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Topology Optimization of Sprocket and 3D Printing

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***Abstract:** A chain drive is designed as a final reduction for an FSAE (Formula Student) Vehicle along with topology optimised geometry. Different geometrical shapes were iterated using the results from the topology optimisation and the design was finalised based on the magnitude of max stress concentration. The topology optimization was done under several constraints.*
***Keywords:** Chain Sprocket, Topology Optimization, Shape-Size Optimization*

I. INTRODUCTION

Formula Student cars are independently designed and built by team members and enter FSAE competitions funded by universities or automotive companies under rules promulgated by the Society of Automotive Engineering (SAE). Designers must consider structural design rationality, design cost, performance, fuel efficiency, driving stability and durability, and the overall design requirements are high. As one of the key parts of power transmission, the main reducer has been introduced in many publications over the years.

Chain-Sprocket is one of the most crucial elements of the drivetrain system. With its wide range of applications right from basic final reduction of two wheelers to precise timing chain of internal combustion engines. It offers up to 98% efficiency and being a positive drive, it has the ability to transmit power without any slip or lag.

As there is higher torque transmission and torsional load, the geometry that is fully filled leads to more weight of the overall sheet. Weight reduction is extremely important especially in any motorsport, as it directly affects the responsiveness to acceleration performance of a vehicle due to increased inertia of the vehicle. Also, the sprocket is a rotating component of the power transmission system, and the rotational moment of inertia of all rotating components directly affects the efficiency of power transmission and power loss. So, it's important to optimise all the rotating components for a lesser moment of inertia, and all other components for lesser weight. The geometry obtained through topology optimization is extremely complex with irregular shape and size `and not feasible to manufacture as it is. However, with appropriate shape and size optimization, the sprocket can be 3D printed easily. 3D printing is arguably only 30 years old, but it is already having a tremendous impact on a wide range of industries, from medical devices to consumer goods and pretty much everything in between1. A key driver of growth has been the ability to prototype components quickly and at very low cost. However, as 3D printing technology matures, industry players are experimenting with printing components for production and long-term use, rather than just using prototypes.

II. LITERATURE REVIEW

1) Yixuan Zhang-Topology Optimization of a Chain Drive's Sprocket of Aprilia RS 125 Sport Bike- International Journal of Frontiers in Sociology
2) Parag Nikam1, Rahul Tanpure2- Design Optimization Of Chain Sprocket Using Finite Element Analysis- Int. Journal of Engineering Research and Application.
3) Vishnuvel., Kajendran., Akil Saran- Design and Optimisation of Chain Sprocket of a Formula Student Car- International Journal of Engineering Science and Computing

III. METHODOLOGY/EXPERIMENTAL

A. Design Methodology

The chain drive is designed considering the torque on the driven sprocket. A chain of minimum pitch available for a rated load required. The design needs to be safe enough to resist the torsional loads acting on the sprocket.

Input Data:

Max Motor torque: 150Nm

Reduction ratio required: 5.5

Teeth Ratio Selected: 72/13

The reduction ratio required is estimated from maximum tractive torque the tires can sustain and the max motor torque. The maximum torque capacity of both the tyres before slipping was estimated at 825Nm, hence the ratio reduction ratio of 5.5 was estimated. However, this doesn't mean this ratio will lead to fastest lap for all events (i.e., autocross, skidpad, acceleration etc)

The final reduction will be practically tested after lap time simulations. And the final reduction which leads to fastest lap time for all events is not necessarily the steepest one (i.e., the one which utilises full tyre capacity). The max forces acting on the teeth and chain will be for greater speed reduction hence; maximum possible reduction was considered for chain selection and overall design.

Chain Selection: The tension in chain is roughly estimated using the reduction ratio required and assumed size of the sprocket. From this, the maximum tensile load acting on the chain is calculated to be 6kN. Based on this, the chain is selected. The chain is also subjected to continues dynamic and varying loads with shock loading. Hence, considering a factor of safety of 3, a chain of 18.6kN breaking load is selected.

Chain Specifications:

- ROLON Chain Number: R1278T
- Pitch: 12.7
- Inner Width: 7.9
- Roller diameter: 8.51
- Ultimate Tensile Strength/ Breaking Load: 18.6kN

B. Static Analysis

In reality, the force acting on each tooth is different; it progressively goes on reducing for each consecutive teeth from the first engaged tooth. This force on each tooth is calculated considering the centre-to-centre distance and size of both sprockets.

