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Finite elements analysis and topology optimization of parking brake lever and ratchet

Park freni kolunun ve cırcırının sonlu elemanlar analizi ve topoloji optimizasyonu

Yazar(lar) (Author(s)): *Funda KAHRAMAN[1], Mehmet KÜÇÜK[2]*

ORCID[1]: 0000-0002-1661-3376

ORCID[2]: 0000-0001-9196-0784

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Finite Elements Analysis and Topology Optimization of Parking Brake Lever and Ratchet

Highlights

- *Topology optimization*
- *Finite elements analysis*
- *Parking brake lever and ratchet weight reduction by redesign*

Graphical Abstract

This study aims to obtain light-weighting design of parking brake lever and ratchet through topology optimization.

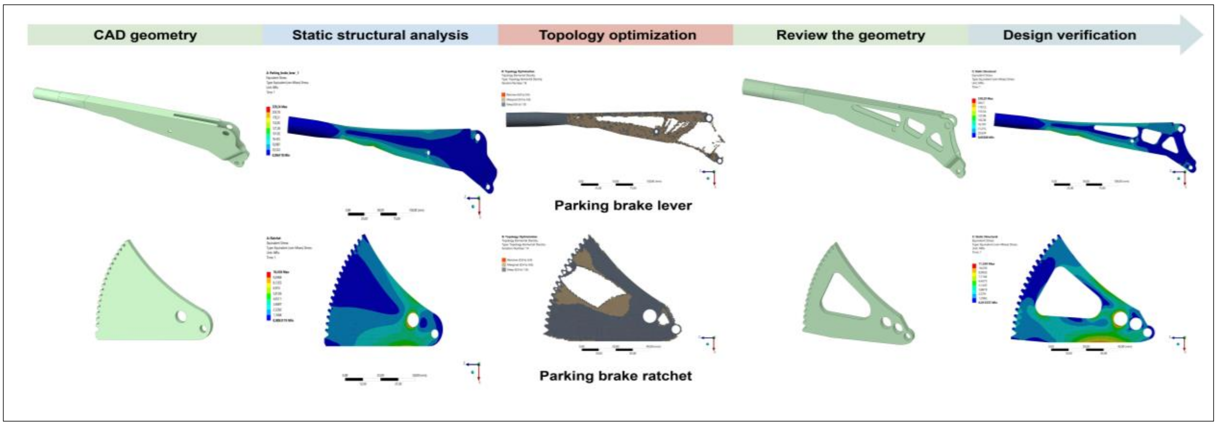

Figure. Topology optimization process flowchart

Aim

This study aims to contribute to the reduction in vehicle weight by applying topology optimization. In addition, it also purposes to promote sustainability in manufacturing by reducing material usage and energy consumption.

Design & Methodology

The topology optimization was performed based on finite element analysis. The static analysis results were used as input data for topology optimization.

Originality

The originality of this study is indicated that using topology optimization contributes to minimizing emissions and environmental effects by increasing material utilization efficiency and manufacturing sustainability.

Findings

After topology optimization the maximum equivalent (von Mises) stress for the parking brake lever is 230,29 MPa, and for the ratchet is 11,559 MPa. The final mass for the parking lever is 0,22622 kg and for the ratchet is 0,061911 kg. The parking brake lever mass decreased by 18,48%. The ratchet mass decreased by 34,85%.

Conclusion

The initial geometry is modified according to the topology optimization results. Light-weighting is achieved through topology optimization.

Etik Standartların Beyanı (*Declaration of Ethical Standards*)

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Finite Elements Analysis and Topology Optimization of Parking Brake Lever and Ratchet

Araştırma Makalesi / Research Article

Funda KAHRAMAN[1*], Mehmet KÜÇÜK[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, Tarsus University, Tarsus, Mersin, Turkey
[2]Graduate School of Education, Department of Manufacturing Engineering, Tarsus University, Tarsus, Mersin, Turkey

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ABSTRACT

Topology optimization is known as one of the basic categories of structural optimization. Topology optimization is received increasing attention in many engineering disciplines. Topology optimization contributes to minimizing emissions and environmental effects by increasing material utilization efficiency and manufacturing sustainability. The mechanical parking brake is still used in many vehicles. This study aims to contribute to the reduction in vehicle weight by applying topology optimization. In addition, it also purposes to promote sustainability in manufacturing by reducing material usage and energy consumption. A CAD model was created by considering the existing mechanism element dimensions. The parking brake lever mechanism component was evaluated using topology optimization and finite element analysis methods. Static analyses were performed using a finite element analysis program. The results of this analysis were used as input data for topology optimization. In the topology optimization, the response constraint mass was increased by 5 increments from 50% to 95%. As a result, the maximum equivalent (von Mises) stress for the parking brake lever is 230,29 MPa, and for the ratchet is 11,559 MPa. The maximum total deformation value for the brake lever is 0,95853 mm and for the ratchet is 0,0079482 mm. The parking brake lever mass decreased by 18,48% from 0,27751 kg to 0,22622 kg. The ratchet mass decreased from 0,095042 kg to 0,061911 kg by 34,85%.

Keywords: Topology optimization, finite element analysis, sustainable manufacturing, parking brake lever and ratchet.

