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# Analysis of a Lightweight Brake Master Cylinder for Formula Student Vehicle

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## Abstract

*The function of a Braking system is to bring the vehicle to rest by converting the kinetic energy of the vehicle into heat energy, which is then dissipated into air. This Energy conversion is facilitated by displacing the caliper pistons equipped with brake pads and pressing them against the surface of the brake rotor. Hydraulic fluid, which is an incompressible fluid, serves as a medium in displacing the pistons. A brake master cylinder is used to generate hydraulic pressure by taking the input from the brake pedal, via a pushrod. The paper explores the design and analysis of a brake master cylinder tailored for a formula student vehicle. It is a single-circuit spherical bearing mounted type master cylinder, equipped with a bore diameter of 5/8". The objective was to design a compact master cylinder that is lighter in weight compared to Original Equipment Manufacturer (OEM) master cylinders. The design was made using 3D CAD Modelling software and Finite Element Analysis (FEA) was applied to conduct the structural analysis. Two Aluminium grades, Al 6061-T6 and 7075-T6 were finalized on the basis of their strength-to-weight ratio and thermal conductivity. Results showed that Al 7075-T6 had a higher FOS of 4.3 compared to 6061-T6. Hence, Al 7075-T6 was selected as the material for the master cylinder and the design also showcased a weight reduction of 39.89% as compared to an OEM master cylinder.*

**Major Findings:** *Six materials, namely Aluminium Alloys 6061-T6 and 7075-T6, Gray Cast Iron, AISI 316, Acrylic, and Acetal Copolymer were evaluated for the master cylinder using Finite Element Analysis (FEA). Based on a comprehensive analysis, Aluminium Alloy 7075-T6 emerged as the most suitable material for developing the master cylinder. This selection resulted in a weight reduction of 39.89%.*

**Keywords:** *Bore Diameter, Finite Element Analysis, Hydraulic Brake, Master Cylinder*

## Abbrivations

$Fc$ = Clamping Force
$Fi$ = Input Force
$Am$ = Area of Master Cylinder Bore
$Ac$ = Area of Caliper Pads
$Pb$ = Burst Pressure
$Ps$ = Pressure in System
$C$ = Spring Index
$K_w$ = Wahl's Stress Factor
$\tau_{max}$ = Max Tensile Strength
$F$ = Force
$\delta$ = Spring Deflection
$k$ = Stiffness Factor
$G$ = Modulus of Rigidity
$Y$ = Tensile Strength
$t$ = Thickness

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## 1.0 Introduction

A master cylinder plays a crucial role in the braking system. The Formula Student vehicle is equipped with a twin-circuit master cylinder setup. Both the front and rear brakes have an independent hydraulic circuit, each equipped with a master cylinder. The Brake pedal is equipped with a balance bar to adjust the brake bias. The master cylinders are actuated, via the balance bar, when the pedal is pressed[1]. A diagonal split system involves additional tubing and connections compared to a front-rear split system[2]. In Tune To Win, Carroll Smith explains brake force adjustments for the front and rear brakes and how brake balance can be fine-tuned with the help of a balance bar[3]. In Brake Handbook, Fred Puhn has discussed about the working of the master cylinders in detail[4]. The weight of the brake assembly acts as an important factor in a formula student vehicle. Maximizing the vehicle's performance comes down to strict weight reduction. Weight reduction will also boost the vehicle's handling and performance. A lighter assembly will result in a lesser contribution to load transfer and quicker lap times. Thus, weight reduction is essential in braking system components, like brake pedal and master cylinder. Rani, B. Sandhya *et al.*,[5] have shown a detailed analysis of the design and performance evaluation of a plastic master cylinder, showcasing the potential benefits of lightweight materials in enhancing vehicle efficiency. Weight reduction in a brake system can be achieved if the structural components and master cylinders are made using aluminum[6,7]. Rao, K. Prahalada *et al.*,[8] discussed the master cylinder, a vital component of the hydraulic brake system in vehicles. Their study also includes a CAD model using 3D modeling software and FEA to optimize the shape and analyze stress and deformation under different pressure conditions. This paper contains the design of a master cylinder for a high-performance FS vehicle. The identification of diameter and thickness are important considerations when building the master cylinder body[9]. Absorbing the mechanical shocks in the cylinder generated during braking is necessary. Cylinder cushioning helps in preventing damage to the cylinder. Cylinder cushioning is a system included to decelerate and halt the motion of the cylinder at the final position of its stroke[10-13]. The compensating hole is a crucial structural component in regulating the brake master cylinder's reservoir and pressure chamber[14]. AP Racing 7855 series Master cylinder was used as a reference for the design[15]. The aim was to design a master cylinder with reduced weight compared to a OEM master cylinder, and that could sustain high pressure range.

