Assessment 1

Design of a Compact Rear Brake Calliper for QUTM FSAE EV Car

Project Background and Literature Review

EGH420 – Mechanical Systems Design

Group M5

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1 Introduction

Braking systems were developed to facilitate the control of automotive vehicles allowing a means to slow and stop a vehicle. Despite the extreme technological advancement and innovation in the automotive industry, the concept and history of brake systems remains relatively tame. Traditionally, brakes slow a vehicle down through the conversion of its kinetic energy to heat using kinetic friction between two surfaces [1]. Disc brakes were first patented in 1902 by William Lanchester however, they were not practical until the mid-1950s when lowered cost and widespread uptake saw them replace drum brakes on a wide scale [2]. Disc brakes provided significant improvement in thermal efficiency and heat dissipation, reducing brake fade and allowing for more compact, lighter weight designs [2]. In a hydraulic brake system, driver input actuates a master cylinder containing brake fluid. The fluid pressure is transmitted to the brake calliper via fluid lines connected to the master cylinder where it exerts a force on the brake pistons, displacing them from the calliper body. The pistons apply a thrust force to brake pads contained within the calliper, pressing opposing pads onto the brake rotor. A brake torque is generated on the wheel which the driver can modulate by varying the force on the brake pedal.

Additions to some brake systems may include automated braking systems (ABS), regenerative braking or brake bias adjustment. The QUT Motorsport team's Formula SAE (FSAE) electric vehicle (EV) utilises disc brakes on all four wheels actuated by two separate hydraulic circuits. The design of this system encompasses several significant design factors including braking surface area and material, heat dissipation, cost, strength, weight, and size constraints. The purpose of this project is to design a new, custom rear brake caliper for the QUT Motorsport electric racecar in the FSAE competition. The goal is to design a brake caliper which can fit within the envelope formed due to the electric motors on the rear axle. Currently there are no off-the-shelf caliper systems which can offer the necessary performance in the desired form factor. The closest current braking system which could be implemented is the Wilwood GP200, however areas of this braking system must be improved to meet the requirements for the QUTMS EV, more specifically, the mechanical packaging. As the form factor will change, the thermal performance and stopping ability all need to be evaluated and improved using appropriately detailed analysis techniques. Currently, the Wilwood GP 200 calipers have been selected for use on the front wheels. An example of the brake caliper components to be modified/designed as part of this project is shown in figure 1. It is of paramount importance that an effective brake caliper is implemented for diver safety and high performance of the car.

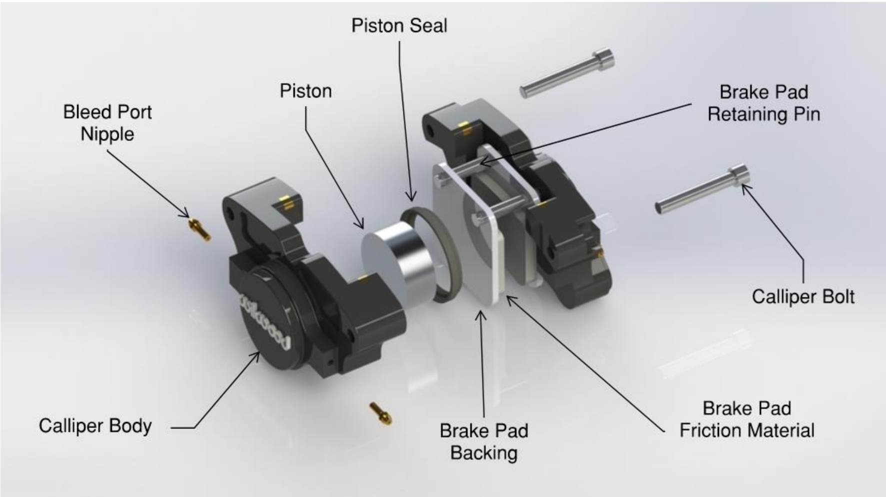

Figure 1 - Exploded view of Wilwood GP200 calliper by Coloma C. L. [3] with key components indicated.

1.1 Project Definition and Scope

The aim of this project is to undertake a full design and analysis of a custom brake calliper to be used by QUT Motorsport in their FSAE EV. The scope of design will extend as far as the brake calliper assembly including the calliper body, pistons, seals, fasteners, shims, brake pads and mounting hardware as indicated in figure 1. The calliper will be designed to interface with the existing hydraulic system and will be constrained as such. Consideration will be given to the line pressure capabilities of the current system, which uses a front/rear split system and bias bar, as this will influence design parameters. The interfaces that will need to be considered include attachment to the larger hydraulic circuit, the brake rotor and the calliper mounts as shown in an example layout in figure 2. Influencing factors including weather, driving conditions, vehicle requirements, driver interaction and maintenance will be considered in the design. Off-the-shelf components, such as brake pads, will be selected and justified where deemed appropriate to reduce cost and provide readily available spare parts compatibility. The calliper body and pistons will require design and analysis to optimise their function to the specific structural and thermal requirements of this application.

