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Development of a Brake Fluid Pipe Cover

Bachelor's thesis

Mechanical Engineering and Production Technology

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Mechanical Engineering and Production Technology | Abstract
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Vehicles utilise brakes for safe speed control and stopping, ensuring the safety of passengers, cargo, and others on the road during transportation. The braking process involves the initiation of the brake pedal that allows hydraulic pressure to be transmitted through the brake fluid to the calipers, activating pistons that press the brake pads against the brake disc, ensuring the necessary friction for vehicle deceleration. However, when a vehicle is in motion, certain brake calipers come with a brake fluid pipe that is exposed to road debris, risking operational issues.

This bachelor's thesis aims to provide a solution for the Sarlin Racing Team to safeguard the brake fluid pipe connected to the brake caliper from environmental factors. Sarlin Racing Team is a local company located in Riihimäki, Finland. The firm supplies vehicle parts to enhance customers' driving experience, ensuring a smooth ride, and improved overall performance for customers' vehicles.

The structure of this thesis constitutes theoretical and empirical components. Initially, a thorough review of the literature on brake calipers, discs, fluid, and their collective impact on vehicle disc brake systems is undertaken. It extends to practical processes, including additive manufacturing, 3D scanning, and reverse engineering. In the practical section of the thesis, a brake caliper is 3D scanned, reverse engineered, modified, and 3D-printed, followed by the creation and evaluation of a brake fluid pipe cover.

Finally, the durable cover is affixed to the modified 3D-caliper to bolster the safety of vehicle disc brake systems. This initiative reduces maintenance needs and highlights the fusion of theoretical knowledge and practical expertise for improving vehicle safety.

Keywords Brake caliper, brake disc, brake fluid, brake pads, 3D scanning, reverse engineering, additive manufacturing

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List of abbreviations

3D	Three Dimensional
AM	Additive Manufacturing
CAD	Computer-Aided Design
AMC	Aluminium-Metal Matrix Composite
MMC	Metal matrix composites
DOT	Department of Transportation
CMM	Coordinate Measuring Machines
CNC	Computer Numerical Control
NURBS	Non-Uniform Rational B-Splines
STL	Stereolithography
ISO	International Organization for Standardization
FDM	Fused Deposition Modelling
PET-G	(Polyethylene Terephthalate Glycol-modified)

List of symbols

X, Y, and Z	Directions in the global coordinate system
mm	Millimetres
MPa	Megapascal
Kg	Kilogram
GPa	Gigapascal
D	Density
m	Mass
V	Volume
π	Pi
r	Radius
km	Kilometer

hr	Hour
s	Seconds
g	Grams

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1 Introduction

This practice-based bachelor's thesis, conducted in collaboration with Sarlin Race Team and affiliated with the Mechanical Engineering and Production Technology degree program at Häme University of Applied Sciences, explores solutions for enhancing the resilience and longevity of brake fluid pipes located on brake calipers. Offering a comprehensive overview of disc brake systems and their main components, the thesis centres on the creation of a durable protective cover that will safeguard the brake fluid pipe. This protective cover is attached to a brake caliper that is reverse engineered based on the real part and produced by additive manufacturing, with data sourced from 3D scans performed on the original brake caliper provided by the Sarlin Race Team company.

In the first chapter, the purpose, objective, and scope of the thesis are discussed. Additionally, it introduces the commissioning company, Sarlin Race Team and highlights the benefits related to the thesis topic, and offers clear definitions of key concepts for clarity.

In the second chapter of the thesis, an overview of disc brake systems is presented. The focus is on the system's components and their distinct roles and functions. This section provides an understanding of the mechanics and operational principles that govern their overall effectiveness.

The thesis's third chapter provides a substantial review of 3D scanning, covering a variety of scanning techniques such as active and passive scanning, their corresponding strategies, and a broad range of uses. This section highlights the scientific principles and practical applications of 3D scanning in several fields, showcasing its adaptability across various fields.

The thesis dives into reverse engineering in its fourth chapter, clarifying its methods and highlighting the key components involved, while the fifth chapter explores additive manufacturing, and a clear summary of its process chains and the many strategies currently used in this industry is provided.

The approach for 3D scanning a brake caliper with an advanced non-contact active structured light scanner is described in the sixth chapter of the thesis. A complete description of the setup and scanning procedure is given in this chapter. The following phase involves reverse engineering where the brake caliper is analysed and modified to incorporate a protective cover for the brake fluid pipe. Finally, the reverse engineered brake caliper is then additive manufactured which will also be explained in this chapter.

The complex design procedure that went into making the brake fluid pipe's protective cover is described in chapter seven of the thesis. This section describes the requirements for the cover, the reasoning for the design, and the different aspects that went into shaping its final shape. Additionally, it includes which prototype is chosen and discusses the design of a drilling jig for use on existing brake calipers.

Chapter eight presents simulations conducted with Ansys software to evaluate the protective cover's effectiveness in counteracting rock impacts. Initially, the simulation involves selecting suitable rock material and investigating its properties. Following that, two scenarios are simulated to examine the stress values generated as a result of the impact and the cover's ability to absorb and disperse impact forces. The findings validate that the cover efficiently safeguards the brake fluid pipe across a range of conditions, underscoring its reliability and the appropriateness of its design for automotive safety applications.

The manufacturing of the selected prototype is described in the nineth chapter, along with a list of parts that are needed, including the main frame of the protective cover, reinforcement plates, screws, nuts, and washers. This section describes the steps involved in producing the products which include laser or water jet cutting, rounding of edges, sheet metal bending, and additive manufacturing.

An extensive analysis and assessment of the thesis findings are finalized in chapter 10. It also provides suggestions for improving the prototype solution in upcoming iterations. Based on the carried-out simulations and the reliability of the sources provided, the chapter evaluates the validity and dependability of the thesis. The article ends with a reflection on the insightful knowledge and useful lessons the author has acquired from conducting the study and carrying out this thesis assignment.

1.1 Background and Significance of the Study

Over four years as a student in the Mechanical Engineering and Production Technology degree program, the author acquired extensive knowledge and valuable experience from the curriculum and projects offered by Häme University of Applied Sciences. Seeking new challenges, the author took part in an internship at the 3D Academy Lab, where skills in reverse engineering, 3D scanning, and additive manufacturing were adopted and developed.

Motivated to apply these skills in a real-time project, the author accepted this proposed thesis that aligned with his interests.

The primary idea of the thesis is that the commissioning firm, Sarlin Race Team, wants to protect a brake fluid pipe attached to the brake caliper. This safety measure is essential since the pipe can be exposed to environmental hazards such as rocks and other materials that may impact at high speeds while driving. A broken brake fluid pipe may cause fluid leakage, affecting the brake calipers' pistons and jeopardising the brake system as a whole.

To achieve a solution, the employment of a series of processes, mainly 3D scanning, additive manufacturing, and reverse engineering is required. Both theoretical and practical applications are integrated into each of these processes to comprehend their significance and functionality.

A successful solution for the Sarlin Race Team in this matter would minimize the risk of brake fluid leakage, reducing the likelihood of compromising the entire disc brake system. This improvement enhances vehicle safety, maintains optimal disc brake system performance for extended periods, and reduces the need for maintenance.

1.2 Project Objectives

To attain the primary aim of this thesis, which is the protection of the brake fluid pipe, specific objectives must be accomplished. These objectives include:

Project Objective 1: Insight into brake calipers, brake discs, and brake fluid, investigating their roles in the vehicle's disc brake system, and identifying the central issue addressed in this thesis.

Project Objective 2: This task entails a detailed examination of three crucial technologies and their applicability to the main goal of the thesis: 3D scanning, reverse engineering, and additive manufacturing scanning. The project begins with an overview of 3D scanning, including its techniques and particular uses that are essential to the thesis. After that, the emphasis moves to reverse engineering, where an adequate grasp is established with a focus on its strategic application and functions inside the thesis. At last, the study looks into additive manufacturing, examining its many processes and their significance in accomplishing the objectives of the thesis. After providing a detailed overview of the technologies, real-world applications based on each of these approaches will be examined closely to highlight their importance in accomplishing the thesis's main goal.

Project Objective 3: Different designs are considered while creating a protective cover for the brake fluid pipe. During this step, the production process, material selection, and other necessary considerations for design limits or constraints will all be carefully evaluated. In addition to that, digital simulation is commenced to view the results of the selected design.

Project Objective 4: Reviewing the effectiveness and outcomes of project objectives related to comprehending brake system components, the application of key technologies utilised in the thesis, the designing process for the brake fluid pipe protective cover, and the selected design.

Achieving the project’s objectives would allow the possibility to successfully safeguard the brake fluid pipe adhering to the main purpose of this thesis. A careful strategy is ensured by assessing the results of the objectives, which facilitates the accomplishment of the thesis's primary goal.

1.3 Research Question

A durable, impact-resistant brake fluid pipe cover requires knowledge of the design approaches, material composition, and different manufacturing techniques. Therefore, addressing these aspects is essential to producing an effective protective cover. To ensure the cover meets the high standards of impact resistance and longevity, two factors must be taken into account: the selection of appropriate materials and the optimization of the designs, as they will determine the suitability of the cover for regular use. Balancing these features is vital for developing a reliable and robust system to protect the brake fluid pipe.

Consequently, the main research question to drive this thesis is: “What approach ensures the optimal design, material selection, and manufacturing of a durable protective cover for the brake fluid pipe?” The knowledge and skills obtained from exploring this question will be applied to offer the best solution for the specific brake caliper case for the Sarlin Race Team.

1.4 Scope and Limitations

The thesis's scope includes developing a protective solution for the brake fluid pipe within a brake caliper given by the Sarlin Race Team, particularly focusing on shielding it from external elements such as rocks and debris that may impact the pipe at high velocity. The thesis involves an exploration of what a disc brake system is and its components such as brake calipers, brake fluid, brake disc, and their respective functions. It also encompasses the theoretical and practical application of advanced engineering processes, specifically, 3D scanning, additive manufacturing, and reverse engineering processes. The objectives involve understanding key components, exploring 3D scanning, reverse engineering, and additive manufacturing, and also developing and evaluating a protective cover for the brake fluid pipe. The thesis aims to address specific questions related to modifying the brake caliper, material selection, and manufacturing processes to create a durable and effective protective cover for the brake fluid pipe.

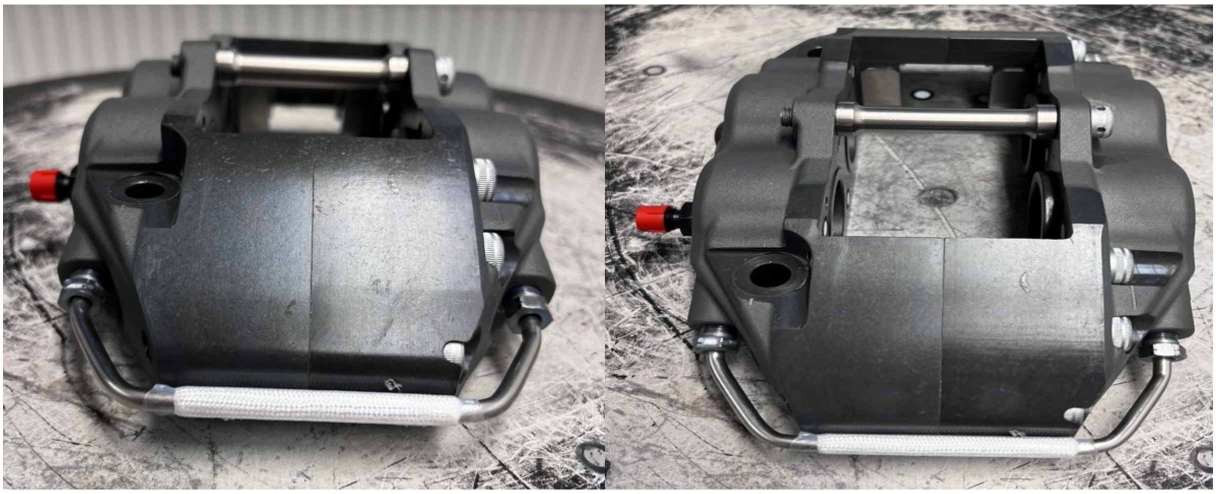
The thesis, however, might encounter limitations in conducting comprehensive real-world testing. Simulating all potential conditions and environments where vehicles operate is challenging, impacting the thorough evaluation of the protective cover's performance. Additionally, the environmental impact of chosen materials and manufacturing processes could pose challenges, as balancing durability and sustainability is crucial. Furthermore, the thesis's findings and solutions may be specific to the addressed disc brake systems and conditions, limiting their applicability to other contexts or vehicle types.

1.5 Commissioning Company

The commissioning company in this thesis is the Sarlin Race Team which was founded by Kalle Sarlin in 1985 after Kalle Sarlin's racing career in track racing was just beginning, thus contributing to more than 30 years of experience in motorsport and the needs of the company's customers. The company, Sarlin Race Team, specializes in selling automotive parts, including brake discs, brake calipers, brake pads, pedals, springs, and other vehicle components. In addition to that, the company manufactures its own range. Having an in-house production capability enables them to offer customized parts as per the specific requests of customers. (Sarlin Race Team, n.d.)

In this thesis, a brake caliper (figure 1) — one of the products handled by the Sarlin Race Team—is provided to Häme University of Applied Sciences for research and the development of protection for the brake fluid pipe situated on the brake caliper.

Figure 1. Fixed brake caliper.



Furthermore, CAD models or other specifications were not provided. Consequently, 3D scanning, and reverse engineering methods were applied to extract CAD information.

1.6 Key Concepts

- **Brake caliper** is a vital component of the disc brake system that houses a pair of brake pads that press against the brake disc. This action is supported by hydraulic pressure generated by the brake fluid, effectively slowing down the disc’s rotational speed. (Tyflopoulos et al., 2021, p. 4)
- **Brake disc** is a component of the vehicle’s braking system that experiences exposure to external airflow where its primary function is to dissipate the thermal energy produced by the friction between its surfaces (Jeong et al., 2023, p. 1).
- **Brake fluid**, which is a form of hydraulic fluid, is utilised in hydraulic braking systems to convert force into pressure. This pressure is exerted on pistons, which in turn push the brake pads against the brake disc. This mechanism enables the vehicle to achieve a complete stop when the brake pedal is applied. (Christian Brothers Automotive, 2021)
- **Brake pads** are key elements in a vehicle's braking system. They function by pressing against the brake disc, creating friction that helps to slow down or stop the vehicle by offering the necessary resistance. (Wahlström, 2016, p. 1)

- **3D Scanning** is a technology that captures the shape of a physical object or environment creating a digital 3D model through the data collected (Haleem et al., 2022, pp. 161–171).
- **Reverse engineering** is a method of creating a digital 3D model using scanned or digitized information obtained from existing objects or products. This allows for a detailed analysis of the physical properties of the item, which can then be used for replication purposes (Raja & Fernandes, 2007, p. 2)
- **Additive Manufacturing (AM)** is a set of technologies that manufacture physical objects layer by layer, using digital 3D model data. The process involves the successive addition of materials to create the desired shape. (ISO/ASTM 52900:2021, 2022, p. 1)

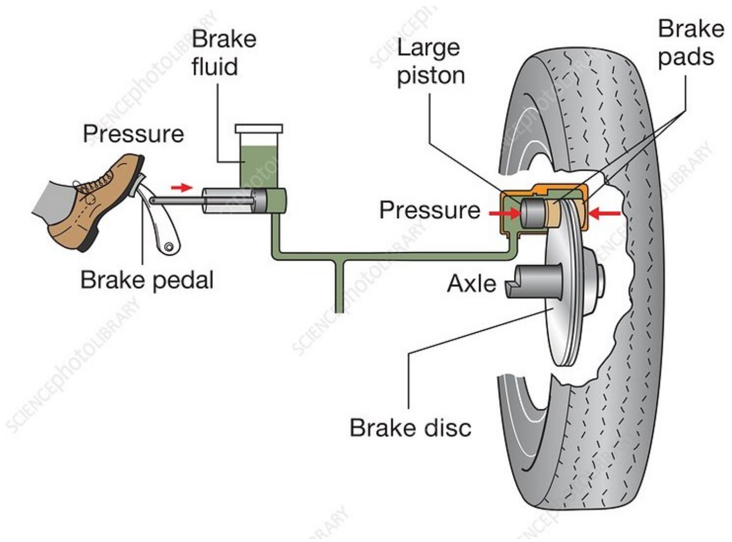
2 Insight into Disc Brake Systems: Overview

The vehicle's disc braking system (figure 2) allows the driver to safely slow down or stop the car. By exerting friction forces on the axles, it transforms the kinetic energy of the vehicle into heat and makes it simpler for the vehicle to slow down or stop altogether, thus, playing a crucial role in ensuring driver safety and preventing accidents on the road (Tyflopoulos et al., 2021, p. 4).

The functionality of brake systems in vehicles is governed by fundamental physical principles and laws that dictate the interaction of elements in the physical world. These principles revolve around the concepts of energy, inertia, mechanics, hydraulics, and friction, all of which play a vital part in ensuring the efficient operation of brake systems (Limberg, 2014, p. 20).

The disc brake system's elements include the brake disc or rotor, the brake caliper which encases the brake pads, pistons within the caliper, and brake fluid. These components are essential for the system's operation, as illustrated in figure 2. (Tyflopoulos et al., 2021, p. 4)

Figure 2. Car disc brake system (Science Photo Library, n.d.).



2.1 Brake Disc

The rotor or automotive brake disc (figure 3) is a component of the vehicle's braking system, tasked with slowing down or stopping the motion of a rotating wheel at a specific speed (Maleque et al., 2010, p. 1). Its primary function is to dissipate the heat that results from the friction that occurs between its contact surfaces, while also being exposed to the external airflow (Jeong et al., 2023, p. 1). Figure 3 below shows the different designs of brake discs that fulfil this function.

Figure 3. Brake disc parts, types, and functions (Mechanicfixa, 2022).

2.1.1 Varieties of Brake Discs

Brake discs are available in various classifications, each designed to meet specific performance requirements and applications. These include:

- Solid Discs: Are single-piece brake discs that are commonly used in smaller vehicles.
- Vented Discs: These discs come with internal vanes or spaces to improve cooling, making them ideal for high-performance and larger vehicles.
- Slotted Discs: These discs feature grooves on the surface for more efficient expulsion of heat, gas, and other elements. However, they may produce more noise due to the grooves rubbing against the pads.
- Drilled or Dimpled Discs: Have holes or dimples that improve heat dissipation and are often used in combination with slotted rotors.
- Composite Discs: Are made from materials such as carbon fibres or ceramics, which make them lighter and more durable. Composite discs are typically used in high-performance cars. (Mechanicfixa, 2022)

In summary, a variety of brake disc alternatives are designed for various vehicle types and driving circumstances. For smaller cars, solid discs are easy to use and reasonably priced; for larger, high-performance cars, vented, slotted, drilled, or dimpled discs provide enhanced heat dissipation. Composite discs combine resilience and lightweight, demonstrating advances in brake disc technology. They are made of materials such as carbon fibre or ceramic. This selection of choices guarantees that a suitable brake disc is available to improve practically any vehicle's performance and safety.

2.1.2 The Constituent Materials of Brake Discs

There are several materials available for the construction of brake discs, each with its own unique set of properties and benefits that make them suitable for diverse automotive applications. Such materials could be:

- Cast iron: Automotive brake rotors are commonly made from cast iron due to their cost-effectiveness, ease of production, and excellent thermal stability. However, the weight of cast iron components is a major drawback as it increases fuel consumption.
- Titanium alloys: The use of titanium alloys and their composite materials for brake rotor discs is proving to be a potential solution for weight reduction. These materials can reduce the weight of rotors by up to 37% compared to traditional cast iron rotors of

the same dimensions. Additionally, they offer improved strength at high temperatures and increased resistance to corrosion.

– Aluminium-Metal Matrix Composite (AMC): Metal matrix composites (MMCs) based on aluminium alloy and reinforced with ceramic particulates are gaining popularity as an attractive alternative for brake rotor applications. With their lower density and superior thermal conductivity compared to conventional grey cast iron, these advanced materials are expected to substantially reduce the weight of brake systems, potentially achieving weight reductions of 50-60%. (Maleque et al., 2010, p. 2)

To put it briefly, selecting the right material for brake disc production is essential because each option offers unique benefits suited to certain car requirements. Cast iron is often used because it is less expensive and has superior thermal properties; however, its heavier weight decreases fuel efficiency. On the other hand, titanium alloys may be able to reduce rotor weight without compromising corrosion resistance or strength. Aluminum-Metal Matrix Composites (AMCs) are a cutting-edge material replacement because they provide notable weight reductions and excellent thermal conductivity. Through continuing research and deployment of these materials, the automotive industry is exhibiting its dedication to enhancing braking system design by increasing sustainability, efficiency, and performance.

2.2 Brake Caliper

The caliper plays a vital role in supporting the brake pads while the piston applies the clamping force. To achieve optimal braking force, the caliper must have high stiffness and evenly distributed pressure on the pads. This, in turn, results in even heat distribution, which is necessary to avoid wear and noise caused by variations in disc temperature. Therefore, the choice of material, manufacturing precision, and caliper design are significant in achieving the desired characteristics such as low weight, high stiffness, and even pressure distribution. (Ingale et al., 2016, p. 227) A brake caliper typically consists of a housing structure, brake pads for friction, and pistons to apply pressure (Tyflopoulos et al., 2021, pp. 4–5).

2.2.1 Types of Brake Calipers

In braking systems, two varieties of calipers are employed: fixed and floating. Fixed calipers often have many pairs of opposing pistons to clamp on both sides of the disc and do not move in relation to the disc. Although this design is more costly and intricate, it is less resilient to disc imperfections.

Conversely, floating calipers are made to move in a line parallel to the rotation of the disc. These calipers enable pressure application on both sides because a piston on one side presses the inner brake pad against the disc, bringing the caliper body and outer brake pad into touch with the other side of the disc. (Santos et al., 2016, p. 2) Figures 4 and 5 highlight the distinctions between fixed calipers and floating calipers respectively.

Figure 4. Fixed caliper operation (MaXpeedingRods, 2020).