## 2.0 Material Selection

Master Cylinder for high-performance vehicles undergo a huge amount of pressure up to 150 bar. Therefore, selecting a suitable material that can sustain high values of pressure is necessary. A wide variety of materials were considered, ranging from plastics to metals. Aluminium Alloys 6061-T6 and 7075-T6, Gray cast iron, AISI 316, Acrylic, and Acetal Copolymer were the six materials that were shortlisted based on their mass density, strength, and availability for master cylinder design. When selecting the material, the key material considerations included a high strength-to-weight ratio, easy machinability, widespread availability, and satisfactory thermal conductivity. According to these considerations, the above listed six materials were compared on the basis of their strength-to-weight ratio and their Thermal Conductivity. The comparison of Yield Strength vs Mass Density between these six materials is shown in Figure 1 and mass density vs thermal conductivity in Figure 2.

From Figure 1. It can be concluded that both aluminium alloys have the highest strength-to-weight ratio compared to other shortlisted materials.

It can also be concluded from Figure 2. that both the Aluminium alloys possess the highest thermal conductivity and are lightweight at the same time in comparison to other shortlisted materials.

Thus, Aluminium alloys 6061-T6 grade and 7075-T6 grade were selected due to their machinability, high tensile strength, corrosion resistance, and low density resulting in lightweight design.

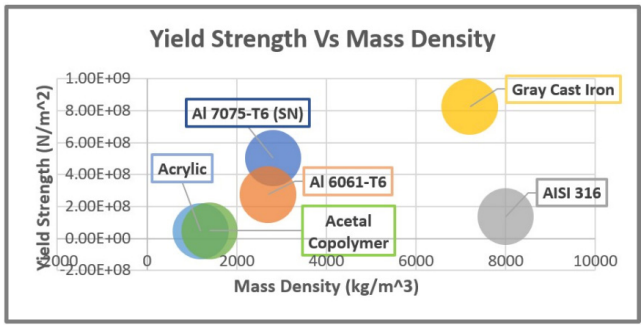



**Figure 1.** Yield strength vs mass density.

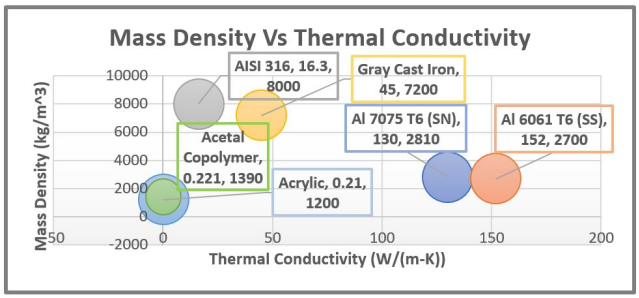



**Figure 2.** Mass density vs thermal conductivity.

# 3.0 Mathematical Analysis

## 3.1 Bore Diameter Selection Calculations

**Table 1.** Input parameters for calculating the bore diameter

| Parameter | Magnitude |
|---|---|
| Pedal ratio | 1.4 |
| Master cylinder inclination (degree) | 70 |
| Master cylinder inclination (radians) | 1.222 |
| Radius of rotor (m) | 0.079 |
| Coefficient of friction between pads and rotor | 0.55 |
| Force applied by the driver (kg) | 55 |
| Deceleration | 1.6g |
| Brake bias | 0.5 |
| Input force Fi (N) | 1104.277 |
| Required front brake torque (N-m) | 457.806 |
| Caliper piston area ($mm^2$) | 3925 |
| Rotor diameter (mm) | 158 |

$$Required\ Stopping\ Force = \frac{Required\ Brake\ Torque}{Radius\ of\ Rotor} = 5795.01N \quad (1)$$

$$Fc = \frac{Required\ Stopping\ Force}{Coefficient\ of\ friction} = 10536.38N \quad (2)$$