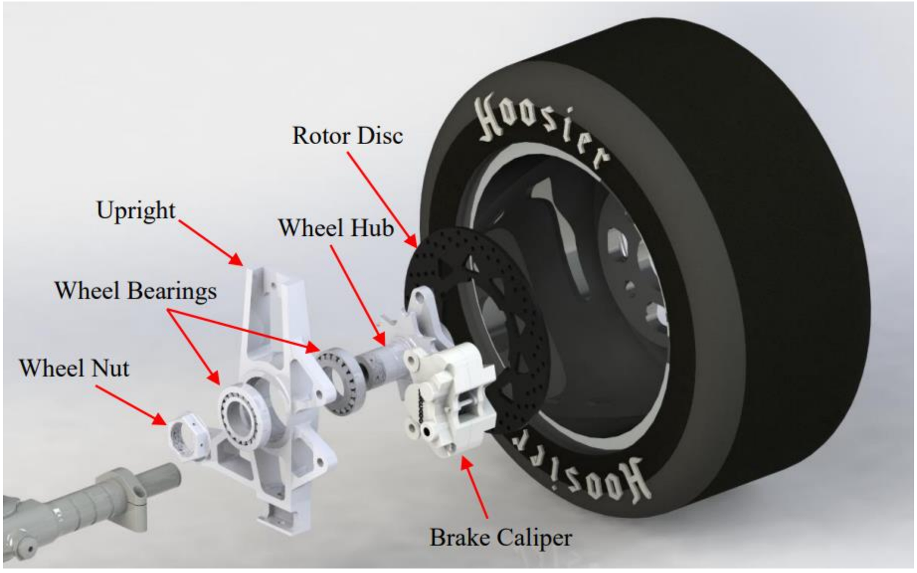

Figure 2 - Example layout of brake calliper interface with wheel/upright components and associated nomenclature [4].

Outside the scope of design is any option that would require re-design or modification of other components or systems on the car. The brake calliper shall be designed to fit in the available space on the vehicle and utilise standard mounting points with threaded fasteners. The brake calliper must fit within the 246 mm diameter rim and be able to operate the brake pad between the 141mm to 184 mm diameter disc rotor. The calliper should bolt to the two 8mm bolt holes which are 63.5mm spaced apart with a 146mm diameter spacing from the centre of the drivetrain assembly. The calliper space available on the outside of the rotor is at a maximum in the midpoint of the wheel with an allowance of 66mm wide and 29mm deep to allow the wheel spokes to clear the calliper. The calliper must bolt between the 18.8mm space available from the mounting bolt points and the back side of the rotor and then has a space 45mm by 45mm which the calliper must fit to allow clearance for the drivetrain motor. Detail drawings taken from the QUTMS EV assembly model are included in appendix A.

The design will assume no assistance from regenerative braking so is to account for the most extreme stopping requirement of the fully laden vehicle at race speeds. The interface with the brake rotor shall consider the standard brake rotor used by the QUT Motorsport vehicle and the hydraulic line shall securely attach at the calliper body. The brake rotor has an outer diameter of ~185 mm and a pad contact width of ~21 mm. Manufacturing data will be communicated as a project deliverable;

however, manufacture of the component and physical testing/validation is outside the project scope. This limits the certainty of function of the component to analytical analysis methods (FEA, material data, etc.)

The brake calliper design must integrate with other existing vehicle systems and comply with all relevant Formula SAE rules on braking systems. The design shall also be suitable for use on left and right sides of the car with identical performance characteristics in each case. Mounting points of the calliper are fixed; however, adapters may be used if appropriate. The required clamping force shall be calculated by analysing the stopping requirements of the car. Formula SAE 2020 rules state that the brake system must be at least capable of locking all four wheels. The rules also state that all fasteners used in the brake system are considered critical and must comply with, at minimum, one of the following standards:

- SAE grade 5
- Metric Grade 8.8
- AN/MS Specifications

The effective design will involve determination and implementation of key design parameters applicable to the formula SAE car and the bounding rules. Key technical specifications were identified and are listed below. These will form part of the final design justification:

- Calculation of the required maximum brake force to be exerted by the piston/s based on vehicle requirements and FSAE rules.
- Calculation of required piston size/number of, with consideration of the fluid pressure required to achieve the desired force.
- Stress analysis under maximum static and cyclic loads.
- Specific material selection for each component.
- Nomination of all off-the-shelf components to form part of the working calliper assembly. This includes justification of the brake pad performance with respect to the operating conditions.
- Specification of all fastener sizes.
- Measures to mitigate heat transfer from the braking interface to the brake calliper and brake fluid.