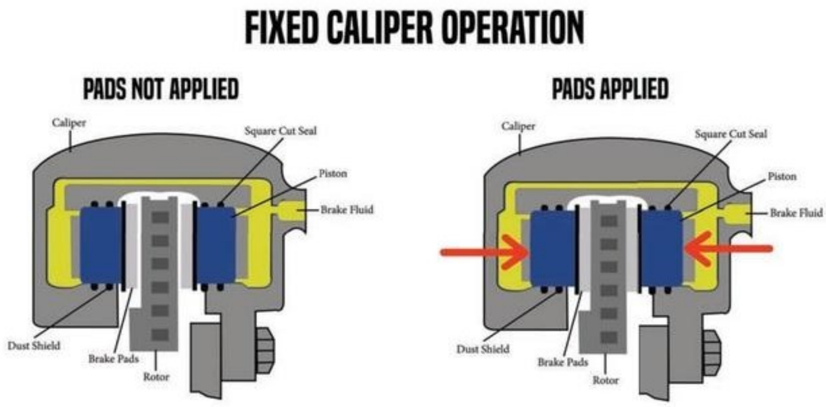
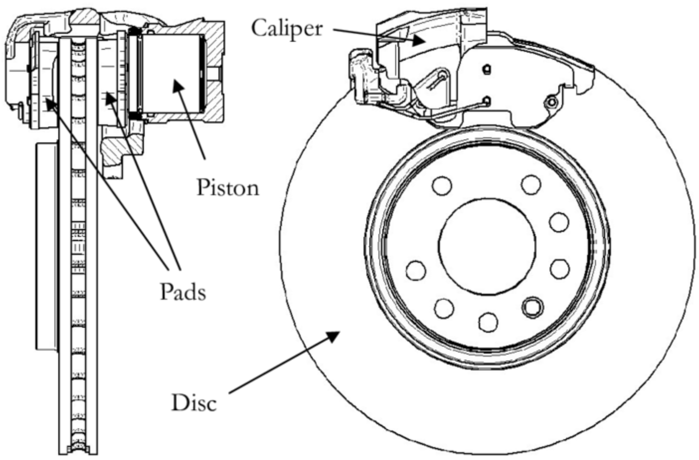


Figure 5. Disc brake assembly with a single-piston floating caliper and a ventilated disc (Wahlström, 2020, p.1).



2.2.2 Material Composition of Brake Calipers

According to Phad (2015), when it comes to brake caliper bodies, the choice of material depends on various factors, with rigidity, weight, and modulus of elasticity being the most critical ones. The material should be rigid enough to minimize deflection while also being light enough to reduce the overall weight of the assembly. However, the modulus of elasticity is the most critical attribute for calipers, as stiffness is more crucial than strength.

Commercial vehicle brake calipers often use cast iron due to its affordability, high modulus of elasticity numbering between 200 GPa and 210 GPa, and ease of machining. However, the downside of cast iron is its high density, making it heavier than other materials.

Aluminium is another material option for caliper manufacturing, favoured for its lower weight. However, its modulus of elasticity is significantly lower, being around 72 GPa to 80 GPa.

Metal matrix composites (MMCs) are a newer material choice that combines a base material such as aluminium or beryllium with ceramic fibres aligned in specific directions to achieve the desired strength and stiffness. MMCs typically have a modulus of elasticity of approximately 180 GPa and are lighter in density compared to other materials, although they are the most expensive option. (Phad et al., 2015, p. 5)

In selecting materials for brake calipers, a balance between cost, weight, and stiffness is significant. Cast iron is a cost-effective option but can be heavy, while aluminum is lighter but less stiff. Metal matrix composites offer a strong alternative, but they come with a higher price tag. The decision ultimately depends on which attributes are deemed most important for optimal brake performance.

2.3 Brake Pads

The brake pads (figure 6) have a major role in the vehicle's braking system. Their primary job is to exert pressure on the brake disc to create the necessary friction for the car to slow down or come to a stop. This resistance plays a critical role in decreasing the wheel's spin. (Maleque et al., 2010, p. 2)

Figure 6. Brake pads (Deaton, n.d.).

The market is filled with many kinds of brake pads, each having a special set of advantages and disadvantages. These brake pads include:

- Organic Brake Pads: Made from sustainable materials including rubber, glass, and other resins, these brake pads are occasionally strengthened with Kevlar. They are ideal for small vehicles that are used for regular, light driving. They have the benefit of quieter braking because of their softer composition, but they also wear out more quickly.
- Ceramic Brake Pads: These brake pads are renowned for their exceptional durability and performance. Because they are composed of ceramic compounds, they are exceptionally light and have excellent heat management capabilities. Although they are ideal for high-performance cars, their sophisticated features are more expensive.
- Metallic Brake Pads: These brake pads are commonly found in many different types of automobiles. They are made of graphite mixed with a mixture of metals, including iron, copper, and steel. These pads are reasonably priced while maintaining good durability. Their weight and propensity to hasten brake rotor wear are their only disadvantages, aside from their efficiency in heat conduction.
- Motorcycle Brake Pads: Ceramic or organic materials are commonly used to make brake pads for motorcycles. The decision is based on the need for less weight and wear, taking into account the particular needs of motorbike use as opposed to that of cars and trucks. (Deaton, n.d.)

A broad variety of brake pads that fit different motor vehicles and road conditions are offered on the market. Eco-friendly organic brake pads are ideal for light driving and operate quietly but wear out quickly. Ceramic brake pads are more expensive but are ideal for high-performance cars since they are durable and effectively control heat. Metallic brake pads are more affordable and long-lasting, and they fit a variety of car models. However, they are heavier and may result in more rotor wear. Motorcycle brake pads are chosen with decreased weight and wear in mind, taking into account the unique requirements of motorcycle performance. Motorcycle brake pads can be formed of ceramic or organic materials. Each type of brake pad presents a strategic choice for drivers, weighing the pros and cons to meet their specific driving needs.

2.4 Brake Fluid

The brake fluid (figure 7) is essential to a vehicle's braking system's proper operation. The brake fluid's chemical composition is particularly engineered to fulfil the requirements, including stability in a variety of chemical environments, high-temperature operation, and corrosion protection for the brake system's constituent parts. Brake fluids in modern cars usually consist of ethylene glycol, silicone-based fluids, isobutyl alcohol, and polyglycols; each of these components enhances the overall functionality and safety of the braking system. (Caban et al., 2016, p. 10; Kao et al., 2016, p. 1)

Figure 7. Brake fluid (StudentLesson, n.d.).

There are three primary categories of brake fluid, each having unique properties and applications:

- DOT 3: Based on glycol, this type of fluid is commonly used in standard automobiles. It has a boiling point of roughly 204°C. But what sets DOT 3 apart from the other brake fluids is its capacity to absorb water from the atmosphere since it is hygroscopic. Its boiling point can eventually decrease as a result of this tendency.

- DOT 4: Based on glycol, just as DOT 3, DOT 4 boils at a slightly higher temperature of roughly 232°C. As a result, it can be utilised in numerous domestic and European automobile types. Similar to DOT 3, it absorbs water, which could eventually alter its boiling point.
- DOT 5: This silicone-based brake fluid does not absorb water because it is not hygroscopic. With a boiling point of about 260°C, it is ideal for use in heavy-duty and racing cars. Its boiling point remains constant over time since it does not absorb water, but any water that enters the braking system could form pockets and lead to corrosion of the brake system. (What are the different types of brake fluid?, 2008; Kao et al., 2006, pp. 1–4)

It is essential to minimise air exposure when handling DOT 3 and DOT 4 fluids to prevent water absorption. Tight seals on reservoirs and containers maintain the brake fluid's effectiveness. DOT 5 is less likely to produce air pollution due to its special composition, but it still requires careful monitoring for any potential water contamination in the braking system.

3 3D Scanning

In 3D scanning, a physical object or its surroundings are precisely measured, and its shape is recorded using cutting-edge technology. The data collected is then used to create a detailed digital 3D model. (Haleem et al., 2022, pp. 161–171)

Figure 8. Scantech AXE-B11 3D-handscanner (CascadeOy, personal communication, n.d.).

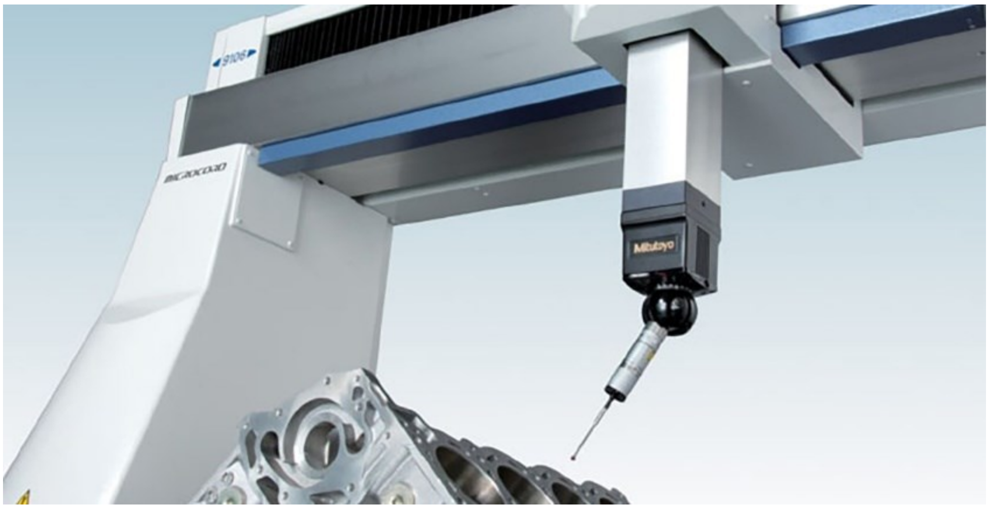
3.1 Types of 3D Scanning

A number of technologies can be used to digitally capture the shape of a 3D object. These gadgets fall into two broad categories: contact and non-contact 3D scanners. In addition to that, active and passive scanners are the two primary types of non-contact 3D scanners. There are numerous technologies included in each of these groups.

3.1.1 Contact 3D Scanners

Contact-based 3D scanners are usually fitted with a robotic or manually operated probe at the end of a mechanised arm. Most of the time, these scanners are calibrated for stationary use. The location of the armature when the probe makes contact with the object is recorded by the scanner, which then uses this information to determine the X, Y, and Z coordinates of the object's surface. A 3D mesh is created by processing the point cloud created by the recorded positions. Because of their great accuracy, contact 3D scanners are widely used in the industrial sector to examine parts and spot early assembly problems. However, because of their modest scanning speeds and the possibility of surface damage or alteration from physical contact, these scanners might not be appropriate for delicate objects like priceless artwork. An example of a CMM, showcasing its design and measurement capabilities, is represented in figure 9. (Ebrahim, 2015, p. 324)

Figure 9. New CMM allows ultra high-speed 5-axis scanning (S&H Machine, n.d.).



3.1.2 Non-Contact 3D Scanners

According to Ebrahim (2015), non-contact 3D scanners do not need to come into direct contact with the object to be scanned. These scanners record the surface information of the object using either active or passive techniques. This leads to the creation of an accurate point cloud that can be utilised for numerous purposes, including reverse engineering, virtual assembly, engineering analysis, surface and feature inspection, and fast prototyping.

To scan an object or environment, active scanners work by first generating radiation or light such as laser, ultrasound, or x-rays and then measures the reflection of the emitted radiation or light. Under the category of active scanning, Ebrahim (2015) discusses that 3D laser scanning is often divided into three primary groups according to how it operates: phase shift, time of flight, and laser triangulation.

- By calculating the round-trip time of light pulses, a laser rangefinder is used by a time-of-flight 3D laser scanner to accurately measure distances. To generate intricate 3D models, it scans its area of view one point at a time.
- By comparing the phase shift of reflected laser light to a standard phase, phase shift laser scanners calculate distances. This method offers more accurate and faster scanning than a vernier scale on a caliper, while still producing finer measurements. In contrast to time-of-flight scanners, phase shift laser scanners have a smaller range and generate noisier point clouds.
- Using a laser to illuminate a subject and a camera to determine the location of the laser dot, triangulation 3D laser scanners are an active scanning technology. To precisely locate the laser dot, the position of the dot fluctuates inside the camera's field of vision according to the surface distance, generating a triangle with defined lengths and angles. To obtain data more quickly, they frequently employ a laser stripe.

A multitude of technologies are used in the field of active non-contact 3D scanning, such as magnetic resonance imaging (MRI), computer tomography (CT), structured optical light, modulated light, and laser scanners.

In short, non-contact 3D scanning technologies that use active methods such as phase shift, time-of-flight, and laser triangulation enable precise object detail capture for a range of applications without the need for direct contact. These methods demonstrate the accuracy and versatility of contemporary scanning technology and are extremely helpful to sectors that require comprehensive models for research and prototyping.

Additionally, techniques for passive, non-contact 3D scanning do not include energy emission onto the subject. Instead, they rely on identifying background radiation that bounces off the item in a natural way. Because visible light is so readily available, the majority of scanners in this category focus exclusively on capturing it.

Rather than emitting radiation of their own, passive 3D scanners record and examine background radiation that is reflected from objects. While infrared radiation can also be detected, visible light is the type of ambient radiation that is most frequently detected. Because passive approaches are less expensive and frequently require regular digital cameras rather than specialised technology, they are advantageous. Stereoscopic video scanners, photometric scanners, silhouette scanners, and image-based modelling scanners are examples of common passive non-contact 3D scanner types. (Ebrahim, 2015, pp. 326–328)

3.2 Applications

3D scanning is essential to so many different applications that enhance various facets of our existence. It is an invaluable instrument in many industries due to its remarkable efficiency and precision. Several notable domains where 3D scanning is extensively implemented are:

- In medicine and healthcare, 3D scanning offers the creation of highly accurate 3D models for prosthetics, orthopaedic applications, and surgical procedures. This technology enables medical solutions to be tailored to patients' specific needs, significantly improving healthcare services' quality and efficiency.
- In historical preservation and archaeology, 3D scanning plays a critical role in digitally preserving historical artifacts and archaeological sites. It allows for the production of precise replicas of important cultural items, contributing significantly to restoration efforts and protecting heritages from the impacts of time and environmental changes.
- In the automotive and aerospace industries, 3D scanning is integral to designing, prototyping, and maintaining stringent quality controls, guaranteeing the precision and quality of part production, minimizing errors, and enhancing overall safety.
- In construction and architecture, 3D scanning is instrumental in the design and renovation processes, offering precise site surveys and structural analysis. This

technology significantly simplifies project planning and boosts the accuracy of architectural endeavours.

- 3D scanning is also a vital tool for manufacturing, facilitating reverse engineering and comparing finished products with their original design models, ensuring adherence to high-quality production standards, and fostering the development of innovative products.
- In education and research, particularly in anthropology, biology, and engineering, 3D scanning is an invaluable resource for in-depth study and experimentation, promoting active learning and meticulous analysis.
- In environmental studies and geology, 3D scanning aids in the examination of geographical formations and environmental locations, supporting research and conservation initiatives.
- In the arts, particularly in art and sculpture, 3D scanning is utilized by artists and conservators to digitize sculptures and artworks, aiding in their preservation, replication, or digital exhibition.
- Finally, for custom manufacturing, 3D scanning enables the creation of unique, tailor-made items, ranging from personalized furniture to custom automotive components, providing precise and high-quality custom designs. (Javaid et al., 2021, pp. 6–8)

As a result, 3D scanning is an innovative technology that offers accuracy and customisation to numerous industries. It ensures quality, speeds up the design process, and helps preserve historical sites and artefacts. This makes it a useful technology for research, innovation, and the creation of unique solutions in a variety of sectors, such as healthcare, automotive, and aerospace.

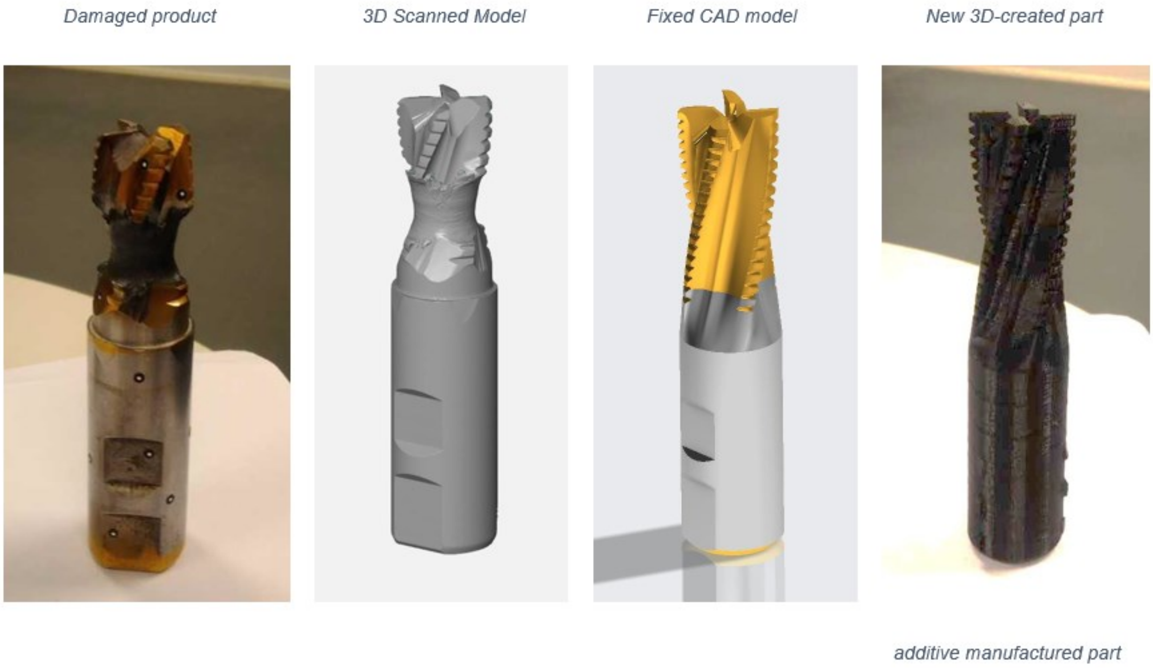
4 Reverse Engineering

Reverse engineering from the industrial point of view involves the process of creating a geometric CAD model from three-dimensional points that are obtained through scanning or digitizing existing parts or products. Numerous industries, including manufacturing, industrial design, jewellery making, and replication, heavily rely on this technology. For instance, automakers frequently buy new models from their rivals, dismantle them to learn about their design and functionality, and then incorporate this knowledge into their creations.

Physical items or clay prototypes can be swiftly transformed into digital versions by using reverse engineering. After that, the digital model can be improved upon, changed, and applied to production, tooling, or quick prototyping using methods like multi-axis CNC machining or additive manufacturing as visualized in figure 10.

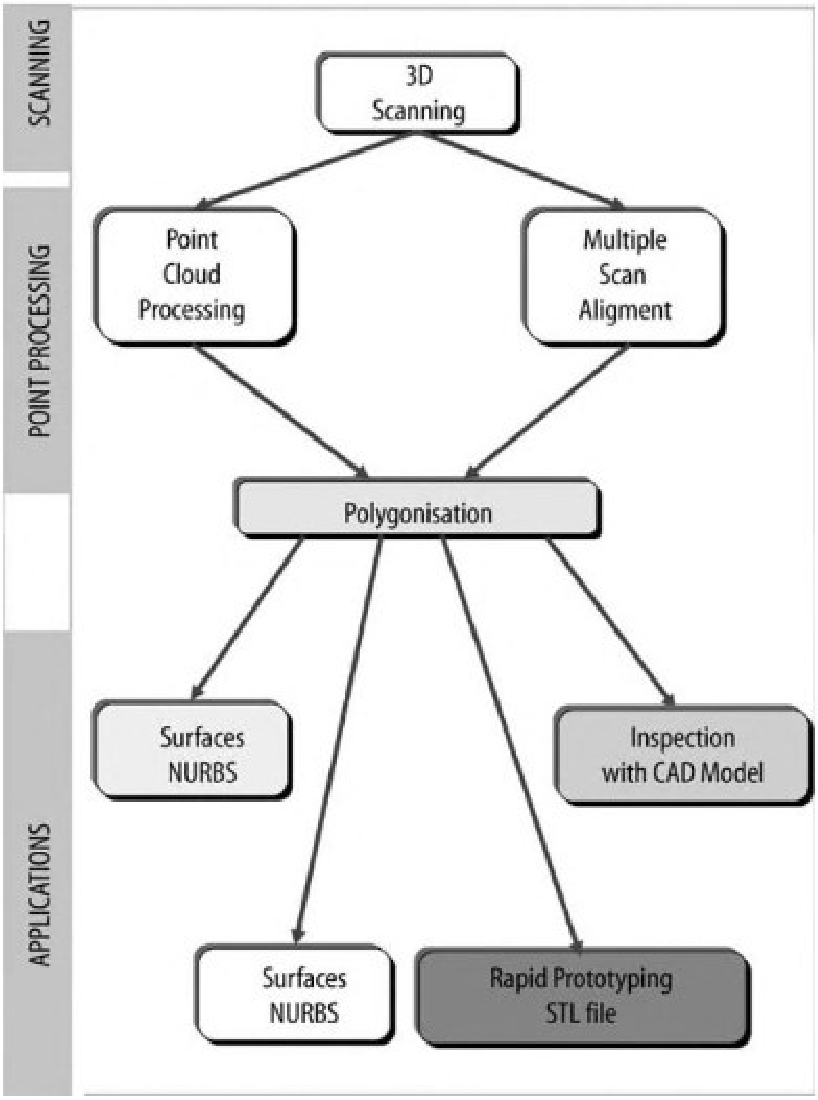
Reverse engineering is particularly useful when the original manufacturer has ceased operations, but there is still a demand for their product. Reverse engineering is also important for quality control and inspection procedures, as well as for determining the advantages and disadvantages of competing products. This makes it possible to innovate and make well-informed product design enhancements. (Raja & Fernandes, 2007, pp. 2–3)

Figure 10. Manufacturing of a new milling cutter (HAMK 3D Academy, personal communication, n.d.).



The process of reverse engineering is comprised of a three-phase process. The three phases are scanning, point processing, and application-specific geometric model development. (Raja & Fernandes, 2007, p. 4) Figure 11 shows a flowchart that describes the details of the reverse engineering process.

Figure 11. Reverse engineering, generic process (Raja & Fernandes, 2007, p. 4).



The steps demonstrated in figure 11 are as follows:

- 3D Scanning: The first step involves using a 3D scanner to capture the physical form of an object. This creates a set of data points that represents the surface geometry of the scanned item in space.
- Point Cloud Processing: A point cloud is a collection of vertices in a three-dimensional coordinate system, and this is how the raw data from the 3D scanner is obtained. To produce a useful model, these points must be analysed.
- Multiple Scan Alignment: To precisely depict the whole surface of the item, several scans that were collected from various positions or angles must be aligned and combined into a single point cloud.

- Polygonization, or Meshing: The point cloud has to be transformed into a polygon mesh in the following stage. Through the use of lines to join the points, a net-like structure made mostly of triangles is formed, giving the item a three-dimensional shape.
- Surfaces NURBS: Non-Uniform Rational B-Splines, or NURBS for short, are mathematical representations of three-dimensional geometry that can precisely model any shape, including intricate three-dimensional organic structures and basic two-dimensional lines, circles, and arcs. NURBS is frequently used to transform the polygon mesh into a smoother, more realistic surface representation.
- Inspection with CAD Model: The generated NURBS or polygonal model can then be compared to a CAD (Computer-Aided Design) model for inspection. This is to ensure the reverse engineered model matches the design intent or to inspect for any deviations from the original specifications.
- Rapid Prototyping STL file: The final model can be used to create an STL (stereolithography) file, which is a standard file format used for 3D printing. This file can be utilized in rapid prototyping to create a physical model of the object using additive manufacturing techniques.

In conclusion, this flowchart shows the process of 3D scanning an object through different data processing phases, culminating in a final model suitable for physical replication or examination.