From Pascal's law, the area of the master cylinder bore may be obtained from,

$$\frac{Fi}{Am} = \frac{Fc}{Ac} \quad (3)$$

Therefore, the diameter of the bore required was 23.99 mm.

**Table 2.** Yield strength of aluminium alloys

| Parameter | Material | |
|---|---|---|
| | Al 6061-T6 | Al 7075-T6 (SN) |
| Yield strength (Pa) | 275E+06 | 505E+06 |

## 3.2 Casing Design Calculation

Burst Pressure is calculated to validate the Casing Design[16].

*Burst Pressure* (Pb) = 0.875 (2*Y*t/D) (4)

D = 23.01mm and t = 7.13mm

For, Al 6061-T6 (SS)

*Pb* = 1492.62 *bar*

For, Al 7075-T6 (SN)

*Pb* =2740.99 *bar*

Pressure (Ps) in the system is calculated to be 55.8 bars. Since, Ps < Pb in both cases, therefore the casing design is safe for both the materials Al 6061-T6 and Al 7075-T6 (SN).

## 3.3 Spring Design Calculation

Number of turns required for the spring is calculated[17].

Spring Material = Spring Steel (*2D series)

Ultimate Tensile Strength = 2000 $N/mm^2$

Outer Diameter (OD) = 7mm and Inner Diameter (ID) = 3mm

Diameter of coil (d) = 2mm and Centre Diameter (D) = OD – d = 5 mm

$$C = D/d = 2.5 \quad (5)$$

$$k_w = \frac{4C-1}{4C-4} + \frac{0.615}{C} = 1.7 \quad (6)$$

$$\tau_{max} = k_w \times \frac{8FD}{\pi d^3} \quad (7)$$

$$k = \frac{F}{\delta} = 36.95 \quad (8)$$

$$number\ of\ turns = \frac{Gd}{8C^3k} = 32\ turns \quad (9)$$

### 3.4 Seal Calculation

First, we calculate the inner diameter of the O-ring using the formula,

$$O-Ring\ ID = \frac{Groove\ Diameter}{\%\ of\ stretch + 1} \quad (10)$$

## 4.0 Modelling of Components

The entire design was prepared using 3D CAD Modelling on SOLIDWORKS 2022-23. Numerous iterations of the components were created to achieve a very lightweight and durable design. The entire assembly of the final design is shown in Figure 3.

The casing, pushrod, end cap, and piston cup are designed using Al 7075-T6 (SN) to withstand high pressure. The casing generates pressure and accommodates the components, as shown in Figure 4. (a) The pushrod accepts input force from the brake pedal, generates hydraulic pressure, and pushes the piston, as shown in Figure 4. (b).

The end cap encloses the casing, guides the pushrod, and accommodates seals, as shown in Figure 5. (a) The piston cup, made of EPDM 60, is mounted on the pushrod and expands to act as a seal, with its CAD model shown in Figure 5. (b) The guide pin holds the spring in position during actuation of the pushrod. The design is made from SS 316 and the CAD model is shown in Figure 5. (c) The function of the spring is to bring the piston back to its initial position when the brake pedal is released. The design is made from Spring Steel and CAD model is shown in Figure 5. (d) The washer, made of SS 316 as shown in Figure 5. (e) is placed between the piston cup and piston to allow fluid flow only during brake pedal retraction. A shim, designed using Al 6061-T6 as shown in Figure 5. (f) fills the gap and prevents contact between the piston and end cap.