A detailed 3D model of the brake calliper assembly and all individual parts will be developed to ensure proper fit and verification of the design. ANSYS Workbench software will be used to conduct a structural analysis of strength and deflection. Thermal analysis of the calliper body and each critical component will be undertaken analytically (or numerically if deemed appropriate). Fatigue life of the components will be assessed using ANSYS also. Upon completion of the calliper design, detailed manufacturing drawings will be produced including an assembly, individual parts, bill of materials and exploded view.

1.2 Design Goals / indicators of success

The following list outlines the goals of this design project with respect to the function of the brake calliper design, its manufacture and servicing requirements:

- Cost
    - The overall cost is to be comparable to current brake system components used on the car. Teams are scored on overall cost so this should be minimised where possible.
    - If bespoke parts are required such as rotor mount, calliper mount, reduction in manual labour will be considered regarding manufacturing processes.

    - Use of readily available replacement (off-the-shelf) or easily manufactured parts i.e., Pads, mounting bolts, guides, shims, seals, dust boots.
- Safety requirements
    - Brake calliper integrates with the brake system such that it aligns with requirements of FSAE braking standards (T.3 – T.3.1.11).
    - Brake callipers must be able to stop the vehicle in the event of an emergency-unpowered/stop the vehicle with full race weight (wet weight with driver/all fluids).
    - The brake effectiveness should remain unchanged in extended use cases such as the FSAE endurance event.
- Function
    - Brake calliper to be operated through the brake pedal with the calliper connected to the dual master cylinder and have a balance bar or brake bias controller.
    - Must generate compressive force on the brake pads using hydraulic fluid pressure generated by the existing braking system used on the QUT formula SAE EV.
    - Mounting position of the calliper must be adjustable to facilitate fine tuning of the brake pad position (off the track) relative to the brake rotor.
    - Loaded material shall resist deformation throughout the range of temperatures for all events (short use through to endurance) and possible track conditions.
    - Weight of entire rear brake calliper assembly should be minimised whilst still meeting safety requirements and maintaining robustness.
    - In the event of debris from racetrack or other vehicles contacting the calliper assembly / wheel the calliper should have sufficient strength and bracing to resist damage that could cause a critical failure such as becoming loose or forming a leak.
- Operation
    - Shall be able to operate in hot or cold environments without any changes to brake pressure and be resistant to leaks through the seals.
    - As the FSAE is a performance application DOT 4, 5 or 5.1 brake fluid will be used as higher dry/wet boil points are expected in a race application due to higher speed and smaller size of the fluid system. Materials will be compatible with DOT 4, 5 or 5.1 fluid.
    - Full locking of the rear wheels should be achievable before full 2000N application pressure (with no brake bias adjustment).
    - Calliper should be capable of locking the wheel before brake pedal reaches end of the stroke in all possible conditions.
- Maintenance
    - Brake pads should be able to be replaced with only calliper bolts/clevis pin & retainer removed and brake rotor still in place
    - Calliper should be able to be removed with only the wheel removed from the vehicle with metric bolts and common hand tools (wrenches, screwdrivers, circlip pliers)
    - Brake piston/s and all seals must be serviceable using off-the-shelf tools.
    - Fluid seals and brake pads must be off-the-shelf items, readily available to the QUT team unless otherwise justifiable.
    - The calliper must feature standard bleed ports to facilitate bleeding of air from the brake system and replacement of spent fluid effectively.
- Lifespan
    - The calliper itself should be designed to outlast the vehicle itself so is not to require replacement with normal operation.
    - The design must achieve high cycle fatigue resistance characteristics through the selection of geometry and materials and verified using numerical simulation.

- Sustainability

- Mounting componentry will be sourced from materials that can be recycled at the end of the lifecycle (aluminium, mild steel, non- rare metals).
- Materials of the manufactured components will be non-toxic and reusable wherever possible to minimise environmental impact.
- As the fluid will need to be changed at regular service intervals, attempts to minimize wastage such as using bleeding containers to catch dirty fluid be used or additional use of system pressure bleeder if available.
- If subtractive manufacturing is required, minimization of waste material must be accounted for with weight of material before and after to be calculated to reduce cost to team and environment.

2 Literature Review

Brake callipers are designed with a number of variables, however there are two main types of automotive brake calliper, namely floating callipers and fixed callipers. A fixed calliper has at least two opposing pistons and thus the brake pads are actuated independently of the calliper body allowing the calliper to be fixed directly to the upright [1]. Floating callipers have one or multiple pistons on either the in-board or out-board side with the opposite pad fixed to the calliper body. The calliper body is mounted to guiding pins allowing it to exert equal force on both brake pads. B. Vasseljen [5] opted for a fixed calliper design as it offered improved brake feedback and more compact size over the floating design. It is generally accepted that fixed calliper designs offer higher brake force in comparison to floating callipers for their size and more uniform brake wear is achieved [1, 6]. As the size factor is of key significance for this project, a fixed calliper design will be further investigated as the preferred option.

