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Structural Optimization of the Brake Pedal Using Artificial Intelligence

Özlem Akçay[1*], Cumali İlkılıç[1]

0009-0002-2316-6540, 0000-0001-5651-7621

[1]*Automotive Engineering Department, Faculty of Technology, Firat University, Elazığ, 23000, Turkey*

Abstract

In this study, weight reduction was performed on the brake pedal, which is one of the most important parts of the braking system, by using topology and shape optimization, one of the structural optimization methods, respectively. The aim of the study is to develop an optimal design that reduces vehicle weight by finding the optimal material distribution for the brake pedal. The weight reduction process was carried out in two steps. In the first step, static analyses were performed on the starting brake pedal model. Later, topology optimization was performed for weight reduction purposes. After the topology optimization, new brake pedal design was created and weight reduction was performed. In the second step, shape optimization was performed using a genetic algorithm to obtain the optimal dimensions of the brake pedal. According to the optimization results, the weight of the design was reduced from 437 grams (g) to 326 grams (g) by topology optimization in the first step. So the new design is 25.4% lighter compared to the first design. Later, as a result of shape optimization performed using a genetic algorithm, the weight was reduced from 326 g to 298 g and the optimal dimensions of the brake pedal were determined. Thus, with shape optimization, a lighter brake pedal design of about 8.5% was achieved compared to topology optimization. As a result, the weight has been reduced from 437 g to 298 g, and the weight of the ideal brake pedal model is 31.8% lighter compared to the main model.

Keywords: Structural analysis, Topology optimization, Shape optimization, Genetic algorithm, Brake pedal.

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* Corresponding author
Özlem Akçay
ozlemakcay044@gmail.com
Address: Automotive Engineering Department, Faculty of Technology, Firat University, Elazığ, Turkey
Tel: +905459107339

1. Introduction

The automotive sector is a sector that plays an important role in the economies of countries in the world and develops with continuous improvements due to the fact that it is an industry that is open to development [1]. In this sector, the diversified user expectations such as cost, quality, durability, vehicle performance, fuel economy, and compliance with environmental norms increase the sectoral competition [2]. This pushes companies to reveal the most suitable product that clearly responds to expectations [3]. Otherwise, companies will lose their ability to compete and will not be able to ensure their continuity [4]. All these expectations are the driving force for the development of design in automotive, and at the same time, weight reduction studies have also increased their importance [5].

Reducing weight in the automotive sector is a very important issue. A lighter vehicle will improve performance and benefit fuel efficiency, as well as reduce exhaust emission rates [6]. For this reason, since reducing the weight of the parts will affect the total weight of the vehicle, designers make design improvements in the parts by maintaining the same quality with the appropriate material selection and performing weight reduction by turning to optimization studies [7]. Thus, an innovative product design that can reduce costs can be put forward while still at the design stage, and lighter parts can be obtained with the strength to withstand loads under working conditions [8]. Therefore, the first choice of designers to improve a part will be to make a change [9]. At this point, optimization methods are used for the best distribution of the material in the designed variable parts [10].

Izgı et al. performed topology optimization to reduce the mass. They created the first design with solid modeling and performed structural analysis by applying topology optimization for a brake pedal with an optimal design. For topology, they used the Altair Inspire software and applied 823 N force from the pad section to the brake pedal in the -Z direction and obtained a new design as a result of the analysis. When the new design was analyzed, it was found that the maximum stress value of the brake pedal was 92.37 MPa and the maximum displacement value was

0.4159 mm. When the optimum design model and the structural analysis data of the first design are compared, the total mass of the first model is 1.164 kg, and the mass of the new model is 0.6 kg. As a result of the obtained new design structural analysis, they achieved a weight reduction of 54.07% in the total mass [11].

Arun et al. performed topology optimization of the brake pedal and reduced the weight by 21.2%. The researchers used steel material in their research and preferred the SLS method as a pedal production method. When 1100 N force is applied to the pedal, which will be produced with steel material using the SLS method, respectively the maximum displacement and stress values are 3.10 mm and 215.80 MPa. After topology optimization, they created a new design by changing the geometry of the brake pedal. The maximum displacement is 3.19 mm and the stress is 221.00 MPa when force is applied to the new design part. When the analyses were compared, it was observed that the weight decreased from 0.8374 kg to 0.6598 kg. As a result, they achieved a 21.2% weight reduction on the brake pedal [12].

