Topology Optimization of the Bell Crank Lever

R. Narasimha Rao
Professor
Department of Mechanical Engineering
National Institute of Technology Warangal
Warangal, Telangana, India
rnrao@nitw.ac.in

Ch. Sri Chaitanya
Asst. Professor, Department of Mechanical Engineering
Velagapudi Ramakrishna Siddhartha Engineering College, Kanuru
Vijayawada, Andhra Pradesh, India
srichaitanya178@gmail.com

Abstract

Bell crank is a kind of lever which is used to alter the course of the movement. It is exposed to huge stress but designing it with heavier mass creates the requirement of heavier actuation. In the present study, the basic design of the bell crank was modelled in CAD software. Four generally used materials for bell crank (1060 alloy steel, Al Bronze, AISI4130 mild steel, nodular cast iron) were used in the design. The stress in the bell crank during operation was measured using solidworks software. Based on the stress distribution in the bell crank, the Solid Isotropic Material with Penalization method was utilized to optimize the shape of bell crank. The manufacturing constraints were also considered during optimization. Using the topology optimization algorithm, fifty percentage of mass was reduced without compromising the weight to stiffness ratio of the bell crank. The material was removed within the boundary of the standard bell crank. The linear static loading was assumed to identify the optimal locations for material removal. Among the materials that are utilized, the nodular cast iron is best for the shape optimization although all four materials can be used to reduce fifty percentage of the material from standard bell crank. Except the alloy steel, all three materials have further room for optimization but due to its low density compared to other three, alloy steel is preferred material for the bell crank.

Keywords
Topology Optimization, Bell crank, specific strength, stress distribution.

1. Introduction
Bell crank lever is a rectangular L shaped crank which is fixed at the point of intersection of the two arms by a pivot joint. This crank is used to change the motion through an angle. The change of angle can be anywhere from zero to 360 degrees. Bell cranks found their applications in automotive and aircrafts. These industries have huge cost operation in terms of fuel consumption. The reduction of the fuel consumption can be achieved by reducing the load on the vehicles. The reduction of the weight can be achieved by optimizing the shape and geometry of the components. The optimization of structural shape can be for safety like in seismic proof structures (Zakian and Kaveh 2023) and for fuel savings in automotives. The reduction of the material by optimizing the shape can lead to complex geometries which are difficult to manufacture (Sowjanya et al. 2021). The research to create simple but optimized geometries that can reduce the weight of the existing components is of high interest (Fornace 2006).

The brake pedal and the bell crank are similar products that can be optimized for the shape and topology (Dange et al. 2014, Patil and Patil 2017). The bell cranks are generally optimized for lowest weight that can carry without damage while the brake pedal is optimized for the maximum stiffness and strength. The optimised bell crank weighs approximately one hundred and forty grams less than the current design, resulting in a fifty nine percent decrease in component weight. This optimization was done by reducing the weight by material removal from the components low stress zone. By optimising the topology of different automotive components, fuel consumption can be decreased without compromising material strength, and the dynamic performance of the vehicle can also be enhanced.

Reverse engineering can be used to create a 3D bell crank model, and the findings of laser vibrometer tests were used to confirm the related FE bell crank model (Hasan 2018). Less than 5% separated the experimental and FE values of the natural frequency at the fourth mode, which was considered to call for additional examination. Initially, the design domain for material elimination was chosen during the optimisation process. The geometry designs generated by the optimisation algorithm were converted into CAD models using the topology optimisation approach. These models were then used to smooth the geometry to remove holes, irregular forms, and complicated edges before producing the prototype for additional testing. The design optimisation methodology's results showed that it could be applied and produced an optimised bell crank that reduced weight by 3%, maximum principal strain by 4.3%, and maximum von Mises stress by 16.5%, all while increasing overall stiffness and natural frequency (Essienubong et al. 2016). This research showed that structural topology optimisation may be accomplished successfully with reverse engineering and non-destructive testing techniques, resulting in an acceptable lightweight product. This makes a major contribution to solving intricate designs without sacrificing the integrity and performance of the structure. A computational design technique called topology optimisation seeks to maximise the performance of the design while optimising the material distribution in a particular design space in relation to loads and limitations. (Kulkarni and Javed 2014). Topology optimisation tools can be used to encourage creativity by providing solutions that engineers would not have considered, as well as to lessen the time engineers must put into the iterative processes of developing and assessing many design variations. Along with shape and size optimisation, topology optimisation is one of the three primary subcategories of structural optimisation. Shape optimisation takes into account certain contour parameters determined by node placements in order to meet given design goals and criteria (e.g., reducing fatigue life or stress concentrations). (Venkayya 1978). In order to discover the best solution for weight, stress, displacements, and other factors, size optimisation modifies the values of design parameters pertaining to the cross-sectional areas of the elements. The latter is frequently used to address issues with construction frames, support bars, and truss constructions. Structural Shape Optimisation via Coupled FE–MM and Swarm Intelligence-Based Algorithm. This establishes a more modern approach to mechanical shape optimisation by combining a stochastic "zero-order" search mechanism based on swarm intelligence (SI) with a coupled finite element (FE) method–meshfree method (MM). This is similar to the FE approach, which aids in overcoming MM's drawbacks, such as the high computational burden and ease of enforcing necessary boundary conditions (EBCs). (Spillers and Keith 2009, Sahab et al. 2013).

