

Casting Simulation of Air Disc Brake

**Parameter mapping through the amalgamation
of Casting Simulation and FEA results**

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Acknowledgement

This thesis is executed as a completion to the Master's in Production and Materials Engineering at Lund University, Sweden. The course program, which enables us to take on leadership positions in dynamic manufacturing markets around the world, gives us the expertise, experience and imagination needed to address technical problems in manufacturing, industrial automation and product development. It blends manufacturing and the engineering of materials with an emphasis on sustainable production, digital production, globalization of production, industrial production and the global economy. Our thesis Topic, Casting Simulation of Air Disc Brakes, helps in perfectly realizing the intent of the course program.

The Thesis work has been conducted at the behest of Haldex Brake Products AB, which is situated in Landskrona, Sweden. Haldex is a Swedish company with branches in 18 countries worldwide. Haldex designs and delivers effective as well as creative technologies to enhance the global commercial vehicle industry's safety, vehicle dynamics and environmental sustainability. They are the worldwide leading provider of drum brake adjusters, and their market share for air disc brakes is rising rapidly. The present employee strength of Haldex is 2176 and they are spread across four continents in challenging conventional thinking every day to ensure that the products they deliver focus on safety, efficiency and uptime. Haldex is listed on Nasdaq Stockholm and has a sale of approximately SEK 4.4 bn.

At Haldex Brake Products AB, the brake discs constituting the Carrier and the Caliper are procured from various suppliers around the world. These brake discs are manufactured by Casting methodology. Also, the casted components are rigorously examined in FEA before prototypes are ordered. Yet, unexpected failures occur during the testing phase. The stresses indicated by the FEA are intermediate but are not expected to cause failures. The FEA uses a uniform material model and does not take varying material quality and casting defects into account. So, we have compared and combined the FEA and a casting simulation for a wider understanding of the

failure. The design has been adjusted for improved castability and to avoid expensive workarounds in the casting process, resulting in a cheaper and stronger product.

We have been reading about the topic since the onset of February. It was challenging to learn various software from scratch. But we received ample guidance from Chief Engineer Mechatronics Design, Kristoffer Örndahl who is also the reason for this thesis to happen at the first place, industrial supervisor Martin Wollstad and from Novacast contact person, Erik Stivnert. Erik is the Senior Software Application Engineer at NovaCast. Their immense experience and expertise helped us get over the obstacles. We specially appreciate the time and effort put in by Martin in guiding us throughout the thesis and also for introducing us to his amazing cat, Themsen. We will forever be grateful for all the things that he taught us and for helping us in developing a new perspective towards this field of Engineering. Completion of the thesis would have been difficult without his guidance. Finally, we would like to thank our parents and friends for the constant support and encouragement. After carrying out various simulations of carrier and caliper and combining with the FEA information, we have achieved satisfying results and were able to realize our objectives to a larger extent and confirm the motive.

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Abstract

Casting Simulation software which have become popular tools for modern metal casting industries and foundries, are on the verge of becoming the epicenter of virtually replicating the process of casting and its optimization. Our aim is to combine and compare results from Casting simulation and FEA of Air Disk Brake, utilize these results to map parameters that affect the quality of Cast components to Structural analysis. This would help confirm the theory of - “if residual stresses induced in casting process play a major role in contributing towards failure of components in Air Disc Brakes”. The results obtained will also be used to improve castability and avoid expensive workarounds. The importance of this study can be emphasized by the fact that even after rigorous simulations in FEA, unexpected failures occur during physical testing and, it is a well-known fact that the form of physical testing is money and time intensive. With help of the results obtained through this study, the resources invested in testing can be reduced, resulting in overall process improvement. Creo, Inspirecast, Nova Flow & Solid, Ansys Workbench, Compose were the tools used to achieve the stated objectives. Learning new software like Inspirecast and Nova was challenging as well as rewarding. The project yielded useful results and improved our ken about Casting Simulation and FEA. We were able to confirm the theory by analyzing the results, observing the trend and corroborate the pre-existing information as well as speculations.

Keywords: Casting Simulation, Air Disc Brakes, Casting Defects, Residual Stresses, Parameter Mapping, Novacast

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List of Abbreviations

ABS	Anti-Lock Brake System
ADB	Air Disc Brake
ANN	Artificial Neural Networks
CFoS	Compression Factor of Safety
CAD	Computer Aided Design
CSV	Comma-Separated Values
EBS	Electronic Brake System
FEA	Finite Element Analysis
FoS	Factor of Safety

1. Introduction

Employing Computational methods and numerical solutions for virtually simulating the process of Casting is the new engineering sector that is gaining immense popularity due to the sheer ease and efficiency offered. Generally speaking, future predictions based on recent findings and general observation state that the offline processes in engineering which are resource-intensive will be emulated virtually with the help of software prior to implementations in reality. The reason for performing this additional step may be to identify, evaluate problems in the process setups as well as troubleshoot the same as early as possible. The results obtained from these emulations can be used to get estimations and calculate the changes that are required to achieve the desired objectives. There are limitations to the use of this technology, such as incomplete replication of parameters, the requirement of a skilled workforce, additional knowledge to interpret the results obtained and derive a logical conclusion. Despite these limitations, the pros outweigh the drawbacks and make it a possible action to be included as a standard process and a pre-requisite in the time to come.

Liquified metal, when poured into a cavity of the desired shape with controlled as well as calculated flow rate, temperature, and then allowing it to solidify and cool down, results in end products that have the required shape, dimensions, accuracy, etc. The finishing may not be as refined, but additional machining can help address this problem. This process was first implemented all the way back in 4000 BC. Thousands of years later, an unusual yet interesting factor led to the development of this technique, and that was religion. It may seem an odd and anachronistic reason, but it was influential in the development of Casting as metals like bronze were used to build Churches, Cathedrals, and other establishments. It was not too late for people to notice this and utilize the technique for different areas of interest. Leading this path, the first Cannon was cast, and as ironic as it may sound, it was a monk who made it happen. Over 150 years after the Casting process was utilized for weaponry, Vannoccio Biringuccio who is also known as father of foundry documented various processes including Casting and

foundry, smelting, assaying, minerals and alloys in his work *De Le Pirotechnia* which is one of the first and oldest technical documents from the renaissance era [1].

The thesis topic – "Casting Simulation of Air Disc Brakes" deals with casted components that are rigorously examined in Finite Element Analysis (FEA) before prototypes are ordered. Even after intensive simulations in FEA, unexpected failures occur during testing. The stresses indicated by the FEA are intermediate but are not expected to cause failures. The FEA uses a uniform material model and does not take varying material quality and casting defects into account. This leads to limitations in interpreting and using analysis results. The goal of the Master thesis is to combine FEA and casting simulation software like Novacast to gain a wider perspective of the possible defects that could be encountered and help improve castability as well as improve identification of high-risk areas of the component.

1.1. Background

Ever-increasing development in computer-aided technology has changed the course and the way in which the industries carry out their work. For instance, the design of a product or a component of a product was done manually by skilled, experienced engineers prior to the Computer Aided Design (CAD) era. This resulted in the requirement of qualified design engineer acquisition, and even then, the process was time-consuming, tedious, and prone to errors. The introduction of Computer-Aided Design software has been an immense blessing for basically any field of Engineering. Similarly, all the other engineering processes which were carried out manually or based on trial-and-error methods in the past have been replaced with highly advanced as well as feature-rich applications. One of the many areas that underwent a similar transition is the Casting process.

The thesis report employs the latest casting simulation software to carry out simulation on components of Air disc brake model DBT22MD manufactured

by Haldex Brake Products AB and identify the problematic areas, defects that can be improved. Alphabets and numbers in the nomenclature of the Air Disc Brake model DBT22MD is explained as Disc Brake (DB), Tellus (T), Medium Duty (MD) and 22 (22.5 to be precise) is the wheel diameter in inches. It is one of the popular medium duty brake models for trucks. The brake setup undergoes physical testing for quality assurance, where any kind of defects developed in any component of the setup such as cracks will lead to direct rejections and thus losses. As mentioned in the previous section, although most of the defects are forecasted in the FEA results, there are at times defects that are unexpected. Our goal involves extracting the data from various casting software and using it as inputs to analysis software like Ansys. This amalgamation will provide ample opportunities towards developing/ refining the analysis methodology to reduce the unexpected failures that the cast parts experience. Confirmation of mapping of the parameters would be a challenge as it would require the development of a perfect theory that suits the problem statement at hand. The mapping process is complicated which is one of the limitations of the topic.