Park Freni Kolunun ve Cırcırının Sonlu Elemanlar Analizi ve Topoloji Optimizasyonu

ÖZ

Topoloji optimizasyonu, yapısal optimizasyonun temel kategorilerinden biri olarak bilinir. Topoloji optimizasyonuna birçok mühendislik disiplininde ilgi artmaktadır. Topoloji optimizasyonu, malzeme kullanım verimliliğini ve üretim sürdürülebilirliğini artırarak, emisyonların ve çevresel etkilerin azaltılmasına katkı sağlamaktadır. Mekanik park freni hâlâ birçok taşıtta kullanılmaktadır. Bu çalışmada, topoloji optimizasyonu yardımıyla araç ağırlığının azaltılmasına katkı sağlamak da amaçlamaktadır. Ayrıca malzeme kullanımını ve enerji tüketimini azaltarak imalat alanında sürdürülebilirliği katkı sağlanmak da istenmektedir. Mevcut park freni dikkate alınarak CAD model oluşturulmuştur. Park freni kolunun elemanları sonlu eleman analizi yöntemleri ile analiz edilmiş ve topoloji optimizasyonu gerçekleştirilmiştir. Statik analizler için sonlu elemanlar analiz programı kullanılmıştır. Statik analizin sonuçları, topoloji optimizasyonu için girdi verileri olarak kullanılmıştır. Topoloji optimizasyonunda, kütle yanıt kısıtı 5 artımla %50'den %95'e kadar artırılmıştır. Sonuç olarak, park freni kolu için maksimum eşdeğer (von Mises) gerilme 230,29 MPa ve park fren cırcırı için 11,559 MPa'dır. Fren kolu için maksimum toplam deformasyon değeri 0,95853 mm ve park fren cırcırı için 0,0079482 mm'dir. Park freni kolu kütlesi %18,48 oranında azalarak 0,27751 kg'dan 0,22622 kg'a düşmüştür. Park fren cırcırının kütlesi %34,85 oranında azalarak 0,095042 kg'dan 0,061911 kg'a düşmüştür.

Anahtar Kelimeler: Topoloji optimizasyonu, sonlu elemanlar analizi, sürdürülebilir imalat, park freni kolu ve cırcırı.

1. INTRODUCTION

Sustainable manufacturing focuses on maintaining the future of the world by avoiding wasteful manufacturing approach that overexploitation resources in a way that will not meet the requisitions of succeeding generations. Today, sustainability is crucial in many fields such as engineering, and manufacturing, it can be incorporated into design, during all phases of the design process.

Design engineers need innovative design ideas to develop lightweight eco-friendly solutions. Topology optimization as a powerful design optimization tool for sustainability purposes has a much capability (Azad et al., 2022 [1]; Rosen and Kishawy, 2012 [2]).

Innovative technologies and engineering knowledge are intensively used in the automobile industry. Nowadays, automobile manufacturers consider constantly changing and evolving consumer demands to sustain their competitiveness in the global market. The automobile industry plays a major role in the growth of the country's economy, including many types of manufacturers. Besides, the automotive industry in developed countries is the main category of the manufacturing industry (Saberi, 2018 [3]). The recent sophisticate approaches and methods increased the progression of manufacturing technologies. Advancements in additive manufacturing technologies ensure considerable alterations in the design

*Corresponding Author
e-posta : fkahraman@tarsus.edu.tr

and manufacturing of components (Vlah, Žavbi and Vukašinović, 2020 [4]). The complex geometries optimized with topology optimization can be made manufacturable without production constraints by additive manufacturing, unlike traditional manufacturing methods. During the last decades, growing interest in additive manufacturing reveals the limits of the available CAD tools therewithal is underlined the so far under-used potential of topology optimization and generative design tools (Barbieri and Muzzupappa, 2022 [5]). Nowadays, not all CAD software but many programs such as SolidWorks, Fusion 360, and Creo add extra features and tools for topology optimization while the design phase to give ideas to the designer. The incorporation of optimization methods in the concept design phase contributes substantially to the emergence of even more innovative solutions.

Finite element analysis (FEA), is attained numerous achievements in many fields of engineering. Utilization of FEA along with the improvement in computer sciences increased both for academic research and in engineering applications, which need to realize advanced calculations. Therefore, FEA turned into a utility tool for modern design in engineering. FEA programs like Ansys, Abaqus and HyperWorks-Optistruct provide powerful tools for topology optimization studies.

Design optimization in engineering is a design approximation, where the design problem is defined as a mathematical, aimed to reach the ideal one among the optimal design alternatives. In this process, the defined objective function is maximized or minimized according to constraints.

Structural optimization is a discipline that studies the optimum design of structures under loading conditions. Structural optimization aims to minimize mass, weight, and design cost, maximize stiffness, and control the vibration or combination of these requirements. Structural optimization is separated into subcategories such as size optimization, shape optimization, topology optimization, topometry optimization, and topography optimization. Structural optimization problems, with defined constraints such as geometry, boundary conditions, and initial conditions, can be analyzed with FEA.

Topology optimization is a computational method. Topology optimization aims to optimize material distributions in the structural layout. Topology optimization, an up-to-date optimization approach in design, produces innovative configurations that are both lightweight and effective. Nonetheless, the production of some designed models is difficult by conventional methods.

The parking brake (Figure 1) is a secondary brake system in vehicles operated by hand or foot and is also defined as an emergency brake or hand brake. The parking brake is utilized to prevent a parked vehicle on a sloping or flat road surface from slipping or rolling. Additionally, in the event of a service brake fault, it is used to securely slow down and stop the vehicle (Lunia et al., 2015 [6]; McKinlay, 2007 [7]; Toyota, n.d. [8]). There are three main components as parking brake lever, cables, and equalizer in the parking brake system (Hıdıroğlu et al., 2016 [9]). The parking brake lever is manufactured using the sheet metal manufacturing method (Hague et al., n.d. [10]). The manual parking brake lever is usually positioned in the center of the cabin and is connected to the parking brake cables.

There are many studies in the literature on topology optimization. Yüksel (2019) [11] presented modern techniques for topology optimization. Barbieri and Muzzupappa (2022) [5] recommend that both topology optimization and generative design in additive manufacturing can be successfully used for robust and lightweight designs. Karaçam and Arda (2021) [12] conducted topology optimization and load-carrying element redesign.