Sargini et al. used additive manufacturing methods using traditional methods (pressing, welding, etc.) have examined the manufacturability of a brake pedal made in their study. In addition to manufacturability, they have done work to reduce the weight of the part. They successfully performed the analysis of the brake pedal and applied topological optimization. As a result of the structural analysis, the weight of the pedal, which was originally 1 kg, decreased by 0.46 kg. According to the study, the structural analysis results showed that the weight was significantly reduced. Consequently, they reduced weight by 54% [13].

Yildiz et al. structurally optimized the brake pedal to obtain an optimal design. Topology optimization was performed by fixing the pedal from the specified places and applying force. By examining the results obtained after topology optimization, they have made a new design in order to reduce the weight on the pedal. Then, in order to maximize the weight reduction process, the salp swarm algorithm (SSA), Harris Hawks optimization algorithm (HHO), dragonfly algorithm (DA) and grasshopper optimization algorithm (GOA), which are among the artificial intelligence optimization techniques, were optimized using. When the topology optimization analysis data is examined, the weight of the part decreased from 1581 grams to 1330 grams. Later, as a result of the optimization performed using artificial intelligence optimization techniques, it was determined that the maximum weight reduction process is in salp herd optimization, which is 1125 grams, and they stated that artificial intelligence optimization techniques can be used in the weight reduction process [14].

Albak examined the topology optimization of the brake pedal for a Formula SAE car with a minimum mass while maintaining quality. He created a pedal design model in accordance with the rules determined by the competition committee and performed topology optimization. The main aim of the study is to minimize the weight of the pedal within affordable costs without compromising the safety factor. He preferred aluminum 7075-T6 material to reduce weight. Topology optimization has been completed with 54 iterations. According to the analysis results, a new design was created after topology optimization and the data of the first model were compared with the new design, the stress of the brake pedal is 312 MPa and displacement value is 0.451 mm. The mass has decreased from 309 grams to 273 grams with the new model, which has been redesigned within the constraints due to the shape formed as a result of optimization, it is 11% lighter than the first design [15].

Optimization methods were used to reduce the weight of the brake pedal, which is one of the most important parts of vehicle components. Literature studies have been examined and it has been seen that in these studies, the emphasis has always been on reducing the weight of the brake pedal by topology optimization. In this study, as presented in figure 1, the brake pedal used in the automotive industry has been optimized, unlike the existing studies, a genetic algorithm from artificial intelligence optimization techniques was used to make more weight reduction. First, a three-dimensional solid model of the brake pedal was created using a computer-aided design program. The designed CAD part was transferred to the finite element program and topology optimization was performed in order to reduce the weight of the part. After topology optimization, a new design model was created. Later, shape optimization was performed on the new design model using a genetic algorithm, and the weight of the part was slightly reduced.