M. Ugemuge and S. Das [7] describes a methodology used to design and test a formula student brake calliper. Figure 2 a) shows the sequence of decisions made regarding the performance required for their specific application. They showed that the selection of key aspects such as piston size, number of pistons and material selection were subject to operational parameters such as the required tangential force as shown in figure 2 b). A two-piston, fixed calliper design was analysed for deflection characteristics using ANSYS Static Structural. Dynamic testing was carried out using a bench test rig which supported their estimated deflection values using 7075 aluminium alloy. They found that adequate stiffness was achievable using a two-piece calliper design. The design methodology and decision-making used in the study is pertinent as the same desirable criteria for low weight and cost apply to the QUT FSAE car.

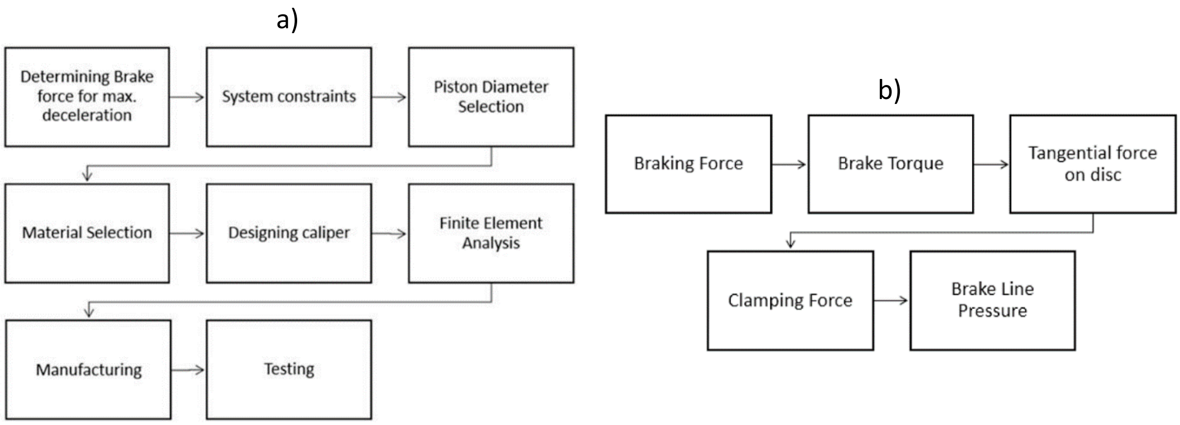

Figure 3 - Design methodology used by M. Ugemuge, et.al. for the design of FSAE brake calliper.

In several studies involving FSAE cases, N. Galbincea [8], L. Mora [9] and Mahajan et al. [10] stated that braking friction coefficients could be over-estimated by manufacturers and not include the capacity for the drop in friction coefficient seen in extended heavy braking scenarios. The final brake performance was below the calculated number unless a brake dynamometer was used to calculate the actual performance of the proposed braking components as seen in L. Mora's analysis [9]. Mora demonstrated that actual performance and manufacturer's measurements can leave considerable room for improvement with a deceleration of 0.9 g measured and the expected tire friction coefficient would allow 1.4g [9]. On any motorsport vehicle this difference can lead to large increases in performance thus needs to be factored in when calculating the benchmark braking performance.

As the most of FSAE teams opted to use an off the shelf calliper, the gains for the braking system were then focused on the brake rotor which could be designed for minimal weight and heat dissipation [8, 10, 11]. The decision to choose rotors that were fully floating and secured with button pin/rivets allowed for a greater distribution of the force from the rotating mass and isolate the thermal expansion of the braking assembly as different materials could be selected for the subsequent parts [8]. Furthermore, this allowed the selection of 17-4PH stainless steel for the inner mounting assembly and 4130 steel alloy which would save weight and ensure the brake system remains below the yield strength of each material even under heavy extended braking application.

Moreover, rotor design can significantly influence calliper design and overall braking performance. Large surface areas allow excellent stopping power and increase dissipation of waste heat [12]. However, prolonged braking periods with limited heat dissipation methods can create brake fade, generally when temperatures start to exceed 588 Kelvin [13]. Brake fade occurs as the rate of heat absorption exceeds the rate at which it can be dissipated, raising the temperature to a point where pad material is affected and the fluid heats up considerably. Furthermore, temperatures which exceed brake fluid vapour-saturation levels can completely disable the hydraulic system creating a compressible gas system [14]. Therefore, the brake fluid within the system must be able to withstand the temperature generated under the worst loading conditions. In addition, as temperatures rise above the brake pads design limit the material starts to deteriorate. A thin layer of gas and material is worn off onto the rotor which significantly decreases its frictional coefficient [14].