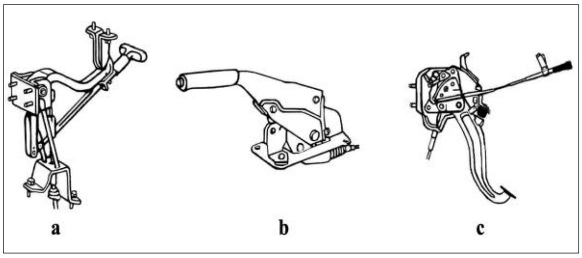

Figure 1. Mechanically controlled parking brakes a) stick type, b) central lever type, c) pedal type (Toyota, n.d. [8])

Matsimbi et al. (2021) [13] shared a study which topology optimization techniques and applications for automotive body structures. Kahraman and Küçük (2020) [14] evaluated reduce weight through topology optimization for the automotive sector. They mentioned that topology optimization is a useful approach to designing lighter components in the automotive industry. Koçak and Korkut (2023) [15] applied topology optimization in the design of the landing element component of an unmanned aerial vehicle. Kara, Taşkın and Demirhan (2022) [16] applied topology optimization to a steering system support element. Under the determined boundary conditions, they observed the maximum von Mises stress as 97,3 MPa, and total deformation as 0,015 mm. The initial model weight decreased from 2332,5 g to 577,9 g after topology optimization. Demir et al. (2021) [17] studied lighter mobile transportation robot design with shape optimization, and energy efficiency improved, using topology optimization and structural analysis. They obtained robotic system weight %20 reduction under the desired safety limits.

Studies on parking brakes are evaluated and summarized. Dalfidan and Erol (2020) [18] conducted design optimization under the fatigue behavior of the connection elements used in parking brake cables. Deshpande, Badadhe and Khan (2021) [19] presented an assessment of topology optimization applied on a hand brake that is made from glass fiber composite material. Işıtan, Eroğlu and Binici (2020) [20] studied topology optimization on handbrake components, which are utilized in light-duty vehicles and attained 43,82% lightening. Sasane and Burande (2019) [21] investigated the existing handbrake lever with FEA analysis and experimental. According to the study, they attained close results from numerical and physical tests. Top et al. (2019) [22] and Top et al. (2020) [23] achieved the optimized form of a brake bracket to be manufactured using selective laser sintering (SLS), one of the additive manufacturing methods, by applying topology optimization. Patel, Sarawade and Gawande (2017) [24] reported an experimental and topology optimization study for existing and optimized a parking brake handle to reduced weight by 10% later the optimization. Patel and Sarawade (2017) [25] conducted finite element analysis and topology optimization for a parking brake handle, changed material from structural steel (S235) to Aluminum alloy (A356), and applied force as 20 N, 40 N, 60 N, and 80 N and evaluated the results. Mask, Tuljapure and Satav (2016) [26] presented a new design concept for the parking brake system which replace the traditional connections with an electric motor unit. Mansor et al. (2014) [27] developed a parking brake lever rather using kenaf fiber polymer composites than existing steel material, and in addition to this, aimed to decrease weight with sustained strength for safety and functionality in performance. Yıldız et al. (2020) [28] utilized Henry Gas Solubility Optimization Algorithm (HGSO) for the design optimization of automotive brake pedal. Doğan et al. (2020) [29] employed topology optimization, shape optimization, and design of experiment methods to decrease the weight of the brake pedal in heavy trucks. Akçay and İlkılıç (2023) [30] conducted a study on topology optimization for weight reduction of the brake pedal. Then, they conducted shape optimization by genetic algorithm from artificial intelligence methods. Savran et al. (2023) [31] used numerical analysis methodology to characterize the mechanical behaviors of the front bumper middle bracket of automobile. Altınel et al. (2023) [32] examined the X-arm which used in heavy commercial vehicles for connecting the axle and the chassis in suspension systems, under the service conditions by finite element model according to two different analysis scenarios. Zhong et al. (2023) [33] conducted a statistical analysis of papers about structural topology optimization over the past 20 years in the CNKI and WOS databases. The design requirements for a parking brake lever is illustrated in Figure 2.

A parking brake lever mechanism component is evaluated using topology optimization and finite element analysis methods. This present study aims to both reductions of vehicle weight and contributes to sustainability in manufacturing with a reduction of used materials amount and consumed energy.

2. MATERIAL AND METHOD

Parking brake systems are divided into three types of control mechanisms. They are named fully mechanical parking brake (traditionally used), electro-mechanical parking brake (EMPB) and electronic parking brake (EPB) systems. A mechanically controlled parking brake mechanism was chosen for this study.

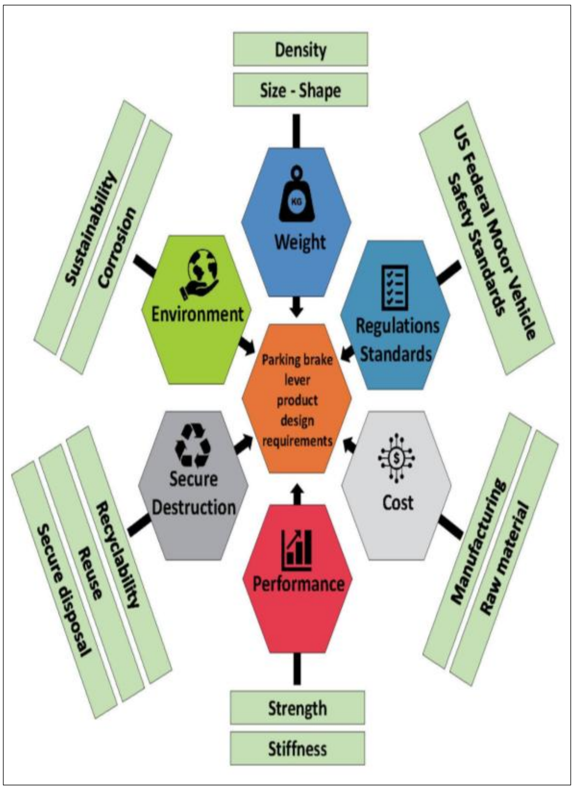

Figure 2. Product design requirements (Mansor et al., 2014 [27])

Parking brake lever mechanisms are similar in function, although they have different designs according to the manufacturing companies. The basic elements of a parking brake mechanism are the pawl, ratchet and lever, the other elements are considered as accessories and assembly elements. The parts that make up a typical parking brake lever are shown in Figure 3. In this study, parking brake lever and ratchet elements were studied.