To understand the topic of Casting Simulation, one needs to understand the terminologies and their meanings, the phases involved, and the science behind it. This will help an Engineer develop a profound and deep knowledge that will lead to Rapid development over time. There are various steps involved in Casting Simulation, right from Data gathering, Methods Design, Simulation, Optimization, and Conclusion Report. There are several sub-steps that involve CAD software like Creo, AutoCAD, Catia, etc. to form a solid 3D model of the Product, Gating system, and other components as required, assemble them and save them in a file format that is compatible with the Casting simulation software. Once this stage is completed, the file is imported and processed to get results that can be used to identify defects in Casting.

1.2. Aim and Purpose

The Caliper in the DBT22MD brake setup experienced a crack during physical testing but the FEA results did not predict any major stress distribution in that area that could have raised a red flag. This led to the theory that the cracked region experienced low yield stress. To tackle this problem, it was speculated that stresses induced during Casting process may be one of the contributing factors for the cracks. The theory is feasible and completely logical as the Finite Element Analysis does not take into consideration the varying Material quality or the casting defects. The theory can be checked for validity by introducing stresses developed in casting as loads in the FEA tests, test the setup and check if the cracked region exhibits higher stresses in the new results.

As stated in the introduction, the thesis report aims at utilizing the latest simulation software such as Novacast to perform casting simulations on the Caliper, and Carrier Component of the Air Disc Brake model DBT22MD and employ the results obtained to find problematic areas that can be improved. Based on the outputs from the simulations, mapping of mechanical properties such as yield strength, elastic modulus to structural Analysis with the help of software like Ansys Workbench was carried out. This also led to the development of plot results that combined material quality and structural loads to identify areas with low fatigue in the product.

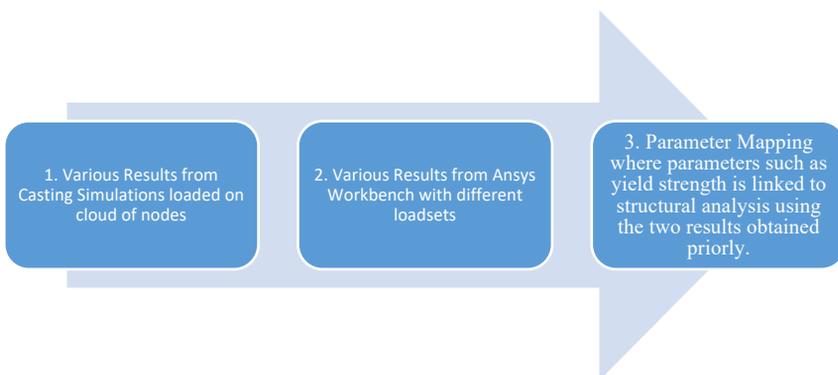


Figure 1: Flow of objectives

A significant part of thesis work involved developing, re-creating, and modifying the existing gating system (designed by suppliers) for Caliper and Carrier, making minor modifications using CAD software CREO, saving it in a compatible file format for further simulations. Casting Simulation software is used for running simulation by providing inputs and setting the values of parameters such as Flow rate, pouring height in case of Gravity Casting, adjusting the position of Gating points, shape and size of risers, the orientation of the product during Casting, and direction of the flow of molten metal, as closely as possible to simulate real-time casting environment. More details about each of these parameters have been provided later in the report.

Creating a workflow for setting up a generic casting simulation and relating the results in an attempt to identify problematic regions in the design and to improve castability have been carried out. Upon completion of simulations, the results from simulation and Analysis are mapped to get an estimated idea of how properties like yield strength can be related to structural Analysis in order to derive a safety factor. Figure 1 shows the chronological flow of objectives. This knowledge will hopefully contribute towards improving the process of Product quality improvement.

2. Literature Review

This section of the report explains concepts and terminologies that are required as pre-requisites to understand the Aim, Objectives of Master Thesis topic and the tools used in the process.

2.1. Air Disc Brakes

2.1.1. History

Europe has initiated the history of the usage of air disk brakes on commercial vehicles. Although air disc brakes for North American cars were tested and improved in the early 1980s, performance and reliability issues prevailed, and these early assessments were soon discontinued. Air disk brakes were commonly used in all-wheel positions in Europe even 20 years earlier.

A technological change in the EU on the braking systems took place in the mid-1990s. An Electronic Brake System (EBS) was supported by the truck industry and Daimler, in particular, over the conventional Anti-Lock Braking System (ABS). The technology at the same time changed from the drum brake to the disk brakes (ADB). These improvements mainly resulted in improved braking efficiency by better brake force management (EBS) and more reliable braking output over the wheel end temperature range, and reduced hysteresis (ADB). The EU truck and trailer industry moved from ABS w/drum to EBS w/ADB over a time of almost 5 years, and by the beginning of 2000, about 70% of the sector accepted emerging technology [2].

Generally, the European truck industry and its supplier base vary greatly from North America, and these variations facilitate fast adoption of the technology of air disk braking systems. One of the crucial distinctions was that many variations of tractors and trailers in Europe were really combinations – as a unit [3].

The fact that each car maker manufactured and developed versions with its own drum frequencies in Europe was also a critical factor in the fast introduction – unlike the case on the North American market with a few drum brake manufacturers competing – Meritor and Dana, for example. The lack of uniform frequencies for Europe's tractors continued to lead to higher drum brake and related material part costs. Therefore, until recently, in the US industry, the jump to the more expensive air disc brake was not regarded as a significant obstacle [4].

In August 2011, the federal government launched a three-year tractor stopover scheme. The first part of its new stopping distance legislation included three-axle tractors with gross weight ratings (GVWR) of up to 59,600 pounds. The program, which ended in August 2013, included the National Highway Traffic Safety Association (NHTSA) rules for all other tractors with GVWRs above 59,600 pounds. The objective of the NHTSA program was to get cars similar to a standard passenger vehicle. Then North American fleets of all kinds became seriously interested in or at least contemplating switching to the air disc brakes. Although all were sure to follow the new rules, the forward-looking and protection fleets saw a chance and began to explore the fleet potential. In addition to the OEM-specified bigger steering axle brakes, a great deal of those fleets, whose chosen technology to remain, saw the need to improve their performance with broader brake shoes and more aggressive fitting stuff. The additional expense of these improvements has further reduced the distance between the air disc brake and the drum brake [3].

The prominent features leading to the development of Air Disc Brakes are:

- Essential braking demand for a response to higher speeds and minor average delay
- Increased safety and success expectations
- Reduced maintenance requirements, faster service times, and long lining life
- Improved durability of disc-breaking technology

The advantages of Air Disc Brakes are:

- The fading is significantly more minor when compared to the drum brakes
- They are very consistent and perform exceptionally well in cold climatic conditions
- The disc pads are easily replaceable
- The vehicles with air disc brakes have higher stopping capability due to the higher brake torque generated.

2.1.2. Working of Air Disc Brakes

Instead of hydraulic oil, air brakes operate using compressed air. Air frequencies may be either a drum brake, a disk brake, or both. An engine-mounted compressor pressures air. Air pressure. The air compressor pumps the air into the air storage tanks, where compressed air is stored until necessary. For applying the service brakes and releasing the brake, air pressure is used. The machine contains many air loops. As air pressure is released into the chamber, the parking brake is engaged by a spring force in the spring brake chamber. The parking brake can also be used as an emergency braking mechanism. When the air pressure is too low, the spring force in the chamber will surmount the air force on the diaphragm and use the brakes on all the wheels. Figure 2 displays an Air disc brake assembly that is considered for the study with the components marked out.