There are several significant rotor designs. Vented disc brakes dissipate heat via radiation through vanes/spokes present in between two discs, slightly increasing weight [12]. Drilled disc brake rotors provides greater surface area by the drilling number of holes improving braking and heat dissipation while decreasing weight [12]. In addition, drilled rotors allow routes for brake pad particles, heat, and gases to escape while retaining its structural integrity [12]. Similarly, slotted, or grooved disc brake rotors are designed at angled directions of the rotation which increases friction and airflow while allowing a self-cleaning mechanism to easily get rid of dirt and debris [12]. Kulkarni, et al. [12] studied the most effective rotor design based on these design parameters and found optimal performance was realised with a combination of the drilled and slotted or grooved disc.

The brake pads are equally as important as the brake rotors in slowing down a vehicle. Brake pads are mainly made from three compounds: semi-metallic, organic, and ceramic brake pads [15]. Organic brake pads consist of many different materials such as rubber and Kevlar etc. but consist of five main components; reinforcing fibre, binder, abrasive, lubricants and fillers which work to influence the structural, tribological and thermal properties of the pad [15]. Organic brake pads are designed for everyday road vehicles as they are generally the least expensive, and work well in many conditions however, poor high temperature properties and shorter lifespan make them mostly inappropriate for racing, hence they were ruled out for this project [15, 16].

Ceramic brake pads are popular on performance vehicles and race cars due to their ability to resist brake fade [17]. Ceramic brake pads are typically the most expensive of the three brake choices due to their manufacturing costs but offer the best balance in terms of no noise and good braking performance [17]. Metallic brake pads offer superior braking performance to ceramic brake pads because they are able to consistently perform under a wider range of weather conditions in comparison [18]. Metallic brake pads are used in cold or hot climates, and extreme off-road vehicles [18]. Both ceramic and metallic brake pads are suitable for the QUT FSAE race car, however a metallic brake pad may be more suitable due primarily to lower cost and adequate performance characteristics.

With continuous applications of the brakes, the pistons tend to advance from the calliper body and must be retracted by some mechanism to return the piston to its neutral position after application and avoid brake drag. The piston seal performs a dual function in hydraulic brakes; sealing the gap between the piston and the calliper while also elastically deforming under brake application and retracting the piston afterwards [19, 20]. The performance of the piston seal is affected primarily by the configuration of the seating groove, the seal material, and the friction at the piston-seal and groove-seal interfaces [19]. The need to reduce brake drag often means retracting the piston further into the calliper. This can have a negative effect on brake response and cause increased pedal travel resulting in poor brake feel. This parameter is largely affected by seal and groove design and must be considered for optimal drivability. Dalal K. and Karnik A. [20] used a nitrile rubber seal in their design of a mono-block brake calliper considering it had optimal deflection properties, a pressure rating of 200 bar and a safe temperature range, up to 150 degrees Celsius. As QUTMS is interested in maintaining optimal pedal feel with this new calliper design, an appropriate seal will be selected based on the dual function characteristic and will consider the possibility of higher temperatures due to the advanced performance requirements of FSAE. An issue raised in the literature is that of designing piston size with the availability of the piston seals in mind. Using off-the-shelf seals means piston diameter selection is limited by the availability of standard seal diameters [1]. Mirajkar, et al. stated a workaround to this issue would be to consider using 4 or 6 pistons of smaller diameter instead of attempting to use overly large 2 piston designs. This applies to the need for compact envelope in this project.

Mechanical and thermal analysis of the calliper and its components will be critically important in this project as in-field tests and experimental analysis is beyond the scope of work. Mirajkar, et al. [1] performed a structural analysis on a hydraulic calliper using ANSYS Workbench R18.1 Static Structural. They applied directional loads to the calliper to represent the loads generated by the clamping action, friction force and pressure loads behind the pistons to represent brake fluid pressure. The single piston floating design yielded a factor of safety of 2.1 under static conditions. Similarly, Ugemuge, et al. [7] used FEA to perform structural analysis of a FSAE car brake calliper. Their analysis indicated a maximum static deflection of 0.172 mm and a deflection of 0.09-0.11 mm at the bridge of the calliper. They determined that this level of deflection was within acceptable range based on maintaining seal between the two calliper halves and providing adequately stiff pedal feel to the driver. Figure 3 shows the boundary conditions and general calliper configuration designed. Thermal analysis was used in addition to structural analysis by Dey [16] in 2015 to investigate the fluid vaporisation phenomenon in FSAE brake callipers. They used thermodynamic principles to analytically calculate the thermal conduction, convection and radiation properties of each component (pads, pistons, calliper body, rotor) including the brake fluid itself. By analysing each component/interface separately, the study was able to validate that the brake fluid stayed below its critical temperature in the expected peak operating conditions. From this analysis, they recommended the use of DOT 5 or DOT 5.1 fluid as it has the highest wet and dry boiling point. This analytical method will be used to evaluate the thermal performance and limitations of the design produced in this project due to its simplicity.

