Topology Optimization of a Bell Crank Lever Based on Stiffness and Mass using Finite Element Analysis

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Abstract. The following paper represents the topology optimization of a bell crank lever used in trucks. Current trends indicate a steep rise in the use of topology optimization in all fields. There arises a need for such optimized parts in the automotive industry to increase the overall efficiency of any vehicle. The aim of the present research is to optimization of a bell crank lever arm made of AISI A514 Steel used in trucks and maximizes its performance based on criteria of stiffness and mass. Initially, the model is subjected to loading conditions in accordance with a worst-case scenario and optimized accordingly. The optimized and existing bell crank lever is subjected to static analysis using FEA. Results show a 22 % mass reduction of the crank (3395.71 grams to 2641.02 grams) and a 40% stiffness increase (389.32N/mm to 644.988N/mm) which suits the purpose of the study.

Keywords: Bell Crank lever (BCL), Finite Element Analysis (FEA), Stiffness, Topology Optimization, von Mises Stress

1. Introduction

The recent advancement in the automotive industry demands components that are aesthetically as well as structurally sound. Trucks encompass bell cranks which are a part of their leaf spring suspension system. Trucks being traditionally known for carrying loads need components to be optimized to reduce their own weight while carrying payloads. This calls for the need of topology optimization of components which can drastically reduce the weight while having the same performance [1]. A bell crank lever is a linkage used in the suspension system of vehicles [2]. The crank works on the principle of mechanical advantage. It is a structural component consisting of 3 holes, with one hole acting as the pivot point.

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The other 2 holes are connected to the suspension (leaf spring) and the connecting rod of the truck respectively [3]. The overall easy manufacturing and implementation of this mount make it favourable for optimization purposes.

Abhishek Mahesh Sharma et al [4] focused on determining bell crank dimensions followed by static structural analysis and optimization of Formula Student Bell Crank along with change in material from Aluminium 7075 to Titanium 6Al-4V Grade 5. T. Y. Pang et al [5] concentrated on the reverse engineering of bell crank on the basis of its natural frequency. They validated their FEA modal analysis experimentally using a laser vibrometer, manufactured their crank, and assembled it in their vehicle.

Tanmay Nandanwar et al [1] emphasized the weight reduction of a bell crank and a brake pedal used in automotives to increase vehicle dynamic performance and fuel efficiency. J. Mesicek et al [6] also optimized bell crank on the basis of stiffness and to reduce weight. The final optimized prototype was manufactured using Metal 3D Printing. Keun Park et al [7] reverse-engineered a steering knuckle used as a structural component in FSAE prototypes after doing a multibody dynamic simulation to find out the forces acting on the knuckle ,opt optimized accordingly and manufactured using 3D Printing. Ji-Hong Zhu et al [8] in detail explained the principle of topology optimisation ,current trends and need of topology optimization of aircraft structures .

Marco Cavazzuti et al [9] uniquely optimised both a spider and a coupe automotive chassis used by Ferrari SpA and specifically focused on the stiffness of the chassis subjected to bending, torsion and possible failures in all directions. P Srivastava et al [10] has done optimization of centre pivots which are vital to carry the weight of the bogie in trains. M N Sudin et al [11] analysed and redesigned a brake pedal subjected with the aim of material saving approach. Chacón Santamaría et al [12] optimized control arms used in vehicles. Rupali Patil et al [13] has done a stress analysis of a bell crank used in sewing machines. Jeong Woo Lee et al [14] has done optimization of structural brackets for holding compressors with a verification by experimental testing and dynamic loading. Pu Wo et al [15] optimized automotive engine bracket and has done considerable mass saving for the mount.

The bell crank needs to be subjected to topology optimization to increase it's performance [6]. Topology Optimization has become a vital technique while designing and analyzing components. It refers to a method wherein optimum material is removed when subjected to boundary conditions of mass, stiffness and material [16]. The method helps achieving conclusive designs with lowered material costs and weight without compromising the structural integrity of the component [3, 5]. Usually, the designs obtained from the software are not feasible for further processes. Manual changes need to be done in the CAD model in accordance with the design suggested by the software [17]. The following research focuses on the optimization of a bell crank lever used in trucks. The problem associated with the crank arms used in such trucks is that they add weight to the vehicle and drastically reduce it's performance. We have focused on keeping the structural results as close as possible to the original bell crank whilst reducing the weight.The modelling of the crank was done using Solidworks 2022 Software, analyzed using ANSYS 2020 R1 and optimization was done using Altair Inspire 2021 Student Version. The optimization parameter selected was on the basis of stiffness and minimum mass where 5 models were available. Finally a suitable model was selected and further subjected to structural simulation.