The present paper focusses on the bell crank lever in automobiles. The standard bell crank was modelled using Solid Works. The model was then analysed for the stress distribution and the stress zones were divided into five zones ranking from allowed to remove to not allowed to remove. The material from the allowed zone was removed in terms of 10% of the total weight. The removed zones were then changed to make the manufacturing friendly. This increases the weight. Bell crank made of four materials were then compared to each other. The stresses in the bell crank, the material removal pattern and the weights of the bell crank before and after the optimization were reported.

2. Materials and Methods

2.1. Design of Bell Crank

The bell crank was modelled in the SolidWorks software. The geometrical dimensions of the bell crank were chosen from the Dange et al. The length of the levers is 210 mm and 70 mm. When the load applied is 100 N, the reaction force needed to maintain the couple is 300 N. The reaction force at the fulcrum is calculated using Equation 1.

$$RF = (W^2 + P^2)^{1/2} = 316.22\ N \qquad (1)$$

The CAD model of the bell crank was shown in Figure 1. Four different materials were chosen for the study. The chosen materials are Aluminium alloy 1060, Aluminium bronze, Alloy steel AISI 4130, and Nodular cast iron. These are the commonly used materials for the bell crank applications. The properties of the material and the mass of the bell crank was shown in the Table 1.

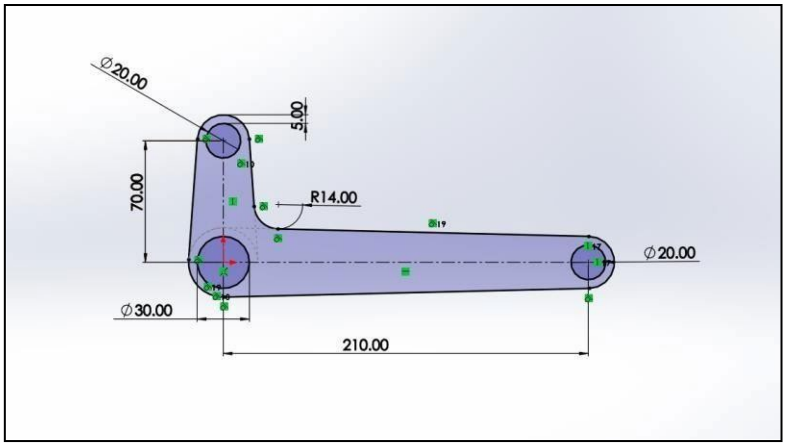


Figure 1. CAD model of the bell crank designed using SolidWorks.

Table 1. Materials and the weight of the bell crank

Material	Density $(\frac{kg}{m^3})$	Weight of the bell crank (kg)
Alloy Aluminium 1060	2700	0.15
Aluminium Bronze	7210	0.4
Alloy Steel AISI 4130	7850	0.43
Nodular Cast Iron	7100	0.39

2.2. Analysis of the Bell crank

The bell crank designed was studied for the stress under the above loading conditions of 100 N. For the stress analysis, the convergent study was conducted to obtain the optimal mesh size. A solid mesh with the element size of 3 mm and 16 Jacobian points was modelled. The maximum aspect ratio of the mesh obtained as 3.5393. With this element size, the obtained meshing has 26,461 nodes and 15,703 elements. The further increase in number of nodes by reducing the aspect ratio increased the computational time but the results did not vary much. Loads were applied at the ends of the bell crank and the fulcrum is fixed for linear motion but rotation was allowed. The materials properties used for the analysis is shown in Table 2.