Reverse engineering requires careful consideration of several critical factors to achieve precise replication of a component. These factors play a guiding role throughout the reverse engineering process and include:

- Purpose: The particular goal of the component's reverse engineering.
- Quantity to scan: Whether one part or several components need to be scanned.
- Part size: Measurements of the component.
- Part complexity: The component's degree of complexity, which ranges from simple to sophisticated.
- Part material: The degree of hardness and flexibility of the material.
- Surface finish: The gloss or matte reflectiveness of the part's surface.
- Shape and features: Part geometry, including whether it is prismatic or free-flowing organic, and how much emphasis is placed on internal versus external aspects.

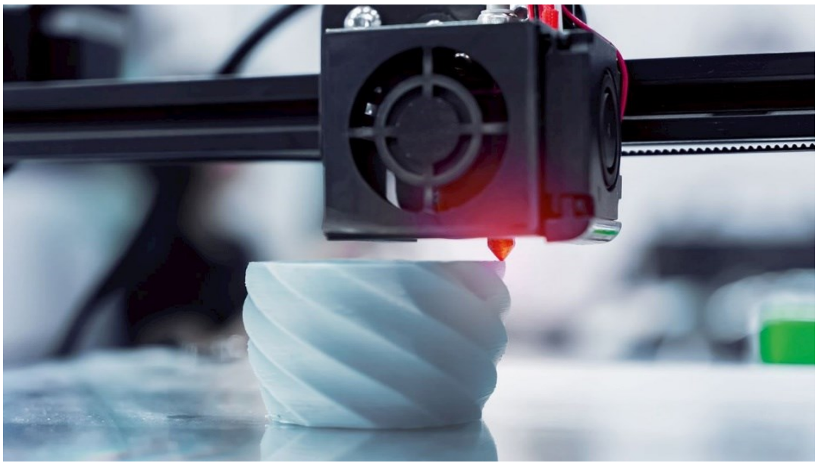
– Accuracy needs: The kind of precision needed in the measurement, such as volumetric accuracy in 3D spaces or linear accuracy in simple dimensions. (Raja & Fernandes, 2007, p. 5)

An analysis of these factors makes sure that the reverse engineering procedure is tailored to meet the specific requirements of the project. This careful consideration not only optimises resource use but also guarantees that the collected data is accurate and valuable, in line with the project objectives, and ensures the success of the reverse engineering project.

5 Additive Manufacturing

Additive manufacturing is a flexible technology that may be applied in different phases of the product development process. It provides methods that can be used to make tools, prototypes, and finished products that are ready for use. Beyond engineering, this cross-disciplinary technology is used in a wide range of industries, including the arts, toys, education, entertainment, and even the fields of medicine, architecture, archaeology, and cartography. (ISO 17296-2:2016, 2016, p. 5)

Figure 12. Additive manufacturing (ABB, 2020).



In additive manufacturing (AM), materials are fused in successive layers to create items using 3D model data. This sets it apart from subtractive and formative manufacturing methods. AM technologies are the three-dimensional counterpart of conventional two-dimensional printing because computers are essential to the conversion of digital models into physical items. This is why the term "3D printing" has become so popular. Over the last thirty years, AM has undergone various name changes, including additive fabrication, layer manufacturing, and rapid prototyping. These changes reflect its evolution and diverse applications. (Bourell, 2016, p. 2; ISO/ASTM 52900:2021, 2022, p. 1)

Additive manufacturing components have the unique ability to serve as both prototypes and final production parts. The choice of materials and processes used for prototyping and production depends on the nature of the part, its intended use, industry standards, and cost and delivery constraints. (ISO 17296-2:2016, 2016, p. 6)

5.1 Process Chains

The process of additive manufacturing involves the direct creation of components from 3D CAD data, thereby eliminating the need for intermediate steps. There are two distinct categories of additive manufacturing technologies:

- Single-Step Processes: In this process, the basic geometric shape and material qualities of the final product are achieved simultaneously while parts are constructed in a single operation.
- Multi-Step Processes: Parts in this category are made using two or more steps. Typically, the first phase creates the part's basic geometric shape, and the next processes concentrate on stabilising the part to obtain the necessary basic material properties. (ISO 17296-2:2016, 2016, p. 6)

5.2 Process Categories

The primary functional characteristics of the machines utilised in the processes define each of the seven categories of additive manufacturing techniques. These categories include a wide variety of processes, including layer-by-layer construction and material fusion or sintering using lasers or other technologies. Within each category, there may be variations in the materials utilised, output precision, and compatibility for different production applications. The categories of processes used in additive manufacturing are as follows:

- Vat Photopolymerization is an additive manufacturing technique where a vat containing liquid photopolymer is selectively solidified by means of light-induced polymerization.
- Material jetting is an additive manufacturing technique where building material droplets are selectively deposited.

- Binder Jetting is a technique used in additive manufacturing that involves using a liquid binding agent selectively to fuse powder materials.
- Powder Bed Fusion is a process used in additive manufacturing that employs heat energy to selectively melt and fuse parts of a powder bed.
- Material extrusion is the technique of distributing material selectively through a nozzle or other aperture in additive manufacturing.
- Directed Energy Deposition in additive manufacturing utilizes concentrated thermal energy to melt and fuse materials as they are deposited.
- Sheet Lamination in additive manufacturing involves bonding layers of material together to form an object. (ISO 17296-2:2016, 2016, p. 7–14)

To sum up, different additive manufacturing processes such as Vat Photopolymerization, Material Jetting, Binder Jetting, Powder Bed Fusion, Material Extrusion, Directed Energy Deposition, and Sheet Lamination provide unique methods of producing objects with different handling of materials, applications of energy, and layering procedures. This wide range of techniques shows how additive manufacturing may be customised for a variety of material kinds and design complexity. These techniques, which push the boundaries of manufacturing with their precise light-induced polymerization, intricate material jetting, and durable sheet lamination, offer creative solutions for everything from complex prototypes to useful final products.

6 Implementing Practical Applications

The practical applications of additive manufacturing, reverse engineering, and 3D scanning processes will be covered in the following chapters where each of these processes was applied by the author personally. Following that, the emphasis will be on creating a protective cover to safeguard the brake fluid pipe. The primary goal of this progression is to improve the safety of the brake fluid pipe that is connected to the brake caliper, which is the major objective of the thesis.

6.1 3D Scanning the Brake Caliper

Upon obtaining the brake caliper from the Sarlin Race Team, it was imperative to perform a 3D scan of the entire component. Through the use of modern 3D scanning technology, each contour and measurement of the brake caliper had to be properly registered. The aim was to translate the caliper's physical configuration into accurate digital geometric information.

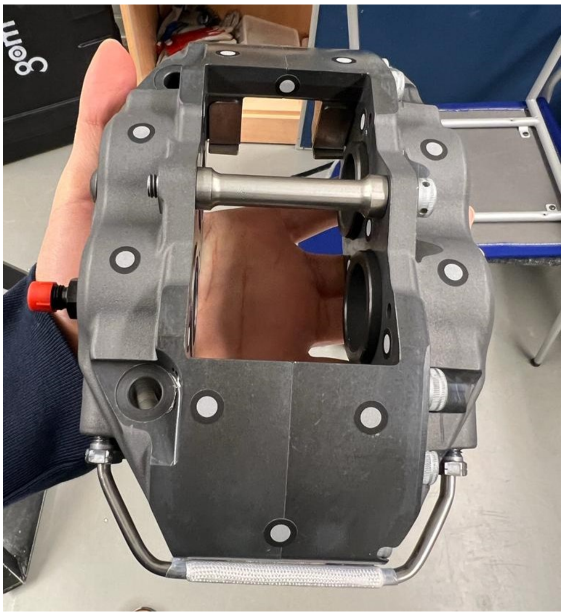
Following the import of this data into CAD software, a highly detailed and modifiable 3D model of the caliper was produced. This digital representation enables a smooth transition from an actual object to a flexible digital format that could be used in various phases of product development and testing, which was necessary for correct analysis, modification, and additional engineering work.

The 3D scanning procedure in this thesis made use of the precise and user-friendly Scantech AXE-B11 3D Hand Scanner which is a non-contact active structured light scanner (figure 13). Its user-friendly design increases operating efficiency and user comfort, which makes it perfect for large-scale scanning jobs. Its volumetric accuracy is advertised to be at 0.020 mm/m (Scantech, n.d.).

Figure 13. Scantech AXE-B11 3D hand scanner.

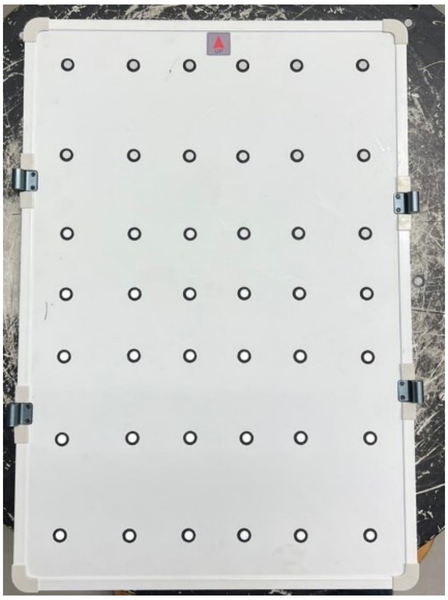
To start the process, setting up reference points on the product (figure 14) would be the first step, which enables many scans to be aligned into a single 3D model. For applications that require great spatial accuracy, these reference points act as trustworthy landmarks throughout a range of scans, ensuring precise alignment.

Figure 14. Reference points on the brake caliper.



The next step is to calibrate the hand scanner after setting the reference points on the brake caliper. The process begins by placing the calibration plate (figure 15) on a stable and flat surface, ensuring there are no reflective objects nearby that could interfere with the accuracy of the scanner. After that, the hand scanner is positioned so that it is perpendicular to the calibration plate at a distance of about 20 cm from the plate's centre. Once the scanner is positioned and turned on, the user follows the guidelines provided by the scanning programme, and the calibration is then performed accordingly.

Figure 15. Calibration plate.

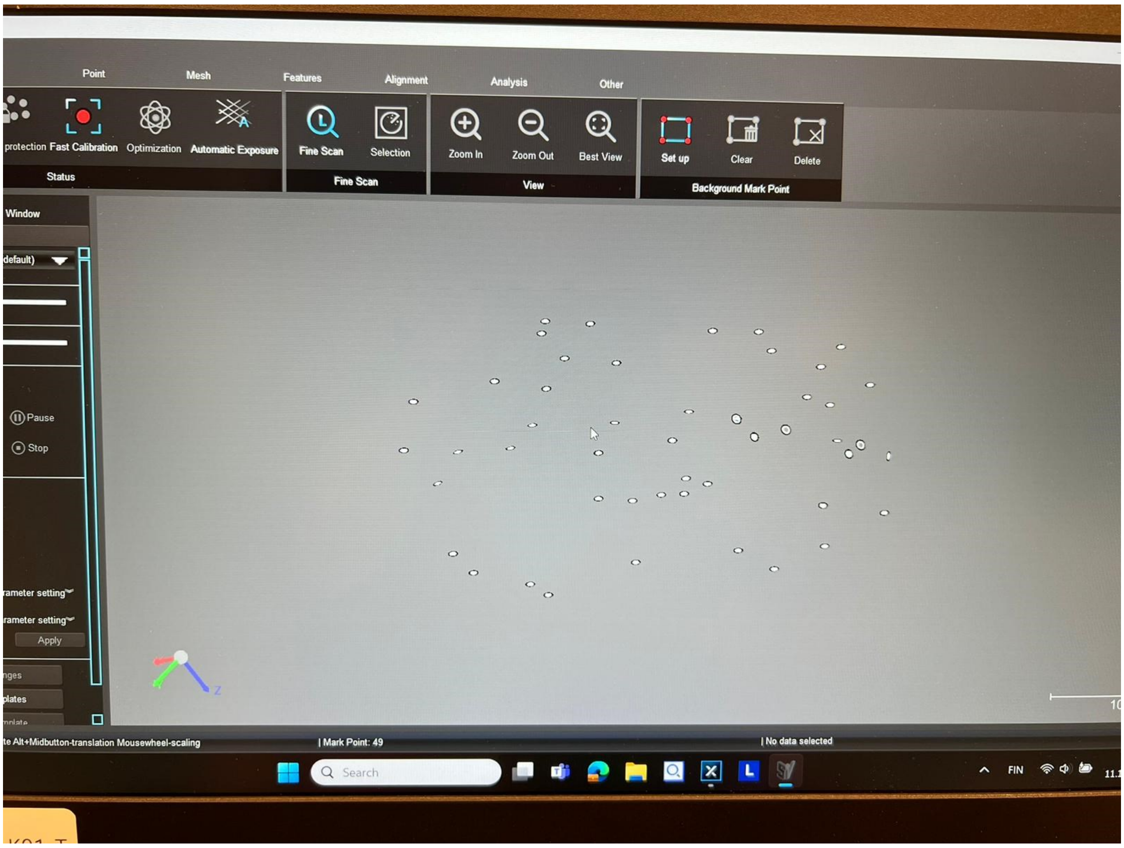


The following action in the 3D scanning process involves the adjustment of light exposure of the scanner (figure 16) as the sensitivity of the scanner to light is essential for capturing the features of the scanned object. When the scanner is pointed in the direction of the object to be scanned and is activated, the light exposure of the scanner is automatically set.

Figure 16. Automatic light exposure adjustment.

Afterwards, the scanner is used to locate every reference point on the product and its surroundings (figure 17). To integrate multiple scans, this step is essential for aligning at least three common reference points. Furthermore, by designating a particular scanning plane, the scanner can set a boundary that would narrow its focus to the region of the caliper, avoiding the need to collect data below the plane and creating a more accurate and useful 3D model.

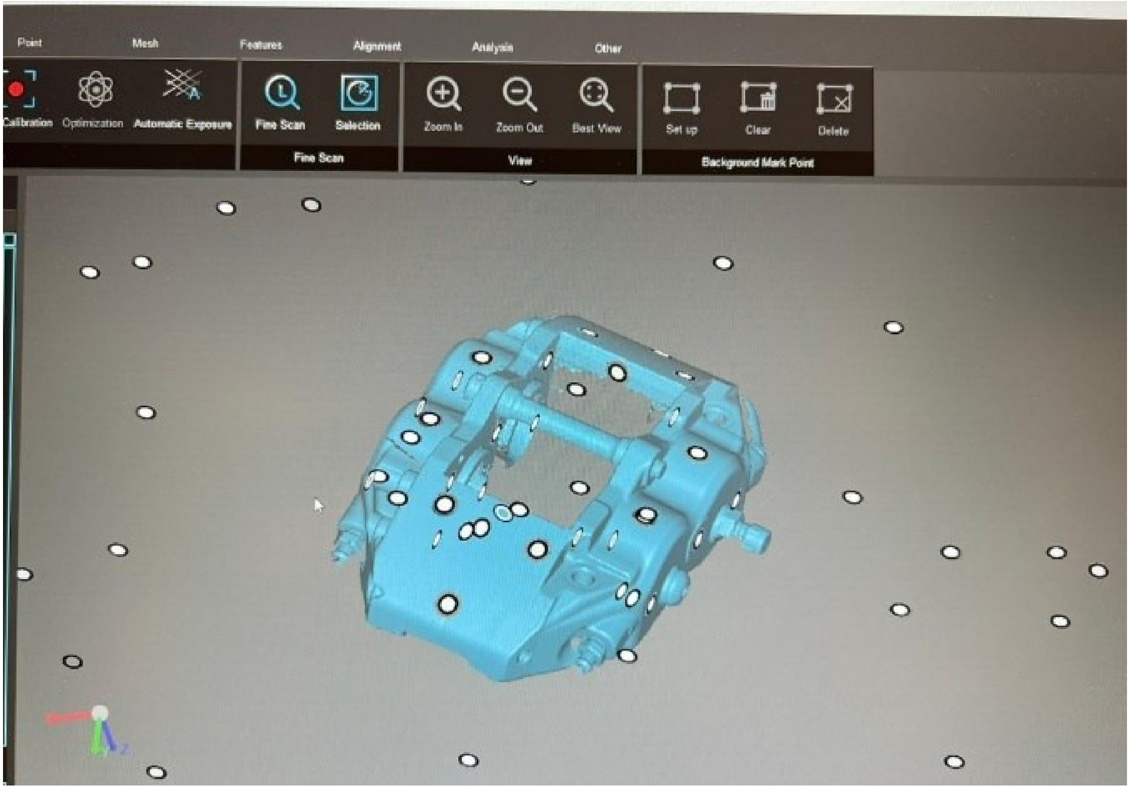
Figure 17. Scanned reference points.



Upon finalizing the initial setups and verifying scanner settings, the scanning of the brake caliper can begin. This process includes systematically moving the scanner around the caliper to capture a complete set of data. Once one side is scanned (figure 18), the caliper is turned over to scan the opposite side, ensuring no details are missed. However, it is helpful if any unnecessary mesh is deleted when scanning each side of the caliper.

The final step is to merge the data from both scans, creating a unified, detailed 3D model of the entire brake caliper. The merged model would provide a complete and detailed representation, essential for analysis or further applications.

Figure 18. Scanned part of the brake caliper.



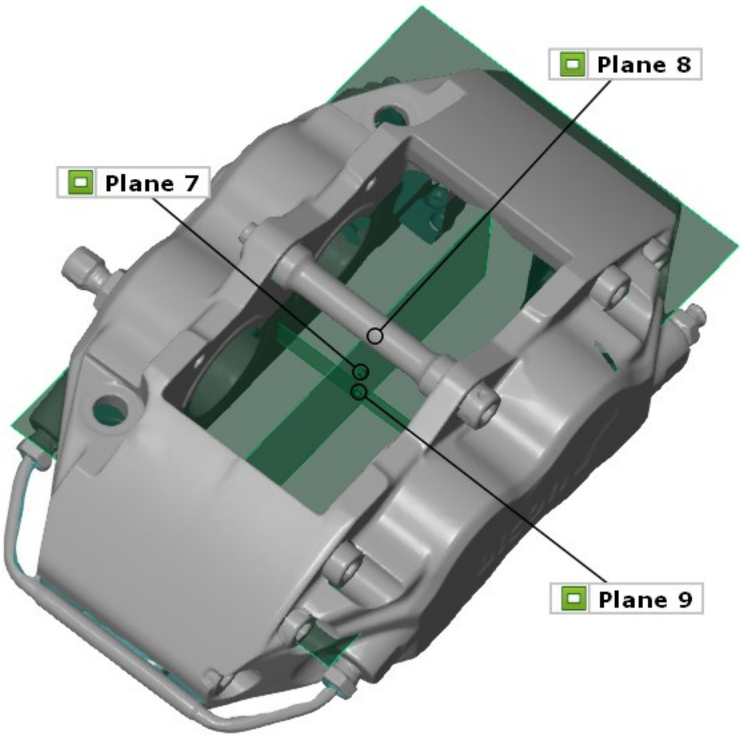
Improving the quality of the scanned image is the next stage where critical modifications are carried out to enhance optimisation and smoothness in addition to repairing little flaws such as scan gaps.

The final step in the 3D scanning process is saving the corrected scan in .STL file format, which works with a broad range of programmes, including CAD and 3D printing software.

6.2 Reverse Engineering in Practice

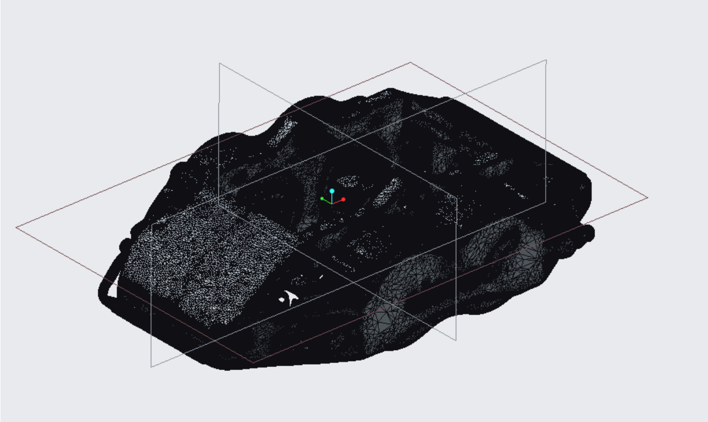
Upon receiving the .STL model of the brake caliper, the file was imported into GOM software (Zeiss GOM Metrology, n.d.), which is well-known for its superior 3D scanning, measurement, and analysis capabilities, capable of handling intricate geometric data with ease. In this phase, the software is used to precisely align the centre of the brake caliper model within the three-dimensional space defined by the X, Y, and Z coordinates. The geometric elements feature was used in the alignment which involves the creation of three intersecting planes ensuring that the model is accurately positioned in the software's workspace as depicted in figure 19.

Figure 19. Alignment using geometric elements feature.



Next, the aligned model was imported into CREO (PTC Creo, n.d.) seen in figure 20, a sophisticated CAD software. In CREO, the reverse engineering process began where the brake caliper model was analysed and modified by using the software's features. From 3D scanning to engineering design, the interface between GOM and CREO software is an example of an efficient workflow.

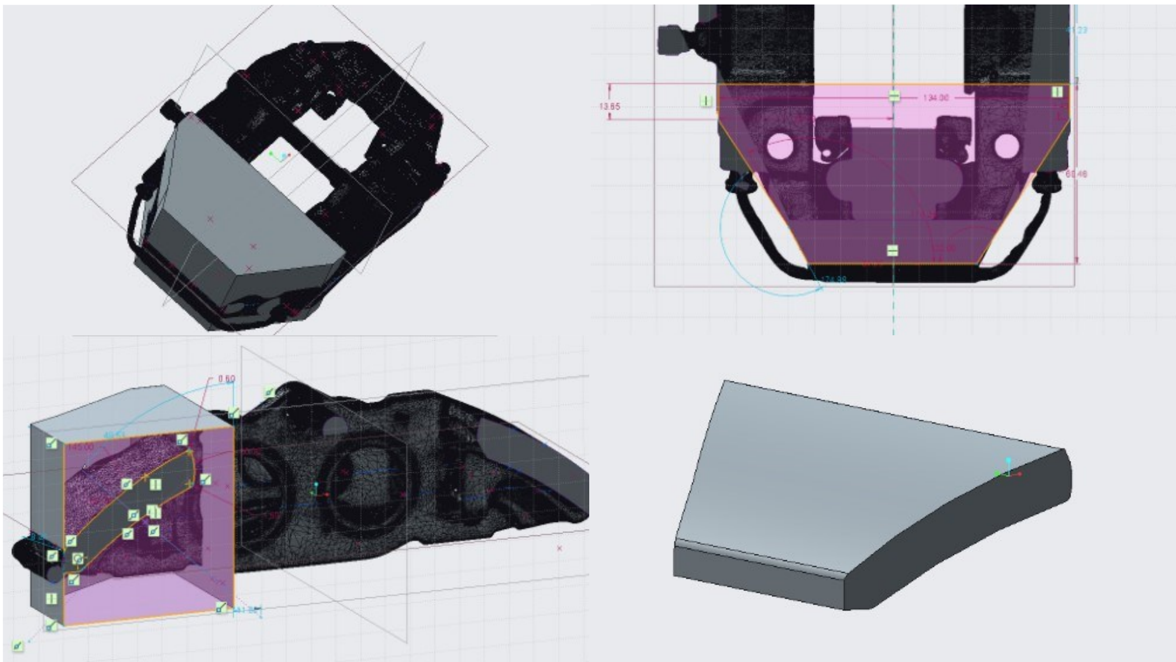
Figure 20. Aligned scanned model in CREO.