2. Materials and Method

2.1 CAD Modeling

The bell cranks models available were based on size, shape, material and ergonomic specifications. The factors of structural integrity and manufacturability played a major role in deciding the type of bell crank to be designed[18]. The software used for modelling was Dassault Solidworks 2022 Student version [19, 4]. The dimensions of the crank are given below in tabular form. Solidworks was chosen as the software because of its adaptable and user friendly modelling features, convenient exporting to ANSYS and Altair Inspire Software and supports TO functions of stiffness, mass and displacement [20].The overall dimensions are finalized from the data available and manufacturing constraints. Three control arms have an eye to eye length of 262.5 mm, 200 mm , 170 mm and a hole diameter of 47 mm for mounting purposes. The mount has a thickness of 78 mm.

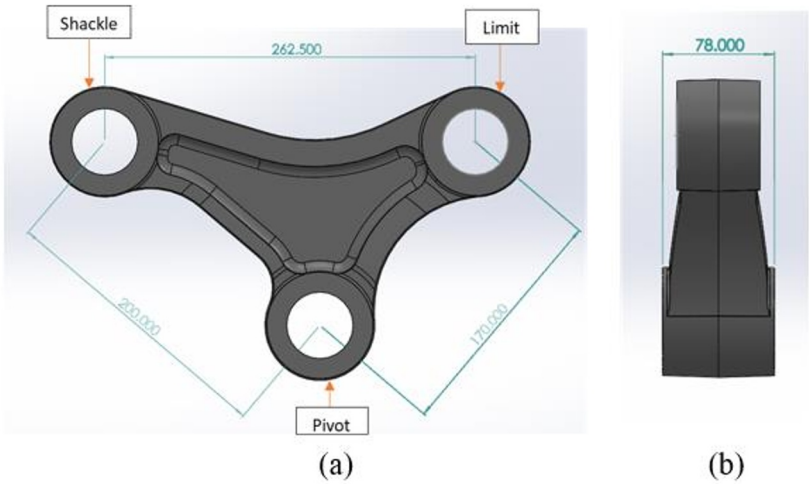


Fig 1: 3D Model of Bell Crank Lever with Front View(a) and Side View(b)

2.2 Design Space

In topology optimization, the volume in the model which can be subjected to optimization refers to design space. The material which cannot be removed is indicated by designating it as non-design space[21, 6]. Non-design space consists of usually holes as well as highly stressed and deformed regions which cannot be removed for mounting as well as failure purposes [7]. Fig 2. describes the design region as well as the non-design region wherein the whole block is considered, and material is removed accordingly.

2.3 Topology Optimization

Topology Optimization has become a vital technique while designing and analyzing components. It refers to a method wherein optimum material is removed when subjected to boundary conditions of mass, stiffness and material [16].

2.3.1 Input

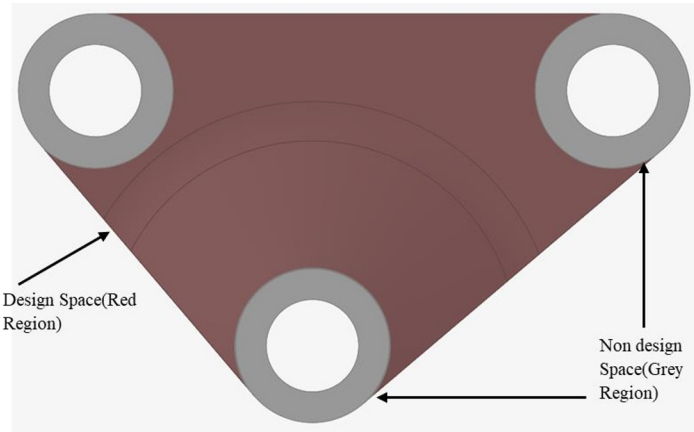


Fig 2: Model containing design as well as non-design space

In the setup, the type of optimization was selected as topology and criteria of maximum stiffness and minimum mass were selected with allowance of optimization being only 30% of the design space volume and having sliding contact only with a minimum thickness of 33 mm [6]. The criteria of minimum frequency were rejected as the component was subjected to structural analysis and not to modal analysis.