The forces are calculated as shown below:

$$P_n = t_n \frac{\sin\alpha}{\sin(\phi)} = t_0 \left[\frac{\sin\alpha}{\sin(\alpha+\phi)}\right]^{n-1} \left[\frac{\sin\alpha}{\sin\alpha+\phi}\right]$$

$$P_1 = t_1 \frac{\sin\alpha}{\sin\phi} = t_0 \frac{\sin\alpha}{\sin(\alpha+\phi)}$$

P_2-P_6 are calculated similarly.

Teeth Number	Value
P1	3948.57
P2	2686.43
P3	1827.73
P4	1243.5
P5	846.02
P6	575.59

6 Holes are constrained with all degrees of freedom locked.

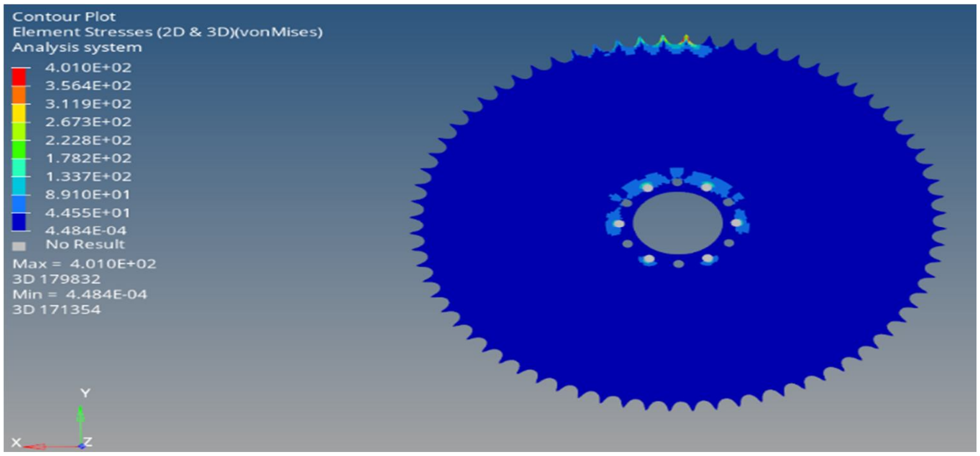

Figure1: Stress Distribution

C. Topology Optimization

As the static analysis of fully solid sprocket has almost no stress concentration within the geometry, there is a great scope for optimization for weight reduction.

The topology optimization was done in Hypermesh Software. A fully filled geometry of the 72 teeth driven sprocket is made according to the chain's pitch as shown below.

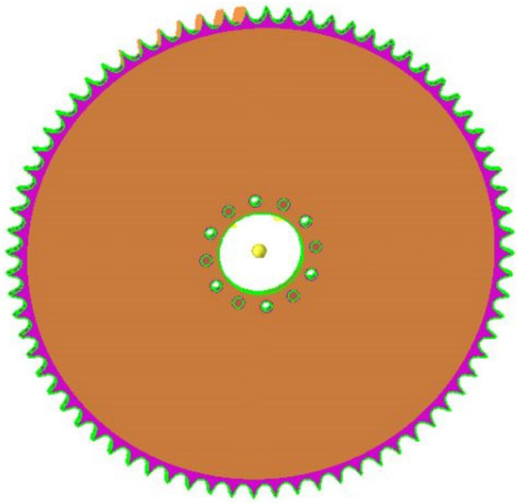

Fig. 2 – Solid sprocket

Mesh convergence criteria was used to select the mesh size of 1mm.

D. Conditions for Material Removal

- 30% volume must be retained.
- The Sprocket must have maximised stiffness. Minimize mass.
- Permissible stress is 500MPa.
- Radial symmetry must be maintained.

A total of 80 iterations were run for the convergence of the results, which are sufficient for precise results.