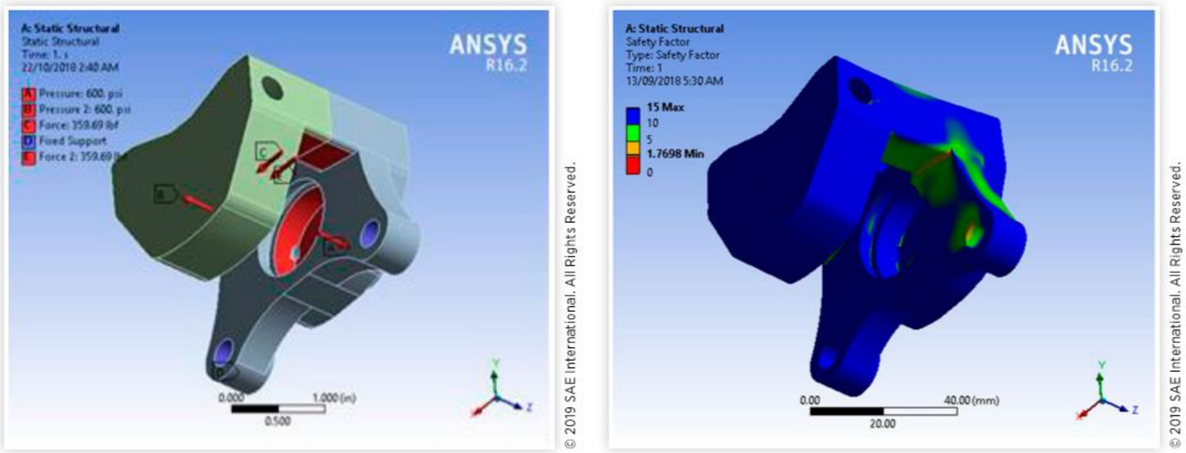

Figure 4 - Ugemuge, et al. [7] depiction of brake calliper body static structural analysis with boundary conditions and stress concentrations.

As discussed previously, brake pistons are housed in the calliper and apply force to the pads [6]. Brake pistons are predominantly made from three different materials; Aluminium, steel, or a Phenolic compound [6]. Aluminium is lighter than steel however it has a higher thermal conductivity of 239 W/mK compared to 45 W/mK of steel which causes large amounts of heat to be transferred to the brake fluid [21]. This is not ideal as prolonged heat exposure to other components may decrease the braking ability of the vehicle. Steel is generally stronger than aluminium, however both metals suffer from corrosion over time [21]. On the other hand, Phenolic based pistons use a plastic-like compound which is resistant to corrosion and has relatively low thermal conductivity of 0.2 W/mK [21]. For racing purposes, a metal-based brake piston is ideal as they can take a larger load than Phenolic based pistons due to higher yield loads [22]. This higher yield load means there is a lower chance of deformation and allows the option to increase brake pressure in the system, improving braking performance [22]. Additionally, the anti-corrosive characteristic of Phenolic callipers is relatively redundant in a racing scenario as the braking assemblies are replaced often and hence before any corrosion can take place [22]. As such, metallic pistons will be used for the design in this project.

In a racing scenario there is equal use between steel and aluminium brake pistons [23]. Although aluminium is weaker than steel, it is significantly lighter which reduces unsprung mass, hence aiding handling [24]. Aluminium pistons are used for race cars which may not achieve high speeds but instead are going under short, repeated braking loads (typically a winding track). However, steel can take a higher load and is used in heavier, more powerful vehicles which achieve high top speeds and have prolonged braking events [24]. As the QUT FSAE race car is designed to be lightweight and nimble on a short track, it is recommended that aluminium brake pistons are used. Due to the high thermal conductivity of aluminium, geometrical optimisation to reduce heat transfer through the piston will be implemented.

3 Team Code of Conduct

The project team has collaboratively established and agreed to a code of conduct which outlines the standard practice expected of all members throughout the duration of the project. It is expected that the following agreed practices are upheld by the team in the interest of achieving the best possible results in the project and wider unit. Any deviation from the code will be agreed to by the team.

Communication:

- Members shall communicate and respond to communications fully and in a timely fashion or notify the team if they are unable to.
- General communication shall be via the established Messenger group. Members are expected to reply to messages within a 6-hour timeframe (except overnight).
- Members shall respond to emails as soon as reasonably practicable, or no longer than 24 hours after receipt.
- Contact a member via mobile phone shall be made as a last resort when the matter is urgent and contact via other avenues has failed.