Table 2. Properties of the Materials used for the analysis

	Alloy Aluminium 1060	AISI 4130 Alloy Steel	Aluminium Bronze	Nodular Cast Iron
Elastic Modulus GPa	69	205	117	165
Poisson's ratio	0.33	0.285	0.34	0.22
Mass Density kg/m^3	2700	7850	7210	7100

2.3. Topology Optimization

The lever with basic design can withstand the applied load with ease. The topology can be optimized by the removal of material to reduce the weight of the component. For better mass to stiffness ratio, a weight reduction of 10-60% have been targeted and subjected to the topology optimization in SolidWorks CAE. The weight of the bell crank was reduced by removing the material. The material removal was done in the steps of 10 % of the original weight of the bell crank. After each step of material removal, the stress analysis of the bell crank was done and the possibility of further material removal was explored. The material removal process was stopped when the factor of safety of one of the four materials was reached one.

3. Results and Discussion

The designed bell crank was subjected to the load of 100 N on one hand and equivalent reaction force on the other hand. The fulcrum hinge was fixed in translation motion and allowed for the rotation. The stress distribution of the bell crank was measured using solid works. The Von Mises stress in the original bell crank was shown in Figure 2.

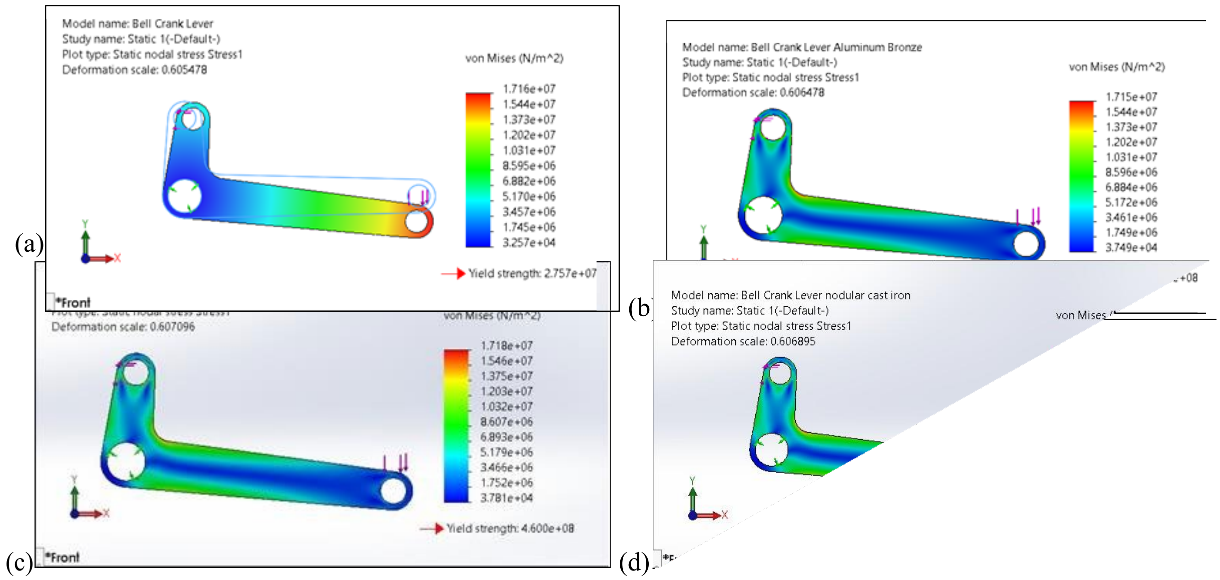
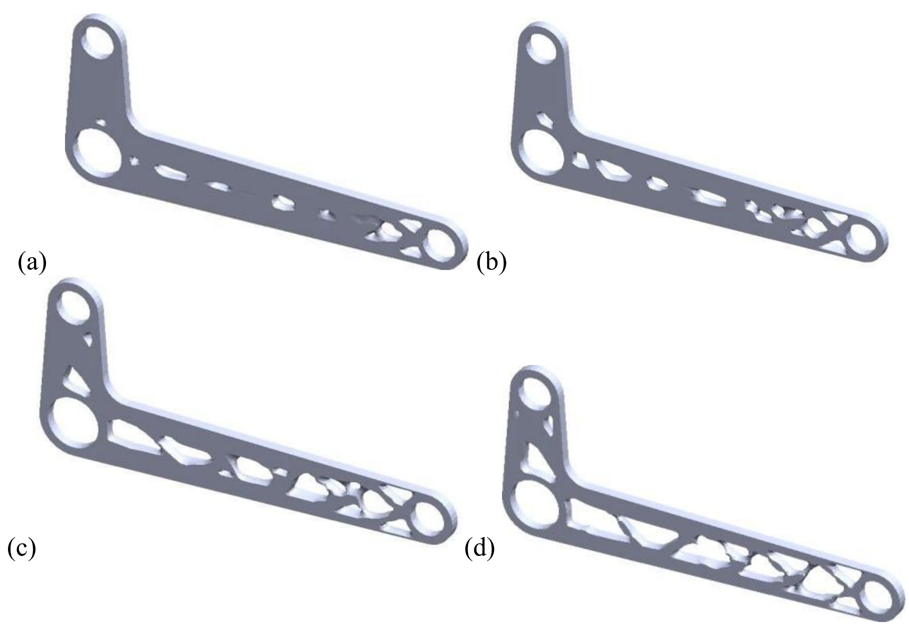
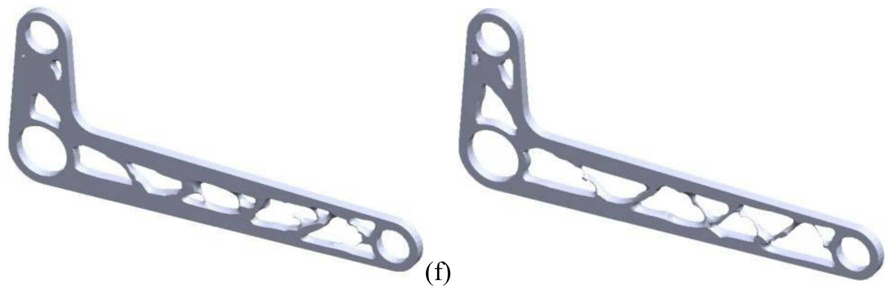