**Figure 3.** CAD model of full assembly.

## 5.0 Finite Element Analysis

To calculate the Deformation, Von Mises stress, Strain, and the Factor of safety values of the master cylinder on the application of pressure inside the compression chamber, a static structural analysis was performed using FEA. The software used was ANSYS 2023R2. The required results were calculated for 2 materials, Al 6061-T6 (SS) and Al 7075-T6 (SN) respectively, and were later compared to find which grade of aluminium is more suitable to construct the master cylinder. A 3D CAD model of the master cylinder was created on SOLIDWORKS 2022 and the geometry was later imported to ANSYS 2023 R2 to carry out the static structural analysis on application of Pressure. The geometry of the Master Cylinder is shown in Figure 6. For the analysis, a tetrahedral mesh was implemented for its geometric flexibility and accuracy in calculating stress distributions under high-pressure loads. The mesh generated was a fine mesh where the total number of elements and nodes respectively were 36307 and 63001 as shown in Figure 7.

To conduct the static structural analysis of the master cylinder, a few boundary conditions were applied to the geometry. The mounting point of the master cylinder was set as fixed support as shown in Figure 8. And a pressure of 150 bar was applied inside the compression chamber in the normal direction to the surfaces as shown in Figure 9.



**(a)** **(b)**

**Figure 4.** CAD model of **(a)** casing **(b)** pushrod.

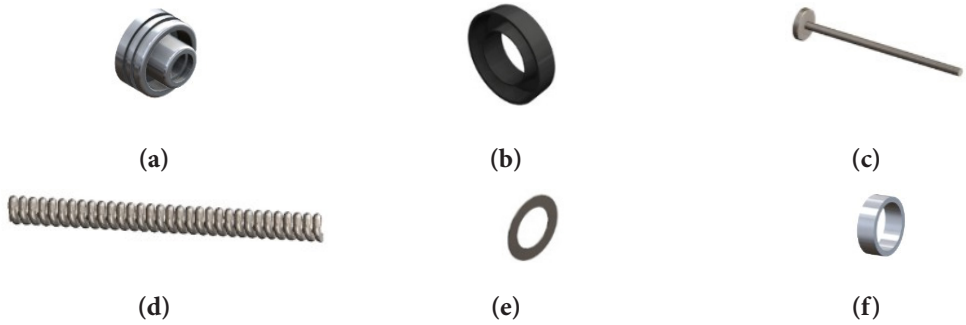



**Figure 5.** CAD model of **(a)** end cap **(b)** piston cup **(c)** guide pin **(d)** spring **(e)** washer **(f)** shim.



**Figure 6.** Geometry of the master cylinder.

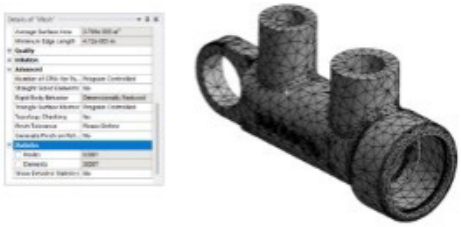


**Figure 7.** Meshed geometry.



**Figure 8.** Boundary condition applied to the geometry.



**Figure 9.** Boundary condition applied to the geometry.

## 6.0 Result and Discussion

FEA was implemented and results were obtained for the deformation, von-mises stress, equivalent strain, and FOS values were obtained for both grades of aluminium.

### 6.1 Deformation

Figures 10 and 11 shows the deformation results for both grades of aluminium on the application of pressure. The maximum deformation for Al 6061-T6 and Al 7075-T6 were found to be 3.265E-05 m and 3.135E-05 m respectively.