The flowchart explains the exact procedure that was followed for the optimization purpose of BCL.

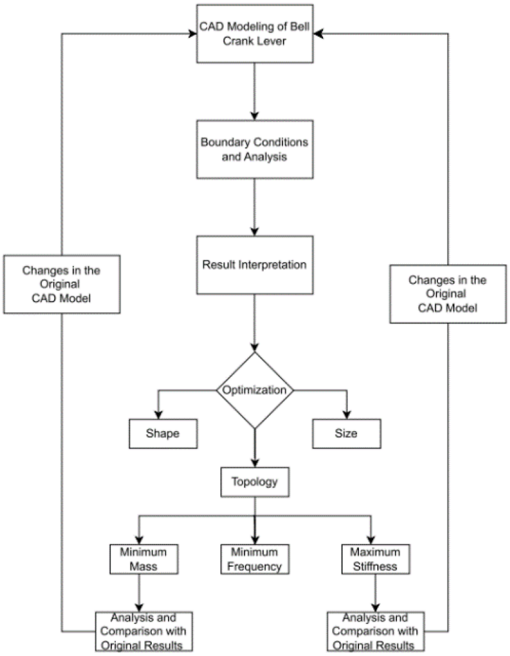


Fig 3: A flowchart depicting the entire process of the paper [15]

2.3.2 Output

The designs obtained were in compliance with the inputs maintained. Overall 4 optimized designs on the basis of the constraints of minimum mass and maximum stiffness were obtained. These designs suggested the changes that needed to be done in the CAD model as the designs were suggestive and additional changes were needed in the CAD geometry of the original crank [17]. All the four designs have the same outer dimensions are the original BCL. These designs vary only in mass and stiffness.

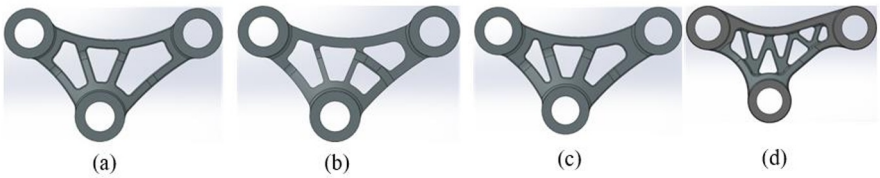


Fig 4: Optimized designs of BCL according to minimum mass (a), (b) and optimized design based on maximum stiffness (c), (d).

2.4 Material Selection

Traditionally, various materials have been used for manufacturing bell cranks, based on their field of application as well as the loading and working environments they are subjected to .Some of the most common materials used are Aluminium 2014 T6, Aluminium 7075 T6, Aluminium 6061 T6,Mild Steel AISI 1018,Titanium 6Al-4V Grade 5,SAE 1030 and A356 Cast Aluminium.[4, 6, 22, 23].

Apart from that recent trends also indicate an increase in 3D printed levers made of Carbon fiber reinforced materials as well as titanium alloys [22]. AISI A514 Steel was selected as the appropriate material for the research as it isotropic, has high yield strength which suited the application of the component and excellent wear strength as well as low cost making it suitable for mass production [24].

Table No.1 Material Properties of AISI A514 Steel

Sr No.	Material	Yield Strength(Y)	Youngs Modulus(E)	Poisson's Ratio(Y)	Density(g)	References
1	AISI A514	690MPa	210 GPa	0.27	7.8g/cm3	[25][26]

2.5 Loading Conditions

The pivot is the fixed point, hardpoint limit is the point connected to the connecting rod and shackle is the point coupled to the suspension in the assembly. The analysis has been performed with the Load Case data considering a worst-case scenario condition in all three principle direction (Fx, Fy and Fz). The pivot acts as the fixed support, and a net force of 26355N due to the bumps and undulations on the road is subjected to the shackle connected to the leaf spring. The limit is subjected to a net force of 23600N which is further transferred to the connecting rod (Fig. 5) [6]. The summation of the forces have been included on the table below [4].