Having encountered challenges during the reverse engineering process as the first two attempts were unsuccessful, the author decided to concentrate primarily on the section of the brake caliper that was attached to the braking fluid pipe. This choice was motivated by the belief that concentrating on this specific region would reduce the possibility of creating errors and that no changes were intended for the other side of the brake caliper. In addition to that, time would also be saved. Therefore, only the side of the brake caliper that had the brake fluid pipe is developed for potential modifications, while the rest of the caliper will not be reverse engineered as it will remain unchanged, highlighting the importance of concentrating on this particular section.

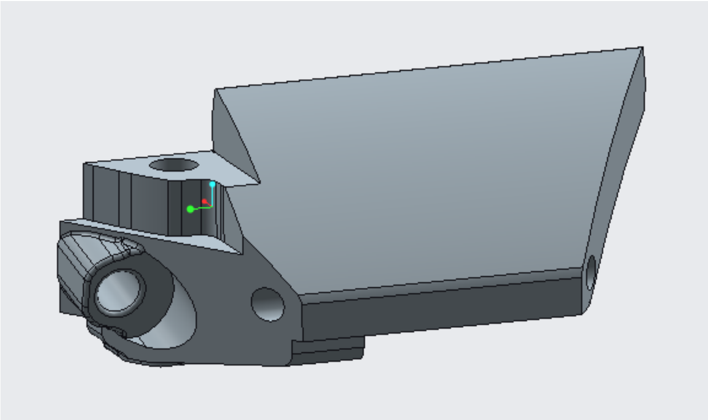
As seen in figure 21 where multiple images are shown, the reverse engineering was started such that a trapezoidal shape was extruded on the section of the brake caliper that is focused upon and material from that extrude was cut or added based on the data from the scanned brake caliper.

Figure 21. Different stages of the reverse engineering process (starting top right and anticlockwise)



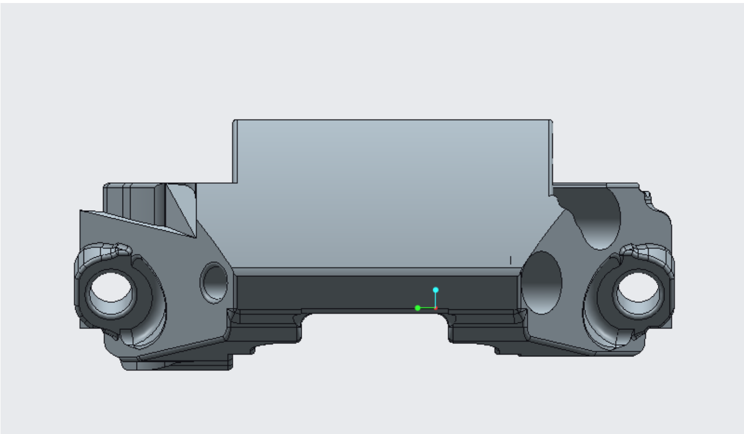
The reverse engineering method transitioned from one side of the component to the other as illustrated in figure 22 and figure 23 below. By focusing on one side at a time, a detailed examination of the complicated geometry was possible improving the accuracy and effectiveness of the reverse engineering process.

Figure 22. One modelled side of the brake caliper.



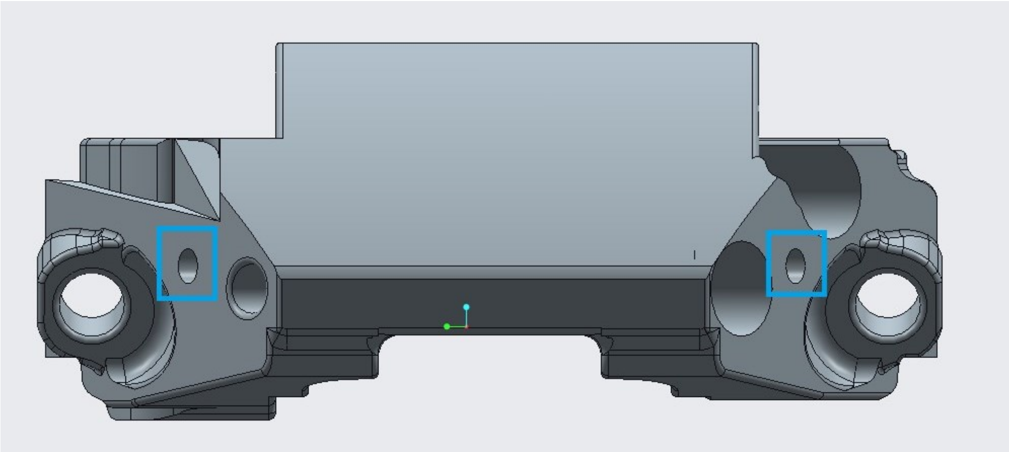
The reverse engineering of the brake caliper, as visualized in figure 23, where every geometric detail including the positioning of holes and the rounding of edges was carefully recreated. However, the brake caliper requires a specific modification where two holes are added near the brake fluid pipe. This is necessary as the protective cover would use the holes to attach to the brake caliper through screws or other fastening methods to ensure a secure and effective assembly.

Figure 23. Complete design phase of the specific section of the brake caliper.



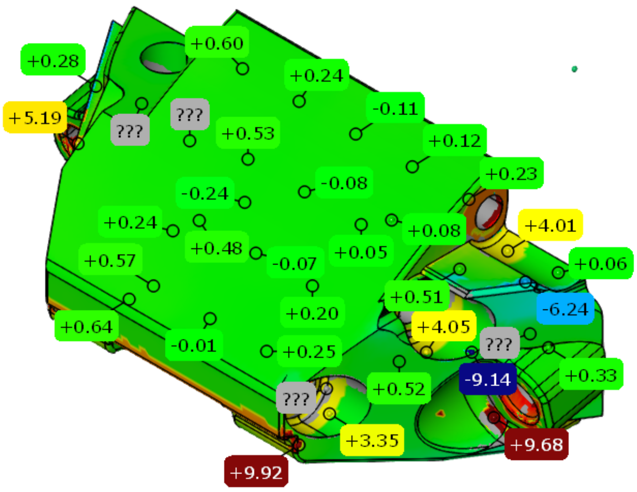
Initially, the project plan called for the use of M4 screws, which was mutually agreed upon by the author and the commissioning company. However, after considering the available space, it was found that larger screws, such as M6 screws, could be used instead as it would offer a more secure fastening in comparison to M4 screws. Other fastening methods, for instance, snap-fit connectors, quarter-turn fasteners, and other quick fastening techniques which are mentioned in the seventh chapter of the thesis were also researched, however, M6x35 hex head screws were selected, which comply with DIN 933 standards and require a 5.1 mm diameter drilling hole. Figure 24 presents the engineering design's adaptation of the additional holes.

Figure 24. Addition of 2 holes for the protective cover.



Following the completion of this phase, conducting a comparative examination between the reverse engineered model and the original 3D scanned model is a crucial step afterwards as it is important to validate the accuracy of the reverse engineered model with respect to dimensions and characteristics against the real physical part (figure 25). This allows for the identification of any differences and allows the possibility of conducting adjustments to guarantee that the reverse engineered model precisely reflects the real-based brake caliper in all aspects. To make this step easier, GOM software was utilized again.

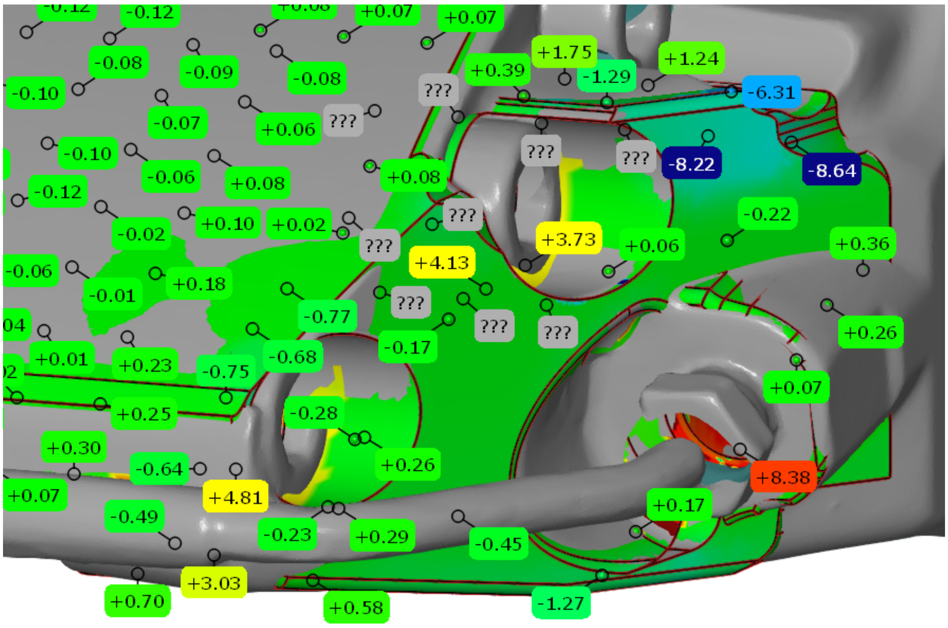
Figure 25. Scanned and reverse engineered brake caliper models comparison.



There are several similarities and distinctions between the reverse engineered CAD model and the scanned brake caliper displayed in figure 25. The question marks on the caliper indicate areas that might not have been scanned because of equipment limitations or the complicated design of the brake caliper. The green indicators suggest minor differences when comparing the scanned brake caliper to the CAD design, indicating a close match in those areas. Significant deviations are shown by red and blue marks, with red denoting a greater-than-expected material presence (positive variance) and blue denoting a material deficit (negative variance). Yellow marks indicate mild deviations. This color-coded mapping provides a straightforward visual assessment of the reverse engineering process' accuracy.

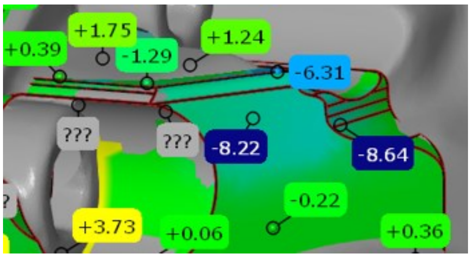
Throughout most of the geometry, the reverse engineering process appears to be accurate, as indicated by the minor deviations observed. However, yellow, blue, and red marks are present, and this is due to scanning inaccuracies that resulted in incorrect data. For example, only the holes where screws and bolts are placed are reverse engineered and not the fasteners themselves, and as a result, false data is registered thus there are the existing blue and red marks (figure 26).

Figure 26. A close view of the comparative analysis.



In addition, the area shown in figure 27 is correct in terms of inaccuracy and that is because the reverse engineering process in that area was not very precise due to the complex geometry of the actual brake caliper. Nonetheless, this is not a problem as that area is just for demonstration purposes and was not utilized to serve the thesis.

Figure 27. Inaccurate reverse engineered area.



As a conclusion, in the reverse engineering of the brake caliper, the effective utilization of GOM and CREO software is demonstrated in the recreation of a detailed digital model. The comparative analysis between the 3D scanned model and the reverse engineered model in GOM software reveals the precision achieved and the areas of deviation marked by a color-coded system. This detailed examination resulted in the necessary modifications for attaching the protective cover, confirming the successful adaptation and validation of the reverse engineered brake caliper.

6.3 Producing the Reverse Engineered Brake Caliper: Additive Manufacturing

After performing reverse engineering and a comparative investigation of the brake caliper part, the next stage involved using additive manufacturing to physically manufacture the component as it transforms the computer-digitalized design into a physical product.

After completing the reverse engineering process, the CAD model was transformed into an .STL file once again, setting the stage for 3D printing. Responsibility for this file, including its management and the supervision of the printing operation, was entrusted to a faculty member overseeing the 3D printing laboratory. The chosen method for 3D printing the model was Fused Deposition Modelling (FDM), a material extrusion additive manufacturing technique that fabricates objects by heating and extruding thermoplastic filaments layer by layer.

For this project, PET-G (Polyethylene Terephthalate Glycol-modified) was selected as the printing material. PET-G has a modulus of elasticity ranging from 1.1 GPa to 20.3 GPa (Matweb, n.d.), and a Poisson's ratio of approximately 0.35 to 0.40. However, the values can vary slightly based on the specific brand of filament used and the precise settings of the 3D printer. The final product can be observed in figure 28.

Figure 28. Additive manufactured brake caliper.

7 Designing the Protective Cover for the Brake Fluid Pipe

This section of the thesis focuses on the design process of a protective cover for the brake fluid pipe. It outlines the steps taken from the initial concept to the resolution of design challenges and the completion of the final design. Once the brake caliper part was successfully constructed and the necessary modifications were completed, the attention was shifted to designing and creating the brake caliper cover.

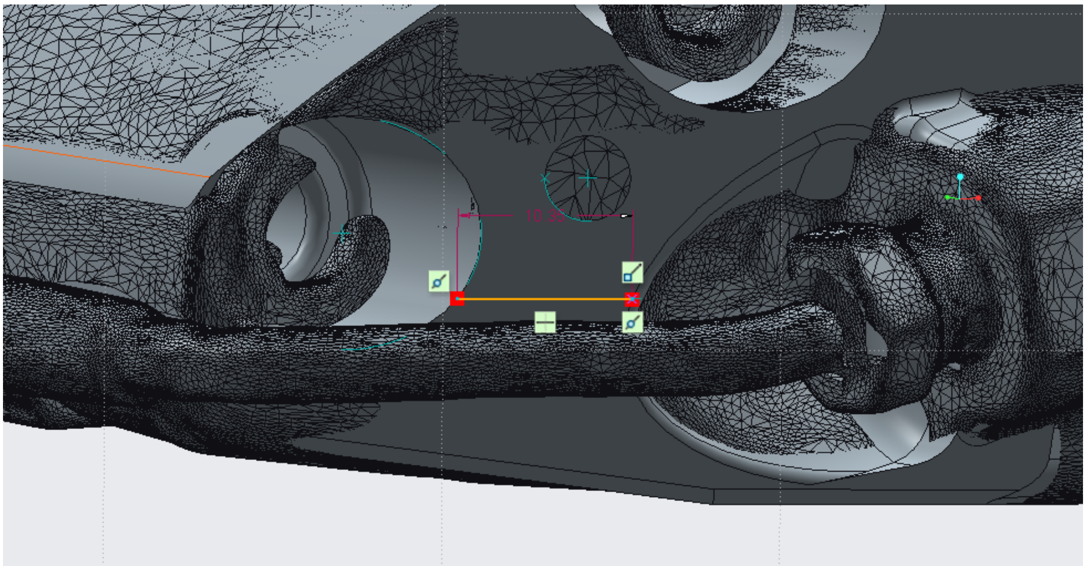
This stage of the project spanned roughly one month, during which a multitude of design concepts were developed. Numerous prototypes were constructed and presented to the Sarlin Race Team company for consideration which will be presented at the end of this chapter. The purpose of the cover is to protect the brake fluid pipe from environmental threats such as rocks, sand, dust, and other debris. By preventing debris from jeopardising the integrity of the brake system, this design phase seeks to maintain the protection of the brake fluid pipe located on the brake caliper to preserve optimal operation in a variety of settings, in addition to improving its durability. As a result, this cover is crucial to maintaining the dependability and security of the brake caliper.

7.1 Design Brainstorming

One of the most significant factors to consider when starting a product design process is how simple the finished product will be to manufacture and use. Designed to be compatible with efficient production methods, the product to be designed will not only reduce manufacturing costs but also facilitate the assembly process and offer the possibility of future expansion.

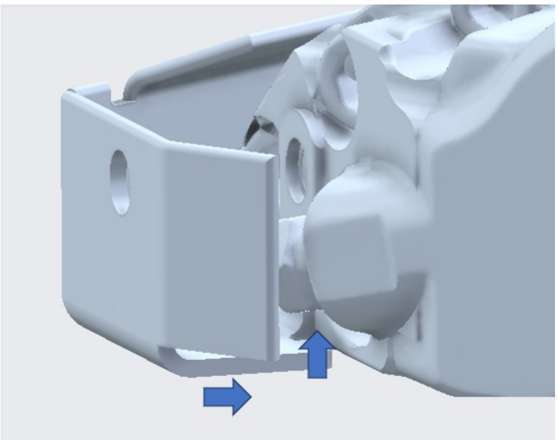
In the initial stages of designing the protective cover, it was essential to carefully consider the installation space when creating the protective cover. There was a restricted space where only around 10 mm of space in the area was provided, as figure 29 illustrates. Moreover, the location of the fluid pipe presented a unique difficulty. This limitation affected the design process, necessitating a blend of imagination and pragmatism to maximise space utilisation without compromising the cover's protective capabilities.

Figure 29. Limitation of space and brake fluid obstruction to certain design approaches.



To address this difficulty, it is possible to insert the cover by sliding it beneath the brake fluid pipe, as figure 30 shows. This method was specifically created to effectively manage spatial constraints. Furthermore, to provide a strong connection, it is necessary to firmly affix the cover. To securely attach the cover to the brake caliper, it is therefore equally important to select an efficient fastening method.

Figure 30. A solution to the obstructing brake caliper pipe when designing the protective cover.



In addition to establishing the foundational design approach for the protective cover, selecting the suitable fastening method for attaching the cover to the brake caliper is equally important. Screws were identified as the superior fastening mechanism in comparison to snap-fit connectors, quarter-turn fasteners, and other quick fastening techniques. The following are strong arguments in favour of this:

- Sturdiness and Stability: Screws offer a sturdy mechanical bond that is resilient to stresses and vibrations that are typical of brake caliper settings.
- Accuracy and Adjustability: Screws enable accurate installations and the capacity to make small changes to guarantee a perfect fit. This is especially crucial in confined areas or other situations where precise alignment is essential.
- Longevity: Compared to snap-fits, which may deteriorate with frequent use, threaded screws are more resilient and have a longer lifespan. They also offer a more stable grip.
- Serviceability: The brake caliper and fluid line can be easily maintained or inspected without jeopardising the integrity of the cover or the attachment points thanks to the easy removal and replacement of screws.
- Stability: When subjected to the extreme heat and strain of a braking system, screws are more dependable than plastic snap-fit components, which are more susceptible to mechanical and thermal damage.
- Compatibility: The material of the screws can be matched to that of the brake caliper cover, guaranteeing that choices resistant to corrosion are available for harsh locations.

With their many benefits, screws are the finest option for securely mounting a brake caliper cover since they offer the right mix of dependability, longevity, and user-friendliness. The consideration of quick fastening methods, for example, snap-fit connectors and quarter-turn fasteners, presents its own set of challenges. These techniques would necessitate intricate internal geometries within the brake caliper, which could only be feasibly implemented during the initial production phase of the caliper itself. Furthermore, these intricate modifications may compromise the brake caliper's structural integrity. Adding possible weak areas is not a good idea because preserving the caliper's strength is fundamental. This is an important consideration, particularly in light of the caliper's critical function in vehicle performance and safety. Consequently, the benefits outlined above justify the decision to utilize M6x35 screws in this project.

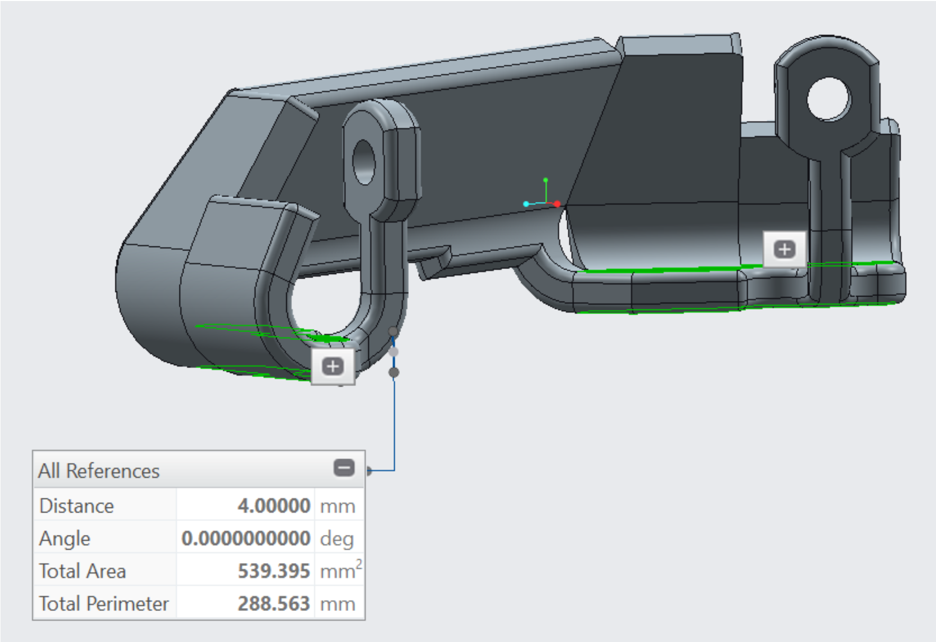
7.2 Planning the Design’s Manufacturability and Properties

Given the fact that the cover's design must slide underneath the brake fluid pipe, this would mean that specific angles or bends are necessary to apply in the design. Thus, utilizing sheet metal processes is identified as the optimal approach for this task. Sheet metal is favoured for its flexibility in shaping through techniques such as bending, punching, and cutting. Hence, the thickness of the protective cover is one characteristic that must be thought of so that bending operations and water or laser cutting methods could be applicable.

It is important to consider several elements while using sheet metal methods for production. Some of these factors are the thickness of the cover, which directly affects its protection and durability; the choice of material, which determines the cover's resistance to corrosion and environmental effects; and the design of the cover, which influences its functionality, ease of installation, and compatibility with the existing structure. To make sure that the protective cover satisfies the necessary requirements and performance standards, each of these components is essential.

During the designing phase, careful consideration of the cover's thickness was given, which was initially set at 4 mm as demonstrated in figure 31. However, it was later decided to thin the cover to 2 mm as it was challenging to bend a material that was 4 mm thick. In particular, the bending procedure may become challenging or perhaps impossible at this thickness, especially if the design of the cover leaves insufficient room for the bending operation to be completed successfully. This modification emphasises how pivotal it is to match design specifications with realistic production limitations to guarantee that the cover can be manufactured effectively and still fulfil the required standards.

Figure 31. Thickness of sheet metal to be used in the early protective cover model.