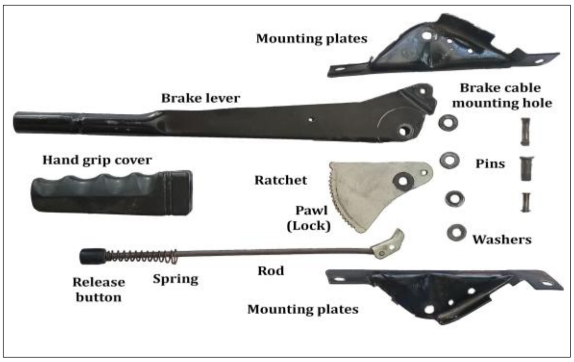

Figure 3. Parking brake lever mechanism parts

An existing parking brake lever and ratchet were measured and modeled in a CAD program. The 3D models are shown in Figure 4.

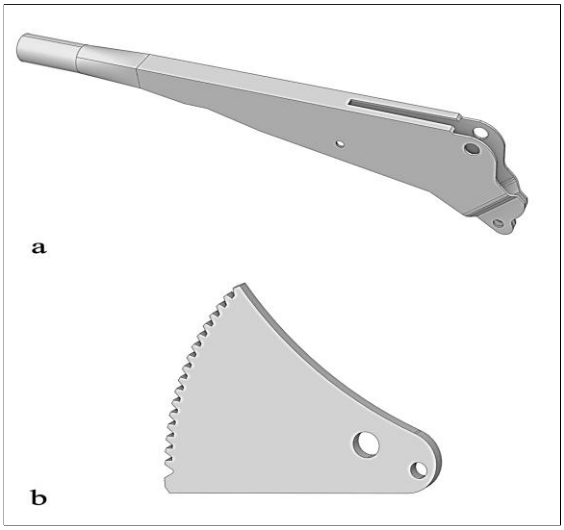

Figure 4. CAD models a) parking brake lever, b) parking brake ratchet

Generally, it is considered that topology optimization aimed at additive manufacturing processes due to the production of complex geometries. Recently, new manufacturing constraints is added to the topology optimization programs for conventional manufacturing methods. In the topology optimization study based on finite element analysis. Firstly, FEA analysis is run according to the determined criteria. The data obtained from FEA analyses such as static structural, modal, and thermal analyses constitute the input data of the topology optimization study. After the topology optimization, a verification analysis is performed to determine whether it meets the requirements. The flowchart summarizing this process is depicted in Figure 5. At the end of this process, a new geometry is generated. The geometry obtained after a topology optimization should not be considered as the final model. The designs can vary according to be selected manufacturing method traditional or additive manufacturing, and customer requirements. Topology optimization gives new ideas to the designer to further improve the existing designs.

The designed 3D models were imported to the static analysis module, generated the mesh, and defined the loads and supports. Static structural analysis was solved in the program. AISI 1020 steel was assigned from the software material library. Table 1 shows the mechanical properties of the assigned material.

In the parking brake lever meshing, the element size was selected as 1,29 mm and obtained the number of nodes was 126134 and the number of elements was 62225. In the ratchet meshing, the element size was selected as 0,7 mm and the number of nodes was 97543 and the number of elements was 18960. Both for the parking brake lever and for the ratchet, the mesh was created within acceptable limits. Table 2 and Table 3 summarize the mesh metrics according to the four criteria. The FEA mesh models are shown in Figure 6.

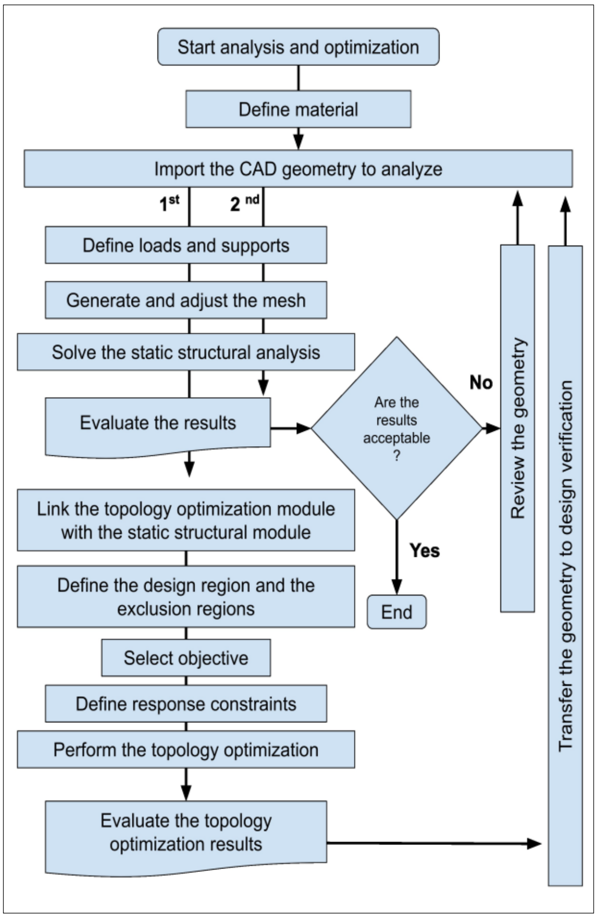

Figure 5. Topology optimization flowchart

Table 1. Mechanical properties of the assigned material

AISI 1020		
Density	kg/mm³	0,00000787
Young's Modulus	MPa	185860
Poisson's Ratio		0,29070
Bulk Modulus	MPa	148000
Shear Modulus	MPa	72000
Tensile Ultimate Strength	MPa	420
Tensile Yield Strength	MPa	350