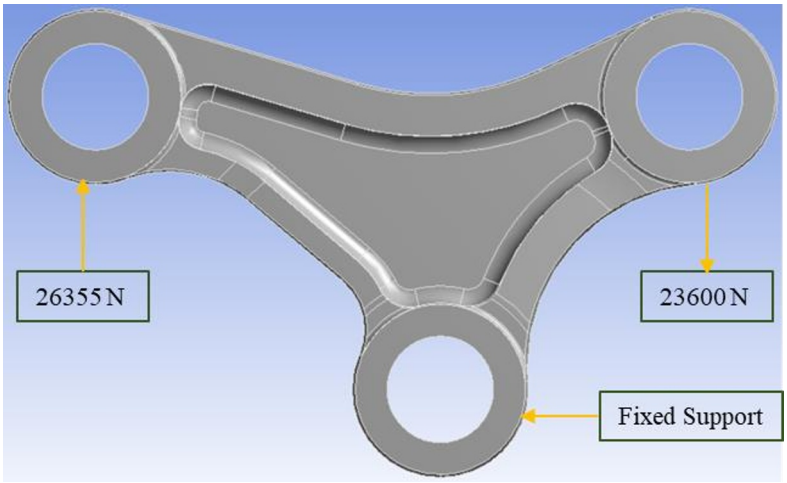


Fig 5: Crank subjected to loading conditions.

Table 2: Static loading conditions of Bell crank lever.

Hardpoints	Fx (N)	Fy (N)	Fz(N)
Equivalent force	0	14651.5	14451.11
Pivot	0	0	0
Limit force	0	-2880.1	-7816.9
Shackle	0	17531.6	22268

3. Finite Element Analysis (FEA)

Finite element analysis (FEA) is a numerical method used to approximate the solutions of a component subjected to mechanical loads and boundary conditions. This helps in validating the analysis before actual manufacturing of the component [27]. Static Structural Analysis using finite element method was performed on ANSYS 2020 R1 to evaluate the total deformation and Von-Mises Stress developed in the crank lever.

3.1 Meshing

All the models were meshed on Altair Hypermesh software and imported to ANSYS for further static analysis. was inferred that the results converged as the element size was minimized to 3.5mm. Several elements like 2D,3D Hexahedral shape elements were available for meshing. A 3D 10 noded tetrahedron element for meshing was chosen as it prevents wrapping of elements during the analysis [28]. The aspect ratio as well as the warpage was kept as 5 respectively.

3.2 Discussion and Results

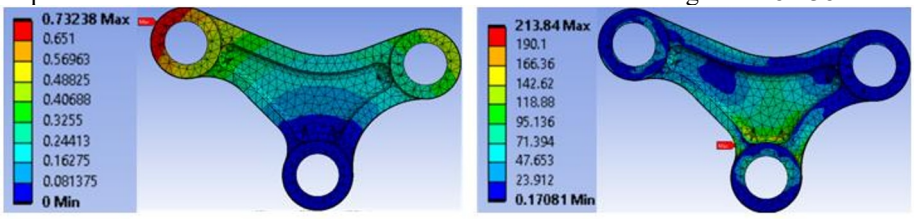
Various studies have been done for bell crank lever analysis. Tanmay Nandanwar et al. worked on static analysis of a crank and results showed a minimum deformation of 0.0675 mm and a maximum Von-Mises Stress of 118 MPa. Their model had a weight reduction of upto 59 %[1] . Rupali Patil et al [13] analysed a crank in sewing machine subjected to minimum forces of 66.5 N in X axes and 18N in Z axes. She varied the thickness of the crank

from 2 mm to 3mm with and without holes and inferred that the stress value gradually decreases from 129.1 MPa to 92.4 MPa with increase in thickness and no. of holes in the crank. I. Aniekan et al [27] focused on a crank used in bicycles for applying brakes on the rim. They aimed to reduce stress generated in the crank. The crank is subjected to 12 KN of force. The initial stress and deformation was 823 MPa and 1.36 mm. After redesigning, the stress and deformation were 234MPa and 0.498mm. However, the weight of the crank slightly increased from 0.914 to 1.133 kgs. A. M. Sharma et al [4] crank is used in student formula prototypes which was subjected to a Pullrod force of 1650N , a Damper force of 24N and a Fulcrum force 1674N.Their initial design's stress and deformation was 143.09 MPa and 0.038mm while the final design had a stress generation of 491.65MPa and got deformed by 0.117mm.The material was also shifted from Aluminium 7075 T6 to Titanium 6Al-4V Grade 5 which resulted in weight reduction by 54%. A. Pande et al [3] showed that there is a 55.92% weight reduction in the crank but the displacement varied from 0.0024 to 0.0021 mm only and the stress changed from 0.018MPa to 0.02 MPa.. T. Y. Pang et al [5] had their crank subjected to 2609N in Y direction and 460N in X direction. The original and optimized crank stress values varied from 239.3MPa to 199.8 MPa whereas mass increased by 2.6%. J. Mesicek et al [6] also have the application of their crank in formula student cars .Their crank was subjected to forces of 4000N from the suspension and 2412N from the anti-roll bar . The drop in von-Mises stress from the original to the optimized crank was 650.5MPa to 381.45MPa. The mass reduced by 7% whilst stiffness increased by 32%.

