Generative Design Optimization and Analysis of Connecting Rod for Weight Reduction and Performance Enhancement

Nishanth R1, Sreedharan M2, Pranav Rajesh3, Dhanush Babu Allam4, Radha R5*

1,2,3,4,5 School of Mechanical Engineering, Vellore Institute of Technology, Chennai Campus, Vandalur- Kelambakkam Road, Chennai, Tamil Nadu - 600127, India.

1Email: nishanthrajkumar153@gmail.com, 2E-mail:sree18july@gmail.com, 3E-mail:pranavrajesh2000@gmail.com, 4Email:adhanush.babu2018@vitstudent.ac.in, 5*Email:radha.r@vit.ac.in

Abstract. This research paper aims to explore opportunities for weight and cost reduction in the design and development of connecting rods. Two phases are involved in the analysis. The first part is to analyze the loads (compressive and tensile loads) acting on the connecting rod as a function of time to optimize its weight and manufacturing cost using generative design. The generative design is an iterative design process that produces a certain number of outputs based on the power, stress and other constraints applied. The primary considerations are weight, material, and cost for the connecting rod design, we generate which in turn, provides sufficient strength, stiffness, and fatigue resistance. The second part involves the analysis of finite elements that was performed at several crank angles and examined whether the generated designs withstand loads ranging from the tensile load, corresponding to 360° crank angle as one extreme load at the maximum engine speed and compressive load corresponding to the peak gas pressure as the other extreme load. Thus, a wide variety of materials are analyzed to obtain the cost-effective and optimum design of the connecting rod that can be manufactured by additive manufacturing.

Keywords. Connecting rod, Generative design, Titanium, 17-4PH Stainless steel, 3D printing, Weight and cost reduction, Finite element analysis

1. Introduction

A connecting rod is also called a Con Rod and is the connecting point between the crankshaft and the piston within an engine. The role of the connecting rod and the crank is to convert the piston's reciprocating motion to the crankshaft's rotational motion. The linking rod transmits from the piston the compressive and tensile forces and rotates at both ends. Connecting rods are commonly used in internal combustion engines or in steam engines [1]. In the beginning of 1700’s, the first steam engine used a chain drive instead of a connecting rod because the piston only generated force in one direction. Double-acting steam engines, so that the force was generated in both directions, led to the invention of connecting rods to turn one type of motion into another (rotational). The basic steam engine design is a cross head with the joint between the connecting rod and the piston mounted outside the cylinder, requiring a seal around the piston rod. The cranks in a steam locomotive are usually mounted directly on the driving wheels. The connecting rod is being worked out between the crosshead and crank pin. The connecting rods are called lateral rods, or coupling rods, in diesel locomotives. The design of the internal combustion engines connecting rod consists of the small end, the rod and the wide end. The small end is attached to
the gudgeon pin, as the wrist pin or piston pin will swivel within the piston. The broad end is connected to
the crank pin with the aid of a single bearing in order to prevent friction, whereas a rolling-element
bearing is used in small engines to avoid the need for a pumped lubrication unit. The pinhole is drilled
through the bearing of a small circular hole’s wide end so that the oil used for lubrication leaks to the
wall’s thrust side to allow the piston and piston rings to move[2]. A continuous programming process
involving a series of programs that will produce a given number of outputs that satisfy the specific
constraints is known as generative design. Generative design is becoming increasingly important. Except
for those designers with very primitive programming skills, the modern programming environment has
made it very simple. This approach offers a solution to very difficult problems that are typically very
resource-intensive, making it a very appealing choice. This is also encouraged by instruments in
commercially available CAD kits [3]. In order to optimize part design automatically, generative design is
a novel approach. The design has to achieve the optimal solution, in relation to design parameters,
requirements and limits [4]. A connecting rod for single cylinder 4-stroke petrol engine was designed and
analysis and topology optimization of the same connecting rod was carried out [5]. Attributes like material
and shape of the connecting rod and manufacturing process of the connecting rod was selected [6]. All
these papers discussed about the designing of connecting rod, analysis of connecting rod, choosing
attributes and manufacturing process and about the importance of generative design. Generative design is
an important skill which should be acquired by all the designers in order to produce highly efficient
optimized products. It can be particularly useful to produce lightweight highly complex products. The
main objective was to explore the cost and weight reduction possibilities and this was possible by laboring
generative design during the designing of the connecting rod. A connecting rod was designed and
generative design was opted for weight reduction. A proper alternative material suitable for addictive
manufacturing of the connecting rod was proposed.