Table 2. Mesh metrics for parking brake lever

Parking brake lever			
Mesh Metrics	**Min**	**Max**	**Average**
Skewness	1,87421e-3	0,82878	0,29538
Element Quality	0,42253	0,99996	0,79888
Aspect Ratio	1,19141	4,68771	1,95761
Orthogonal Quality	0,17122	0,99295	0,70408

Table 3. Mesh metrics for parking brake ratchet

	Ratchet		
Mesh Metrics	**Min**	**Max**	**Average**
Skewness	5,27163e-5	0,77482	0,09906
Element Quality	0,27478	0,93225	0,71382
Aspect Ratio	1,38761	4,49071	2,13081
Orthogonal Quality	0,64947	1,00000	0,98766

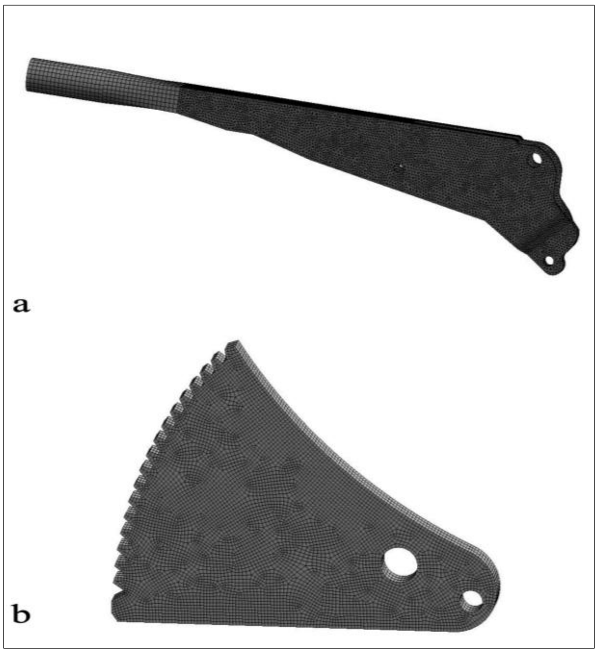

Figure 6. FEA mesh models a) parking brake lever, b) parking brake ratchet

The force applied to the parking brake lever varies according to the driver's gender, age, etc. According to the US Federal Motor Vehicle Safety Standards, the force applied to the parking brake lever of a light passenger vehicle less than 3,500 kg is 400 N (Anonymous, n.d. [34]; U.S. Department of Transportation, 2005 [35]). In this study, 400 N force was applied to the lever (Figure 7). This value was determined by considering the studies in the literature (Noble, Frampton, and Richardson, 2014 [36], 2016 [37]; Noble, 2018 [38]; Wakchaure and Borkar, 2013 [39]). A force of 100 N was applied to the ratchet (Figure 7) (Wakchaure and Borkar 2013 [39]; Işıtan, Eroğlu and Binici, 2020 [20]). Cylindrical support is defined at the connection points.

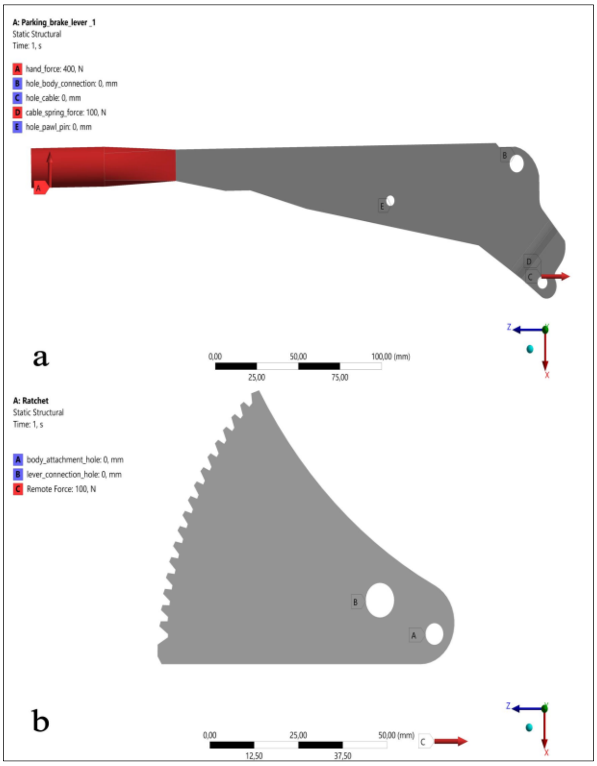

Figure 7. Forces and supports a) parking brake lever, b) parking brake ratchet

3. RESULTS AND DISCUSSION

Static analysis for parking brake lever and ratchet 3D models was conducted with Ansys Static Structural Module. Static analysis results are shown in Figure 8 and Figure 9. The maximum total deformation value for the brake lever is 0,88047 mm and for the ratchet is 0,0043836 mm. The maximum Equivalent (von Mises) Stress for the parking brake lever is 229,24 MPa and for the ratchet is 10,458 MPa. The initial mass for the parking lever is 0.27751 kg and for the ratchet is 0,095042 kg. The initial volume for the parking lever is 35261 mm³, and for the ratchet is 12077 mm³.

In the topology optimization analysis, were set parametric analysis to monitor the final mass and volume change at different percentages of retained mass. Percent to retain is chosen as the input parameter, final mass and final volume as output parameters.