Additionally, selecting the right material for the protective cover was significant as it also plays a role in terms of the durability and longevity of the protective cover. For that reason, after weighing the advantages and disadvantages of several options, two main contenders surfaced: Grade 5 titanium alloy Ti-6Al-4V and stainless steel 316. Every material had distinct benefits of its own, thus choosing the best material for the particular requirements of the cover required careful consideration. Following extensive deliberation, stainless steel 316 was selected as the material most appropriate for the project. Some of the factors that made stainless steel 316 superior to titanium alloy include the following:

- Corrosion Resistance: Stainless steel 316 is highly resistant to corrosion, especially against chlorides and other industrial chemicals. This makes it an ideal material for use in harsh environments, ensuring the cover's long-term integrity.
- Durability and Strength: The robustness of titanium alloy and stainless steel 316 is well known. Nevertheless, stainless steel 316's strength-to-weight ratio is sufficient to satisfy the protective cover's criteria without requiring the more expensive titanium alloys.
- Cost-Effectiveness: The primary limitation of adopting titanium has been its relatively high cost (Boulton & Betts, 1991, p. 287). Compared to stainless steel 316, titanium alloys have significantly higher manufacturing and raw material costs. Stainless steel 316 shows up as a more cost-effective solution that nonetheless satisfies the project's

requirements for durability and corrosion resistance when the special advantages of titanium are not necessary.

- Fabrication Ease: Stainless steel 316, in contrast to titanium alloys, may be easily processed for cutting, welding, and shaping using standard production procedures without the need for specialised tools. This flexibility in manufacturing can speed up production schedules and save a lot of money.
- Material Availability: Stainless steel 316 is widely accessible in a variety of shapes and sizes, which simplifies the purchasing procedure and may result in cost savings.

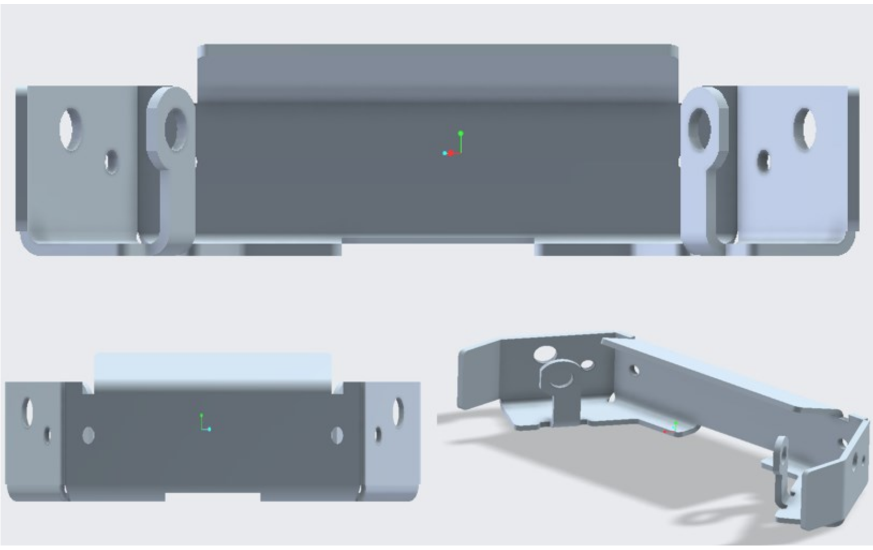
Although titanium alloys are distinguished by their exceptional strength-to-weight ratio and superior corrosion resistance, stainless steel 316 is the best material for this application due to its cost-effectiveness, adequate strength, robust corrosion resistance, and ease of manufacturing.

Once the material, thickness, and design limits are understood and decided upon, the protective cover designing phase can begin. This step involved using the chosen material for strength, setting the right thickness, and working within design boundaries to make sure the product succeeds in its purpose efficiently.

7.3 Design Phase

Following input from the commissioning company and the academic advisor, the main protective cover model that is depicted in figure 32 was created.

Figure 32. Main design of the protective cover.



The model was designed on the basis of having three bending operations, CNC rounding, and the option to involve welding to ensure durability and strength, resulting in an overall weight of approximately 0.133 Kg. The cover is then to be fastened to the brake caliper using two M6X35 screws and M6 washers to reduce vibrations. However, in line with the Sarlin Race Team company's preference for a design devoid of any welding, the original concept was expanded to include a broader range of variations. These new versions were developed to offer both welded and non-welded alternatives, each enriched with additional features to maintain the cover's integrity and functionality while accommodating the company's specific requirements.

Two optional features that could be incorporated into the protective cover were developed. These two additional features offer distinct characteristics that enhance the overall solution provided to the Sarlin Race Team company.

7.3.1 Cylindrical Tube

The design involves a cylindrical tube, as illustrated in figure 33, positioned inside the cover at a strategic position. The tube is 23 mm long, with an outside diameter of 7.2 mm and an interior diameter of 6.4 mm. This tube is positioned to serve as a conduit for the screw, improving the cover's foundational strength by minimising the possibility of bending during the fastening procedure which is clear in figure 34. There are various techniques that can be used to insert this reinforcement tube into the cover, such as welding, adhesives, or using an interference fit, also known as a friction fit. Every technique provides a different way to guarantee the tube's tight fit, adding to the cover's overall robustness and performance while meeting different manufacturing needs and preferences.

Figure 33. Illustration of the cylindrical tube support and its position in the protective cover.

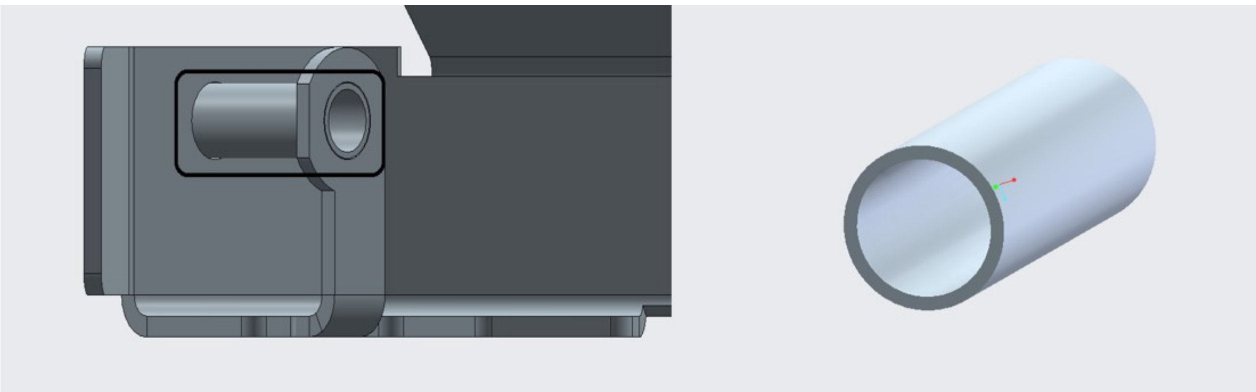
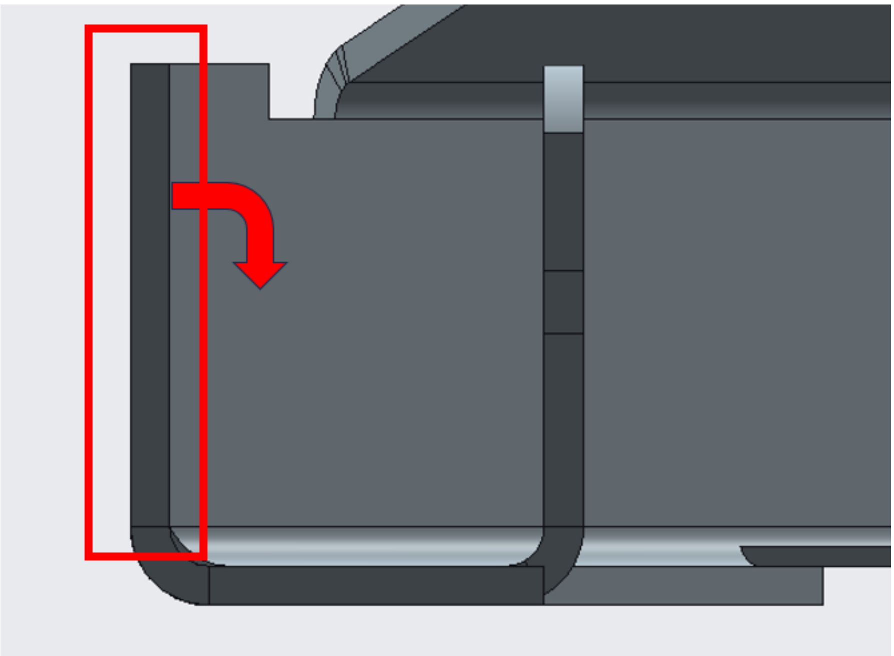


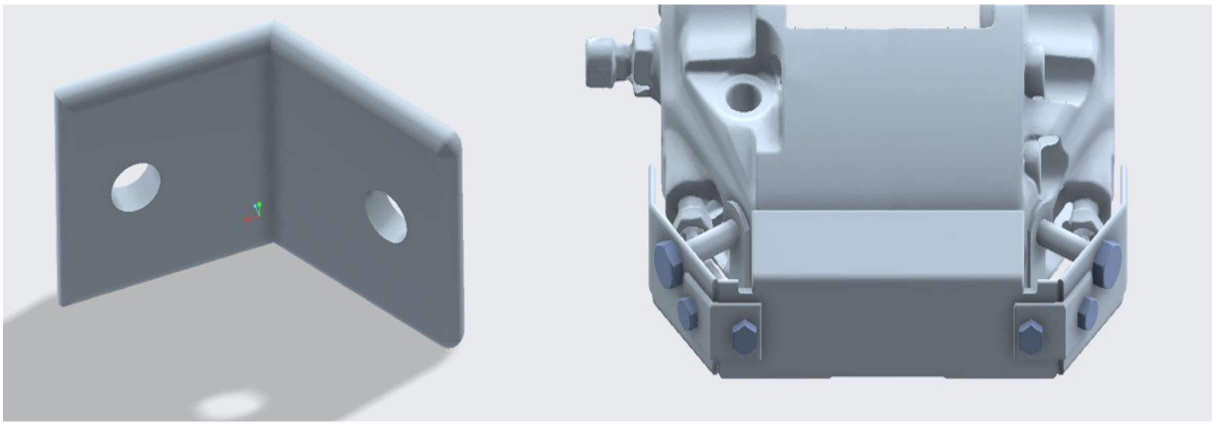
Figure 34. Bending of the sheet metal wall while fastening.



7.3.2 Reinforcement Plates

Addition of a 2 mm thick reinforcement plate (figure 35) where two M4x10 screws can be inserted with the usage of M4 nuts to replace welding and strengthen the overall structure of the cover. The cover would require two of these reinforcement plates, thus, 4 M4x10 screws and 4 M4 nuts would be needed.

Figure 35. Depiction of reinforcement plates that can be added to the protective cover.



7.3.3 Bonus Feature for the M6 Screws Used in Fastening the Protective Cover.

It is suggested to also use a general-purpose thread locker that forms a medium-strength bond to strengthen the screws' resistance to loosening due to shock and vibration. Loctite 243 (figure 36), which was created especially for this use, provides a suitable illustration of a thread locker.

Figure 36. Loctite® threadlocker blue 243 – medium strength (Loctite, n.d.).

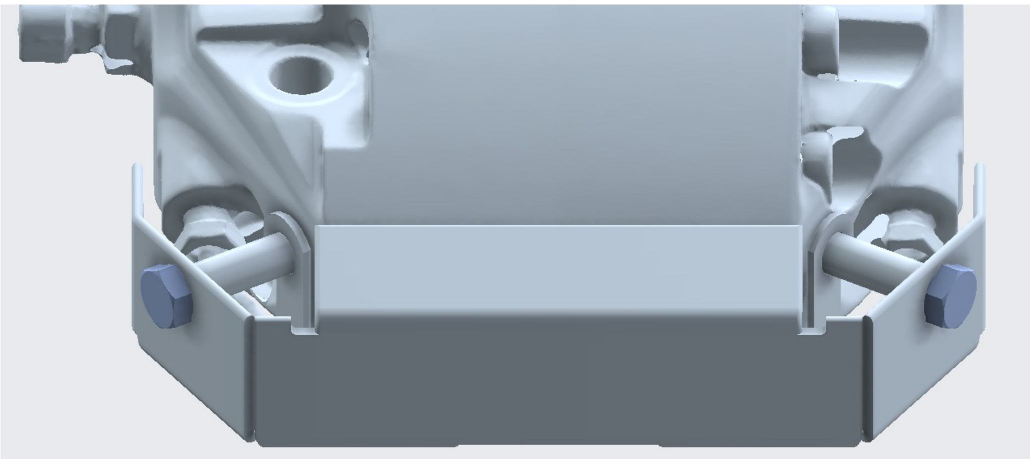
7.4 Prototypes

The company was presented with eight alternative versions of the cover, all of which were based on the same core design concept. However, these prototypes differed in their construction details, such as the inclusion of welding, the addition of reinforcement plates, or other unique features. Each prototype was created to investigate different methods of achieving the desired functionality and strength, providing the company with a variety of possibilities to evaluate.

7.4.1 Prototype 1: 2 Tubes, 6 Welds, No Reinforcement Plates

Prototype 1, depicted in figure 37, includes the additional cylindrical tubes to improve stability but otherwise adheres to the cover's fundamental design. The purpose of the strategic placement of these tubes is to avoid any potential bending during the fastening procedure of the two M6x35 screws. Six welding operations are to be executed in this variant. To ensure that the three portions of the cover form a cohesive unit, two of these welds are to be used to join them. The additional pipes are then firmly fastened to the structure using the remaining four welds, enhancing its robustness and ability to withstand physical strain.

Figure 37. Prototype 1



7.4.2 Prototype 2: 2 Tubes, No Welds, No Reinforcement Plates

Prototype 2 keeps the cover's basic shape and includes the two cylindrical tubes to strengthen its construction and prevent deformation by maintaining the rigidity of the cover when two M6x35 screws are tightened. The tubes are carefully positioned and fastened into position using either an interference fit for a snug insertion or powerful adhesives for a solid bond. However, this prototype does not involve welding operations or reinforcement plates.

7.4.3 Prototype 3: No Tubes, 2 welds, No Reinforcement Plates

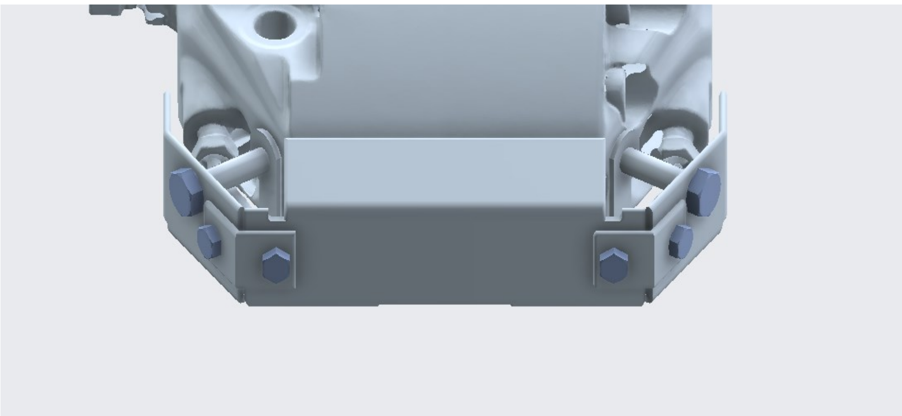
By eliminating the tubes, prototype 3 simplifies the design of the cover. This approach focuses on the underlying structure that preserves the natural form of the cover. The overall strength of the cover is enhanced by two strategically placed welds (figure 38) that combine its three parts, reinforcing the design. Two M6x35 screws are inserted straight into the assembly to finish it off; tubes are not needed. This optimised method puts an emphasis on a straightforward assembling process while maintaining the cover's robustness and capacity to bear the stresses incurred during operation.

Figure 38. Location of the two welds in blue on prototype 3.

7.4.4 Prototype 4: No Tubes, No Welds, Reinforcement Plates

Prototype 4 (figure 39) is designed to be simple by eliminating the tubes and welding operations. Rather, it has two reinforcement plates that fasten to the cover directly with four M4 screws and matching M4 nuts. A pre-drilled 3.3 mm diameter hole is threaded to fit the M4 screws into both the plates and the cover. By providing structural support without the need for welding, this technique speeds up assembly while preserving the integrity of the cover. Two M6x35 screws are used to finish the installation, eliminating the need for tubing, and guaranteeing a simple and sturdy construction.

Figure 39. Prototype 4.



7.4.5 Prototype 5: 2 Tubes, No Welds, Reinforcement Plates

To increase stability and prevent bending when tightening the two M6x35 screws, prototype 5 adopts the design of the main cover, which includes the two cylindrical tubes and reinforcement plates. To provide a tight and immovable assembly, the tubes are positioned strategically and secured in place using adhesives or by producing an interference fit. Two plates that are attached to the cover with four M4 screws and nuts further boost its rigidity. The 3.3 mm diameter precision-drilled holes on the plates and the cover are threaded to fit the M4 screws, which eliminates the need for welding while offering adequate reinforcement and support.

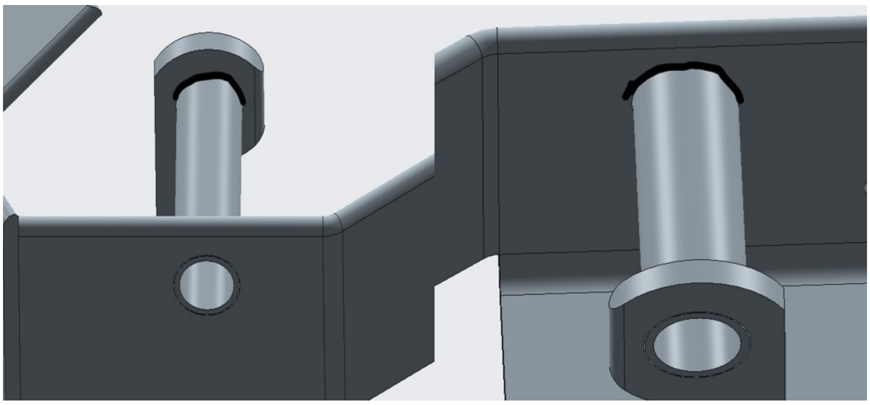
7.4.6 Prototype 6: No Tubes, No Welds, No Reinforcement Plates

Prototype 6 is a simple design that terminates away the tubes, welds, and reinforcement plates while maintaining the cover's basic structure. Easy assembly and maintenance are ensured by the two M6 washers and two M6x35 screws used to secure the cover. The cover's design prioritises ease of installation and simplicity, relying on the material's inherent strength and precision engineering to ensure enough protection and preserve the integrity of the cover.

7.4.7 Prototype 7: 2 Tubes, 4 Welds, Reinforcement Plates

The design of prototype 7 contains multiple reinforcing features within the main structure of the cover. To avoid any flexing of the cover while the two M6x35 screws are tightened, this design integrates the two cylindrical tubes. To strengthen the assembly's structural integrity and secure the tubes, four welding operations are added (figure 40).

Figure 40. Welding sites on a single tube for prototypes that require tube welding.

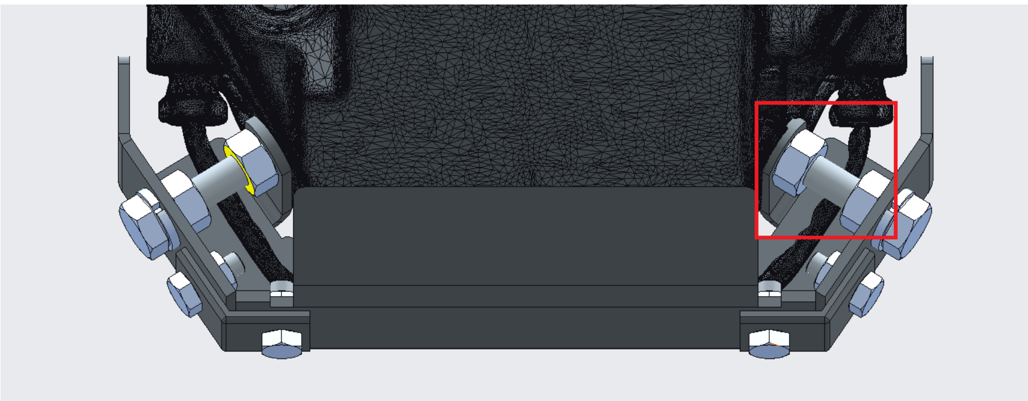


There are two reinforcement plates included to increase the rigidity of the cover and replace the welding of joining the 3 walls of the cover. Four M4 screws and nuts are used to precisely fasten these plates, and 3.3 mm diameter holes are bored through both the plates and the cover before being threaded to accommodate the M4 screws. This creates a strong and long-lasting protective cover by fusing the extra strength and stability supplied by the plates with the stability given by the welded cylindrical tubes.

7.4.8 Prototype 8: No Tubes, No Welds, Reinforcement Plates, M6 Nuts

The idea behind prototype 8 is the same as that of prototype 5, with one significant exception: instead of employing two tubes, two M6 nuts are used for each M6 screw (figure 41). This version was created later after it was determined that adding the tubes may complicate the process of manufacturing. Their fabrication becomes necessary because there are no commercially available products that match the dimensions of the tubes. Nevertheless, making the cylinders can take more time and lead to an increase in potential financial implications.

Figure 41. Prototype 8 showing the location of the 2 M6 nuts.



In summary, the eight prototypes that were shown to the company offer a thorough investigation of several design and construction approaches for the protective cover. Despite differences in how the cylindrical tubes, welding operations, and reinforcing plates are used, every model was engineered to maximise functionality, longevity, and ease of installation.

7.5 Selecting the Ideal Prototype for Advancement

In the provision for choosing the best prototype for the brake caliper cover, it is necessary to weigh simplicity, effectiveness, and efficiency against the commissioning company's specific criteria. After taking into account the company's preference to avoid welding, prototype 8 emerged as the leading candidate. It ensures the stability and support of the brake caliper by using 4 M6 nuts and 2 reinforcing plates. Replacing each cylindrical tube with 2 M6 nuts for every M6 screw would lessen the time and cost needed to produce the cover as nuts are commercially available, unlike the specifically dimensioned cylindrical tube. In addition to that, the only components that would be needed for prototype 8 besides the main frame of the protective cover are the two reinforcement plates, unlike other prototypes that involve welding, cylindrical tubes, or both.

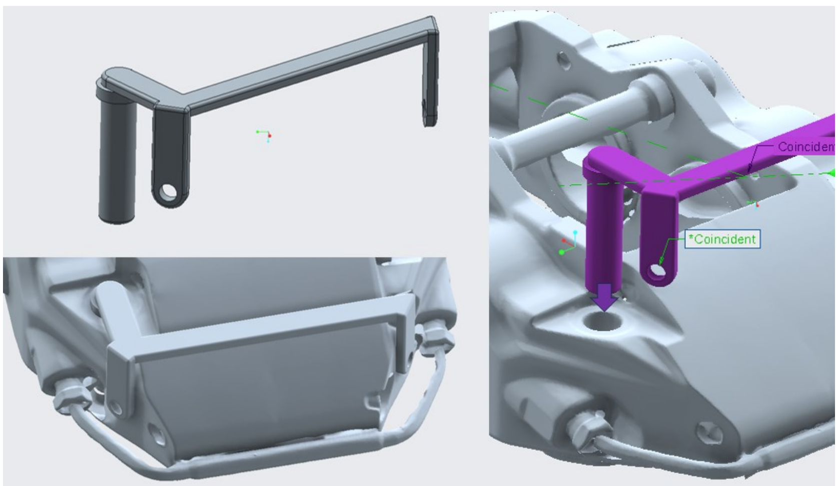
On the other hand, prototype 1 is notable for its robustness in situations when welding is allowed. The brake caliper's support is much improved by the welding and tubes together, which removes the requirement for reinforcement plates. Because of this, prototype 1 is also incredibly durable and dependable.