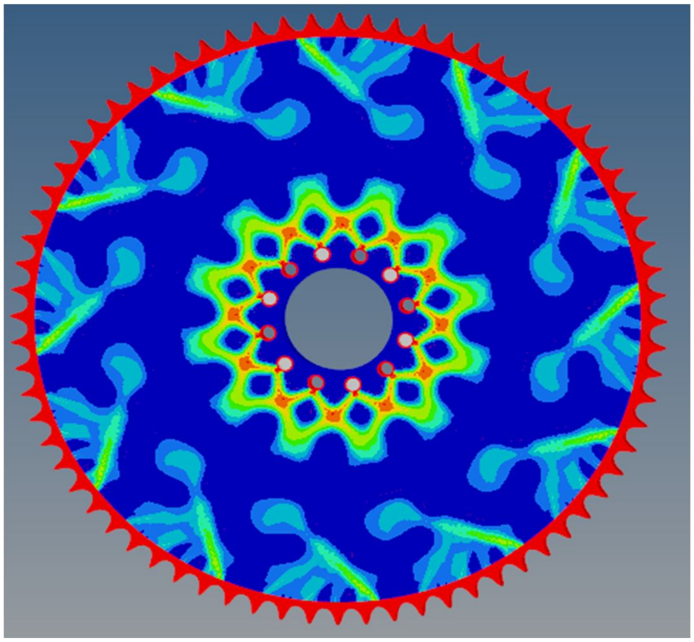

Fig. 3 Element density estimation

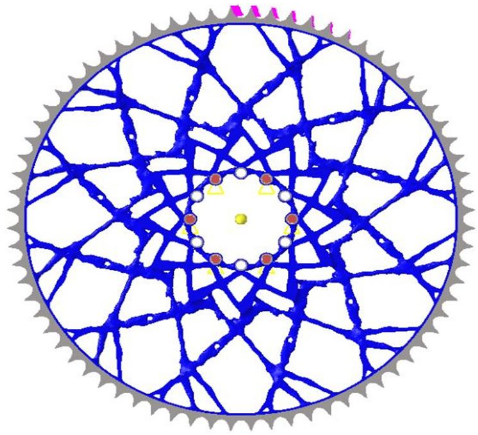

Fig. 4 Topology optimization results

E. Shape and Size Optimization

The pattern achieved through the topology optimization is further used as a reference to cut out material from the sprocket. The topology optimized geometry cannot be directly used for manufacturing, as it has a very irregular shape and size, this is why shape and size optimization need to be done. Shape and size optimization enhances the existing geometry with standard curves which allows even stress distribution and better stress flow. However, some weight gets added as this process is done.

The refined, manufacturable cad after shape and size optimization is as shown below:

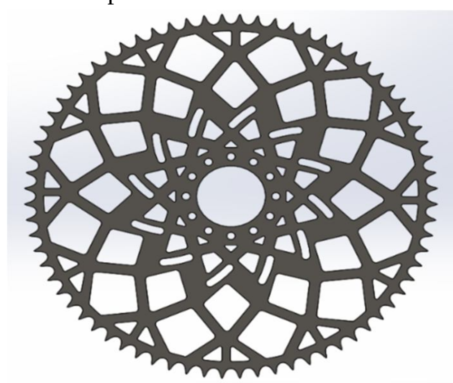

Fig. 5 Shape and Size Optimized geometry.

F. 3D Printing

Fused Deposition Modelling (FDM) is used to print the topology optimized sprocket. The CAD was scaled down by 50% for 3D printing. The finalized CAD is converted to stl file format for 3D printing compatibility.

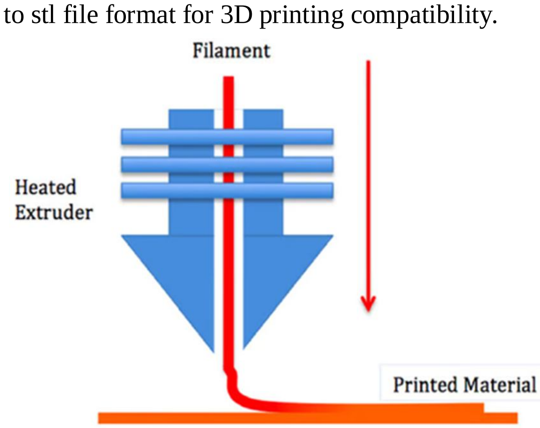

Fig. 6 Working of FDM printer.