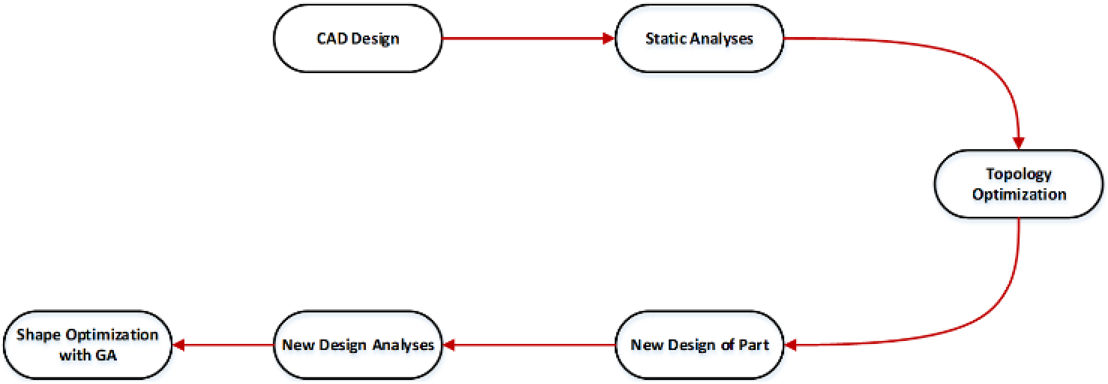

Fig. 1. Optimization flow chart of brake pedal

2. Structural Optimization

With the development of technology, CAD and analysis have started to be widely used in all fields. The use of computers in design and production enables rapid design and production, which changes and improves product functionality in a rapidly developing competitive environment [16]. Competition and rising product costs are forcing manufacturers to achieve optimal designs that are durable, lightweight, cost-effective, and with as few materials as possible. For this reason, it has become possible to create an ideal structure by focusing on the design and production process of high-performance, lightweight products and optimizing the parts [17]. In this context, optimization techniques have been started to be used to achieve an optimal design. Optimization, which is the study of finding the most appropriate result in the solution space of a problem under certain boundary conditions, aims to achieve the most appropriate design possible with the materials available in engineering [18]. For this reason, optimization contributes to this goal by designing the highest quality and best product with few materials. In this context, the goals of optimization that come to the fore can be listed as minimizing mass, increasing robustness, reducing stress, ensuring appropriate manufacturability, and reducing manufacturing costs [19].

Optimization is based on data obtained from simulations processed in a computer environment. The problem to be solved is defined not only by the existence of continuous variables but also by the choice of components [20]. In optimization, while the draft design is evaluated on the one hand, new models are created on the other hand. According to the proposed optimization strategy, different or new solutions are also obtained [21]. In Fig. 2, the optimization stages are listed.

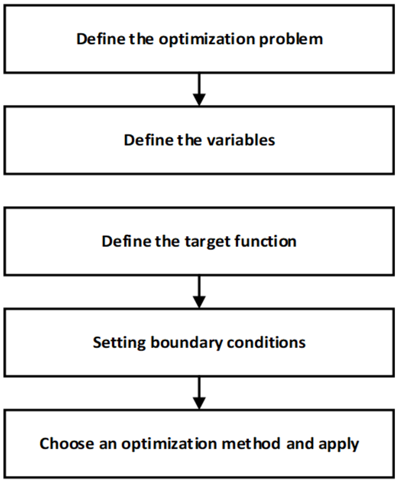

Fig. 2. Optimization stages

Structural optimization, one of the optimization applications, is widely used in optimal part design and is a key element in reducing product development time [22]. Structural optimization has long been a subject of interest, starting with the first studies of Maxwell in 1869 and Michell in 1904 [23]. Therefore, the design process applies structural optimization to the product in order to achieve the ideal structure. In general, optimization solutions are carried out by three methods for an optimal geometric model under the heading of structural optimization. These methods are shape, size, and topology optimization. Fig. 3 shows the structural optimization methods [24].

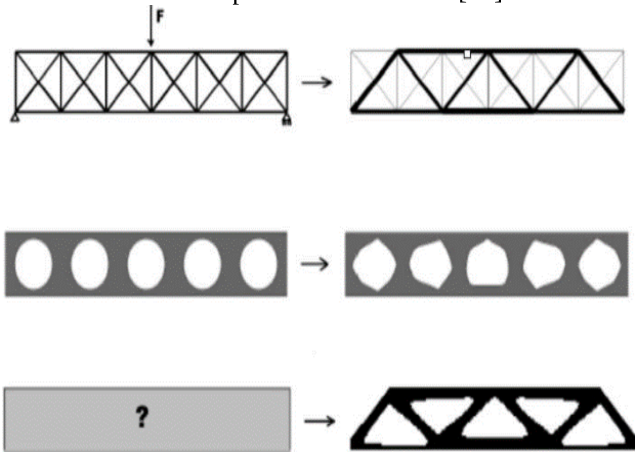

Fig. 3. Types of structural optimization

Along with the innovative optimization methods that have emerged thanks to technological developments, the problem-solution process is also positively affected, and it is aimed to optimize the part designed with structural optimization in terms of topology, size, and shape [25]. Dimension optimization, the first structural optimization method, has the simplest algorithm and allows one to obtain an optimal design by using the boundary conditions of the structure and the hole geometries contained in the structure and making only dimensional changes without changing the design [26]. With shape optimization, the structure of a structure whose configuration is predefined is preserved, but from size optimization, a formal change of a different structure is made. The purpose of this optimization algorithm is to try to get an ideal geometry by changing the boundaries on the surface of the structure and the hole geometries in the existing design [27]. Another widely known technique, which is one of the three areas of structural optimization, is topology optimization, which achieves optimal material distribution by maintaining strength according to the functionality and boundary constraint values of a structure in its current design to improve the design [28].