Following careful consideration, prototype 8 was chosen due to its overall efficacy and adherence to the company's no-welding policy. Following the company's approval, CAD files for prototype 8 were prepared for prototyping using additive manufacturing techniques, moving the project forward with a design that promises both simplicity and strength.

7.6 Drilling Jig

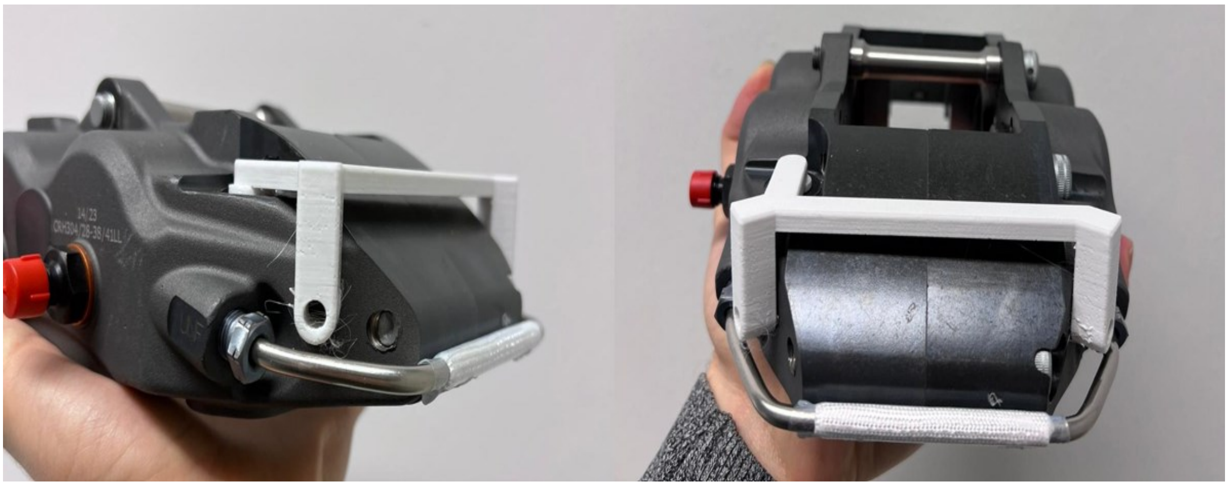
A drilling jig must be created to guarantee precise hole creation in existing similar brake calipers. To come up with a practical design, it is necessary to closely inspect the caliper's surroundings. A hole that goes all the way through the left side of the caliper is noticed during this procedure and it is deduced that this hole has the ability to anchor the drilling jig (figure 42) and assist in steady and accurate drilling operations.

Figure 42. Demonstration of attaching the drilling jig to the brake caliper.



Moreover, since the drilling jig is intended to be used in ambient temperature settings, additive manufacturing techniques can be used in its construction, thus, 3D printing material can be utilised to create the drilling jig. Once the drilling jig was approved by the commissioning company, the CAD model was additive manufactured from PET-G material as shown in figure 43.

Figure 43. Additive manufactured drilling jig



8 Computerised Simulation of the Protective Cover

Given that it is impossible to replicate a full range of situations and conditions that vehicles encounter, the project has difficulties in conducting real-world testing, which impacts the evaluation of the protective cover's effectiveness. Nevertheless, this does not imply that there are no tools available that can approximate real-world testing results quite accurately. Explicit dynamics, an analysis system used in Ansys, a highly developed engineering simulation program (Ansys, n.d.), was used to mimic a real-world test scenario.

8.1 Determining the physical properties of a small rock

The simulation involves a scenario where a sphere, representing a small rock, impacts the cover. This choice of geometry for the small rock would give the cover a disadvantage, as spheres are known for their optimal handling of stress and other mechanical factors. By subjecting the cover to a situation where the structural advantages of the sphere could highlight any flaws in the material or design of the cover, this method evaluates the cover's durability.

The first step in the simulation process is to choose a material for the small rock and determine its mechanical properties. To ensure the scenario is realistic, a material that is commonly found should be selected. To effectively assess the protective cover's durability, a material with a high density is preferable, as this means the small rock will be heavier for its size, presenting a more significant challenge upon collision. Therefore, granite was selected for its high density in comparison with other materials at an average of 2670 kg/m^3 and likelihood of being present on the Earth's surface, especially in mountainous terrains. Figure 44 illustrates the density of various common rocks and ore minerals, including granite.

Figure 44. Densities of rocks and minerals (Sharma, 1997, p. 17).

Table 2.1 *Densities of rocks and minerals.*

P.V. Sharma, 1997, pg17.

Rock type or mineral	Density (wet) ($\times 10^3$ kg/m^3)
Sand	1.6–2
Moraine	1.5–2
Sandstones (Mesozoic)	2.15–2.4
Sandstones (Paleozoic and older)	2.35–2.65
Quartzite	2.60–2.70
Limestone (compact)	2.5–2.75
Shales (younger)	2.1–2.6 (2.4)[a]
Shales (older)	2.65–2.75 (2.7)
Gneiss	2.6–2.9 (2.7)
Basalt	2.7–3.3 (2.98)
Diabase	2.8–3.1 (2.96)
Serpentinite	2.5–2.7 (2.6)
Gypsum	2.3
Anhydrite	2.9
Rocksalt	2.1–2.4 (2.2)
Zincblende	4.0
Chromite	4.5–4.8
Pyrite	4.9–5.2
Hematite	5.1
Magnetite	4.9–5.2 (5.1)
Galena	7.4–7.6
Granite	2.52–2.81 (2.67)
Granodiorite	2.67–2.79 (2.72)
Syenite	2.63–2.90 (2.76)
Quartzdiorite	2.68–2.96 (2.81)
Gabbro	2.85–3.12 (2.98)
Peridotite	3.15–3.28 (3.23)
Dunite	3.20–3.31 (3.28)
Eclogite	3.34–3.45 (3.39)

Note:
[a] Figures in parentheses are taken to be average values.

Upon obtaining the granite's density, the subsequent step was to calculate the mass of the small rock using the formula m = D / V. However, the volume is needed to proceed. In this case, the small rock is represented as a sphere as mentioned earlier, thus, the volume formula of a sphere is $4 \pi r^3/3$. Considering the rock's total diameter is 20 mm which is a practical size for a small rock, the radius is thus 10 mm, derived from dividing the diameter by two. With a density of 2670 kg/m^3 and a volume of 4188.8 mm^3, the mass of the small granite rock is calculated to be approximately 11.2 grams, making it a realistic approximation in both size and weight. Furthermore, Ansys requires additional mechanical properties for the simulation, including Young's modulus of granite, which is 68 GPa, and its Poisson's ratio, recorded at 0.31, as demonstrated in Figure 45.

Figure 45. Granite mechanical properties (Hampton et al., 2018, p. 3).

Property	Value (units)
Young's modulus (E)	68 (GPa)
Poisson's ratio (ν)	0.31
Cohesive strength (c)	27 (MPa)
Friction angle (ϕ)	55°
Tensile strength (σ_T)	13.63 (MPa)
UCS	172 (MPa)

8.2 Start of the Simulation Analysis

After inputting the granite rock's data into Ansys and selecting stainless steel 316 from the program's database for the protective cover, the remaining steps include designating fixed support locations, generating the mesh, placing the location of the sphere, and determining the impact velocity of the granite rock.

For the simulation, two scenarios were devised: in the first, a granite rock weighing 11.2 grams impacts the cover at a speed of 100 km/hr, and in the second, a granite rock weighing 100 grams with a diameter of 40 mm collides with the cover at 60 km/hr.

8.2.1 Scenario one

In the initial scenario, the centre of the sphere, representing the 11.2-gram granite rock, is positioned 15 millimetres from the cover and launched towards it at a speed of 100 km/hr. Figure 46 illustrates the sphere at 0.0003158 seconds and 0.003 seconds following the start of the simulation, capturing the moment of impact and after the impact respectively. The simulation shows that once the sphere impacts the protective cover, the sphere bounces away from the protective cover causing little vibration and doing little to no damage as shown in figure 46 and figure 47.

Figure 46. Impact simulation of an 11.2-gram rock at different timeframes.

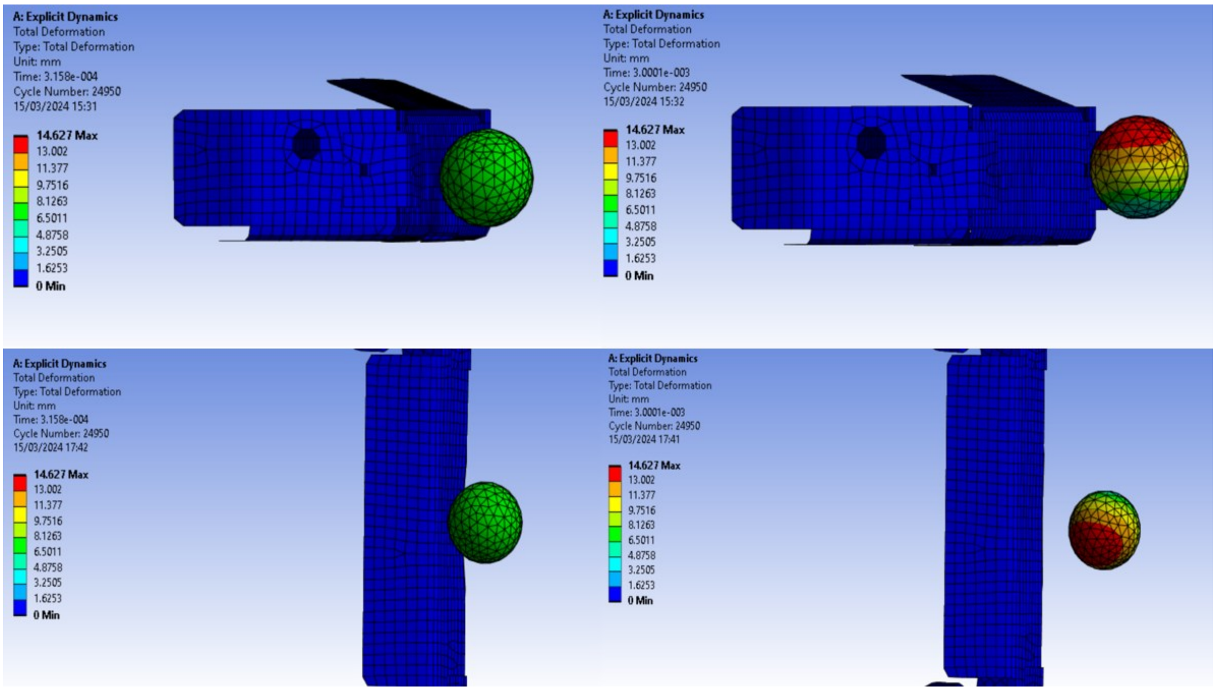
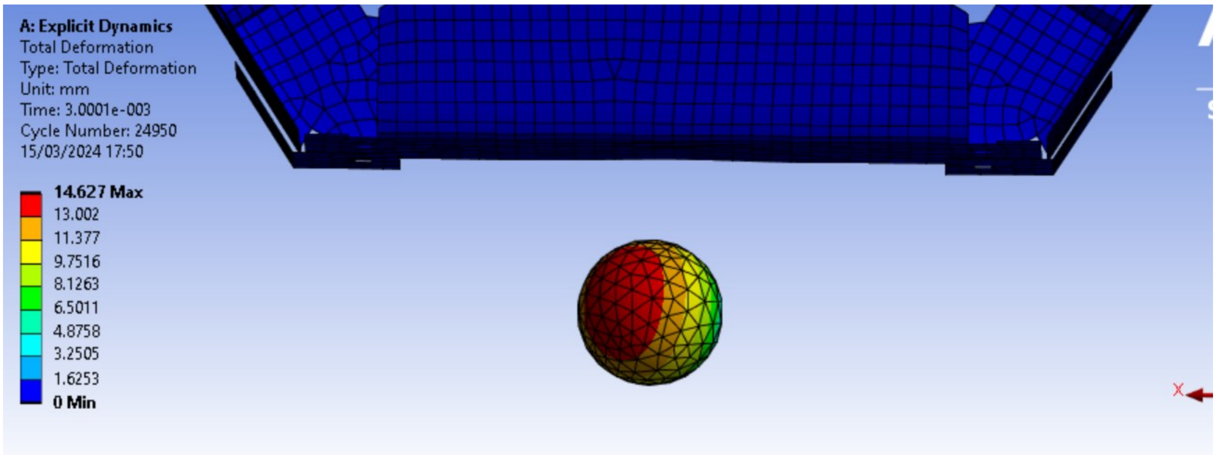


Figure 47. Overhead perspective of the post-collision scene.

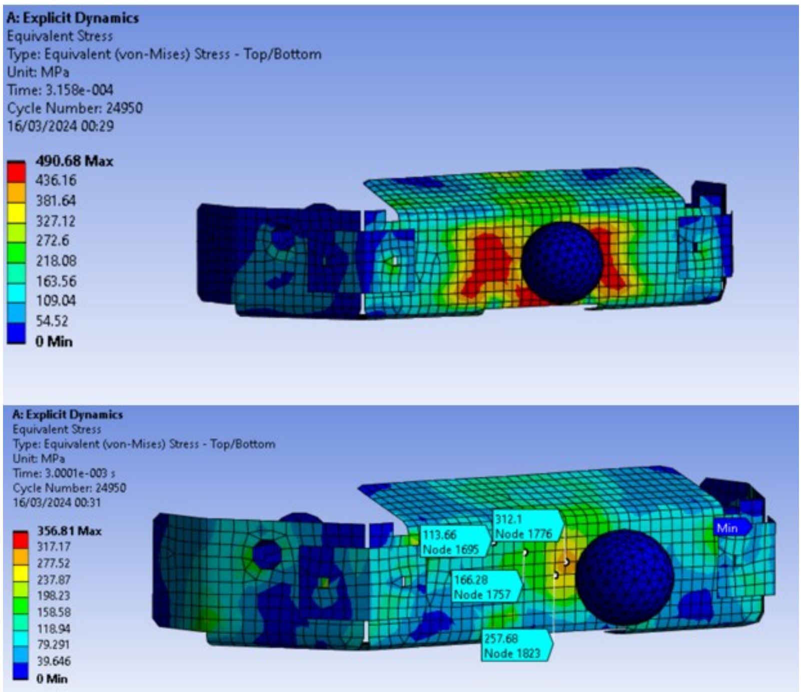


Furthermore, the stress analysis shown in figures 48 and 49 highlights an essential aspect of the protective cover's effectiveness in an impact. The obtained data demonstrate that the moment the granite rock makes contact with the cover is when the maximum stress level is reached which is at 490 MPa. The original collision force directly caused this stress peak. However, over time, stress levels drop significantly, stabilizing at a final value of 356 MPa, indicating that the protective cover has the innate capacity to properly absorb and release the energy emitted during impact.

Figure 48. Stress measurements of the 11.2-gram granite rock across different time intervals.

Row Number	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.18E-38	0	0	0
2	1.50E-04	0	0	0
3	3.00E-04	0	490.68	101.33
4	4.50E-04	0	425.3	104.13
5	6.00E-04	0	470.32	90.997
6	7.50E-04	0	370.71	84.02
7	9.00E-04	0	487.69	96.175
8	1.05E-03	0	414	89.099
9	1.20E-03	0	444.18	73.438
10	1.35E-03	0	337.87	70.508
11	1.50E-03	0	318.64	67.692
12	1.65E-03	0	422.19	84.654
13	1.80E-03	0	387.21	70.127
14	1.95E-03	0	457.07	84.776
15	2.10E-03	0	417.82	81.009
16	2.25E-03	0	473.63	59.55
17	2.40E-03	0	370.13	67.165
18	2.55E-03	0	308.15	64.123
19	2.70E-03	0	366.88	67.508
20	2.85E-03	0	423.26	75.51
21	3.00E-03	0	356.81	68.173

Figure 49. Evaluation of stress patterns at maximum and subsequent values.



This dynamic response to impact stress underscores the engineering principles behind the cover's design, specifically its capacity to mitigate potential damage through energy absorption. Thus, the first scenario clearly shows how well the protective cover shields the brake fluid pipe from strikes by tiny rocks that are around 20 mm in diameter. The simulation demonstrates how the cover can absorb impact energy and disperse it, so minimising potential harm. This demonstrates the cover's usefulness and emphasises its importance in maintaining the brake fluid pipe's longevity and safety in actual use. Therefore, the protective cover successfully carries out its main duty, indicating its dependability as a defence against environmental dangers.

8.2.2 Scenario two

In the second scenario, the intent is to impact the protective cover with a 100-gram granite rock, which is normally about 40 mm in diameter to subject it to a more rigorous test. The rock-representing sphere is positioned 15 mm from the cover, just as shown in the first scenario. In addition to that, the launch velocity is lowered to 60 km/hr. Figure 47 illustrates the sphere at 0.00043679s and 0.003s after the simulation starts, capturing both the instant of impact and the aftermath. Similar to the first scenario, the sphere rebounds off the protective cover. However, in this instance, there is slight damage to the cover, with the main frame exhibiting a minor bend, as depicted in figures 50 and 51.

Figure 50. Impact simulation of a 100-gram granite rock at different timeframes.

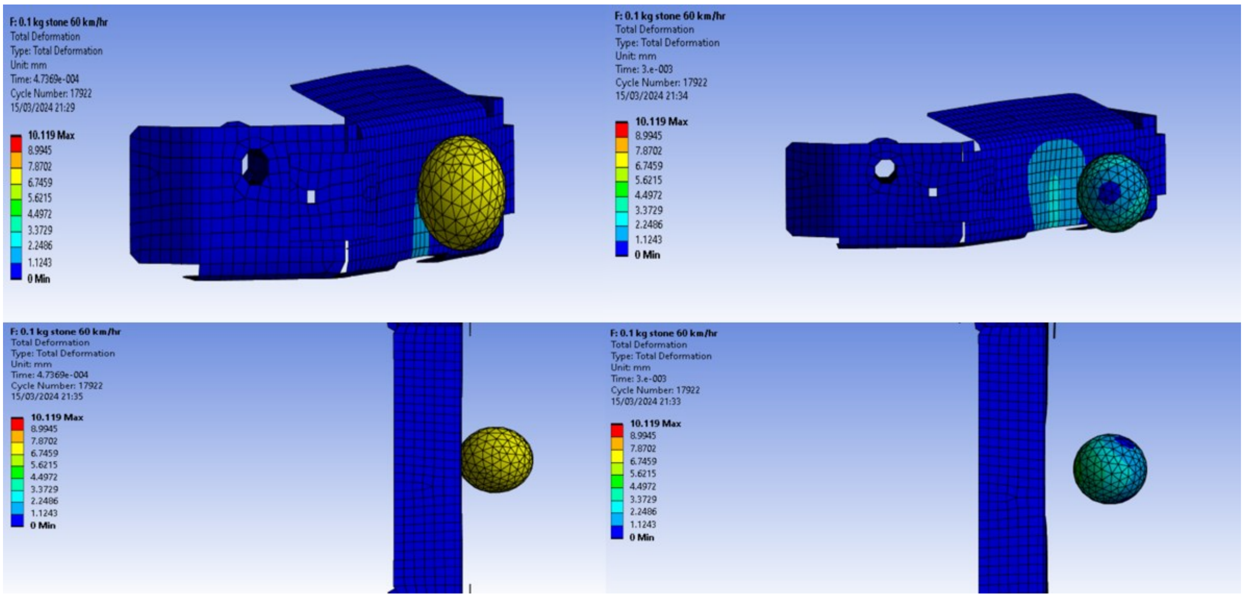
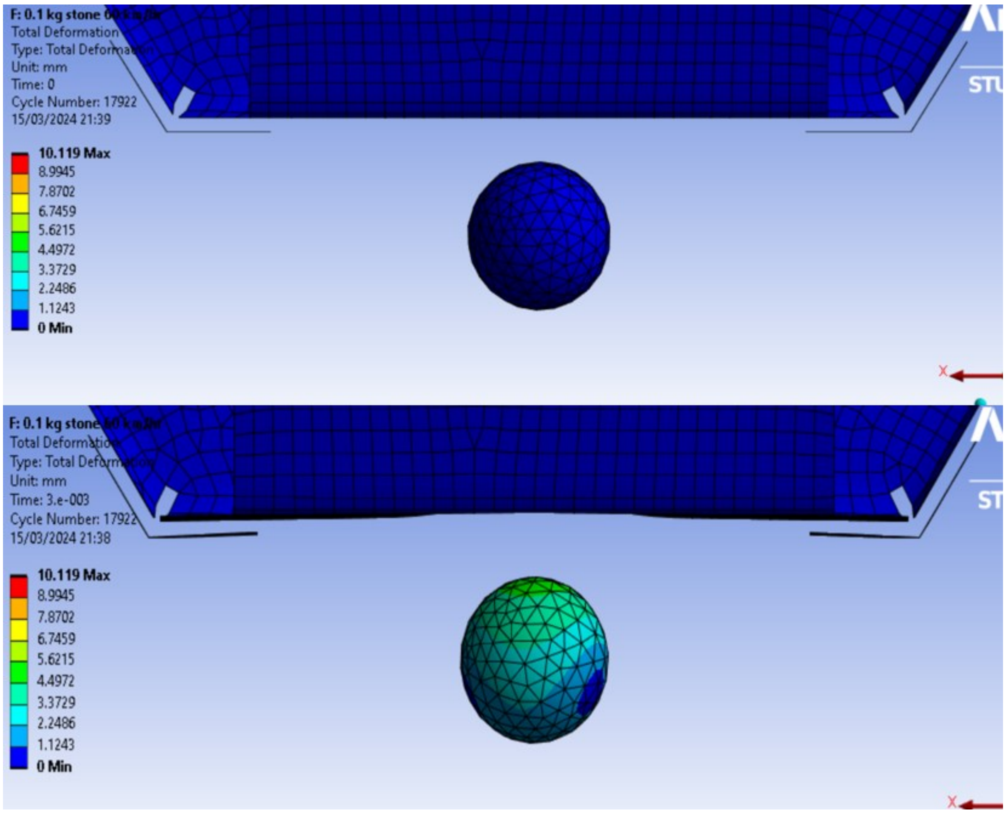


Figure 51. Top view of the damage caused by the 100-gram rock.