The sequence of disc brake operation is [5]:

- The brake pedal is pushed by the concerned person, which actuates the air braking system
- The air from the reservoirs is supplied to the brake valves
- This air is further delivered to the brake chambers
- With the help of the actuators, the chamber actuates the caliper to transfer force onto the inner brake pad
- As the inner brake pad contacts the brake rotor, the caliper slides on the guiding pins

-
- To move the outer pad against the rotor, a bridge moves with the caliper
 - The inner and the outer pads squeeze against the rotor, transferring force to stop the wheel
 - The driver releases the brake pedal
 - The pads are separated from the brake disc
 - The brakes are then released

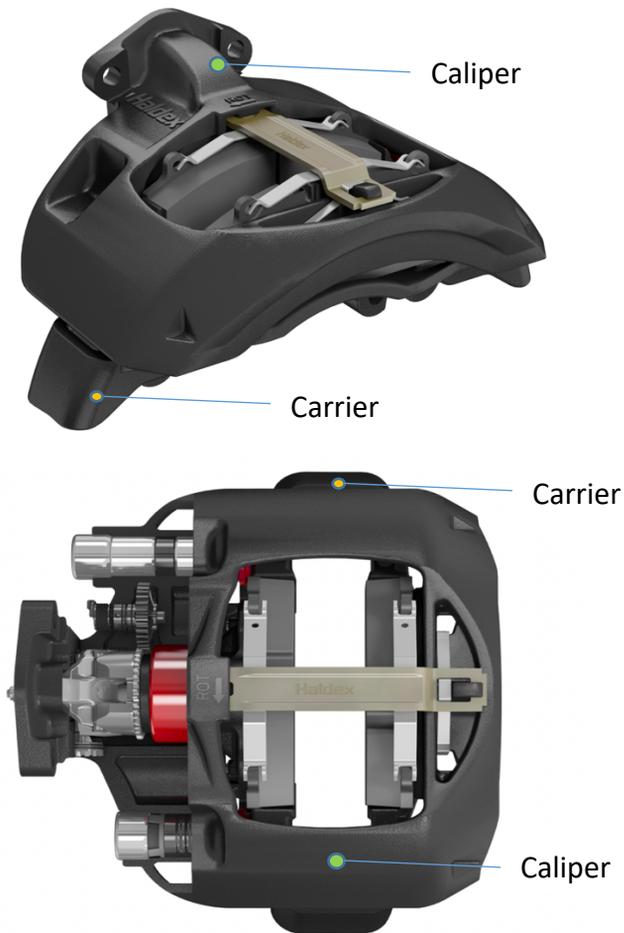


Figure 2: Different views of Air Disc Brake Assembly [6]

2.2. Casting Simulation theory

Even in a fully regulated procedure, casting defects are found, and Casting is regarded as an unstable process that questions the integrity of cast products. The study of fine-tuning defects is the mechanism by which the root cause of defects in Casting is detected, and steps are taken to minimize defects and increase casting performance. To analyze the casting defects, various researchers use techniques such as diagrams of causes and effects, experiment design (DoE), simulation of Casting, if-then rules (expert systems), and artificial neural networks (ANN) [7].

Simulation is a mechanism of using a series of mathematic equations applied in a computer program to imitate a particular phenomenon.

The simulation programs build on a finite element analysis of the 3D castings models, which have an advanced user interface, computing, and display features. The construction of any casting simulator requires an understanding and a model for a host of physical processes such as heat transmission (conduction, convection, and radiation), mass transmission (primarily fluid dynamics), phase transition during solidifying and post-solidification phases, and stress-strength behavior of the cast products. In every simulation program, the basic mechanics of the Casting (heat and mass transfer) and its mathematical models, such as mass recovery, energy, and momentum, along with a reliable material properties database and other physical properties and model parameters relating to cast metals and materials, are incorporated [8].

Casting Simulation is a vital part of the casting process that guarantees flawless Casting for a brief period of time. For casting simulation, the mold filling and solidification analysis are carried out with a finite volume method-based algorithm or program for the identification of hot spots and therefore defects such as porosity shrinkage, hot tears, cracks, etc. It is an outstanding technique to be used during the premature stages of a modern component design project. The simulation approach is very efficient and accurate for a wide range of cast metals and complicated processes. For the creation of the microstructure and consequently the mechanical behavior of a cast-iron component, the local solidification conditions of the cast component are

crucial. The mold filling process is, in fact, quite complicated to model, with the effects of fluid flow, heat transfer, and phase change. During the filling phase, the fluid of molten metal is mostly turbulent. The usual turbulence models demand a very fine grid near the mold walls, and in all portions of a complicated mold, it is unworkable to produce such a fine grid. Therefore, only laminar flow calculations for mold filling forecasts are commonly done [9]. The mechanical designer will assess the chance that the cast is produced in high-load areas without severe defects. Directional solidification is a motto about how the liquid metal front solidifies in the Casting into the finished parts. Casting software is designed to simulate the solidification of liquid metal using thermophysical details [10].

The simulation method usually involves processes, as mentioned, like mold filling, grain structure, stress analysis, deformation, liquid phase, and solidification. The program has material details for hundreds of various alloys and molds with characteristics beginning at a temperature above solidification. It also includes component and tool equipment such as cores, cut-outs, mold layouts, feeders, gating systems, etc., as well as temperature-regulated mold and materials and finally processes parameters such as flow rate, temperature, velocity, etc. This study has shown that casting defects, such as hardpoints, blowholes, cold shuts, shrinking porosity, cracks, and distortions, can be predicted. Many results are empirically gathered. A more extensive explanation of the Casting simulation workflow has been provided in Methodology [11].

2.3. Casting Defects

Defects are the root cause of the majority of problems in Casting apart from the process of setup, calculation of mold size and material, etc. Most of these defects are unpredictable in nature and are formed when the metal is crystallized. They are shaped in and out of the Casting. It is a known fact that manufacturing errors are one of the causes of defects. This results in financial losses for a modern company, extra expenses for casting rework. Figure 3 illustrates all potential causes for Casting defects.

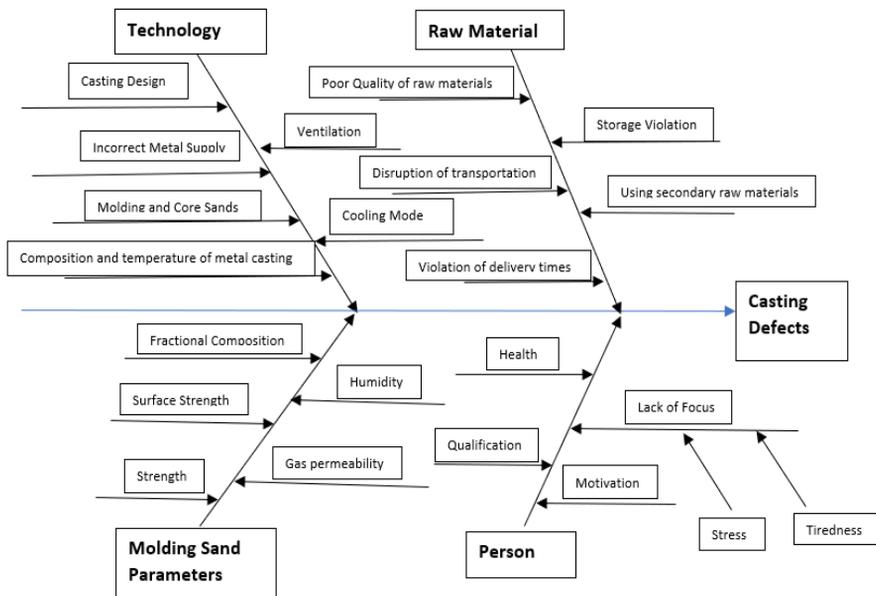


Figure 3: Fishbone Diagram of Plausible reasons for Casting Defects

There are various defects in metallurgy. The most common are the following:

Blowhole defect: As seen in Figure 4, These are cavities created in metal because of poor form gas permeability, lack of temperature control, or insufficient material consistency.

Sand spots: These are metal cavities packed with molding material because they are of poor mold and core sand strength or because the casting nature is low technology.

Porosity: The appearance of multiple tiny pin-sized pores, i.e., the intercrystalline vacuums in the metal, caused by bubbles of gas escaping from solidifying metal is porosity. It is displayed in Figure 6.

Possible reasons:

- Solidification Shrinkage
- Unsuitable Casting and temperature of the metal

Hot and cold cracks: Figure 6 shows Hot Cracks, which are the local metal defects or breakage.

The causes:

- Structural errors
- Mold sand composition
- Metal casting
- Temperature of crystallization
- High mold pressure

Cold lap: Cold laps (Figure 4), are incorrect connections between two or more flows in the mold that result in the molten metal's incorrect union. This is like a crest crack on both sides. It produces quality concerns in functioning components both on an aesthetic part and on a reduced mechanical resistance.

Inclusions: Includes sand or slag fragments that are integrated into the Casting by a highly turbulent mold filling and molten metal oxidation.

Sink mark: It is a smooth depression on the top of a dense part due to volumetric contraction in the top surface. The Casting rejects consistency is dependent in considerable measure on the parameters in the molding materials. The following basic properties must be defined according to the working conditions and technical method of Casting, molding, and core mixtures:

- Strength - capacity of the molds and core not to break under stress
- Strength of the surface - resistance to abrasion forces of the mold surface or of the core
- Gas permeability - a mixture's ability to flow into the gases of the mold and liquid metal; if the mixture's gas permeability is

inadequate, then the gases are introduced through the metal, causing casting defects.