3. Topology Optimization

The importance of topology optimization is increasing gradually because it has a lot of applications in industries involving many different disciplines such as automotive, machinery, and aviation [29]. For highly engineered products, it helps engineers to think outside the box in order to create more innovation. The main aim of TO is to achieve optimal material distribution by maintaining the strength of a structure according to its functionality and boundary constraint values in the current design to improve the design [30]. This method is the most effective structural design method for determining the distribution, geometry, placement, and material gaps of the material contained in the design volume. In this method, where the design variables and the design topology are defined, the constraints are predetermined by the user, and the algorithm optimizes by creating gaps on the structure surface in order to minimize or maximize optimization scales such as mass, volume, or displacement without changing them [31]. With this optimization algorithm, which directly affects the performance and costs of a product, conceptual designs can be created that are light, high-performance, and can reduce costs while still at the design stage by addressing both shape and topology changes [32]. For this reason, weight reduction and topology optimization are often used in new product designs. For structures with lighter weight and maximum strength, the design shape is created in the optimal topology and successfully achieves the optimization goal [33].

4. Artificial Intelligence Optimization Techniques

In recent years, the use of algorithms created with a meta-intuitive approach to solving optimization problems has increased [34]. When these algorithms were created, they were inspired by the events that living beings must do to survive in order to reach the solution to the problem. Artificial intelligence optimization techniques, also known as meta-intuitive research techniques, are used to solve optimization problems [35]. These algorithms are defined criteria or computer methods for deciding which alternative actions are effective in implementing a solution or achieving a goal. Examples of the main artificial intelligence optimization algorithms are genetic algorithm, particle swarm optimization algorithm, gray wolf optimization algorithm, and ant colony algorithm [36].

5. Genetic Algorithm (GA)

The genetic algorithm approach, developed by John Holland by taking inspiration from biological genetics, that is, evolution in living things, and analyzing genetic mechanisms, was proposed in 1975 [37]. GA, which is formed as a result of transferring the genetic evolutionary change process to a computer system together with this proposition, is an optimization method based on simulation theory [38]. The genetic algorithm used in the field of artificial intelligence is an algorithm that searches for the most ideal point [39]. In other words, he is interested in finding the solution to a problem that is looking for the optimal point. Here, instead of a single solution, the genetic algorithm evaluates several solutions simultaneously [40]. The genetic algorithm is quite easy to use and implement.

The terms belonging to the algorithm are defined as population, generation, chromosome, and gene [41]. Genetic algorithms mimic evolutionary processes in computing environments to solve problems [42]. Instead of developing a single structure of the solution like other optimization methods, they create a cluster of such structures [43]. This set represents many possible solutions to the problem and is called a population in genetic algorithm terminology [44]. A population consists of sequences of numbers called vectors, chromosomes, or individuals. Each component of an individual is called a gene [45]. Individuals in a population are determined by a genetic algorithm processor during evolution.

The Genetic Algorithm basically consists of the following steps, as shown in Figure 4;

1. Start: The process of creating a random population from chromosomes is performed.

2. Fitness: The fitness value is calculated.

3. New Generation: New individuals are produced by following the following steps;

a. Selection: Two horses are selected according to their population fitness.

b. Crossover: With the possibility of a crossover, their ancestors are paired with each other to create new offspring. If no crosses are made, the offspring will be exactly the same as the ancestors.

c. Mutation: Mutation operation will be performed on the new offspring with the possibility of mutation.

d. Acceptance: The new offspring are added to the new society.