Meetings:

- Weekly meetings shall be attended by all members. If a member is unable to attend a meeting, they shall give the team minimum 24 hours' notice prior to the meeting.
- If a member is unable to attend a meeting for any reason, that member is responsible for communicating their progress and input to the group prior to the meeting via alternative means.
- Members shall take turns organising and running weekly meetings in addition to recording minutes as specified by an agreed roster.
- The meeting organiser shall inform the group of any changes leading up to the meeting and facilitate meeting discussions relevant to project progress.
- Members shall come to meetings prepared to engage in discussion and give updates on their progress in assigned tasks.
- Changes in meeting time and location shall be communicated by the meeting organiser to the rest of the teem via calendar invite and message to the team chat.

Document and information sharing:

- Members shall use the established OneDrive project folder to retrieve and upload documents and information relevant to the project and wider unit.
- Members shall consult other members before making alterations to their work.

Expectation of work and deliverables:

- All major decision making shall be carried out with input from all members via email, group chat or (preferably) in-person at weekly meetings.
- All members are expected to complete their assigned tasks within the agreed to timeframe. Should a member feel unable to meet specified deadlines, they are responsible for raising the issue with the rest of the group.
- Members shall each review major assessment items and notify the group of any changes they propose. Otherwise, they shall indicate they are happy to submit via the group chat.
- Members are expected to have at least one other member review their assigned work as deemed necessary by the group.
- Members shall aim to complete all work to the highest attainable standard as set by the CRA.

- Members are expected to allow for and contribute the recommended number of hours each week to the project, however this comes second to meeting agreed deadlines.

Other:

- Members shall notify the team immediately if they believe they are not able to complete an assigned task by the deadline or to an appropriate standard. If an assigned task is delayed, the member responsible shall be awarded “did not meet expectations” on the associated timesheet and must seek assistance from the team.
- Should a member unenroll from or leave EGH420, they must notify the team as soon as possible and arrange with the team to have their tasks reassigned.