Warping or Shrinkage: Figure 8 displays Shrinkage, which is caused by a transition in metal's size and shapes under the pressure of stresses

Possible causes:

- The irrationality of casting design (for example, wall thickness differences) leads to internal stresses
- Improper metal supply that has a negative impact on cooling uniformity
- Inadequate composition or temperature of the cast of metal causing additional Shrinkage
- Improper casting cooling mode and poor mold and core versatility.

Below we can see the images of the defects in real life:



Figure 4: Blowhole [12]



Figure 5: Coldshut [12]



Figure 6: Hot Crack [12]



Figure 7: Porosity [12]



Figure 8: Shrinkage [12]

3. Methodology

This part of the report explains the flow of steps and the methods used to create the gating design, perform casting simulation and performance tests for both Caliper and Carrier. Most of the steps in CAD, Casting Simulation, and performance tests were similar for both components; therefore, the steps have been explained in detail for only one component. A more detail-oriented explanation has been provided on software used and their modules as well.

The Casting Simulation is carried out in Novacast software after pre-processing of the model in Creo. Novacast was majorly used to perform various simulations using different combinations of parameters like Flow rate, Gate design, Gating point, Temperature, Riser size, Different Orientations, and flow direction. Novacast has a systematic approach towards Casting Simulation with a dedicated module for 3D import, Simulation Setup, Solidification, Flow & Solid, Flow Simulation, Browser, and Novastress. Figure 9 displays the workflow of Novacast. As seen in the figure, each module has a pre-requisite, and the workflow is arranged in a chronological manner. The CAD model is imported into 3D import, processed, and saved in .CVG format before the Simulation setup module can be used. Building of mesh, assigning of materials, temperature, gating point, setting up of Filling parameters and Shrinkage model are the basic requirements for a typical simulation. All these are carried out in the Simulation setup module. Once the desired values are assigned, the file is saved in .SIM format for the next phase of the simulation.

The selection of the next module to be used depends on the requirement of the company or individual operating the software. If the requirement is for Solidification or Flow Simulation, then the respective module is employed, and if both are to be done simultaneously, then Flow & Solid is utilized. The required options are selected in the modules where one can control the result files to be obtained and the intervals at which calculations are needed. For instance, simulation engineer can decide if readings and results need to be

calculated in steps of 0.5 or 1 and at what value of volume filled or time does the simulation needs to stop, etc.

3D Import	Simulation Setup	Flow and Solid Simulation	Browser	Novastress
<ul style="list-style-type: none"> • Importing Step or STL files from CAD software • Assigning parts such as riser, gating, cooling pins to their respective tabs in the tree • Assigning Orientation • Building of Assembly • Saving in .CVG format 	<ul style="list-style-type: none"> • Importing the .CVG file • Building of Mesh • Assigning Materials and properties for those materials • Setting of Gating Points • Assigning Filling parameters such as Casting type, Flow rate etc. • Assigning Shrinkage model values • Saving in .SIM format 	<ul style="list-style-type: none"> • Importing of SIM files • Setting the required values to be recorded with respect to time and temperature • Setting Autostop criterias • Start of Flow and Solidification Simulation • Autosave 	<ul style="list-style-type: none"> • Browsing the results of successful Simulations • Analysis of the Liquid and Solid phase to check for optimization • Identification of areas of defects • Loading of Cloud of Nodes • Mapping of results onto the nodes to obtain Nodedata file 	<ul style="list-style-type: none"> • Calculation of Stresses using the result file • Mapping the stress results onto the nodes to obtain Nodedata file

Figure 9: Workflow of Casting simulation in Novacast

Results like Temperature distribution, Different types of Shrinkage, Porosity, Hot spots, Micro-Porosity, and Niyama can be obtained, which provide plenty of data that can be used to achieve the objective of the thesis. Details of the process are explained more precisely in subsequent sections.

3.1. CAD Processing using Creo

In any casting setup, the Gating system plays a vital role, and thus the design of the same has to be as refined as possible. The layout of the pattern should incorporate proper positioning of impressions of Casting. This will play a significant role in improving the directional solidification.

The Gating system obtained in this thesis for both Caliper and Carrier was replicated from the already existing setup used by the suppliers. The System consists of Risers, Chillers and cooling pins, etc., wherever required. The

replication of the System is majorly based on approximation of the existing System as the possibility of physically examining the setup at the foundry was unfortunately not possible. The initial options used in Creo can be seen in Figure 10. The sequence after importing is complete looks like this: Create (in active assembly) > Part > ok > Copy from Existing or Create Features > ok.

This sequence of commands is typical for both components. The images of the gating system with and without the complete casting setup have been provided in this section. Different views and orientations have been included, so one has a better understanding of the actual System.

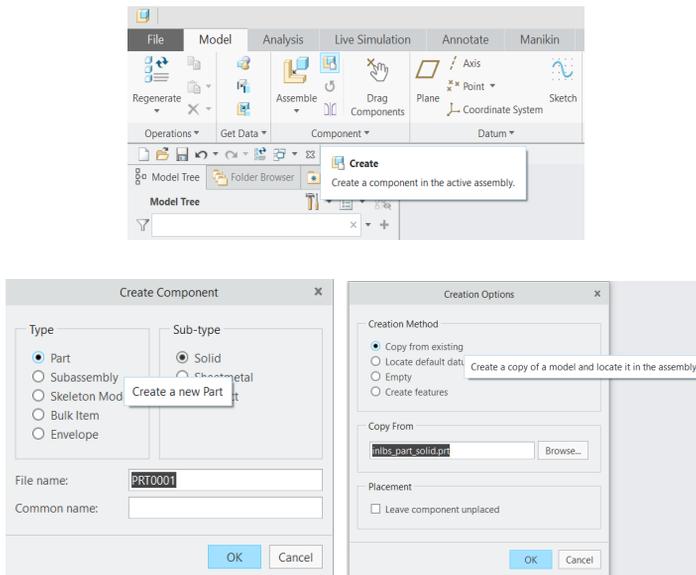


Figure 10: Images of Commands used to create Gating System

The files in both cases (Caliper and Carrier) are saved in STEP or STL format after completion of processing in Creo.

3.1.1. Gating Design for Caliper

The procedure for obtaining a good setup for casting simulation involves a minimalistic design, perfect contact between surfaces of the components, proper selection of the file format to obtain refined meshing, smooth edges to avoid any kind of obstruction of flow, etc.

The CAD 3D model of the Caliper was used as a reference for replicating and building the gating system. Creo was employed for this purpose and the procedure started with selecting assembly as the work platform. Caliper model was imported by using the Assemble command. Building of the gating system was done by selecting the create component command in the assembly window, which lets you create a new component whilst still staying in the Assembly mode. The advantage of creating the gating system using this method is that we get options that can be used to obtain perfect contact between the Gating system and the Component to be cast without having to calculate the exact dimensions. An alternate way is to create the Gating system as a separate model/part in Creo and then assemble it with the Component using Assemble command followed by providing constraints, but this requires exact dimensions to obtain a perfect contact which is crucial and imperative for the simulation process. Additionally, there is a high chance that if the second method is used to create the setup, the Casting software may treat both the parts, i.e., the Gating system and the Component, as a single entity/body or one combined assembly. This will cause a major hindrance as one cannot select the respective parts in the casting software and assign them their roles.

Figure 11 and Figure 12 show the options to create a Component within the assembly window for Caliper.

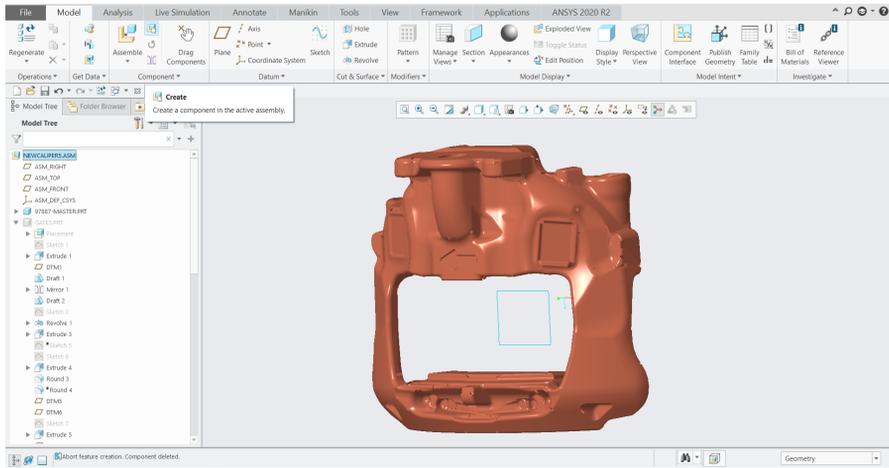


Figure 11: Option to create the Gating system in Assembly mode

After selecting the options as described in the General Procedure (Section 3.1) for the CAD design of the Gating System, we can use the sketch option to start with the initial steps. In the design of Caliper, gating commands like Sketch, Spline, Arc, Extrude, Revolve, Project, Draft/ Taper, Round were used.