The response constraint mass is increased in 5 increments from 50% to 95%. The final mass and volume change according to the percent to retain is shown in Table 4 and Table 5. The iteration number to reach the solution is also shown. The iteration number increases with the removed mass percentage increases.

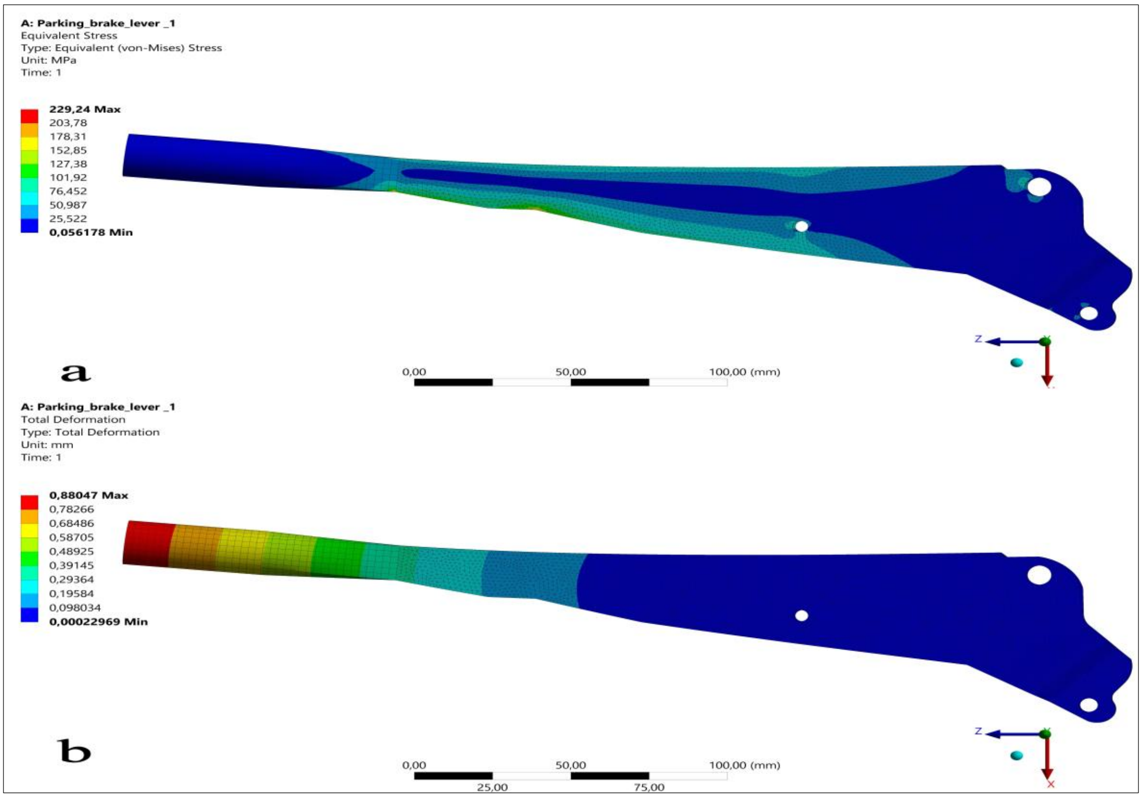

Figure 8. Result of static analyses of parking brake lever a) equivalent (von Mises) stress, b) total deformation

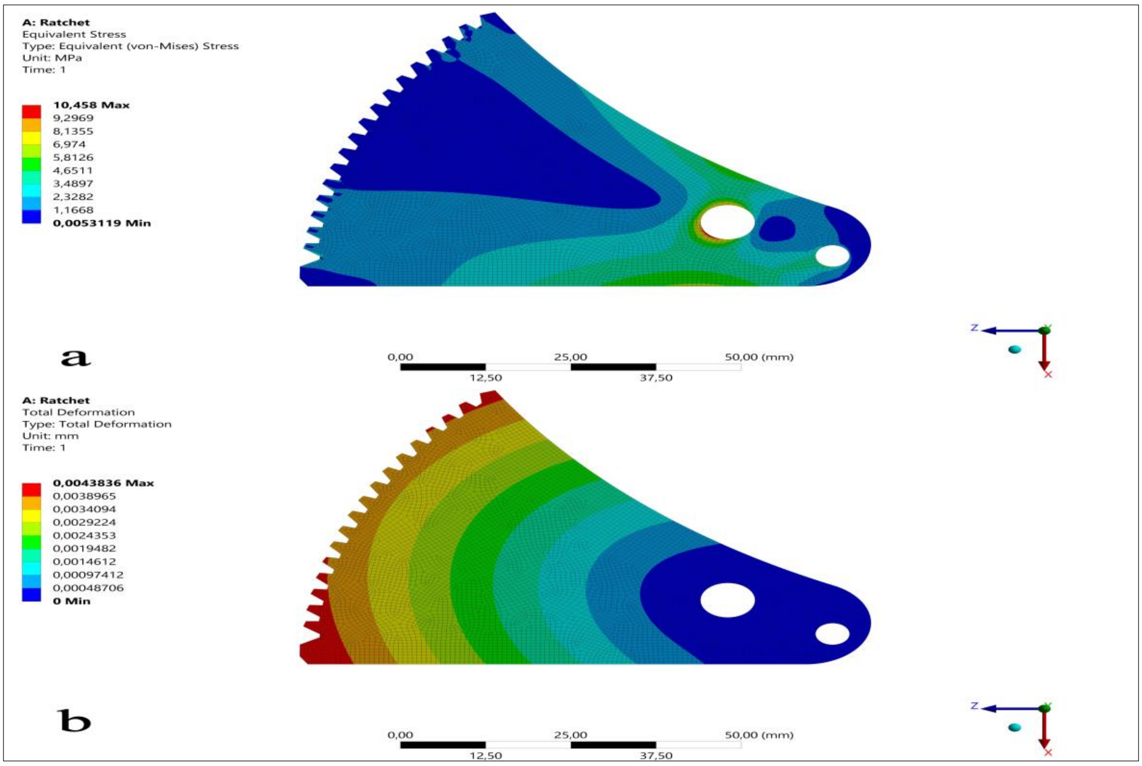

Figure 9. Result of static analyses of parking brake ratchet a) equivalent (von Mises) stress, b) total deformation