2. Design Calculations
The parameters required for designing the connecting rod are given in equations (1-13) [7]:

Suzuki 150cc specifications
Engine type air cooled 4-stroke
Bore x stroke (mm) = 57 x 58.6
Displacement = 149.5 cc
Max. Power= 13.8 bhp @ 8500 rpm
Max. Torque = 13.4 Nm @ 6000 rpm
Compression ratio=9.35/1
Density of petrol C8H18= 737.22 kg/m³ = 737.22E-9 kg/mm³
Temperature = 60 F => 288.855 K
Yield stress of 17-4PH stainless steel= 600 MPa

Pressure calculation:
Mass = Volume x Density = 737.22E-9 x 149.5E3 = 0.11 kg
Molecular weight of the petrol is 114.228 g/mole
From gas equation, PV= (Mrt) R
= R/ Mw
= 8.3143/114228
= 72.76
P= (0.11 x 72.786 x 288.85) = 15.5Mpa
The force Pc is,
\[ P_c = \frac{\pi D^2 P}{4} \]  
\[ = \frac{\pi \times (57')^2}{4} \times 15.5 \]  
\[ = 39532.2 \text{ N} \]

Assuming Fos=5

\[ P_{cr} = P_c \times Fos \]
\[ = 39532.2 \times 5 = 197661.04 \text{ N} \]

\[ a = \frac{1}{7500} \kappa_{x} = 1.78 t^2 \]

Connecting rod length is taken as twice the stroke length = 117.2

\[ A = 11 t^2 \]

Therefore,

\[ 197661.04 = \frac{600 \times 11 t^2}{1 + \frac{1}{7500} \frac{117.2}{1.78 t^2}} \]

\[ => 197661.04^2 + 114254.95 - 6600 t^4 = 0 \]

Solving the equation \( t \approx 5.5 \text{ mm} \)

\[ B = 4 \times t = 4 \times 5.5 = 22 \text{ mm} \]  
\[ H = 5 \times t = 5 \times 5.5 = 27.5 \text{ mm} \]  

Height at small end \( (H_1) = 0.9 \times H \)

\[ H_1 = 0.9 \times 27.5 \approx 24 \text{ mm} \]

Height at big end \( (H_2) = 1.2 \times H \)

\[ H_2 = 1.2 \times 27.5 = 33 \text{ mm} \]

Diameter of bearing at small end \( (d_p) \):

\[ P_c = d_p \times l_p \times (P_b)p \]  
Taking \( l_p = 1.5 \times d_p \)

\[ 39532.2 = d_p \times 1.5 \times d_p \times 13 \]

\[ d_p \approx 45 \text{ mm} \]

\[ l_p = 1.5 \times 45 \approx 70 \text{ mm} \]

Diameter of bearing at big end \( (d_c) \):

\[ P_c = d_c \times l_c \times (P_b)c \]

Taking \( l_c = 1.25 \times d_c \)

\[ 39532.2 = d_c \times 1.25 \times d_c \times 11 \]

\[ d_c \approx 55 \text{ mm} \]

\[ l_c = 1.25 \times 55 \approx 70 \text{ mm} \]

Outer diameter at small end:

\[ O_s = d_p + 2t_b + 2t_m \]

Where,

Thickness of the bush \( (t_b) = 3 \text{ mm} \)

Marginal thickness \( t_m = 10 \text{ mm} \)

Therefore,

\[ O_s = 45 + 2 \times 3 + 2 \times 10 \]

\[ = 71 \text{ mm} \]

Outer diameter of big end:

\[ O_b = d_c + 2t_b + 2t_m + 2t_m \]
Where,
Thickness of the bush \( [t_b] \) = 3 mm
Marginal thickness \( [t_m] \) = 10 mm
Nominal diameter of bolt \( [d_b] \) = 1.2 x root diameter of the bolt
\( = 1.2 \times 3 \approx 4 \) mm
Therefore,
\[ O_b = 55 + 2 \times 3 + 2 \times 4 + 2 \times 10 \]
\[ = 89 \text{ mm} \]