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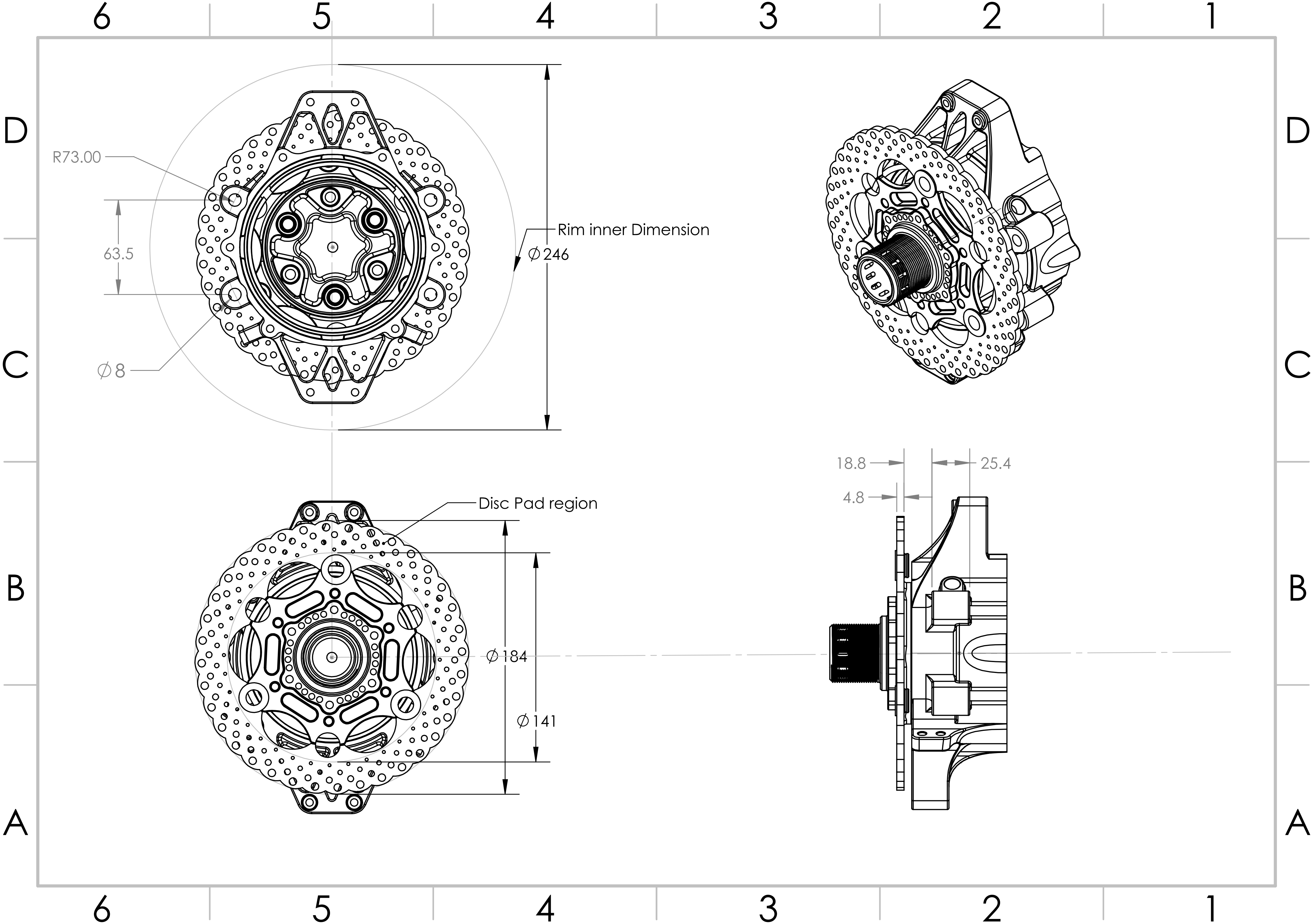
Appendix A – Key Dimensions Pulled from QUTM FSAE Hub Assembly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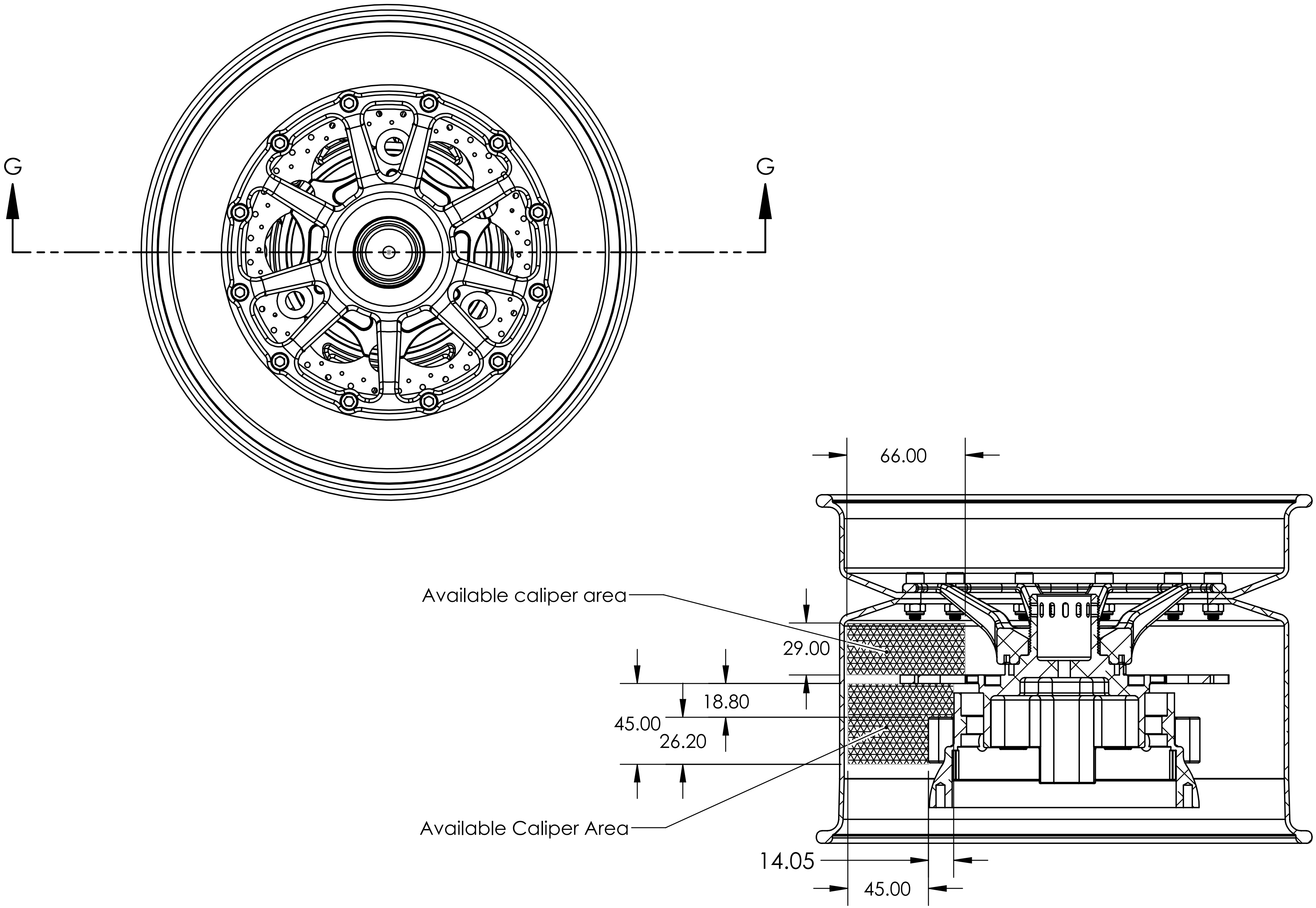
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Available caliper area
29.00
18.80
45.00
26.20
Available Caliper Area
14.05
45.00