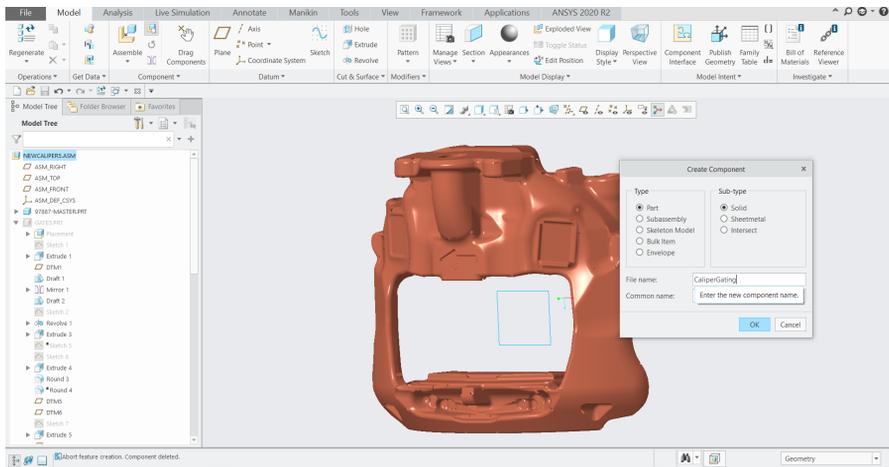


Figure 12: Options selected to create Gating System

The Riser, which is similar to the shape of a wine glass, was created using the sketch, spline, revolve commands. The draft, which is also known as the taper command, was used to narrow the neck of the Gating just below the rectangular block in the mid-section of the Gating, and a taper of 7° to 10° was used. All these features can be seen in Figure 13, where the System is isolated from the assembly.

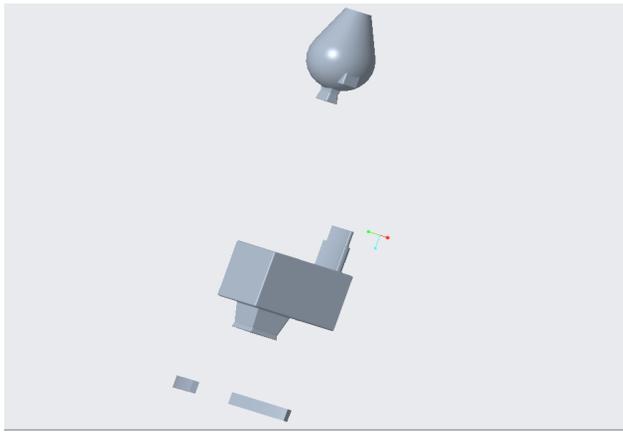


Figure 13: Gating system of the Caliper Isolated from the assembly

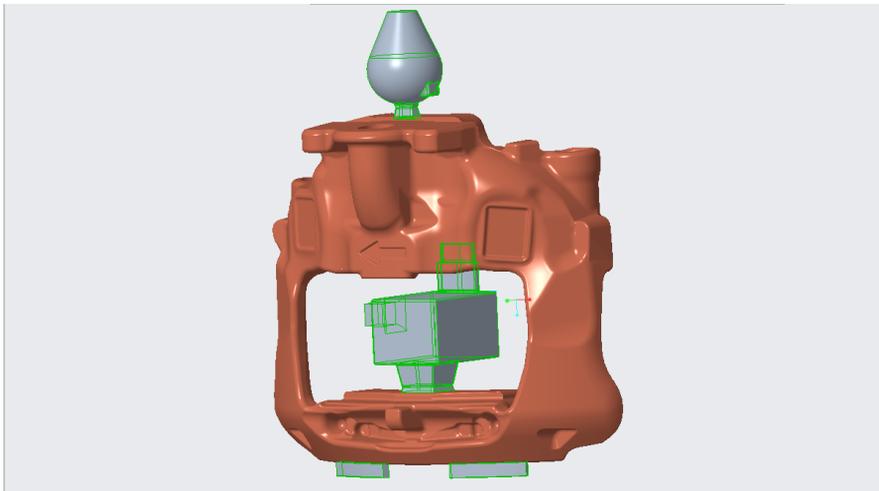


Figure 14: Caliper Casting Setup

Upon completion of the setup in Creo, the file must be saved in a format that is compatible with further processing. A complete Casting setup for Caliper is displayed in Figure 14. The file formats that are supported by the majority of the Casting simulation software are STEP (.stp, .step) and STL (.stl). Saving the setup in either of the file formats in Creo marks the end of the CAD processing phase of the simulation. It was found that the STEP files provide refined and smooth geometry when imported in the Casting Software when compared to STL files.

3.1.2. Gating Design for Carrier

Figure 15 shows the 3D model of the Carrier in Isometric view. The geometry of Carrier may seem simplistic, but the edges and the ribs can cause a bit of challenge during the process.

The procedure used for creating the Gating system for Caliper was followed here as well. Similar commands were employed, and the Gating system for Carrier can be seen in Figure 16.

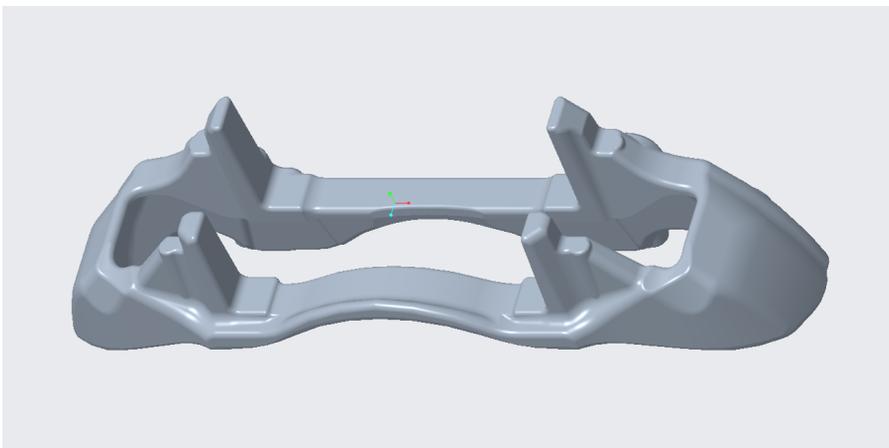


Figure 15: Carrier CAD model

The two Risers used here help in mitigating the chances of porosity and Shrinkage in the Component. The gating system is also symmetric along the

midsection of the Carrier. The rounded edges help in a better and smooth flow.

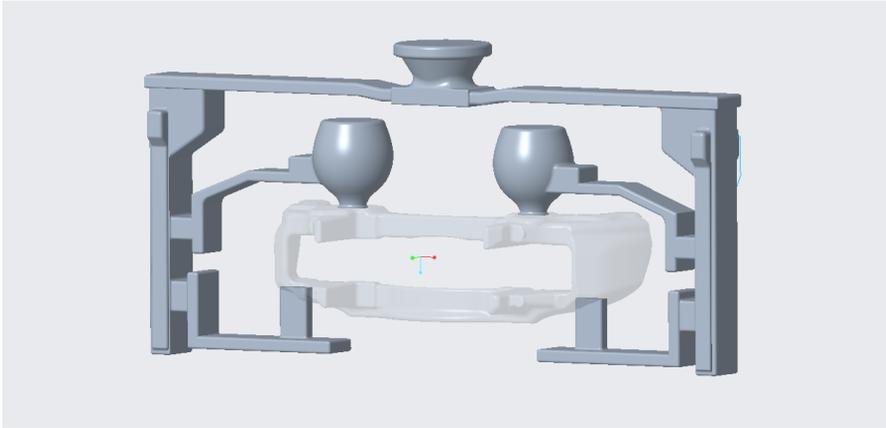


Figure 16: *Carrier Gating System*

The complete Casting setup for Carrier is presented in the figure below. Flow is in the downward direction, and the input is through the cup-like structure in the middle, as seen in the figure. The gate path may seem long but helps in obtaining uniform properties and strength throughout the Component as well as avoid defects. A simulation-ready setup can be seen in Figure 17.