4. Change: The new population is used in the reworking of the algorithm.

5. Experiment: If the end state is achieved, the best solution in society is stopped and returned.

6. Cycle: Go to Step 2.

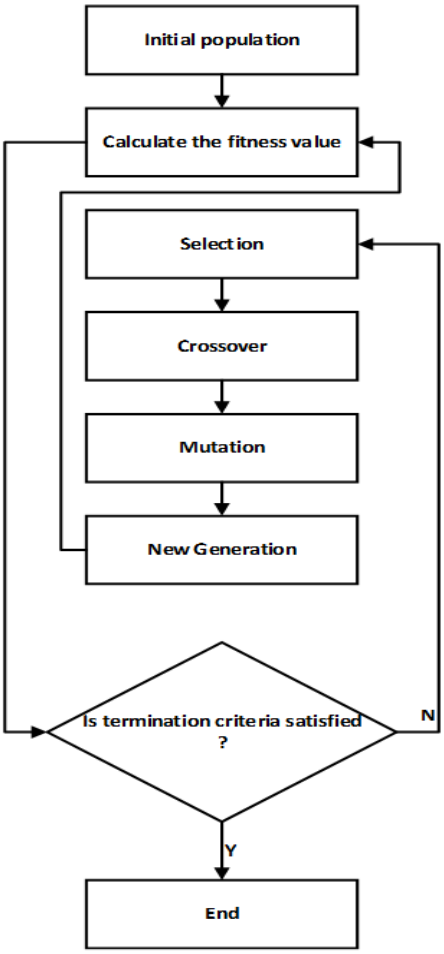

Fig. 4. Diagram of the genetic algorithm

6. Material and Method

In this study, the brake pedal has been structurally optimized for weight reduction purposes. At first, a three-dimensional solid model of the part presented in Figure 5 was created using SOLIDWORKS software, a computer-aided design program. After the part design was completed, it was transferred to the finite element program. Structural optimization analysis was performed using the Hypermesh program, one of the finite element methods. After the static analysis results, topology optimization was applied to the part, and the areas where unloading was desired were determined. According to the data obtained as a result of topology optimization, a new design model was created by changing the geometry of the part, and static analyses were performed on the new design part. Then, shape optimization was performed using the genetic algorithm from artificial intelligence techniques.

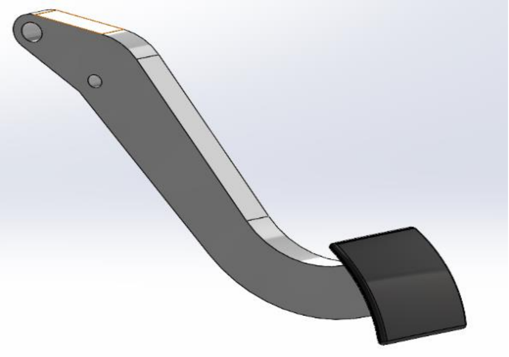

Fig. 5. Brake pedal CAD design

6.1 Static Analysis of the Initial Model

The mechanical properties of 7075-T6 series aluminum were used as the material of the brake pedal, and the mechanical properties of the material are given in Table 1. The optimization process was carried out based on these values.

Table 1. 7075-T6 Al material properties

Young’s modulus (GPa)	70
Poisson’s ratio	0.33
Yield Strength (MPa)	460
Density (gr/cm^3)	2.80

To calculate the weight of the first design material, the Mass Calculation tab in the Hypermesh program is used. In this way, the weight of the entire part was calculated as 437.0 gr. Then the part is divided into two different components. The reason why it is divided into two different components is that it is wanted not to perform weight reduction in the connection areas. In Figure 6, the part is divided into two different components the region fixing point shown in green and the region shown in blue as the region where topology optimization will be performed.

After the creation of the different components, the meshing process was carried out. Mesh dimensions of 4 mm were used in the blue region in Figure 6. The mesh removal process was completed using a mesh size of 2 mm for the green area. After the mesh removal process, fixation was made from the connection points on the brake pedal, and static analysis was performed by defining a force of 823 N on the pressure surface.

Fig. 6. Part representation prepared for analysis

The maximum displacement and maximum stress value realized on the brake pedal are shown in Figure 7. According to the analysis results, In Figure 7. (a) it has been determined that the brake pedal has a maximum displacement value of 0.67 mm. Figure 7. (b) when examined, it was found that the maximum stress value formed in the material was approximately 82.59 MPa.