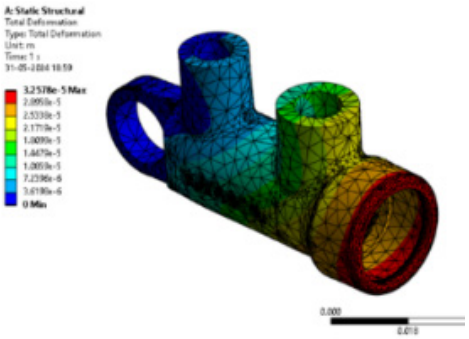


**Figure 10.** Deformation results for Al 6061-T6.

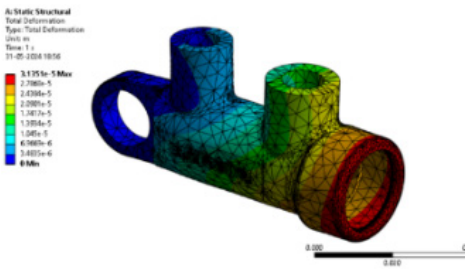


**Figure 11.** Deformation results for Al 7075-T6.

## 6.2 Stress

Figures12 and 13 shows the Von-mises stress results for both grades of aluminium on the application of pressure. The maximum stress for Al 6061-T6 and Al 7075-T6 were found to be 1.1682E+08 Pa and 1.1680E+08 Pa respectively.

## 6.3 Strain

Figures 14 and 15 shows the Equivalent Elastic strain results for both grades of aluminium on the application of pressure. The maximum strain for Al 6061-T6 was 0.0016943 m/m and for Al 7075-T6 was 0.0016305 m/m.

## 6.4 FOS

Figures 16 and 17 shows the Factor of Safety results for both grades of aluminium on the application of pressure. The maximum FOS for Al 6061-T6 was 2.354 and for Al 7075-T6 was 4.324.

From Table 3, Al 6061-T6 exhibits higher deformation, Equivalent Strain, and Von Mises stress compared to Al 7075-T6. The Factor of Safety (FOS) for Al 7075-T6 is superior to Al 6061-T6. Therefore, Al 7075-T6 is the preferred material for master cylinder construction.

Figure 18 shows that the weight of the AP Racing 7855 series (5/8”) master cylinder was 170g. Figure 19 shows that the weight of the designed master cylinder was