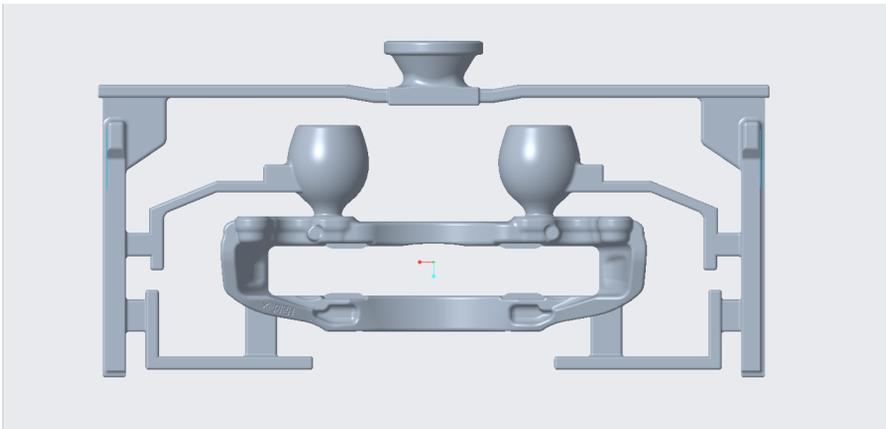


Figure 17: *Carrier Casting Setup*

3.2. Casting Simulation

The simulation employed EN-GJS-600-3 as the cast metal. The chemical composition of the material is:

Table 1: Chemical Composition of EN-GJS-600-3 [13]

Material	Composition in %
Carbon, C	3.4-3.85
Silicon, Si	2.3-3.1
Manganese, Mn	0.1-0.3
Sulphur, S	0.02 maximum
Phosphorus, P	0.1 maximum
Iron, Fe	Remaining around 93%

Table 2: Other Properties of EN-GJS-600-3 [14]

Properties	Values
Tensile strength in N/mm ²	600
Yield strength in N/mm ²	370
Elongation in %	3
Poissons Ratio	0.27-0.29
Elasticity modulus in kN/mm ²	174
Compressive Yield Strength in N/mm ²	870
Density in g/cm ³	7.2
Melting Point in degree C	1150 - 1200 °C

3.2.1. Casting Simulation of Caliper

I. 3D Import:

The Simulation process begins with importing the previously saved STEP or STL file. Figure 18 shows the initial step in casting setup and the compatible file formats for 3D import in Novacast.

The color-coding, as seen in the images, states that the Blue/Cyan color component is the Caliper, Green, and Blue corresponds to Riser, and the Cooling pin, yellow and red components represent Chiller and Gating System. After importing the file, one must check in the list of Solids (usually located on the right side of the screen by default) if the Component is assigned to Casting, Riser, and Chiller is assigned to their respective sections and Gating system is assigned to ingate system.

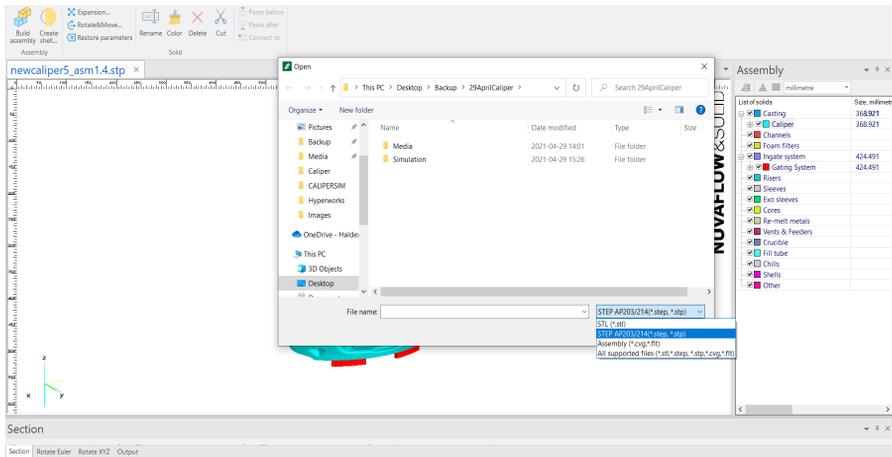


Figure 18: Import option with supported file formats

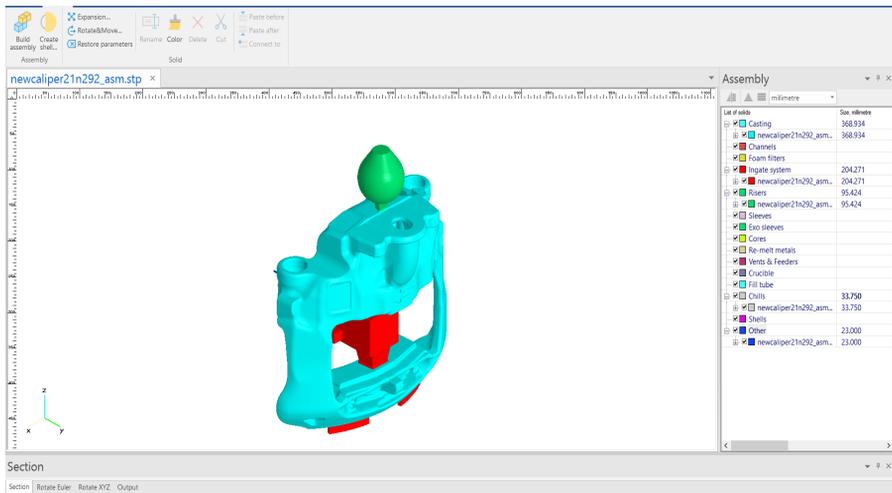


Figure 19: Assigning of components

A simple left-click – drag and drop does the job in this scenario, and the Riser can also be assigned separately. The color coding and names can be assigned as required. Once the assignment of different parts of the setup is complete, the assembly tree looks like Figure 19.

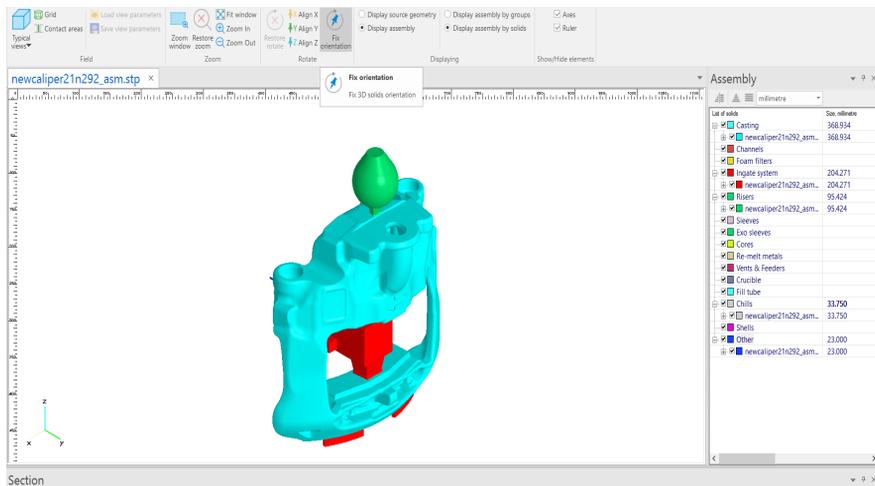


Figure 20: Fix Orientation

The next step would be to fix the orientation in a way that reflects the isometric view of the setup. This step is carried out by using the view tab, rotating the setup to closely align the coordinate System at the bottom left of the screen in a way that it is as close to the Isometric view of the setup as possible. After satisfactory positioning of the setup, alignment in X, Y, Z coordinates is done by clicking the respective options as seen in the top mid-section of the image above. This results in a perfect Isometric view, and it is finalized by clicking the Fix Orientation option (Figure 20). Gravity direction is determined in this step and is thus extremely crucial. Different setups were performed by altering the gravity direction, and each orientation yields a unique result. It is preferred that the direction of flow of molten metal is in a way that there is smooth flow, and no unnecessary or double contact takes place between the molten metal and the cast cavity. In this case, the flow is from the bottom of the setup.

Build assembly would be the next option in sequence. This option can be seen in the top right corner in Figure 21. Completion of this would result in a setup that has contact areas and a rigid build. Check for the contact areas can be done by using the contact areas option in the View tab. This option grays out the components as seen in the picture, and when the gating system, Riser, chiller parts are hidden by unchecking the box in the tree, it reveals the area of contact.