After meshing and applying the loading conditions, the model is solved using FEA. The results obtained are for deformation and Von- Mises Stress.

3.2.1 Original Bell Crank (BCL)

The Von- Mises stress value and the deformation value obtained using FEA for the original bell crank was 213.84 MPa and 0.7328 mm. Here the maximum deformation occurs near the mounting hole which is connected to the leaf spring and the minimum deformation occurs at the pivot point. The high deformation values are due to worst case loading conditions in comparison to other cranks described in previous studies. Similarly, the equivalent von Mises stress is maximum near the pivot hole due to stress concentration at the fixed point. In other studies the von Mises stress is between the range of 118-238 MPa.



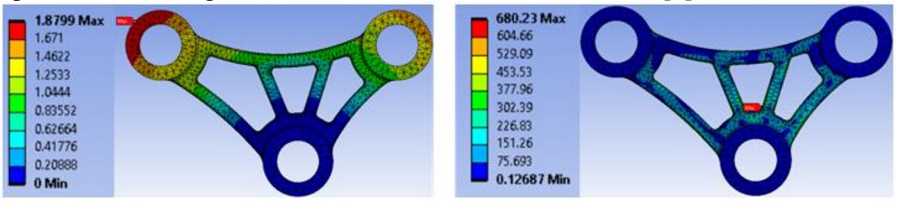
(a) (b)

Fig 6: (a) Von-Mises Stress and (b) Deformation Plot of Original BCL

3.2.2 Optimized Bell Crank (Minimum Mass and Maximum Stiffness)

For the optimized crank having minimum mass and maximum stiffness the stress was 680.23 MPa and deformation was 1.879 mm. The increase in stress as well as deformation was due to material removal from the component to achieve the aim of minimum mass. The equivalent stress was less than the yield strength (690 MPa) which made the crank safe for application purposes. However, the criteria of minimum mass were fulfilled as the weight of the crank reduced drastically.

In other studies, different conclusions were obtained. In [1] ,the crank saw a weight reduction of 59%. The crank used in bicycles resulted in a weight increase but reduction in equivalent stress [27]. Another study saw an increase in stress as well as deformation and this prompted them to change the material to focus on mass reduction [4].



(a) (b)

Fig 7: (a) Von-Mises Stress and (b) Deformation Plot of Optimized BCL

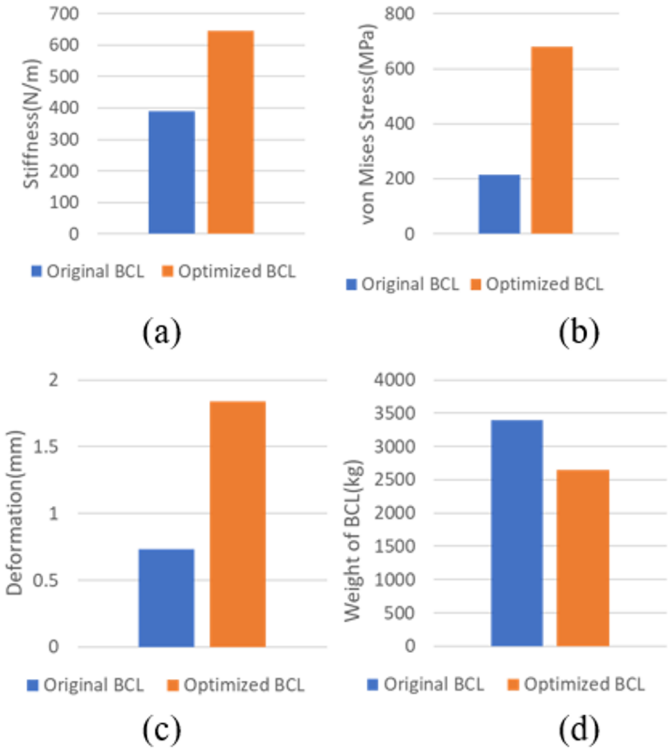


Fig 8: Comparison of various parameters (a) Stiffness (b) von Mises Stress (c) Deformation (d) Weight of BCL