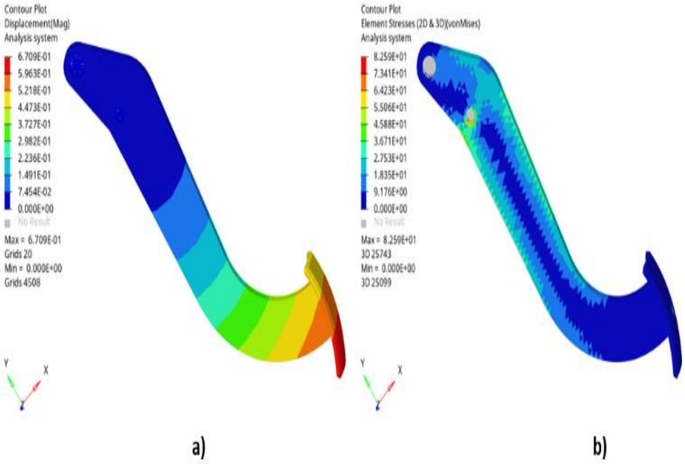

Fig. 7. The results of the analysis; a) Displacement b) Element stress

6.2 Topology Optimization of the Brake Pedal

Brake pedal topology optimization has been carried out in order to reduce the weight of the material by using the analysis data made under the determined fixing and loading conditions. In topology optimization, a weight reduction will be performed on 60% of the part's volume, in other words, a weight reduction can be performed until 40% of the part's volume remains. After defining the constraint, topology optimization was performed by including the constraint to minimize the weight.