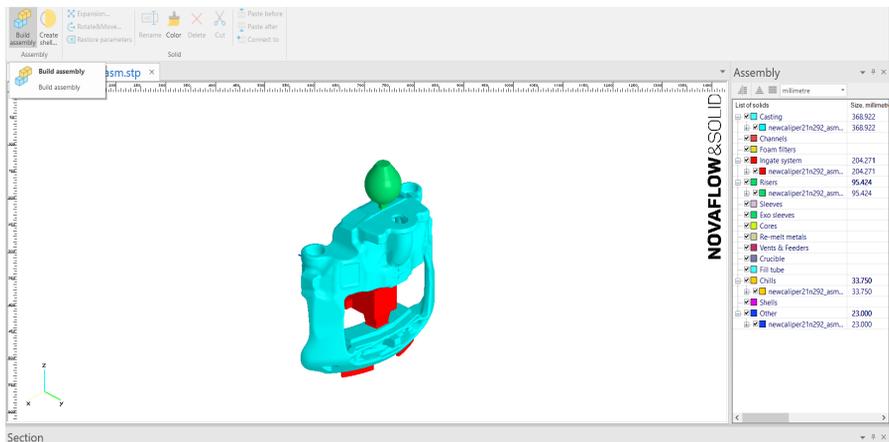


Figure 21: Build Assembly

The colored areas in Figure 22 and Figure 23 show the area and point of contact between the Caliper and other parts of the setup. This represents the path through which molten metal flows into the cavity through the System. If it meets the requirements, further steps can be carried on.

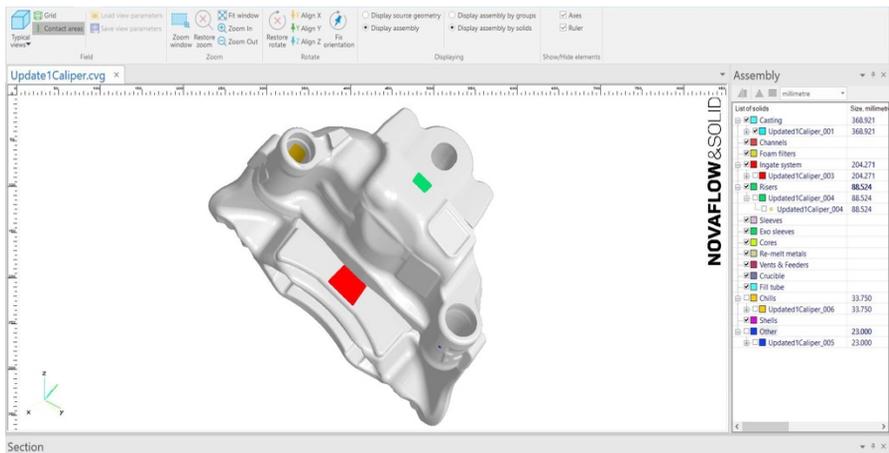


Figure 22: Caliper-Gating Contact Areas

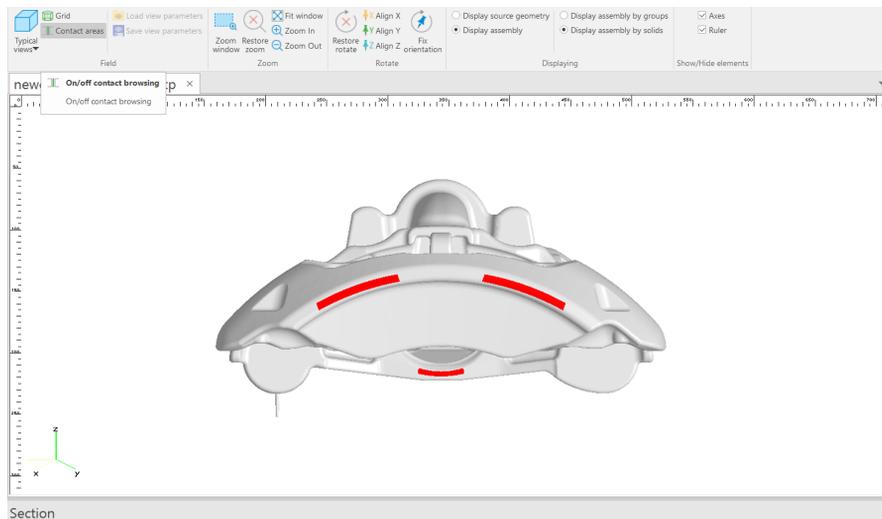


Figure 23: Caliper-Gating Contact Areas bottom view

The color coding for the contact areas can be seen in Assembly tree in Figure 22.

II. Simulation Setup:

The next step in the procedure is the Simulation setup. As stated in the section Casting Simulation, options can be selected as required in this module where the building of mesh, assigning of materials, temperature, gating point, setting up of Filling parameters, and Shrinkage model can be performed. Adding Vents, pins, chokes, and numerous other options are also offered that can be implemented on demand.

The mesh size is directly proportional to the simulation time, and a mesh element of higher order can take a longer simulation time. Time constraint also depends upon the complexity of the geometry. However, this excess of time is compensated by refined and granular results and output files. A balanced meshing would provide an optimum solution. The cells can be adjusted along with different coordinates as well.

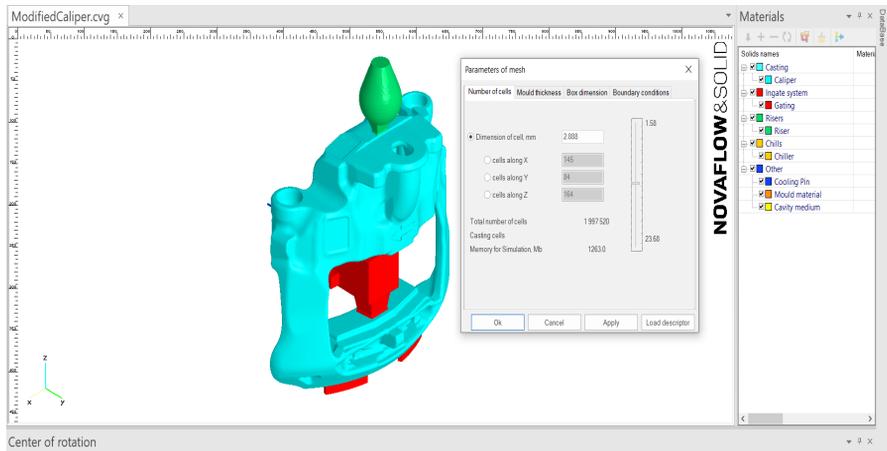


Figure 24: Mesh Building

Along with a number of cells, parameters like Mould Thickness, box dimensions, and boundary conditions can also be applied. The mesh size

used here varied from 4 to 6 mm. This is the first step in the Simulation setup, and the mesh options can be seen in Figure 24.

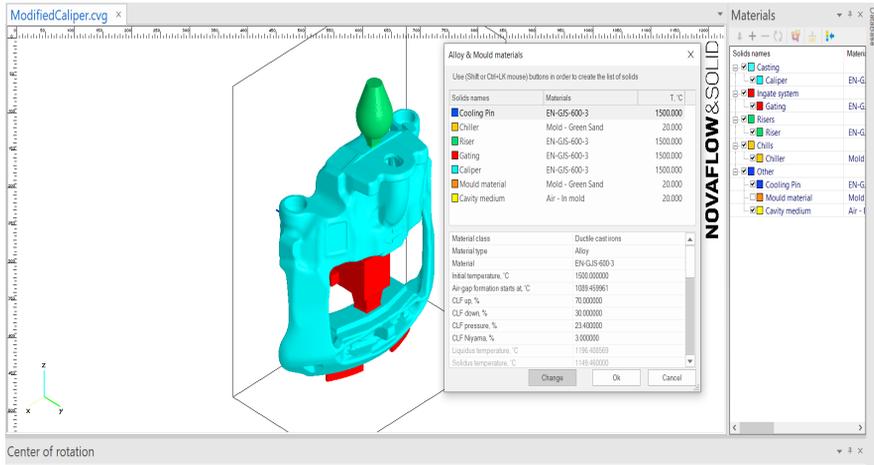


Figure 25: Assigning of materials

Assigning materials or set materials is carried out next, where the type of material being used to cast is fed as input. In this case, the material is EN-GJS-600-3. The material for both the Caliper and Gating system will be the same for obvious reasons. The temperature for this material was set to 1500 °C. This temperature was chosen as it is closer to the temperature in reality. It can vary based on other factors. Greensand was used as a Mold material, and the Cavity medium was Air-In mold. The temperature for these parameters was set to a default of 20 °C. The other parameters, as seen in the image, are left untouched but can be altered and correspond to different result types. All these settings can be seen in Figure 25.