Table 4. Final mass, and volume with iteration numbers according to percentages of retained mass of topology optimization for parking brake lever

Parking Brake Lever			
Percent to Retain (%)	**Iteration Number**	**Final Mass (kg)**	**Final Volume (mm^3)**
50	31	0,09966	12663
55	28	0,10452	13281
60	21	0,10893	13841
65	20	0,11216	14251
70	18	0,11553	14680
75	18	0,11925	15152
80	17	0,12212	15517
85	13	0,12407	15765
90	11	0,12735	16182
95	10	0,13162	16724

Table 5. Final mass, and volume with iteration numbers according to percentages of retained mass of topology optimization for ratchet

Ratchet			
Percent to Retain (%)	**Iteration Number**	**Final Mass (kg)**	**Final Volume (mm^3)**
50	23	0,055014	6990,4
55	18	0,058745	7464,4
60	17	0,063185	8028,6
65	15	0,067711	8603,7
70	14	0,072408	9200,5
75	13	0,076642	9738,4
80	12	0,080734	10258
85	10	0,084716	10764
90	9	0,088831	11287
95	6	0,093029	11821

Obtained geometries after topology optimization is shown in Figure 10 for retaining percentage 70. The geometries were evaluated, and the initial geometry was revised in a CAD environment (Figure 11) according to the attained geometry after topology optimization. Considering of the topology optimization process, the excess materials was removed by cutting in the CAD models. The sheet metal thickness of initial CAD models of components was kept constant in this process.

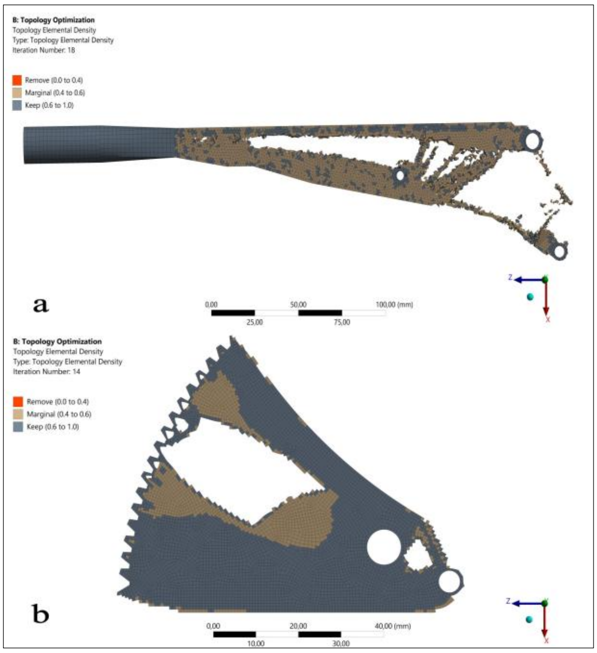

Figure 10. Occurred geometries after topology optimization a) parking brake lever, b) parking brake ratchet

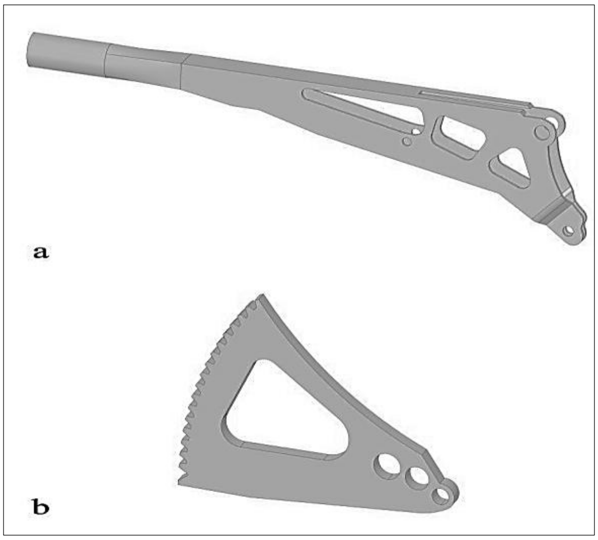

Figure 11. CAD model after topology optimization a) parking brake lever, b) parking brake ratchet

Static analysis was applied to the revised geometry for validation (Figure 12 and Figure 13). The maximum equivalent (von Mises) stress for the parking brake lever is 230,29 MPa and for the ratchet is 11,559 MPa. The maximum total deformation value for the brake lever is 0,95853 mm and for the ratchet is 0,0079482 mm. The final mass for the parking lever is 0,22622 kg and for the ratchet is 0,061911 kg. The final volume for the parking lever is 28745 mm^3 and for the ratchet 7866,7 mm^3.