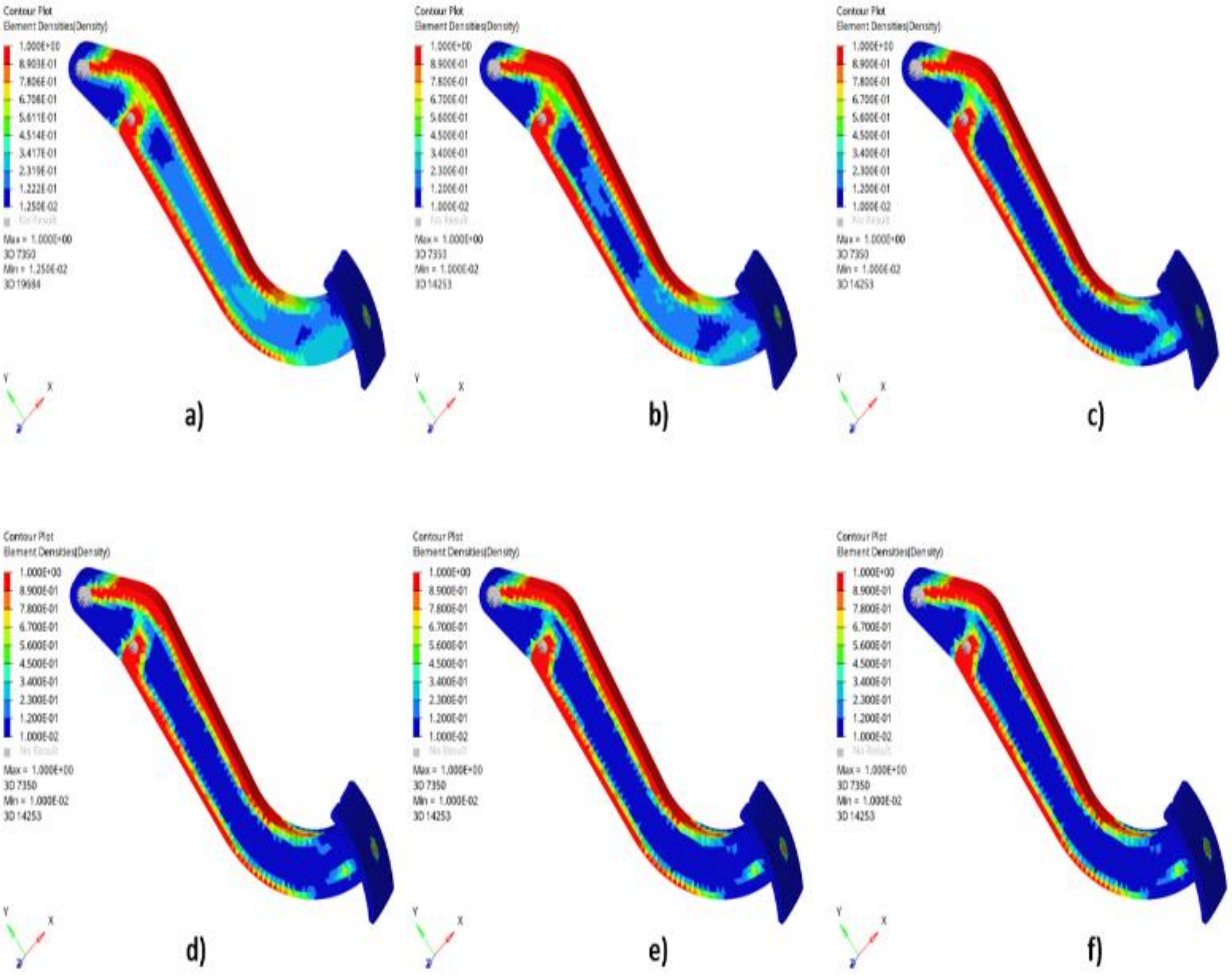

Fig. 8. Optimization iteration numbers; a) Fifth iteration b) Tenth iteration c) Fifteenth iteration d) Twentieth iteration e) Twenty-fifth f) Twenty-seventh

6.3. Static Analysis of the New Model

Topology optimization studies were carried out in order to perform static analysis and weight reduction in the initial model of the brake pedal. Unloading was performed in the determined regions by reference to the iteration data obtained as a result of topology optimization. In other words, a new design model has been created in the computer-aided design program by taking the obtained results as a reference. The new design made after this unloading process is shown in Figure 9.

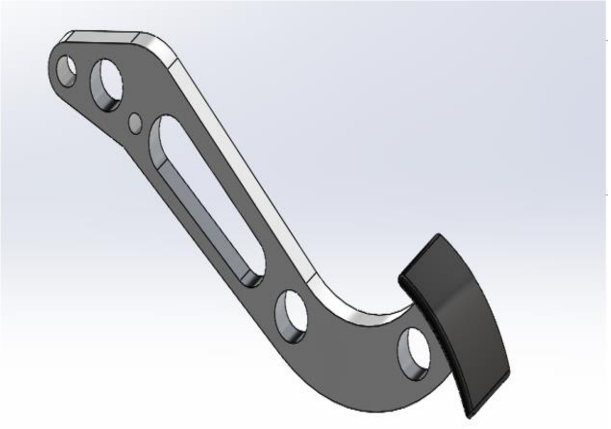

Fig. 9. New design of brake pedal

Static analysis of the part was performed in order to check whether the new designed model is safe or not. The values obtained as a result of the analysis are expressed in Figure 10. When the analysis examines the results, the displacement value is 0.94 mm and the stress value is 103.9 MPa. These values are within the safety coefficient value.

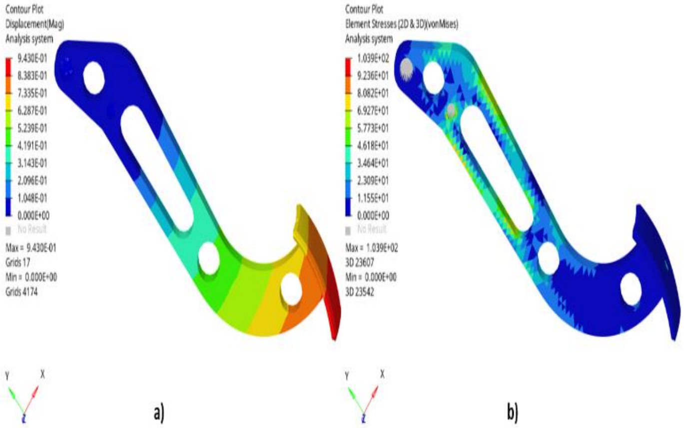

Fig. 10. New design; a) Displacement b) Stress

6.4. Shape Optimization of the Brake Pedal Using Genetic Algorithm

As a result of the topology optimization shown in Figure 11 in the new brake pedal design, shape analysis constraints were given to the regions with five radii that were emptied, and the part was prepared for shape optimization. For this purpose, the radii of the gaps have been increased from r1 10mm to 12mm, r2 12mm to 14mm, r3 10mm to 12mm, r4 10mm to 12mm, and r5 10mm to 12mm.