4. Conclusion

Topology optimization is becoming a vital technique day by day as need for enhanced components has increased. The study completed infers that BCL has a reduction of mass by 22 %, there is an increase in the von Mises stress of the BCL due to a significant reduction of mass and most importantly a 40 % increase in stiffness is observed. The targets of minimum mass and maximum stiffness are achieved. Such cranks when mounted in trucks surely increase the scope for redesigning of other components to decrease the overall weight of the truck and to improve the overall efficiency of vehicles. The study has a future scope

of doing a dynamic analysis as well as a fatigue analysis of the BCL. Another analysis of BCL with different materials to choose the most suitable material is also prospective.

References

1. T. Nandanwar, K. Waghela, E. Gupta, and T. Narendiranath Babu, "Topology Optimization of the Bell Crank & Brake Pedal," in IOP Conference Series: Materials Science and Engineering, 2021, vol. 1123, no. 012035, pp. 1–10. doi: 10.1088/1757-899x/1123/1/012035.
2. J. Balkwill, "Suspension Kinematics," in Performance Vehicle Dynamics, 2018, pp. 197–239. doi: 10.1016/b978-0-12-812693-6.00007-9.
3. A. Pande, O. Ingole, D. Jadhav, D. Dhamecha, A. Dongre, and G. Dongre, "Topology Optimization of Bell Crank Lever," TIJER-INTERNATIONAL Res. J., vol. 9, no. 12, pp. 92–97, 2022.
4. A. M. Sharma, S. Konwar Roy, A. R, and N. Das Thaikoothattil, "Structural analysis of bellcrank in a pullrod suspension system in an FSAE prototype," J. Univ. Shanghai Sci. Technol., vol. 23, no. 10, pp. 236–246, 2021, doi: 10.51201/jusst/21/10743.
5. T. Y. Pang and M. Fard, "Reverse engineering and topology optimization for weight-reduction of a bell-crank," Appl. Sci., vol. 10, no. 23, pp. 1–16, Dec. 2020, doi: 10.3390/app10238568.
6. J. Mesicek, M. Pagac, J. Petru, P. Novak, J. Hajnys, and K. Kutiova, "Topological optimization of the formula student bell crank," MM Sci. J., vol. 2019, no. October, pp. 2964–2968, Oct. 2019, doi: 10.17973/MMSJ.2019_10_201893.
7. K. P. Gyu-Won Kim, Yeong-Il Park, "Topology Optimization and Additive Manufacturing of Automotive Components By Coupling Kinematic and Structural Analysis," Int. J. Automot. Technol., vol. 21, no. 6, pp. 1455–1463, 2020, doi: 10.1007/s12239.
8. J. H. Zhu, W. H. Zhang, and L. Xia, "Topology Optimization in Aircraft and Aerospace Structures Design," Arch. Comput. Methods Eng., vol. 23, no. 4, pp. 595–622, 2016, doi: 10.1007/s11831-015-9151-2.
9. M. Cavazzuti, D. Costi, A. Baldini, and P. Moruzzi, "Automotive chassis topology optimization: A comparison between spider and coupé designs," Proc. World Congr. Eng. 2011, WCE 2011, vol. 3, no. January 2019, pp. 2289–2293, 2011.
10. P. K. Srivastava, Simant, and S. Shukla, "Topology optimization: An effort to reduce the weight of bottom centre pivot," Int. J. Recent Technol. Eng., vol. 8, no. 2, pp. 1489–1494, 2019, doi: 10.35940/ijrte.B2131.078219.
11. M. N. Sudin, M. M. Tahir, F. R. Ramli, and S. A. Shamsuddin, "Topology optimization in automotive brake pedal redesign," Int. J. Eng. Technol., vol. 6, no. 1, pp. 398–402, 2014, [Online]. Available: https://www.researchgate.net/publication/260449002
12. P. A. Chacón Santamaría, A. Sierra, and O. A. González Estrada, "Shape optimization of a control arm produced by additive manufacturing with fiber reinforcement," J. Phys. Conf. Ser., vol. 1386, no. 1, pp. 1–7, 2019, doi: 10.1088/1742-6596/1386/1/012003.
13. M. R. Patil and E. N. K. Patil, "Stress Analysis of Bell Crank Lever in Sewing Machine," vol. 4, no. 6, pp. 102–106, 2017.