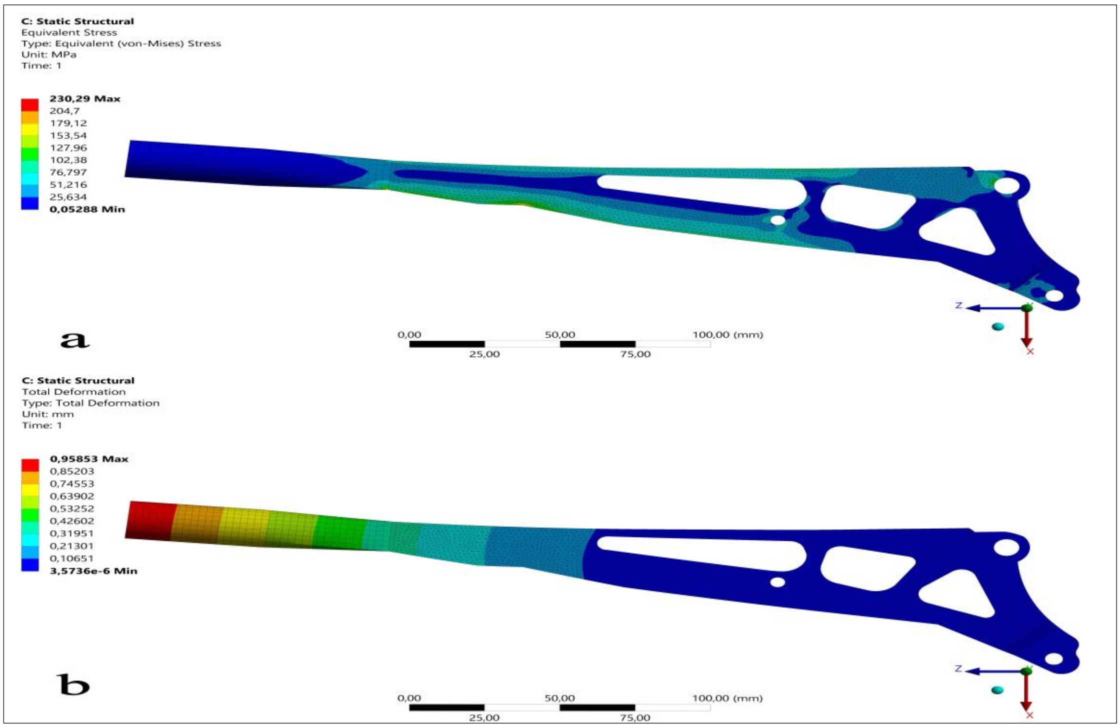

Figure 12. Result of static analyses of parking brake lever a) equivalent (von Mises) stress, b) total deformation

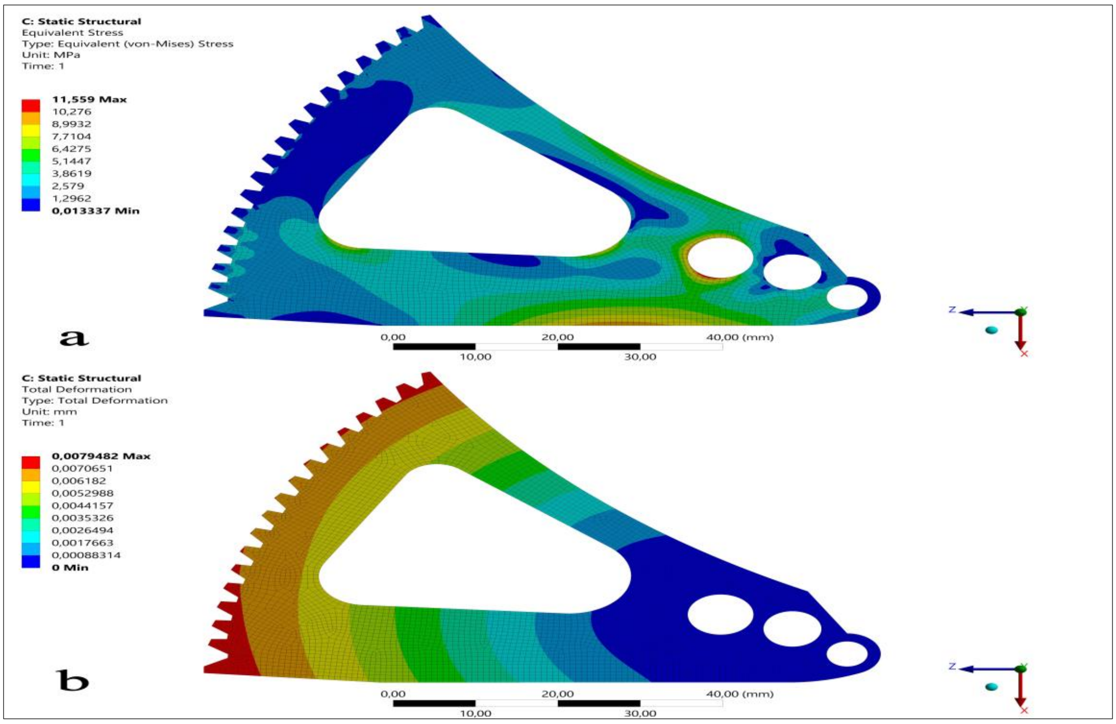

Figure 13. Result of static analyses of parking brake ratchet a) equivalent (von Mises) stress, b) total deformation

4. CONCLUSION

In this study, topology optimization was applied to a parking brake lever and ratchet. In the first step, a CAD model of the existing elements was created, and static analysis was applied. The results of the static analysis were used as input data for topology optimization. In the last step, the static analysis was repeated for changed geometry under the same conditions for verification. As a conclusion, the maximum equivalent (von Mises) stress for the parking brake lever is 230,29 MPa, and for the ratchet is 11,559 MPa. The maximum total deformation value for the brake lever is 0,95853 mm and for the ratchet is 0,0079482 mm. The parking brake lever mass decreased from 0,27751 kg to 0,22622 kg among 18,48%. The ratchet mass decreased from 0,095042 kg to 0,061911 kg among 34,85%.

To enhance cost efficiency and performance in redesigns, it is important to consider the potential for reducing the amount of material used or replacing it with lighter materials.

DECLARATION of ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Funda KAHRAMAN: Conducted and contributed to the study, reviewed, edited and supervised the manuscript.

Mehmet KÜÇÜK: Designed the CAD model, performed the analysis and the data collection.

CONFLICT of INTEREST

There is no conflict of interest in this study.

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