3. Material Selection
Material to be used on the connecting rod was decided based on the following properties:
1. High tensile strength
2. High compression strength
3. Wear and Tear resistance
4. Good elasticity
5. Heat withstanding capacity

\[ m = A L \rho \]
\[ F / A \leq \sigma \]
\[ m \geq F L \rho / \sigma \]
\[ M = \sigma / \rho \]
Where, \( m \) = mass
\( A \) = area of the cross-section
\( L \) = Length
\( \rho \) = density
\( \sigma \) = fatigue constraint
\( F \) = applied force
\( M \) = material index

In order to reduce mass, the material index \( (M) \) is maximized.

![Figure 1. Fatigue Strength vs. Density](image-url)
Graph (Figure 1) is plotted with $\rho$ as x-axis and $\sigma$ as y-axis and applying additional constraint that the fracture toughness which exceeds 15 MPA $\sqrt{m}$ can be used to identify materials with high values of this index. From the above graph, it was observed that steel and titanium alloys have shown excellent properties. In order to do 3D printing, Ti-6Al-4V and 17-4PH Stainless Steel will be the best choice for manufacturing the connecting rod [6].

4. Modeling of Connecting Rod
Fusion 360 has a similar dashboard platform to Grab CAD’s workbench in that collaborators can keep up to date with model and project changes in the cloud using A360. Much of the advantages of having CAD in-built into the cloud are that models and visualizations are supported by browsers enabling display on any device. This satisfies face-to-face meetings but does not facilitate global collaboration where Skype would be utilized. The CAD user interface for Autodesk Fusion 360 is akin to a direct modeling approach-focusing on fast editing and model creation [8]. The first step is to sketch the small end. The dimensions for the small end are given in the calculation section above; similarly the big end was drawn. The connecting rod length ($L$) can be set with the sketch dimension tool. Final sketch should look like the figure 2. The sketch can be extruded further.

![Figure 2. Final Sketch of Small end and Big end](image)

5. Generative Design Procedure
Despite the continuous development of structural optimization software tools, designers’ experience will always remain an essential element of the design process. Indeed, the ability to analyze design problems and to identify driving factors that play a major role in the achievement of a high-quality result remains a human strength that cannot be easily mimicked by AI tools [9]. After modeling, the model has been imported to the generative design module where all the calculated forces, pressures, and constraints need to be applied.
Initially, there is a model property, where we have to set the parameters to either coarse or fine depending on the requirement of the design. So, for this model, the parameter was set slightly above coarse and not fine. The next step is to define the design space around the connecting rod. There are 3 types; Preserve, obstacle, and starting shape. Firstly, preserve is a condition that instructs the software that it’s not permitted to change the geometry. This preserve condition when selected is generally highlighted green in color. Secondly, an obstacle is a condition that instructs the software not to put any material while solving for outcomes. Thirdly, starting shape is the condition where iteration starts with a particular shape that has been designed as seen in figure 3. Here, in the design space, all the conditions have been initialized and have been set. Moving on to design conditions, considered 6 load cases and that has been applied to the model, for example, in the first load case the bottom inner face has been fixed and the upper face has been given load which can be obtained from the model calculations. In the next design, criteria we give the objective as to minimize the mass so that it minimizes as far as possible. The design’s factor of safety is given as 3 to withstand the intended load without any failure. A small preview can be seen in Figure 4.
Two possible alternatives were selected as possible production technologies: additive manufacturing and unrestricted. Each technology introduces some design constraint to allow manufacturing of the produced part. Milling, for example, requires the definition of tool geometry to compute volumes to leave empty to allow tool access. Additive manufacturing considers the generation of overhang surfaces. The unrestricted modality, on the other hand, corresponds to an unconstrained optimization. Two separate analyses have been carried out: a first one, without any starting shape used to guide the optimization, and a second one that uses the shape as starting configuration [10].