14. J. W. Chang and Y. S. Lee, "Topology optimization of compressor bracket," J. Mech. Sci. Technol., vol. 22, no. 9, pp. 1668–1676, 2008, doi: 10.1007/s12206-008-0428-3.
15. P. Wu, Q. Ma, Y. Luo, and C. Tao, "Topology Optimization Design of Automotive Engine Bracket," Energy Power Eng., vol. 08, no. 04, pp. 230–235, 2016, doi: 10.4236/epe.2016.84021.
16. P. Kumar Srivastava and S. Shukla, "Structural Optimization Methods: A General Review," Int. J. Innov. Res. Sci. Eng. Technol., vol. 6, no. 9, pp. 88–92, 2017, [Online]. Available: www.ijirset.com
17. D. Vlah, R. Žavbi, and N. Vukašinović, "EVALUATION OF TOPOLOGY OPTIMIZATION AND GENERATIVE DESIGN TOOLS AS SUPPORT FOR CONCEPTUAL DESIGN," in INTERNATIONAL DESIGN CONFERENCE-DESIGN 2020, 2020, no. 2633–7763, pp. 451–460. doi: https://doi.org/10.1017/dsd.2020.165.
18. Y. Keskar, S. Damkale, and P. Dhatrak, Optimization of Electric Vehicle Ladder Frame Chassis Based on Material and Thickness Parameter Variation Using FEA, vol. 265. Springer Singapore, 2022. doi: 10.1007/978-981-16-6482-3_43.
19. K. Akshay and M. Gagandeep Singh, "Analysis of engine mounting bracket for an automobile using FEA," Indian J. Sci. Technol., vol. 11, no. 28, pp. 1–7, 2018, doi: 10.17485/ijst/2018/v11i28/130778.
20. E. Tyflopoulos and M. Steinert, "A Comparative Study of the Application of Different Commercial Software for Topology Optimization," Appl. Sci., vol. 12, no. 2, 2022, doi: 10.3390/app12020611.
21. V. Ghungarde, S. Awachar, N. K. Vaidya, and T. Jagadeesha, "Design optimization of steering knuckle by adopting bionic design approach," IOP Conf. Ser. Mater. Sci. Eng., vol. 624, no. 1, pp. 1–7, 2019, doi: 10.1088/1757-899X/624/1/012023.
22. L. Barbieri and M. Muzzupappa, "Performance-Driven Engineering Design Approaches Based on Generative Design and Topology Optimization Tools: A Comparative Study," Appl. Sci., vol. 12, no. 4, pp. 1–17, 2022, doi: 10.3390/app12042106.
23. M. A. kumar Satya, B G N, "Topology Optimization of Alloy Wheel," Hyundai, vol. 3, pp. 1–7, 2013, [Online]. Available: http://altairatc.com/india/previous-events/2013/images/presentations/os-15_topology_optimization-hyundai.pdf
24. K. Partin, K. O. Findley, and C. J. Van Tyne, "Microstructural and alloy influence on the low-temperature strengthening behavior of commercial steels used as plates," Mater. Sci. Eng. A, vol. 527, no. 20, pp. 5143–5152, 2010, doi: 10.1016/j.msea.2010.04.092.
25. O. Kurdi, I. Haryanto, G. D. Haryadi, and M. Wildan, "Dynamic Analysis of Electric Bus Chassis Using Finite Element Method," Proceeding - 2018 5th Int. Conf. Electr. Veh. Technol. ICEVT 2018, vol. 978, no. 1, pp. 214–217, 2019, doi: 10.1109/ICEVT.2018.8628452.
26. S. A. Widyanto, O. Kurdi, G. D. Haryadi, I. Haryanto, and M. I. Rokhim, "Stress analysis of electric bus chassis using finite element method," J. Phys. Conf. Ser., vol. 1321, no. 2, pp. 3–8, 2019, doi: 10.1088/1742-6596/1321/2/022014.
27. I. Aniekan, O. Ikechukwu, and P. O. Ebunilo, "Redesign of a Bell Crank to Ensure Compliance with Von-mises Failure Criterion," vol. 7, no. 5, pp. 394–407, 2016.

28. S. Rv, M. Zaki, R. Jain, D. Kumar, and R. Singh, "Design and Fatigue Analysis of Bicycle Crank-Lever," Int. Res. J. Eng. Technol., vol. 08, no. 06, pp. 2906–2911, 2021, [Online]. Available: www.irjet.net