The specifications are as mentioned below:
3D Printer: Creality ender 3
Material: PLA (Poly Lactic Acid)
Infill: 60%
Infill Pattern: Cubic
Layer Thickness: 0.2mm
Wall thickness: 1.6mm
Printing Temperature: 200 deg. C
Plate Temperature: 50 deg. C
Total thickness of sprocket: 3.875mm

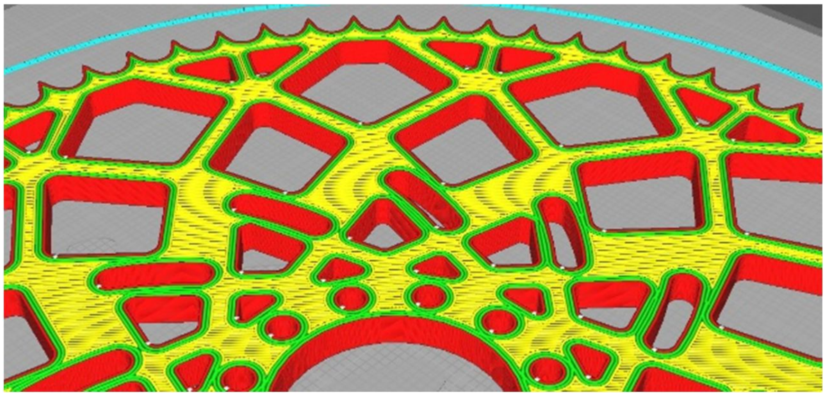

Fig. 7 – 60% Infill Pattern

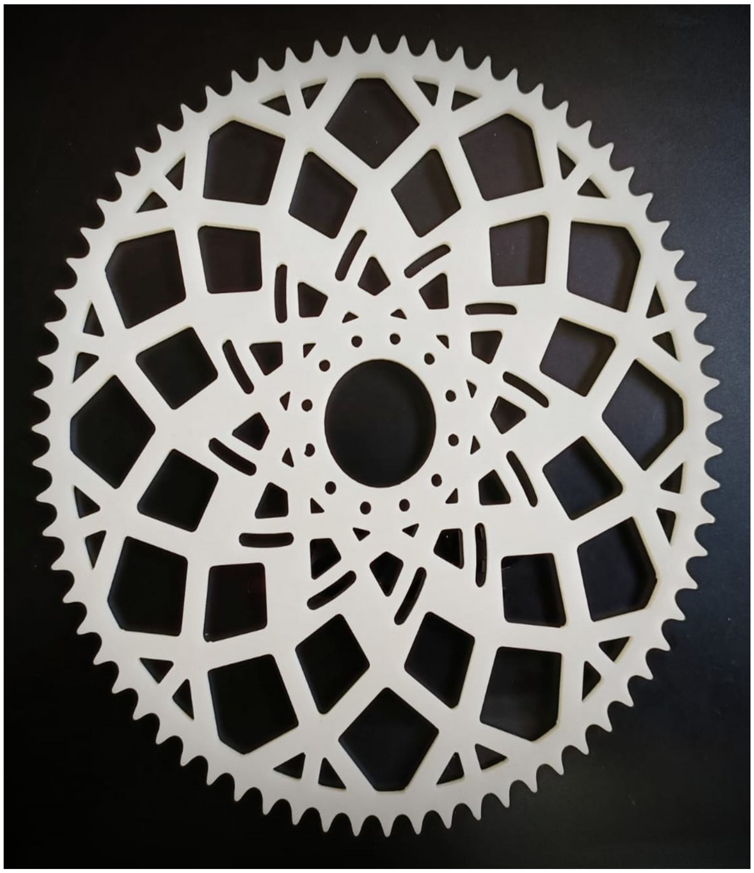

Fig. 8 Final 3D Printed Sprocket

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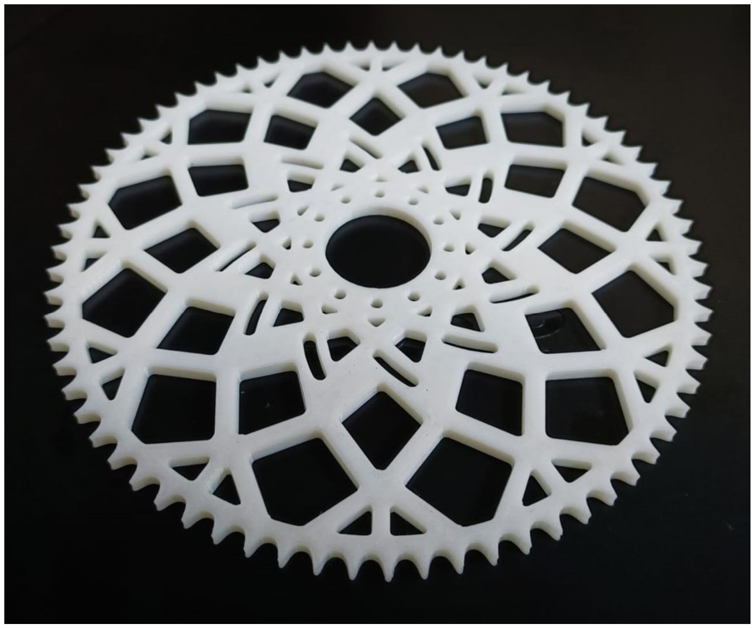


Fig. 9 Final 3D Printed Sprocket

IV. RESULTS AND DISCUSSIONS

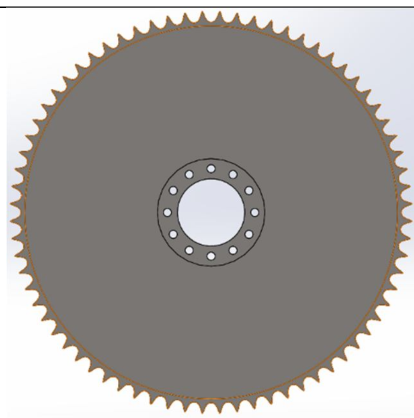
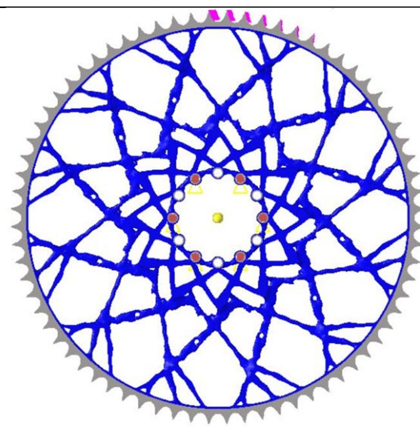
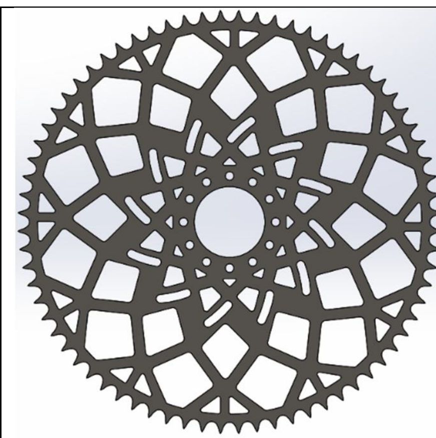
Geometry/ CAD			
Weight	3788.86g	1163.65g	2075.85g
Volume	485.7cc	145.71cc	266.13cc

TABLE I

Topology optimization is an excellent way for weight reduction without disturbing the structural integrity of a mechanical component.

V. LIMITATIONS

The only limitation and requirement t for a topology optimized part is that the boundary conditions should be accurate. That means failure to calculate accurate boundary conditions will lead to failure of part. The major limitation is that the topology optimized part may not sustain loads in different directions apart from what it’s designed for. So unexpected impact loading from other directions or different loading condition may lead to failure of the topology optimized part.

VI. FUTURE SCOPE

The sprocket can be further optimized by varying the chain pitch. The mounting position and the PCD of the bolts can be varied and iterated for further optimization.

VII. CONCLUSION

1) The weight of the sprocket after topology optimization has reduced by 45.2%.
2) The moment of inertia about the axis of sprocket has reduced by 47% after topology optimization.
3) The weight after Shape and Size Optimization has increased by 80%.
4) The overall weight reduction is 1.713 kg.
5) The reduced weight and moment of inertia leads to increased responsive performance and efficiency of the vehicle.

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