Design, Analysis and Development of composite matrix material upright of FSAE vehicle

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Abstract. Lightweight material Upright plays a very important role in improving the performance of the race cars i.e. lowering down the unsprung mass of the car and improving the ride and handling characteristics of the vehicle. Due to excellent characteristic of Nylon66 of reducing noise, wear rate, light weight, simple to design and manufacture and for the same, lightweight composite matrix material i.e. Nylon66 reinforced with Carbon fibre was used. The vehicle upright was designed in SOLIDWORKS in accordance to the Formula SAE (society of automotive engineers) rulebook. The static structural analysis was performed in ANSYS over the vehicle upright to find out the von-miss stress and total deformation. Final optimized design was manufactured using the technique of continuous fibre fabrication in order to get the desired strength of the Upright.

1. Introduction
The upright (automotive spindle) is a part of the wheel assembly of the vehicle which carries wheel hub, brake caliper and steering arm to the chassis of the vehicle. The upright is attached to the chassis of the vehicle through upper and lower wishbones through ball end joints. During dynamic condition upright experience many forces due to road tire interaction hence it is necessary for the upright to be sufficient strong to encounter those forces [4-6]. Conventional automotive spindles are manufactured by various processes like casting which requires making expensive moulds. This can be easily overcome by using the process of 3D printing. We have used the concept of additive manufacturing which enables manufacturing of components to their nearest net-shape. The process used for making the part here is FDM using thermoplastics. FDM uses specialized 3D printers to produce strong, durable and dimensionally accurate components. Filament fused deposition (FDM) is an additive manufacturing technique which uses carbon fiber, Kevlar, glass fiber and other additive as reinforcement material along with the thermoplastics. The FDM process regularly uses a persistent polymer fiber as a feed-stock material. The polymer fiber is feed into an extruder and is heated to a semi fluid state, empowering it to go through a heated extruding opening where it is intertwined set up on a print surface. And in order to improve the mechanical properties i.e. high strength to weight ratio, tensile strength etc. of the printed polymer addition of the reinforcement is done along with layer of polymer material through another extruder simultaneously [1] [7]. Hence with gaining knowledge from the previous research study over FDM we have tried to develop our prototype.
2. CAD Model

Upright was designed using 3D modeling software SOLIDWORKS and analyzed using ANSYS workbench for the static structural condition i.e. von-mises stress, total deformation, stress flow. Numerous iterations were performed to get the final optimized model which can encounter various loading condition during dynamics of the vehicle. The parameters required as boundary condition are calculated through logical calculations. Figure 1 and figure 2 shows the front view and isometric view of the upright respectively.

![Figure 1. Front view.](image1)
![Figure 2. Isometric view.](image2)

3. Force calculations

3.1 Static Loads and Boundary Conditions

The parameters of the vehicle used for static analysis of the front upright are [4] [6]:

- Mass of car and driver=300kgs
- Weight distribution=35/65
- Height of center of gravity=350mm
- Wheelbase=1560mm
- Braking g’s=1.04g
- Wheel Rate=38.78 N/mm

3.2 Longitudinal Forces

These are the forces acting on the front upright when the car is accelerating or decelerating. We consider a scenario that the car applies brake to come at a stop and the weight transfer acts on front upights. The mass transfer during the braking has been calculated with the following equation:

\[
\text{Mass transfer} = (\text{mass of car and driver}) \times (\text{braking g’s}) \times (\text{center of gravity})
\]

Mass transfer= 70 kg = 686.7N. This force acts on both front uprights. The force is equally distributed and thus 343.35N force acts on each front upright.

3.3 Lateral Forces

This is the forces which act on the car while turning or cornering. This lateral force is basically the centrifugal force acting on the car while taking a turn. We consider the total centrifugal force acts
directly on the front upright (worse condition). The upright distributes the forces to its control arms (lower and upper). The centrifugal force is calculated by taking the following conditions:

- Speed while taking turn \( (v) = 19.8 \text{ km/hr. or } 5.5 \text{m/s} \)
- Turning radius of the car \( (R) = 4 \text{ meters} \)

\[
\text{Centrifugal force} = \frac{mv^2}{R}
\]

The total centrifugal force on the four control arms (two upper and two lower) = 2130.18N. Therefore, each control arm experiences a force of 532.54N while turning.

### 3.4 Load Transfer

While braking the front of the car dips and the load acts on the front uprights. The front load is distributed on the two uprights. We calculate the load transfer by the following formulae:

Front load \( (F_m) = 35\% \text{ of the total mass (mass of car and driver)} = 0.35 \times 300 = 105\text{kg} \)  

Force acting on front uprights due to load transfer \( = (F_m \times g) = 105 \times 9.81 = 1030.5\text{N} \approx 1031\text{N} \)  

Hence each front upright experience 515.5N forces.