Soon after generating the design, after 6-7 iterations, various outcomes as shown in Figure 5 had been obtained out of which the best design is taken which is visible in Figure 6. Thus, after generating the design, a finite element analysis has been carried out with critical force applied on one end and stationery (fixed) on the other end in Ansys which can be seen in Figure 7 [7]. In Ansys, firstly the engineering data is fed with the required materials that are suitable for the connecting rod. Secondly moving on to Ansys mechanical, where the meshing of the connecting rod (in Figure 8) has been carried out and further to various constraints where it has been applied to the inner surface of the small and the big end. After fixing up the constraints, equivalent stress, and total deformation and Shear elastic strain modules have been added to the solution and solved [5].
Table 1. Maximum total deformation, Maximum equivalent stress, Maximum Shear elastic strain, Minimum shear elastic strain

| Materials assigned | Total Deformation(m) (Maximum) | Maximum equivalent stress (Pa) | Minimum equivalent stress (Pa) | Maximum shear elastic strain (m/m) | Minimum shear elastic strain (m/m) |
|--------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------------|-----------------------------------|
| Ti-6Al-4V           | 0.0012833                     | 8.0253e8                      | 1.1037e5                      | 0.010626                          | 1.4832e-6                        |
| 17-4PH Stainless Steel | 0.00067253                   | 8.0103e8                      | 94962                         | 0.0054733                         | 6.6489e-7                        |
In ANSYS Work Bench, deformation effects can be shown as total deformation or directional deformation. They're both used to calculate displacements from stresses. The only distinction is that directional deformation measures deformations for a given structure in the X, Y, and Z planes. It gives the square root of the summation of the squares of the x, y, and z directions in total deformation. The complete deformation of Ti-6Al-4V and 17-4PH Stainless Steel can be seen in Figure 9 and Figure 10. A few models have been studied and validated with a factor of safety.
In the Ansys workbench, the connecting rod is seen with a band of colors beginning from blue to red representing from minimum to maximum stress respectively and dealing with different regions as shown in Figure 11 and Figure 12.

6. Conclusion
A connecting rod was designed and subjected to generative design for additive manufacturing, in order to reduce its weight, optimize the shape, and provide the most efficient 3d printable connecting rod. Ti-6Al-4V and 17-4Ph stainless steel are some 3d printable material that are easily available. They were applied to the connecting rod in the analyses carried out by Finite element method through ANSYS, which resulted in a few important computations such as deformation; equivalent (von Mises) stress and shear
elastic strain values for both. On examination, the results concluded that both Ti-6Al4V and 17-4Ph stainless steel possessed the required level of properties but 17-4Ph stainless steel exhibited superior strength and also proved to be a cheaper alternative.

Acknowledgment
We would like to thank the VIT management for the support provided for completing the research work.

References
[1] Lyon and Robert L Steam Automobile 13(3) SACA.
[2] Dempsey GD, Clark and Kinnear D 2015 The Victorian Steam Locomotive: Its Design & Development 1804-1879 Barnsley England: Pen & Sword Transport pp 27–28.
[3] Meintjes and Keith 2018 Generative Design –What's that?-CIM data.
[4] Bagassi S, Lucchi F, De Crescenzo F and Persiani F 2016 Generative design: advanced design optimization processes for aeronautical applications 30th ICAS Congress
[5] Pandiyan A, Arunkumar Gopal and Premkumar G 2019 Design, Analysis and Topology Optimization of a Connecting Rod for Single Cylinder 4–Stroke Petrol Engine Int. J. Vehicle Structures & Systems 11(4) pp 439-442
[6] Somnath Chattopadhyay 2010 Selection of material, shape and manufacturing process for a connecting rod American Society for Engineering Education pp 15.1057.2-12
[7] Leela Krishna Vegi and Venu Gopal Vegi 2013 Design and Analysis of Connecting Rod Using Forged steel Int. J. Eng. Res. 4(6) pp 1014-1024
[8] Barrie and Jeff 2016 Applications for cloud-based CAD in design education and collaboration Proc. E&PDE16
[9] William D Webster, Roy Coffell and Dave Alfaro 2018 A three Dimensional Finite Element Analysis of a High Speed Diesel Engine Connecting Rod SAE International pp 83-95
[10] Francesco Buonamici, Monica Carfagni, Rocco Furfere, Yary Volpe and Lapo Governi 2021 Generative Design: An Explorative Study Computer-Aided Design & Applications 18(1) pp 144-155