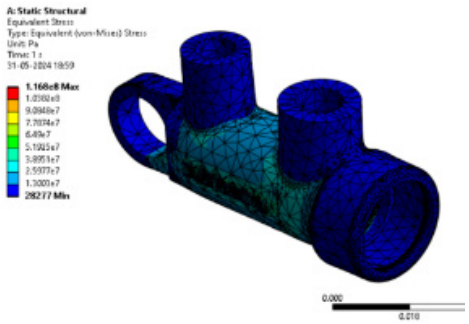


**Figure 12.** Stress results for Al 6061-T6.

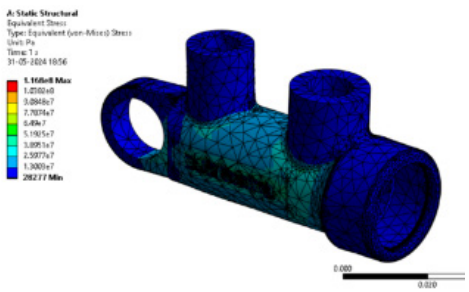


**Figure 13.** Stress results for Al 7075-T6.

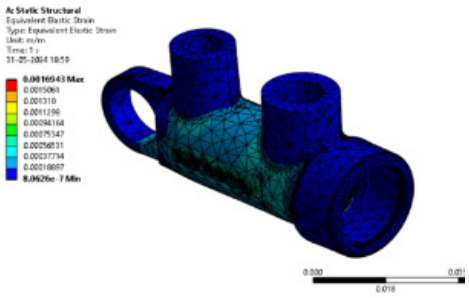


**Figure 14.** Equivalent Strain results for Al 6061-T6.

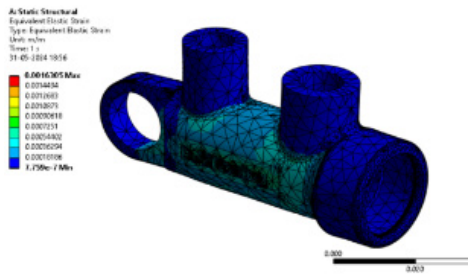


**Figure 15.** Equivalent Strain results for Al 7075-T6.

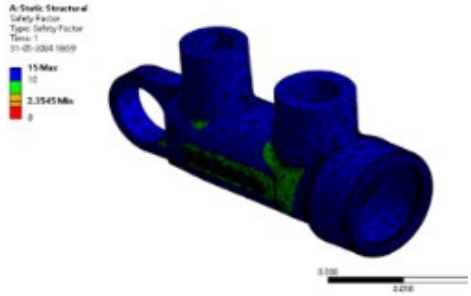


**Figure 16.** Factor of safety results for Al 6061-T6.

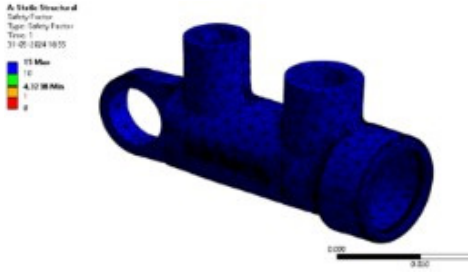


**Figure 17.** Factor of safety results for Al 7075-T6.

**Table 3.** Comparison of results

| | Al 6061-T6 | | Al 7075-T6 | |
|---|---|---|---|---|
| | **Minimum** | **Maximum** | **Minimum** | **Maximum** |
| Deformation (m) | 0 | 3.265E-05 | 0 | 3.135E-05 |
| Von-Mises Stress (Pa) (Pa) | 30273 | 1.1682E+08 | 28277 | 1.1680E+08 |
| Strain (m/m) | 7.589E-07 | 0.0016943 | 7.759E-07 | 0.0016305 |
| Factor of Safety | 2.354 | 15 | 4.324 | 15 |



**Figure 18.** Weight of AP racing MC.

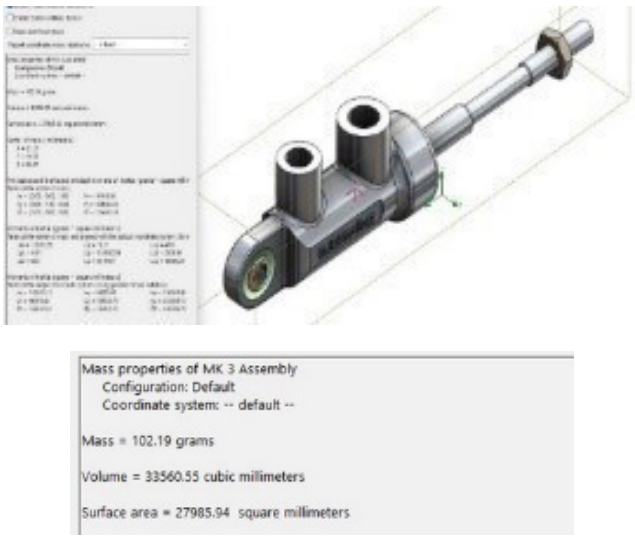



**Figure 19.** Weight of designed MC.

102.19g. Therefore, an overall weight reduction of 39.89% was achieved with this design.

## 7.0 Conclusion

In this study, the design process of a high-performance master cylinder for a formula student vehicle was successfully executed. Meticulous material selection, based on desired material properties was done. Leveraging 3D CAD modeling software, the design calculations were translated into a precise 3D model of the master cylinder. FEA of the finalized design was performed using FEA software for 2 grades of aluminium to determine the more suitable material leading to an optimum design. Comparative analysis revealed that Al 7075-T6 emerged as the optimal material choice for constructing the master cylinder. The weight of the design was compared to the weight of the OEM master cylinder from AP Racing with matching bore diameter specifications. The outcome showcased a remarkable 39.89% weight reduction in overall weight, affirming the efficacy of lightweight design approach.

## 8.0 Author Contribution

Abstract, Darshit Rathod and Vinayak Khatawate; Introduction, Darshit Rathod; Material Selection, Darshit Rathod; Mathematical Analysis, Darshit Rathod; CAD Model, Darshit Rathod; FEA, Darshit Rathod; Result and Discussion, Darshit Rathod; Conclusion, Darshit Rathod; writing—original draft preparation, Dr. Vinayak Khatawate, Dr. Hari Vasudevan and Darshit Rathod; writing—review and editing, Dr. Vinayak Khatawate and Dr. Hari Vasudevan; Supervision, Dr. Vinayak Khatawate and Dr. Hari Vasudevan. All authors have read and agreed to the published version of the manuscript.

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