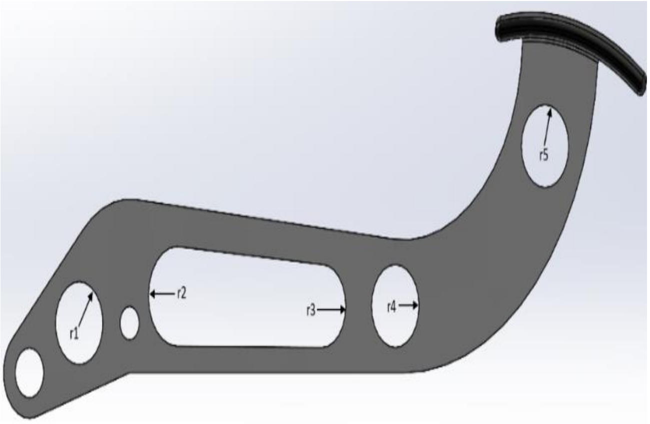

Fig. 11. Limitations of shape optimization with genetic algorithm

Shape optimization was performed within certain constraints by using a genetic algorithm, which is one of the artificial intelligence optimization techniques, in order to reduce more weight on the part by using the data obtained as a result of topology optimization. These constraints are shape analysis constraints and shape optimization constraints. The constraints of the shape analysis are given in Table 2. In the shape optimization, the displacement and stress values are limited to less than 1.1 mm and 120 MPa, respectively. Weight reduction has been defined as an objective function. After the constraints of shape optimization, the track was optimized with a genetic algorithm. When the obtained data were examined later, the displacement value of the part was determined as 1.1 mm, the stress value was determined as 107.6 MPa, and the weight was determined as 298 g.

Table 2. Constraint values

Symbol Representation	**Lower Limit Value (mm)**	**Current Design Value (mm)**	**Upper Limit Value (mm)**
r1	16	20	24
r2	20	24	28
r3	16	20	24
r4	16	20	24
r5	16	20	24

8. Conclusion

In this study, weight minimization was performed on the automotive brake pedal. Linear static analysis was performed in order to find the displacement and stress values of the part, which was initially designed as CAD. Later, topology optimization was performed using the analysis results, and the iterations obtained from the optimization were used and the brake pedal was redesigned by unloading at the designated places on the part in accordance with the design and production method. Static analysis was performed again to examine the displacement and stress values occurring in the new design. Depending on the results of this analysis, shape optimization was performed using a genetic algorithm in order to make further mass reduction.

The results of the analysis are given in Table 3. When these results were examined, displacement of 0.67 mm and stress values of 82.59 MPa were determined on the main model. The initial weight of the model is calculated as 437 g. When the data obtained as a result of topology optimization are examined, the maximum displacement is 0.94 mm and the maximum stress value is 103.9 MPa. These values do not violate the optimization constraints. The weight of the new design model created by optimizing has been calculated to be approximately 326 g. It has been determined that the weight of the new model is approximately 25.4% less than the initial model.

In addition, the genetic algorithm, which is one of the artificial intelligence techniques, has been combined with optimization methods to reduce weight more and the most ideal result has been achieved. According to these data, the weight of the new design, which is 326 g, has been reduced to 298 g. As a result, a weight reduction of 8.5% was performed according to shape optimization and topology optimization. As a result of the topology and shape optimization, the optimal design part has been found. The weight of the brake pedal at the beginning has been reduced from 437 g to 298 g. The weight of the optimal brake pedal model is 31.8% lighter compared to the main model.

Table 3. Analysis results

Model	Displacement (mm)	Stress (MPa)	Mass (gr)	Mass change (%)
Main model	0.67	82.59	437	
After topology optimization	0.94	103.9	326	25.4%
After shape optimization with genetic algorithm	1.1	107.6	298	8.5%

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Özlem Akçay: Conceptualization, Writing-original draft, Validation, Data collection, Formal analysis.
Cumali İlkılıç: Conceptualization, Supervision, Writing-original draft, Validation, Data collection, Formal analysis.

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