was found that the value of the equivalent stress of the armadillo dredging bucket designed by the same method was 164.6 MPa in Weldox900 E steel. Not only were the values found to be close to each other, but the stress distribution was also found to be close to each other. The safety factor of the excavator bucket type armadillo Weldox900 E was determined with a minimum of 5.7563.

Since the deformation values in the static analysis will remain below the yield strength of the material, the comparisons should only be evaluated in themselves. Since there will be no fracture, the performances should only be compared within themselves. It was found that the equivalent stress values determined for St-37 were below the yield strength of St-37 (235 MPa). The same results were found for the steels S690ql (690 MPa) and Weldox900 E (900 MPa). If the yield strengths of the materials are taken into account, the results are therefore within the acceptable value range. According to Şekercioğlu, the specified values of the safety factor for machines in the range of 1.2-2 are considered safe. The results are within the acceptable range of values (Şekercioğlu., 2021). Table 6 indicates the costs per ton of materials used.

Table 6. Costs of Steels Used (SSAB Swedish Steel Foreign Trade)

	St-37	**S690QL**	**Weldox900 E**
Prices (price ($) /ton)	682.21	1784.24	2099.11

Table 7 shows the weight of the standard excavator bucket with the steel used and the production cost as a result of this weight.

Table 7. Standard Excavator Bucket Weight and Production Cost Values

Standard	**St-37**	**S690QL**	**Weldox900 E**
Mass (Kg)	2648.9	2652.3	2632
Production cost ($)	1807.1	4723.33	5524.85

Table 8 shows the weight of the armadillo excavator bucket with the steels used and the production cost as a result of this weight.

Table 8. Armadillo Excavator Bucket Weight and Production Cost Values

Armadillo	**St-37**	**S690QL**	**Weldox900 E**
Mass (Kg)	2611.7	2615	2595.1
Production cost ($)	1781.7	4665.78	5447.4

According to the obtained values from Tables 6 to 8, the following conclusions have been made;

- The designed armadillo excavator bucket design has less weight than the standard excavator bucket. Because more weight reduction has been made on the sides of the armadillo bucket. As a result of this weight reduction, the armadillo excavator bucket is 1.40% lighter than the standard excavator bucket.

- This weight reduction also resulted in savings in manufacturing costs: $25.4 for St-37 steel, $57.55 for S690QL steel, and $77.45 for Weldox900 E steel.

CONCLUSION

In this research, the excavator bucket was designed, and the reactions resulting from the force exerted by the teeth on the ground were analyzed using the finite element method. The analyses were carried out on two different teeth models. First, a standard tooth and an adapter were designed and their values were analyzed and investigated. Then, a one-piece teeth model inspired by the structure of the armadillo claw was designed using biomimetic methods, and the analysis results were examined. The results of this education are as follows.

-The manufacturer wishing to benefit from the results of the analysis and design should determine the design of the armadillo himself, taking into account the costs and the user's requirements (area of use of the machine, workloads, operating conditions, etc.). Different types of steel have different advantages and disadvantages as well as advantages and disadvantages in terms of design. The optimum design and steel combination should be designed according to the manufacturer's field of application. In the study, the current excavator shells perform the digging process using adapters welded to the shell and teeth attached to the adapters with a pin connection. With this new design, the additional fastening requirements have been eliminated and the same function is achieved using only the adapter. In this way, manufacturers can save additional costs for attachments (tooth, pin, etc.).

- It has been observed that the equivalent stresses of the armadillo excavator bucket design in the steels used are spread over a larger area compared to the equivalent stresses of the standard excavator bucket. This is a desired situation.

- It has been observed that the total deformation values of the standard excavator bucket in the steels used are lower than the total deformation values of the armadillo excavator bucket.

- It has been observed that the safety factor values are higher in the armadillo excavator bucket design than in the standard excavator bucket design. The high safety factor value explains that the design is usable.

- Since the designed armadillo excavator bucket design is more efficient at equivalent stress and safety factor values compared to the standard excavator bucket, the armadillo excavator bucket has been determined as a usable design.

In the future, biomimetic methods are thought to be widely used in all areas of technology. Equipment used by humans can be improved by imitating living things in nature. When it comes to construction machines, designs can be made on excavator booms using elephants and giraffes as examples in future studies.

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