### 3.5 Brake caliper mounting force

While braking the caliper exerts an upward force on the upright and downward force on the disc, which just means the brake is helping the bearings and spindle hold the upright up. The following data are needed to calculate the caliper mounting force:

- Braking torque = 88000Nmm
- Radius of mounting point = 78.89mm

Caliper force = \( \text{Braking torque/ radius of mounting point} = 1100\text{N} \)

### 3.6 Bump force

The damper or shock absorber reduces the magnitude of vibration in a car when it overcomes an obstacle by absorbing the force. The damper is attached to the lower part of the upright and thus the upright also experiences a part of the bump force. We take a condition when the car experiences a bump and the damper travel to be 40mm. We calculate the bump force by the following formulae:

Bump force = \( \text{(weel rate} \times \text{damper travel due to bump)} = 38.78 \times 40 = 1551.2\text{N} \approx 1560\text{N} \)

### 4. Material selection

The material chosen for the prototype was nylon-reinforced carbon fiber, which has high strength to weight ratio and fatigue properties than nylon reinforced with glass fiber and Kevlar. The material properties used for analysis taken from the previous research paper [1-2], as shown in table 1, for the analysis were as follows.

**Table 1.** Material properties of the nylon reinforced with carbon fibre.

| Material property         | Value     |
|---------------------------|-----------|
| Density                   | 1400 kg m^-3 |
| Tensile ultimate strength | 350 Mpa   |
| Young’s modulus           | 60 Gpa    |
| Bulk modulus              | 2.5 Gpa   |
| Shear modulus             | 2.72 Gpa  |

### 5. Boundary Condition

A circumstance was reproduced for the front uprights with full lockup of the stopping mechanism, which converted into a force of 1100N applied to the caliper mounting surfaces. Lateral load, load
transfer and longitudinal load of 2130N, 1031N and 686N respectively was applied at upper and lower wishbone ball end joint. The front uprights also experienced a bump load of 1560N which is transferred to the chassis through damper. A fixture was set up at bearing surface of the upright. Figure 3 shows all the force acting on the upright, simultaneously, so that the upright can be tested for the worst case scenario.

![Figure 3. Loading conditions.](image)

5.1 **Static structural result.**
During braking, throttling and steering simultaneously the upright experiences maximum forces, so the upright is designed for a condition in which the car corners while braking and also encounters a bump. So all the before mentioned forces act simultaneously on the upright. The maximum stress and total deformation were obtained as 57.95N and 0.05mm respectively. Figure 4 and figure 5 depicts the stress flow and deformation flow path respectively.

![Figure 4. Equivalent stress.](image)

![Figure 5. Total deformation.](image)

6. **Experimental**
6.1 **The mark one composite 3d printer**
The specialized 3D printer called Mark forged mark one was used, it uses two nozzle deposition techniques to deposit the thermoplastic and the additives on the base layer by layer leading to final dimensions of the product. Both the materials, thermoplastic and additives, are fed through separate
spools to respective nozzles after being heated to a fused state [1]. Mark one offer a variety of orientations in which the layers can be laid, each providing a varying strength. With the reinforcement of carbon fibres, the two possible orientations are Concentric and Isotropic. The carbon fibre printed prototype has a filament thickness (0.35 mm) and is printed in layers of 0.125 mm, therefore only 216 layers were used to fabricate this composite.

6.2 Fibre pattern

The first method lays down the layers in a spirally inwards manner and the later one allows the fibres to be laid at angle specified (30, 45,135). The orientation of fibres plays a crucial role in determining the overall mechanical properties of the part. This can be carried out in software called EIGER that is purposely designed for parts to be 3D printed by Mark one printer. The software allows customizing the part layer by layer that ultimately allows us to change the fibre orientations in each layer. Our part comprised of 216 layers to be exact. We selected both concentric and isotropic orientation having a combination pattern of two concentric layers together for the first two layers and then next two isotropic layers, so on up to the last layer. As shown in figure 6, the 'Concentric' fibre design comprises of a spiral shaped laydown, fibre strands start at the external edge of the part and wrap inwards toward the parts place, shaping annular rings. The user can define the number of these rings, with 2 rings picked for fabrication of our prototype [1-3]. The Isotropic fibre design, shown in figure 7, comprises of standard parallel lines, with zones drained of fibre being filled by nylon before the subsequent layer is printed. The thermoplastic used was ONYX and the reinforcement was carbon fibres, having a full solid infill.

Figure 8 is an in-process image of the part, manufactured layer by layer. The amount of carbon fibres was deliberately increased in the areas having more stress concentration and was limited to minimum possible amount in low stress areas, in order to reduce the weight and overall cost of the part. The total weight of the part was 168g. The final printed part is shown in figure 9.

![Figure 6. Concentric orientation of carbon fiber.](image1)

![Figure 7. Isotropic orientation of carbon fiber.](image2)
7. Conclusions
An upright is the crucial component, as it has to encounter various forces when the vehicle is in dynamic condition so it is necessary for the upright to have desired strength and rigidity to withstand those forces. Nylon-66 reinforced with carbon-fiber has proved to be capable of enduring all loading conditions and helps reducing the unsprung mass of the vehicle by a substantial amount. The additive manufacturing method makes the material suitable for production in automobile industry rather using aluminum alloys for manufacturing of wheel hubs. They will prove to be effective in increase in performance of vehicles in motorsports of all types. The forced acting on the upright are calculated and the design made can be fabricated by additive manufacturing using mark one composite 3D printer thus reducing the weight of the upright roughly up to 53.3%. Hence, this reduction in weight leads to reduction in unsprung mass of the vehicle, which therefore increases the performance to weight ratio of the car significantly.

8. References
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