Figure 2. The Von Mises stress distribution of original bell crank made with (a) Alloy Aluminium 1060, (b) Aluminium Bronze, (c) AISI 4130 Alloy Steel, and (d) Nodular cast iron

The stress measured from the simulation shows that the stress is higher at the edges of the bell crank and lower at the centre of the arm. The material removal can be started at the lowest stress locations. From the above stress distribution chart, the bell crank geometry was divided into five zones depending on the ease of material removal without disturbing the strength of the material. The Figure 3 shows the bell cranks after each iteration of material removal.





(e) (f)

Figure 3. The bell crank after material removal of (a) 10%, (b) 20%, (c) 30%, (d) 40%, (e) 50% and (f) 60%.

The bell crank was unsustainable after 60% of its material was removed. The material removal shown in the above figure has been done by considering the manufacturing constraints. All the material removal can be done on a simple milling machine. The comparison between the initial mass and the final mass of the bell crank is shown in Figure 4. The initial weight is the weight of the bell crank without any optimization and the final weight of the bell crank is 50% removal of material with manufacturing constraints added. The weight should be half of the initial weight if 50 % of the material was removed, but, as some parts are difficult to machine those parts were kept as is.

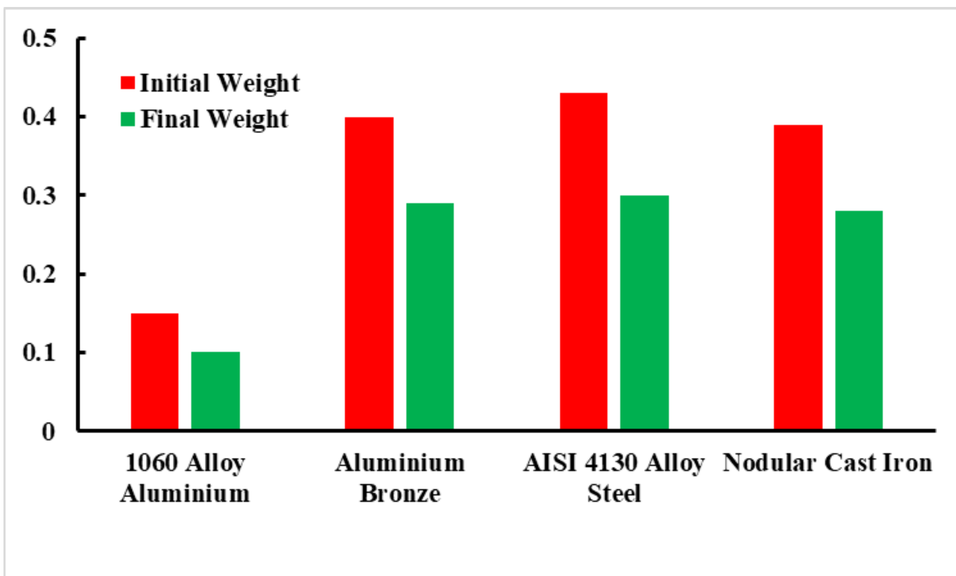


Figure 4. Comparison of initial and final weights of the bell crank

From the results, it was observed that the nodular cast iron can have highest performance with maximum stress in the optimized bell crank of 25.2 MPa while its yield strength is 562 MPa. This amounts to the factor of safety of nearly 20. When compared to the 1060 Alloy aluminium, its factor of safety is near to one. If the weight of the bell crank is considered, the 1060 alloy aluminium has almost 67% less weight of that of nodular cast iron.

4. Conclusion

In the current study, a standard bell crank was designed in solid works with four different materials. These bell cranks were then studied for the stress distribution. Based on the stress distribution, the areas with low stress were removed to reduce the weight. The removed zones were then finished to make the material removal manufacturing friendly. The conclusions of this study are

- 1060 Alloy aluminium-based crank have less weight after optimization compared to other three materials. The weight of the 1060 alloy aluminium is 67% lower than the weight of nodular cast iron.

- The nodular cast iron has potential for further removal of the material but the manufacturing is harder for further material removal. The optimized nodular cast iron bell crank is more than 20 times safer than the 1060 alloy aluminium.
- This type of shape optimization helps in reduction of the weight of the machine components with out reducing the strength of the components. In the present study the final weight of the component reduced by 25 to 30 % from the initial weight.