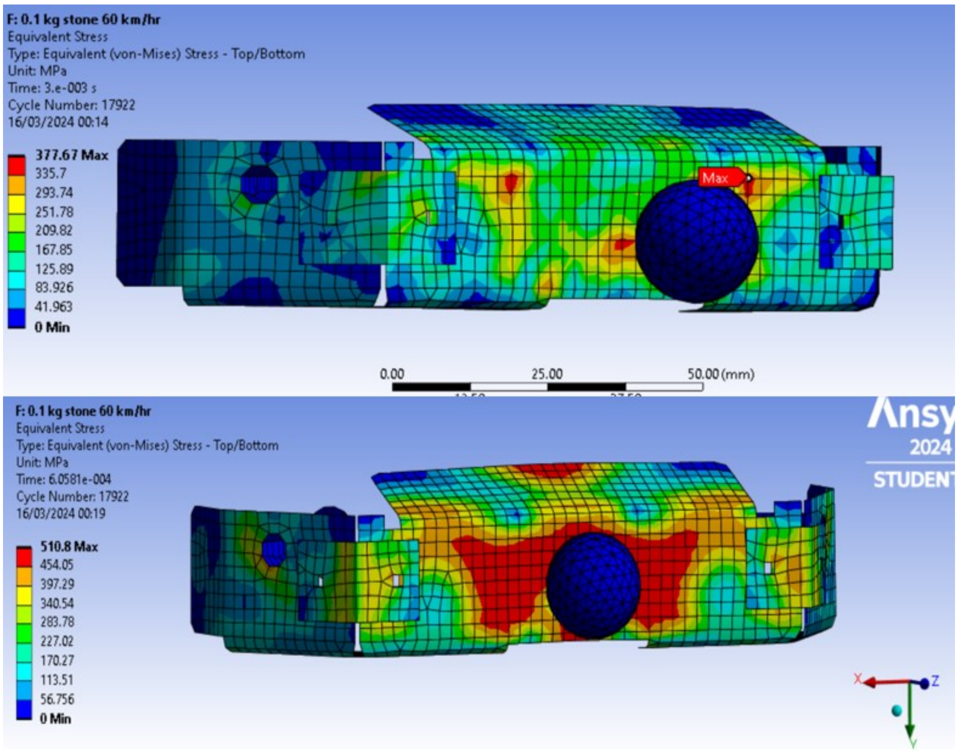


According to the analysis shown in figures 52 and 53, the protective cover experiences stress that peaks at 510 MPa when it impacts the granite rock and stabilizes at a final value of 377 MPa. Just a minor deviation of 21 MPa separates this stabilization from the final stress value found in the initial scenario. These statistics provide strong evidence for the cover's ability to effectively absorb and disperse impact energy, thereby significantly lowering the possibility of granite rock damage. Even though there was minor damage to the cover, the brake caliper pipe was still adequately protected from other risks. It is also important to consider that in practical scenarios, a granite rock weighing 100g with an approximate diameter of 40 mm would encounter numerous obstructions before potentially reaching the brake caliper, further diminishing the likelihood of direct impact.

Figure 52. Stress measurements of the 100-gram granite rock across different time intervals.

Row Number	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	1.18E-38	0	0	0
2	1.50E-04	0	0	0
3	3.00E-04	0	0	0
4	4.50E-04	0	494.96	101.87
5	6.00E-04	0	510.8	187.86
6	7.50E-04	0	502.18	196.18
7	9.00E-04	0	487.71	188.98
8	1.05E-03	0	502.71	146.52
9	1.20E-03	0	433.49	99.087
10	1.35E-03	0	457.77	86.308
11	1.50E-03	0	489.98	115.96
12	1.65E-03	0	492.24	105.43
13	1.80E-03	0	478.5	78.372
14	1.95E-03	0	463.05	80.702
15	2.10E-03	0	474.5	98.362
16	2.25E-03	0	412.78	85.742
17	2.40E-03	0	428.29	68.592
18	2.55E-03	0	478.21	94.189
19	2.70E-03	0	463.73	94.088
20	2.85E-03	0	452.23	73.813
21	3.00E-03	0	377.67	76.261

Figure 53. Analysis of stress dispersion at peak values and subsequent levels.



The Ansys simulations validate the protective cover's ability to disperse and absorb impact energy, protecting the brake fluid pipe from damage while minimising impacts from the granite rock under a range of situations. These intentionally challenging experiments exceed real-world conditions, especially when dealing with spherical rock shapes at high speeds. Generally speaking, a rock would probably strike the brake disc or tyre rims first, decreasing speed before perhaps making contact with the cover. Moreover, the second series of simulations, which include larger rocks, depict extreme scenarios that are unlikely to occur. However, these simulations offer insightful information about how well the cover performs in harsh environments. The results confirm the longevity and dependability of the cover, indicating that its materials and design are suitable for use in automobile safety applications.

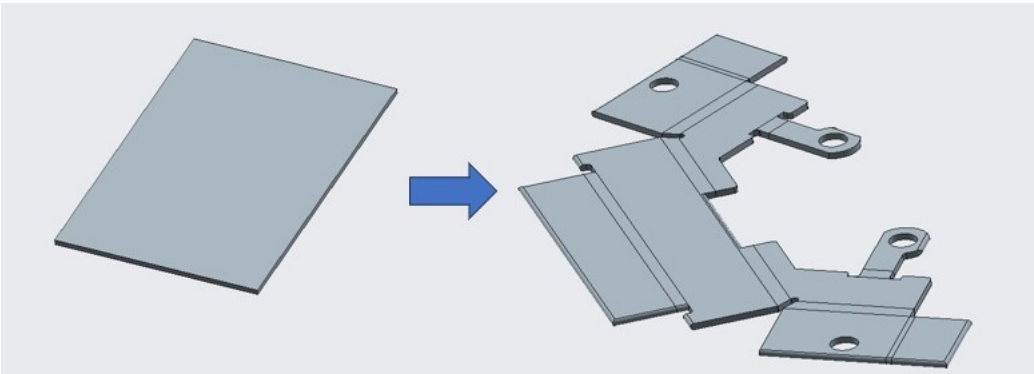
9 Manufacturing the Designed Solutions and the Assembly

Making a list of every component required for production and assembly should be done before prototype 8's manufacturing process is started. The protective cover's main frame is included in this list along with two reinforcement plates for added structural support. To secure the cover, the assembly will also need two M6x35 screws, matching M6 washers, and 6 M6 nuts. Four M4x10 screws and four M4 nuts are needed to secure the reinforcement plates. The drilling jig is required to be manufactured and should come along with the assembled protective cover to create holes in the existing brake calipers. It is also optional to add Loctite® Threadlocker Blue 243 to increase the vibration resistance of the screws. A smooth transition from design to actual manufacturing of the protective cover is ensured by this careful preparation.

The production process of the protective cover does not require welding since prototype 8 has been selected. Thus, there are three main processes in forming the final product: utilizing laser or water jet cutting for precise material shaping, smoothing the edges with CNC machining, and then shaping the product with sheet metal bending to give it the correct shape.

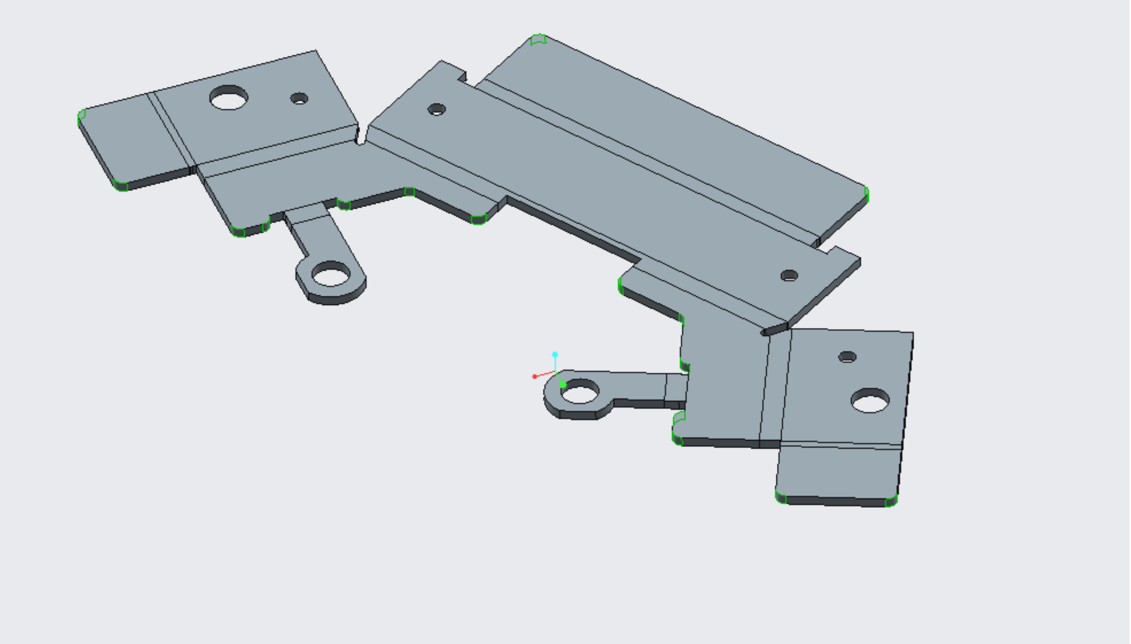
In laser or water jet cutting, a 2 mm thick stainless-steel sheet of metal is cut into the form of the protective cover's flat state, carefully avoiding any deformation. This process is detailed in figure 54, offering a visual representation of how the metal sheet is transformed into the designated shape. The process was then displayed to the company, and it was decided to use laser cutting to create the protective cover's main structure at this stage of production.

Figure 54. The outcome of the laser/water jet cutting method.



Afterwards, rounding the edges is required to minimize stresses throughout the protective cover and to make the product safer when being handled by technicians or a customer. The green-highlighted edges in figure 55 indicate where CNC milling will be applied for this purpose.

Figure 55. Areas for rounding marked in green.



Finally, three exact bending operations are required to recreate the specified pattern of the protective cover's main frame. To precisely produce the final shape of the cover, a certain angle is needed for each bending procedure. The precise places and angles at which these bends should be made are shown in figures 56, 57, and 58, ensuring that the cover meets the necessary dimensions and shapes. Appendix 1 displays the technical drawings of the main frame of the protective cover, outlining the fabrication processes in detail.

Figure 56. Bending the green-marked area to a 70-degree angle.

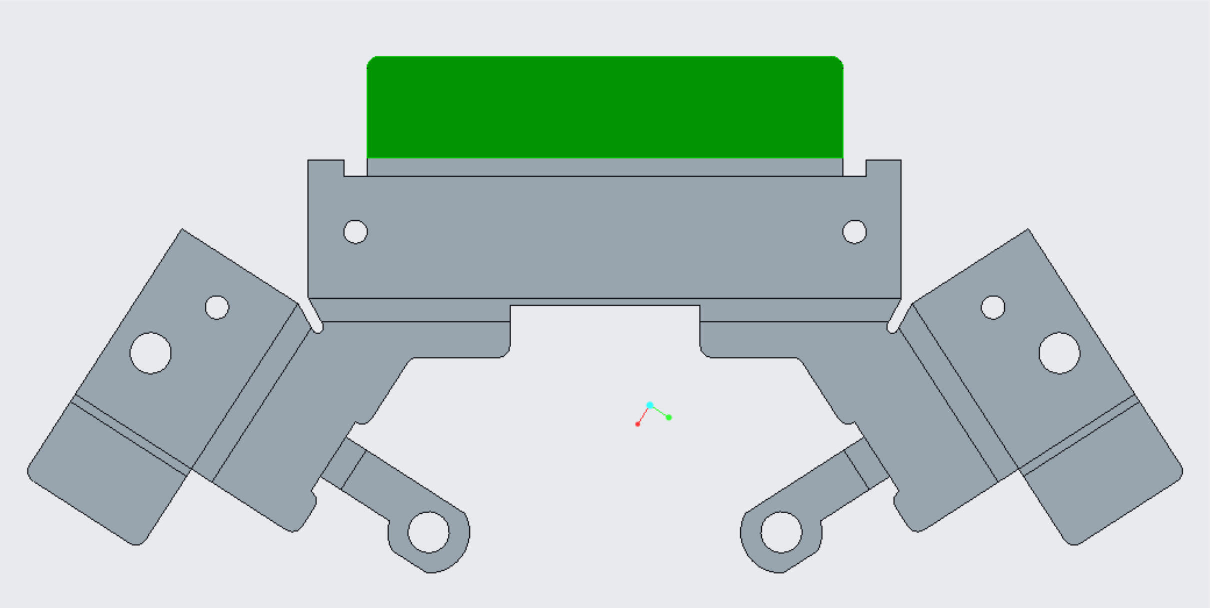


Figure 57. Bending the green-marked areas to 90-degree angles.

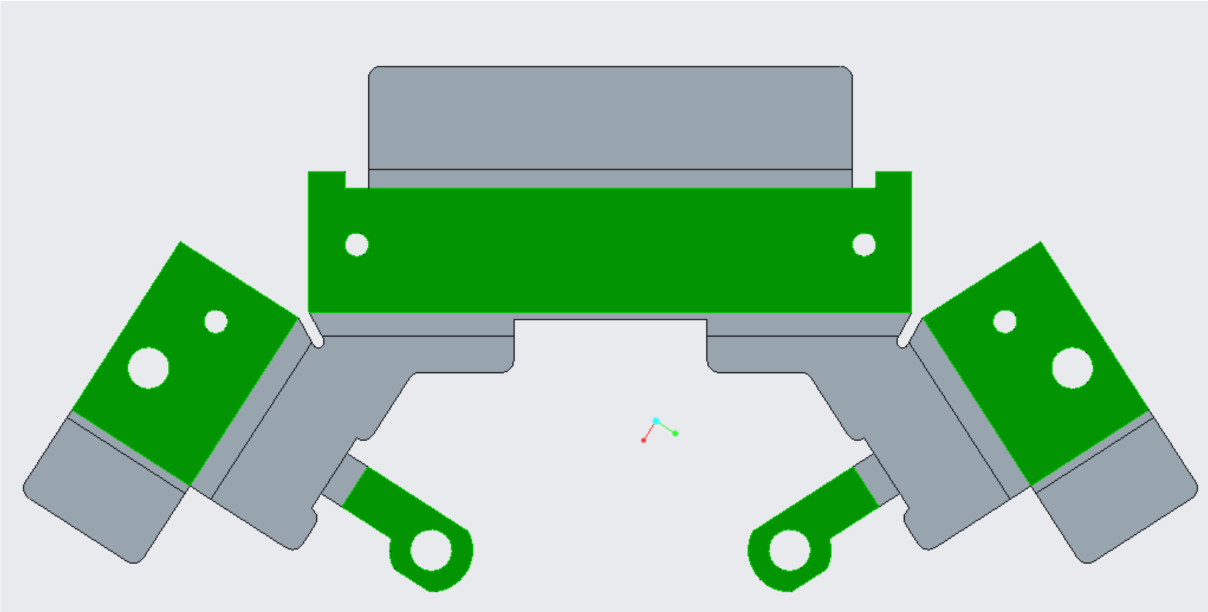
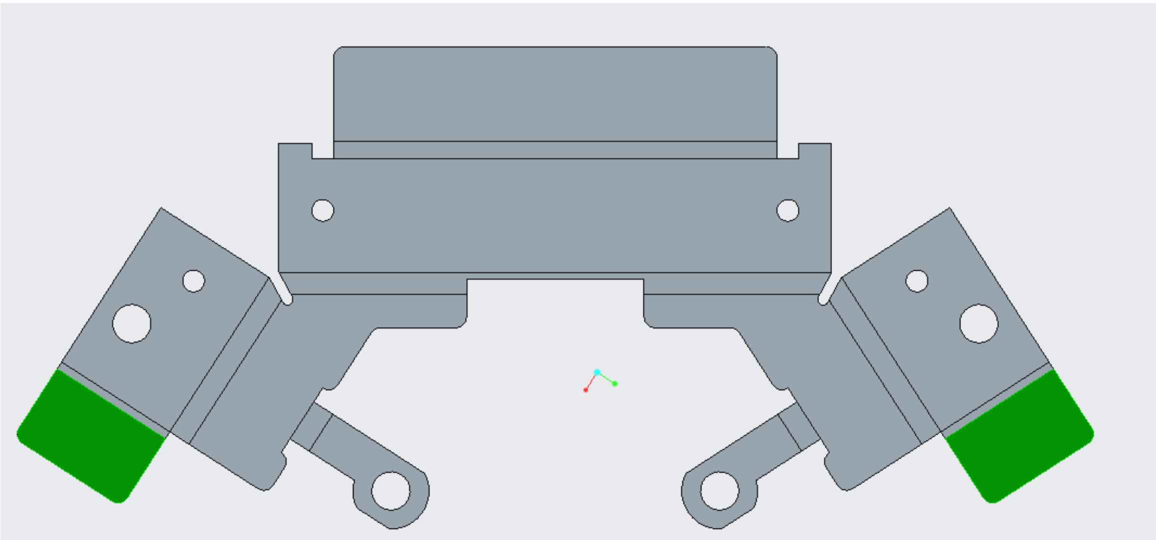
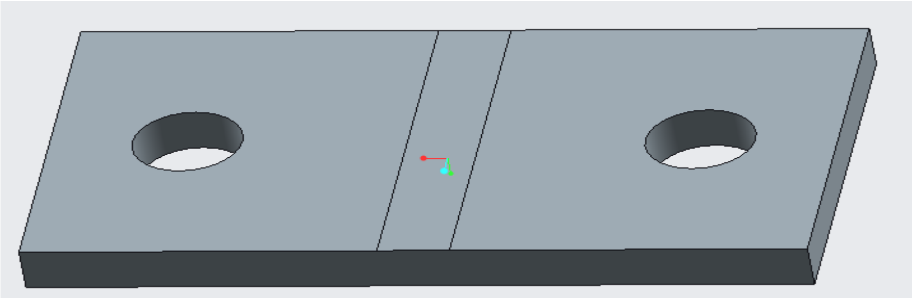


Figure 58. Bending the green-marked area to a 32.75-degree angle.



Another piece that should be fabricated is the reinforcement plate. Sheet metal processes are implemented in the production of the reinforcement plates where a piece of 2 mm sheet metal is cut to produce the flat state of the reinforcement plate displayed in figure 59. Then, the flat piece is subjected to a 57.2 degree bending angle as demonstrated in appendix 2. Finally, the sharp edges of the reinforcement plate can be removed by filing, tumbling, or similar methods.

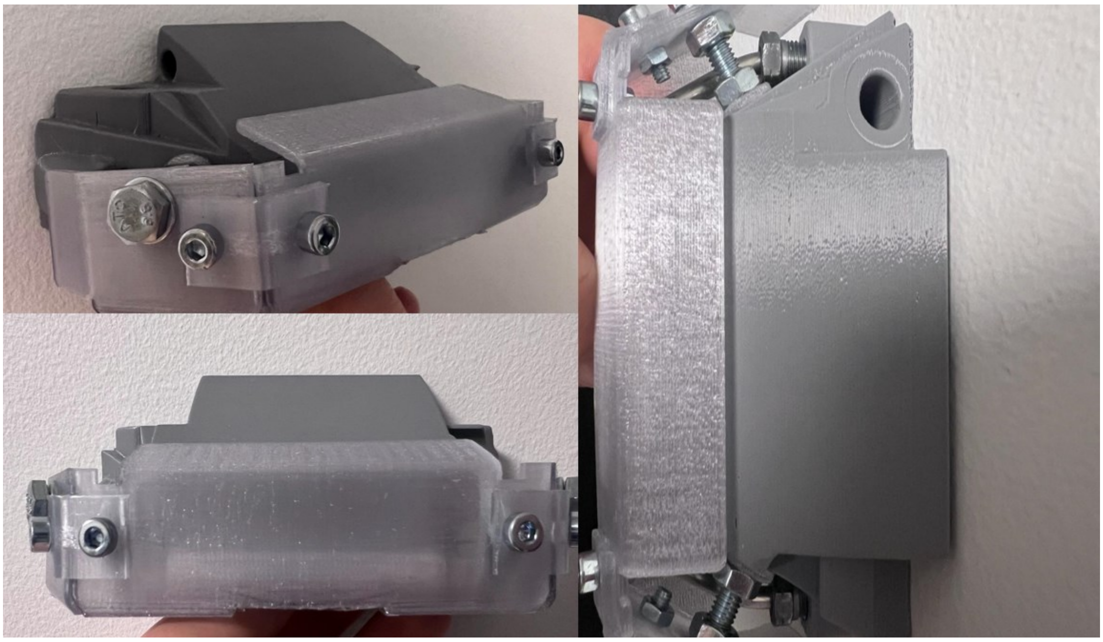
Figure 59. Flat state of the reinforcement plate.



In contrast, the drilling jig is manufactured using additive manufacturing which would be the simplest manufacturing method. This jig is not expected to endure high temperatures that would melt the plastic or perform intricate operations beyond directing the drill to the precise location for creating holes in already existing brake calipers. To produce this drilling jig, the only necessary input is the .STL file, eliminating the need for detailed technical drawings.

Finally, assembly of the protective cover starts when the protective cover's main frame and reinforcement plates are manufactured. The assembly of the cover is then finished by fastening the reinforcing plates to it with four M4 screws and nuts as shown in figure 60 and Appendix 3. The last step is to firmly mount the cover to the brake caliper using M6 screws, washers, and M6 nuts.

Figure 60. The final assembled version of the protective cover safeguarding the 3D-printed brake caliper part.



The protective cover assembly shown in figure 60 is additive manufactured for visual purposes to present the product to the company. The real product should be made of stainless steel 316 and follow the stated manufacturing methods.

10 Conclusion

This thesis concludes by discussing the product's results and offers further guidance for the Sarlin Race Team company. The section is then followed by a reflection on the project evaluation as well as the author’s own learning.

10.1 Discussion of Results and Project Assessment

As the author progressed through the thesis, distinctive challenges and particular milestones were faced. The author's experience and knowledge base were enhanced by each thesis step, which helped the author acquire new skills or improve existing ones.

A theoretical foundation was to be formed to create the basis of the thesis and provide a comprehensive overview of brake system constituents and directly address the core issue. It is essential to recognize that while vehicle brake systems may exhibit operational differences, the presented theory remains broadly applicable across various brake systems.

The author used AXE 3D-Handscanner during the project to perform a targeted inspection of the critical areas of the brake caliper, for instance of the mounting points. Another tool is the ATOS Compact Scan which could have possibly facilitated and improved the overall accuracy of the scans. The author decided to opt for the AXE 3D-Hanscanner because it offered better accessibility, user-friendliness, and adequate focus on the specific tasks. This decision drove successful and effective progress toward the project objectives. However, the usage of the ATOS Compact scan tool could offer positive opportunities for future improvements and similar projects.

Reverse engineering a section of the brake caliper that was supplied by the Sarlin Race team, was carried out effectively, achieving a result that closely matches the original brake caliper. Despite this success, the complex shapes and details of the brake caliper introduced challenges, making it difficult for the author to create an exact replica. Nonetheless, key measurements of the brake caliper such as the area where the cover is to be fixed and the location where the brake disc resides were nearly identical to those of the actual component, as shown through the GOM software.

Additive manufacturing of the brake caliper part and the selected prototype of the protective cover was completed without any challenges, and the process was direct. In this study, additive manufacturing served a visual role, enabling a concrete understanding of the design and attachment method for a factory-produced cover to the brake caliper.

The development of various prototypes provided the company with a chance to review different solutions to their issue and express their preferences. Consequently, this simplified the decision-making process for the author, leading to the selection of prototype 8.