- The weight reduction can help reduce the material usage and the fuel consumption of the automobile.

References

Sowjanya, Ch, V. Nagabhushana Rao, and B. Pavani Sri Kavya. Optimum design and analysis of bell crank lever for an automobile, *Advanced Manufacturing Systems and Innovative Product Design: Select Proceedings of IPDIMS*2020, pp. 189-208. Springer Singapore, 2021.

Fornace, Lucas V. Weight reduction techniques applied to formula SAE vehicle design: An investigation in topology optimization*. Dissertation of University of California*, San Diego, 2006.

Hasan, A. Study the performance of the bell crank lever apparatus*. International Journal of Research in Applied Science and Engineering Technology*, vol. 6, 2018.

Patil, R., and Er NK Patil. Stress analysis of bell crank lever in sewing machine. *International Journal of Innovative Science, Engineering and Technology*, vol. 4, no. 6, 2017.

Zakian, Pooya, and Ali Kaveh. Seismic design optimization of engineering structures: A comprehensive review, *Acta Mechanica*, vol. 234, no. 4, pp. 1305 – 1330, 2023.

Dange, M. M., S. R. Zaveri, and S. D. Khamankar. Stress analysis of bell crank lever, *International Journal on Recent and Innovation Trends in Computing and Communication*, vol. 2, no. 8, 2014.

Essienubong, Ikpe Aniekan, Owunna Ikechukwu, and P. O. Ebunilo. Determining the accuracy of finite element analysis when compared to experimental approach for measuring stress and strain on a connecting rod subjected to variable loads, *Journal of robotics, computer vision and graphics*, vol. 1, no. 1, pp. 12 – 20, 2016.

Kulkarni, Aditya, and Arshad Javed. Performance investigation of topologically optimized manipulator link*, In Proceedings of International Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering*, 2014.

Spillers, William R., and Keith M. MacBain. Structural optimization, Springer Science & Business Media, 2009.

Venkayya, Vipperla B. Structural optimization: a review and some recommendations*, International Journal for Numerical Methods in Engineering*, vol. 13, no.2, pp. 203 – 228, 1978.

Sahab, Mohammed Ghasem, Vassili V. Toropov, and Amir Hossein Gandomi. A review on traditional and modern structural optimization: problems and techniques, *Metaheuristic applications in structures and infrastructures*, pp. 25 – 47, 2013.

Biographies

R. Narasimha Rao is currently a Professor at Department of Mechanical Engineering, National Institute of Technology Warangal, India. His research includes design of machine components using advanced composite materials and tribology. He has more than 200 publications in international journals and conferences in engineering domain. He is also on the board of studies in various engineering universities in India.

Ch. Sri Chaitanya is an Assistant Professor in the Department of Mechanical Engineering at the Velagapudi Ramakrishna Siddhartha Engineering College, Kanuru, Vijayawada, India. His research interest includes tribology and design of machine elements. He has more than 40 publications in international journals and conferences.