The combination of simulation results and the simple production process highlights the effectiveness of the product created intended to safeguard the brake caliper's brake fluid pipe. This validation reveals the cover's strong performance in controlled and theoretical conditions as well as its usefulness in real-world situations, all without the need for complex production techniques. This is demonstrably feasible for automobiles with similar problems, which makes it a good choice for widespread application. Automobiles encountering similar issues favour this product for its suitability across diverse applications. It effectively connects intricate engineering solutions with practical, cost-effective integration into vehicle security. By meeting protective standards and enhancing efficiency, it expands its potential for various applications.

Although the product could not be tested in real life, digital simulations have shown that the protective cover does, in fact, successfully secure the brake caliper's brake fluid pipe from environmental risks, which is in line with the primary objective of this thesis. This accomplishment resulted from strictly sticking to the thesis's original goals and procedures, which were to fully comprehend the brake system as a whole, discover the project's essential procedures, and then put these procedures into effect.

It is worth to note that despite the language barrier between the author and the commissioning company, communication remained excellent, and the author appreciated the company's prompt responses. Additionally, the author acknowledges the potential for improvement in the presented work, however, the company was satisfied with the thesis, showing no indication of requesting changes or expressing any form of rejection. This suggests the company's approval of the product, possibly viewing it as a prototype that could be developed further in the future.

10.2 Recommendations

Prototype 8 successfully meets the objectives of protecting the brake fluid pipe and adheres to the company's specifications by offering a non-welding solution; however, there is an opportunity for further optimization. The author suggests that incorporating welding could simplify both the manufacturing and assembly processes. This approach has the potential to reduce production costs, complexity of the manufacturing processes, and decrease assembly time, making the overall production more efficient. By integrating welding, the structural integrity of the protective cover could be enhanced without significantly increasing the complexity of both the manufacturing and assembly processes.

The author suggests that the three sections of the protective cover be joined with just two welds (figure 38) to increase its strength without the need for additional reinforcing elements. Additionally, altering the design to provide more room close to the braking fluid pipe may simplify assembly, though possibly raising production costs. Increasing the size of the product allows for a thicker sheet of metal, providing the brake fluid pipe with better protection.

The existence of a method to replicate real-world testing would serve as additional evidence of the product's effectiveness since it would provide full confirmation of the product's functionality. Such simulated testing would help facilitate the protective cover's certification for market release while also ensuring that it satisfies the safety criteria. By putting a careful and accurate simulation into practice, the product would be subjected to realistic environmental difficulties including impacts from debris, product vibrations resulting from such collisions, a high-temperature environment that mimics the heat generated around the brakes, and other elements. This would provide a solid foundation for assessing the product's efficacy and durability. This stage is essential for going from theoretical evaluations to real-world validations and, eventually, enabling the product's release onto the market with the assurance that it protects the brake fluid pipe and maintains the safety of the overall brake system.

10.3 Reliability, Authenticity, and Relevance

The credibility of the thesis is supported by the strict simulations carried out with Ansys, a well-known engineering simulation and 3D design programme with certification for its correctness and dependability. The thesis's legitimacy is further reinforced by the inclusion of numerous trustworthy academic references and the adherence to ISO standards. All of these components work together to guarantee that the research methods and findings that are reported are based on accepted engineering principles and meet internationally accepted standards for performance and quality.

The applicability of this thesis continues as long as the utilized sources and tools remain recent as they can be updated and changed. However, the thesis uses mostly recent academic studies, ISO standards, and modern tools or programs, which adds to the thesis’s trustworthiness. Therefore, the thesis's reliability is strengthened by supporting its findings with evidence and validating its impact on the engineering community.

10.4 Insights Gained from the Thesis Work

This thesis offered a comprehensive learning experience, underlining the blend of theoretical knowledge and practical expertise in solving real-life issues. The stages of design, testing, and improvement highlighted the regular and repetitive processes of engineering projects and the need for careful selection of materials and production techniques. Establishing a direct link between feasible design strategies, cost-effective and rapid manufacturing, and straightforward assembly proved essential for the success of a product that fulfils its intended purpose.

In addition to that, the thesis has provided the author with an in-depth understanding of technologies vital to the engineering landscape of the future, such as additive manufacturing, reverse engineering, and 3D scanning. For example, the author learned how to use 3D scanners and how they work and can realise differences in scanning results if a different scanner or scanning approach is utilised. Furthermore, the challenges faced during the reverse engineering process provided valuable learning opportunities that laid the groundwork for the author's future efforts and improved technical proficiency. The CAD and structural analysis courses provided by the university were also fundamental in supporting the thesis work which took part in designing the prototypes and performing simulations.

Reverse engineering integration is becoming more relevant as the engineering industry experiences rapid improvements in 3D scanning and additive manufacturing. These technologies, which offer greater flexibility, efficiency, and customisation, are changing the way solutions are developed, designed, and produced in the mechanical engineering and production technology sector. Through exploring these domains, the author has acquired significant knowledge and abilities that are directly relevant to the changing needs of the engineering industry. The author's technical proficiency is improved by this information, which also puts them in a strong position for future career possibilities by enabling them to innovate and keep up with emerging technological trends.

In conclusion, this thesis not only met its objective of improving vehicle safety through the protection of a vital brake system but also showcased the power of collective effort and innovation in overcoming engineering obstacles, providing meaningful contributions to both the academic and automotive sectors.

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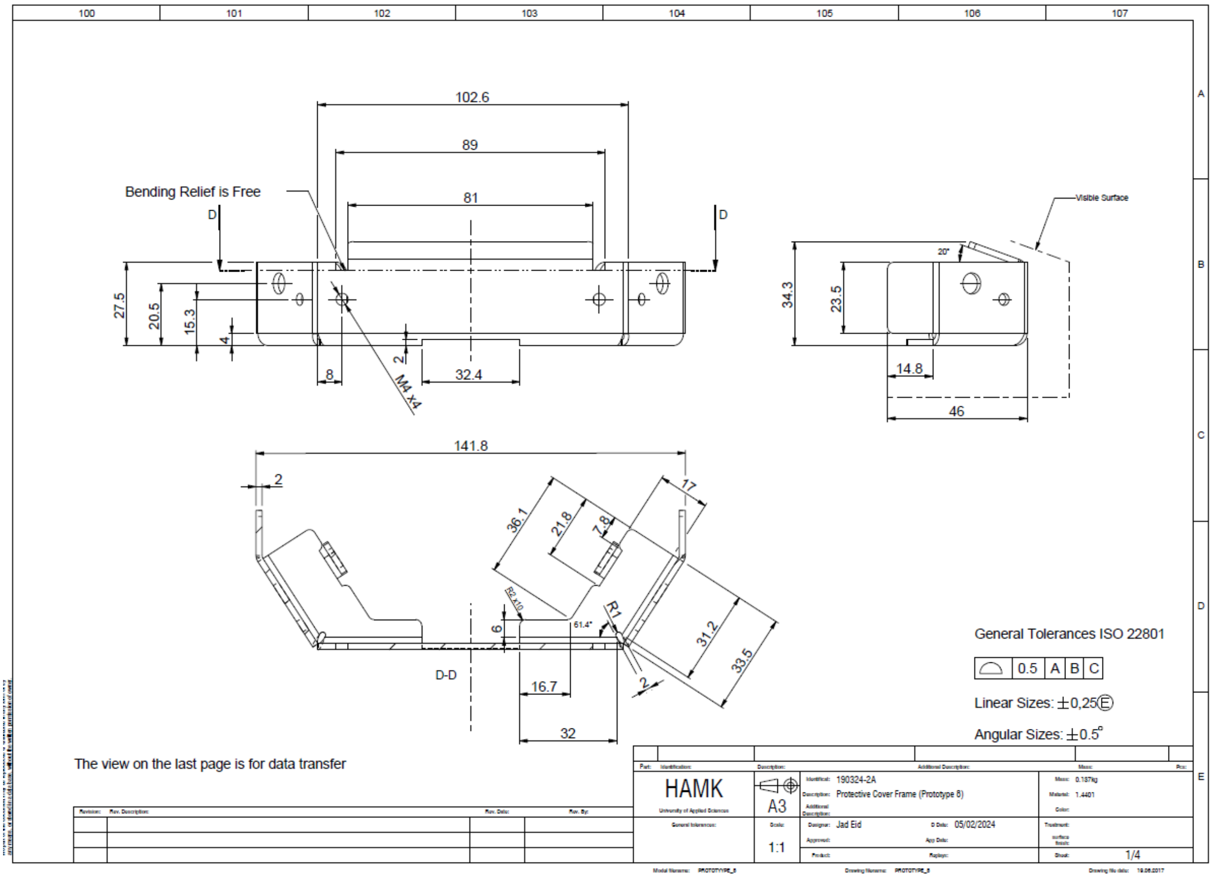
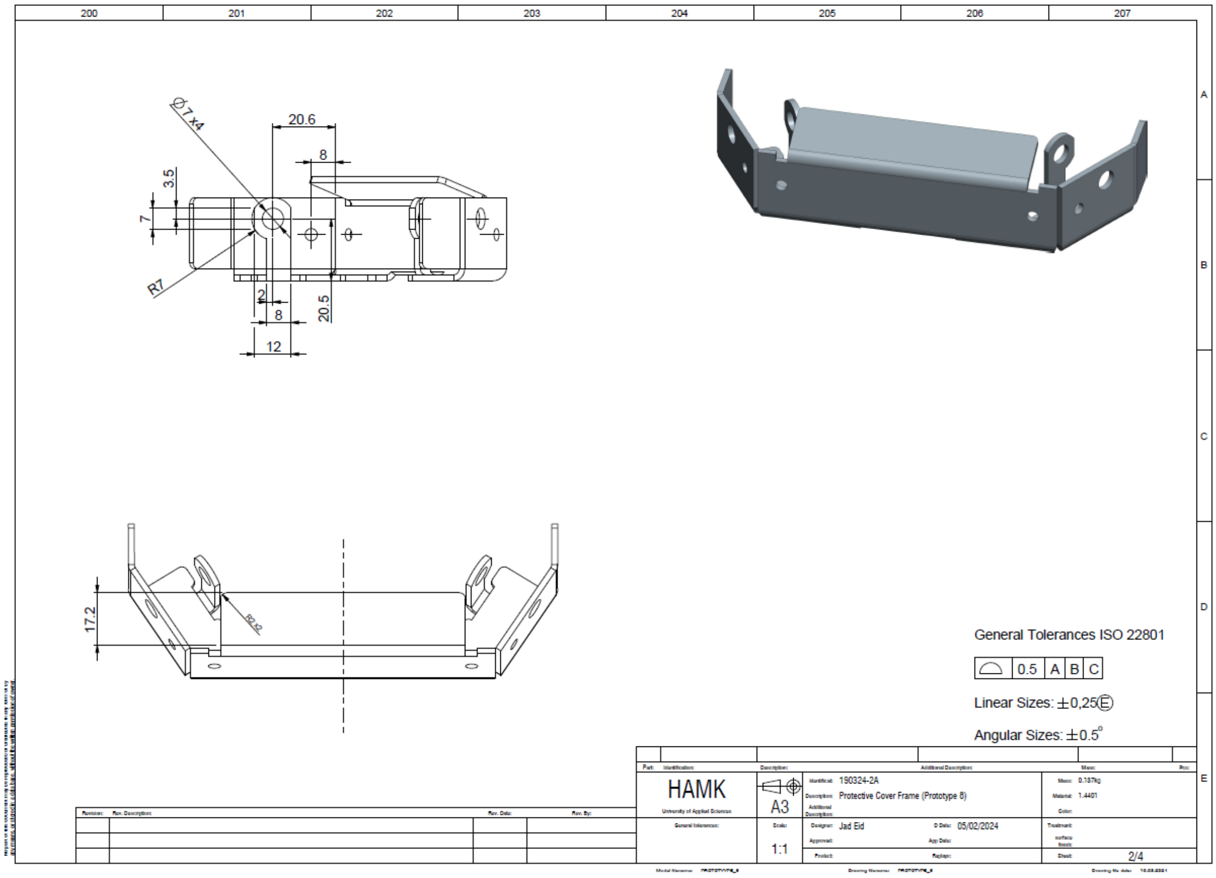
Appendix 1. Technical Drawing of the Cover's Main Frame

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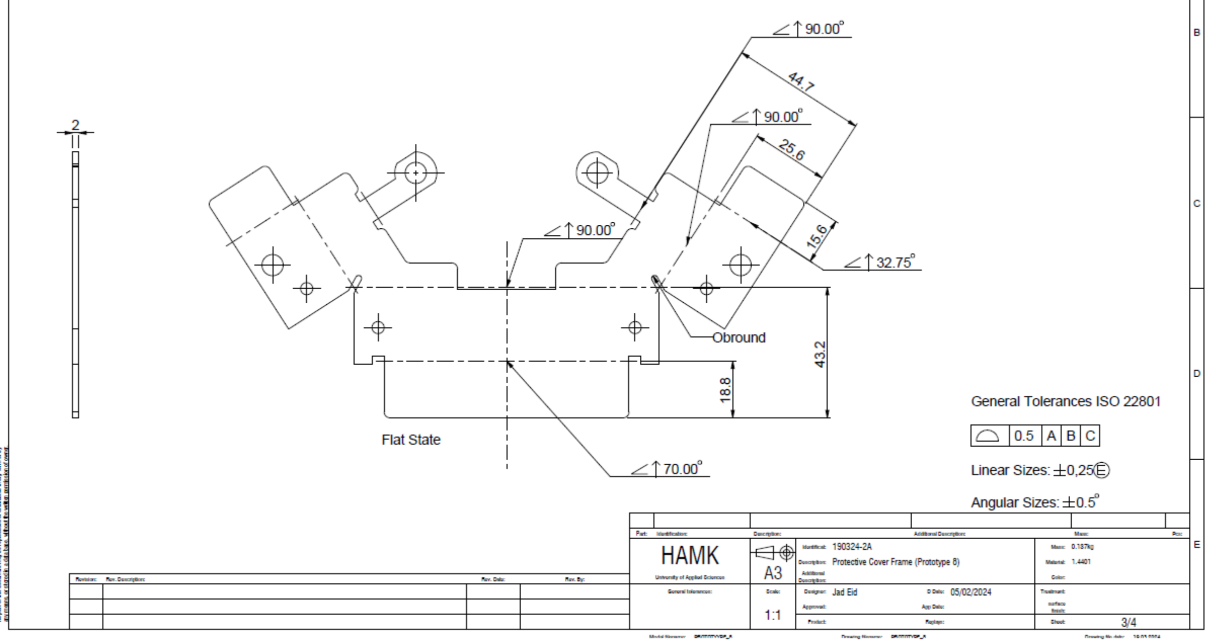
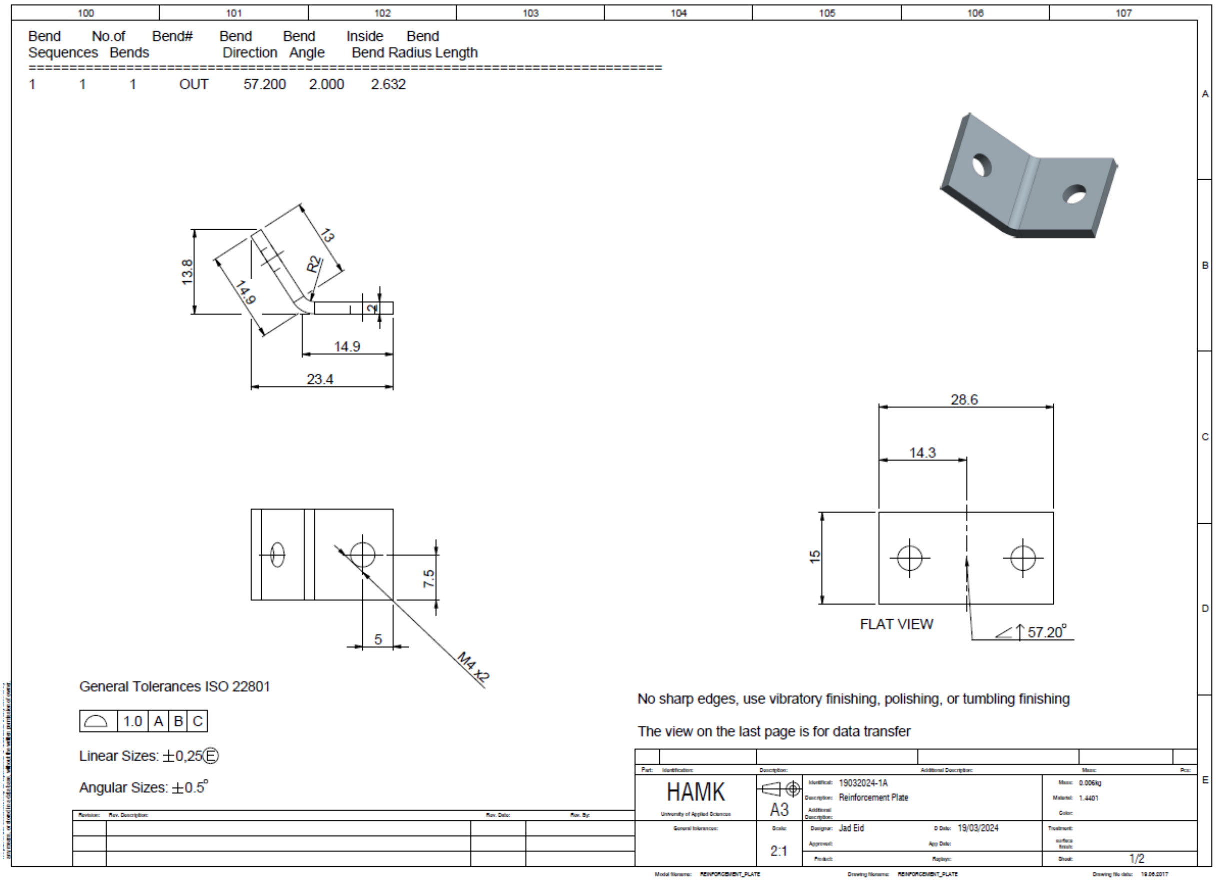
12
17.2
R2.2
General Tolerances ISO 22801
0.5 A B C
Linear Sizes: ±0,25Ⓔ
Angular Sizes: ±0.5°
HAMK
University of Applied Sciences
A3
1:1
190324-2A
Protective Cover Frame (Prototype 8)
0.187kg
1.4401
Jad Eid
05/02/2024
2/4

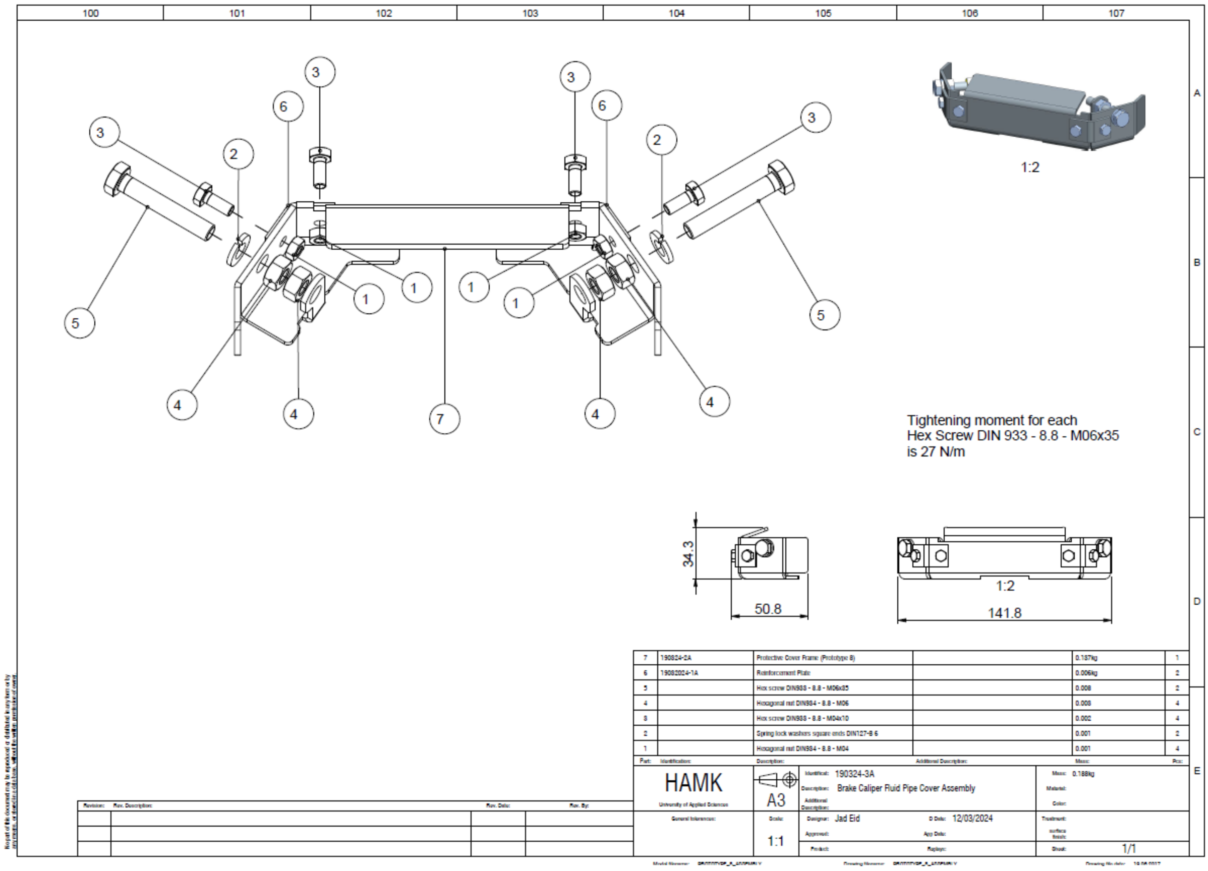
Bend Sequences	No.of Bends	Bend#	Bend Direction	Bend Angle	Inside Bend Radius	Bend Length
1	8	1	OUT	70.000	2.000	3.221
		2	OUT	90.000	2.000	4.142
		3	OUT	90.000	2.000	4.142
		4	OUT	90.000	2.000	4.142
		5	OUT	32.750	2.000	1.507
		6	OUT	32.750	2.000	1.507
		7	OUT	90.000	2.000	4.142
		8	OUT	90.000	2.000	4.142



Appendix 2. Technical Drawing of the Reinforcement Plate



Appendix 3. Technical Drawing of Protective Cover Assembly



Part:	Identification:	Description:	Additional Description:	Mass:	Pcs:
7	190324-2A	Protective Cover Frame (Prototype 8)		0.187kg	1
6	19032024-1A	Reinforcement Plate		0.006kg	2
5		Hex screw DIN933 - 8.8 - M06x35		0.008	2
4		Hexagonal nut DIN934 - 8.8 - M06		0.003	4
3		Hex screw DIN933 - 8.8 - M04x10		0.002	4
2		Spring lock washers square ends DIN127-B 6		0.001	2
1		Hexagonal nut DIN934 - 8.8 - M04		0.001	4

Identification:	190324-3A
Description:	Brake Caliper Fluid Pipe Cover Assembly
Mass:	0.188kg
Scale:	1:1
Designer:	Jad Eid
D Date:	12/03/2024
Sheet:	1/1