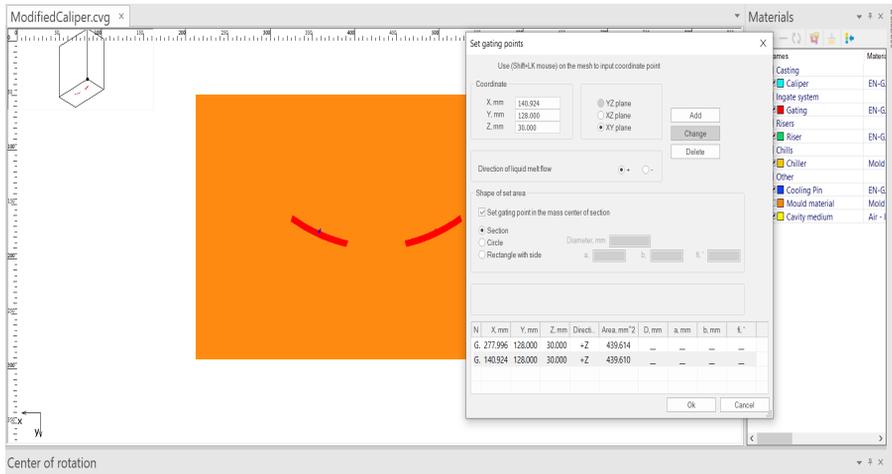


Figure 26: Gating points

This step defines the entry point for the liquified metal. The gating points are provided by selecting the Gating points option, then clicking the View tab, and selecting section. Right-click on or around the rectangular box/mold in the setup view window and select the change section option where using the left click, the required section can be selected from any plane. Moving the mouse up or down will provide a cross-section of the setup. Alternatively, the software allows for a cross-section view using the scroll wheel on the mouse, and when the cross-section of the surface that is to be set as Gating point is reached, a right-click is used to pause and set the section. As seen in Figure 26, the gating points are set on the bottom two surfaces. This is done by selecting the point using a mouse pointer and holding shift. The gatings and vents need to be set on the material – alloy boundary. The direction of liquid melt flow is specified and added. This marks the end of the setting of Gating points.

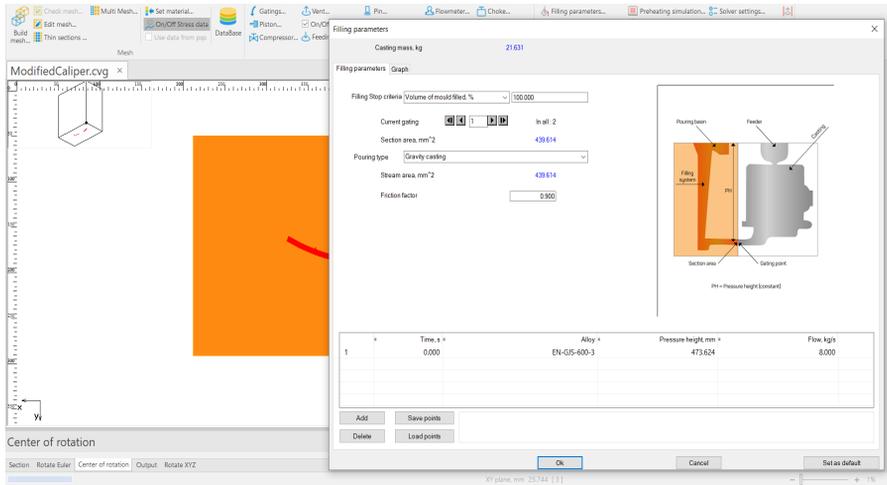


Figure 27: Filling Parameters

When the Gating points are set successfully, the options in the Technology ribbon in the top right of the screen are activated. Filling parameters and Shrinkage model parameters are set in this step (Figure 27 and Figure 28). As seen in the images, filling stop criteria is selected where options like Stop when Volume of mold is filled at "S" %, Mass of mold filled in "S" kg, At the time "S" in seconds, or on reaching trigger "S" mm can be selected. Where S is a variable that can be chosen. 100% volume was selected for our report. Gravity Casting was employed as pouring type, and the flow rate was varied between 4 to 8 kg/s. Specifying either Pressure height or flow is sufficient as the other parameter is automatically calculated. The friction factor is set as default.

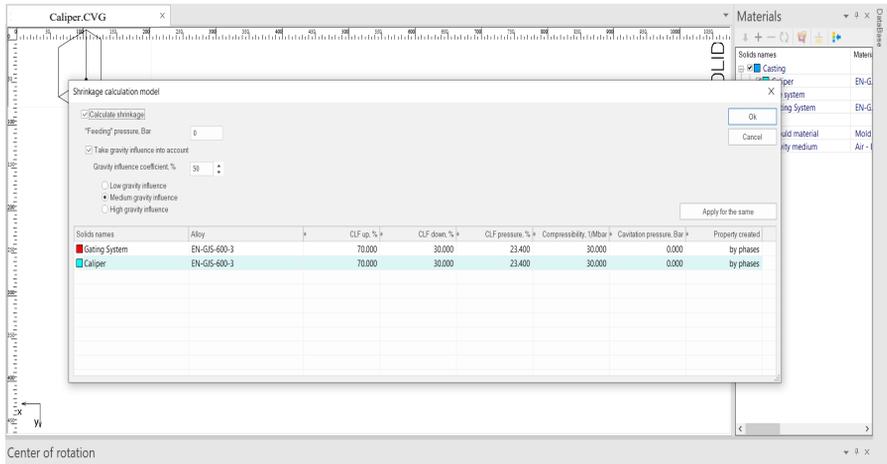


Figure 28: Shrinkage model parameters

The Shrinkage model parameters are set as default, and Medium Gravity influence is recommended for this material type. After this option, the file is saved in .SIM format by default (Figure 29). This completes the purpose of the Simulation setup module.

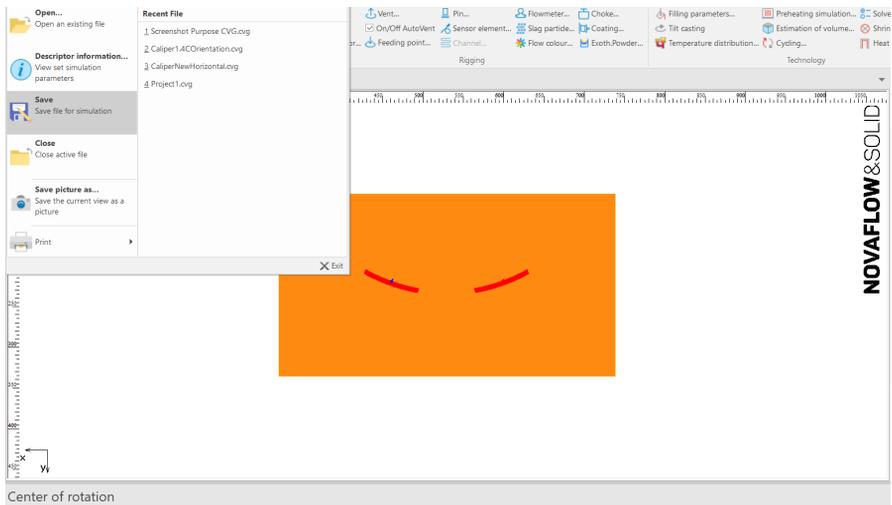


Figure 29: File saved in SIM format

3.2.2. Casting Simulation of Carrier

The steps followed for setting up the Carrier Casting simulation were similar to the Caliper setup. Initial steps are, as stated earlier, common for both components.

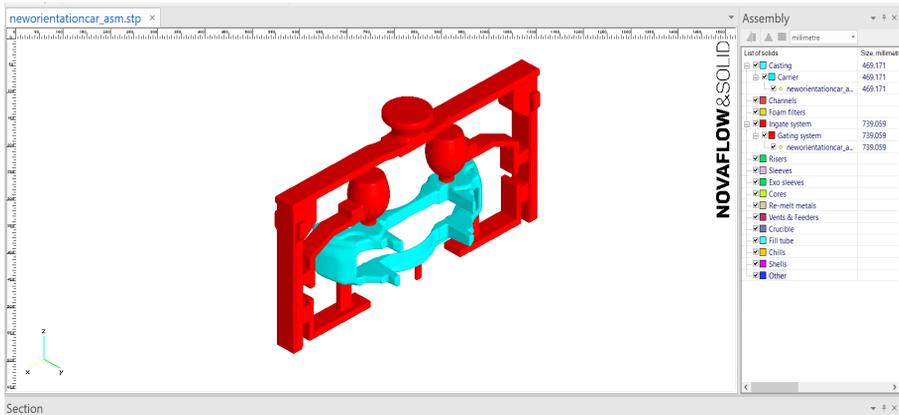


Figure 30: Carrier Casting Setup with components assigned in Assembly tree

Settings including Filling parameters and Shrinkage model were set the same and the major difference is the presence of a single gating point in Carrier.

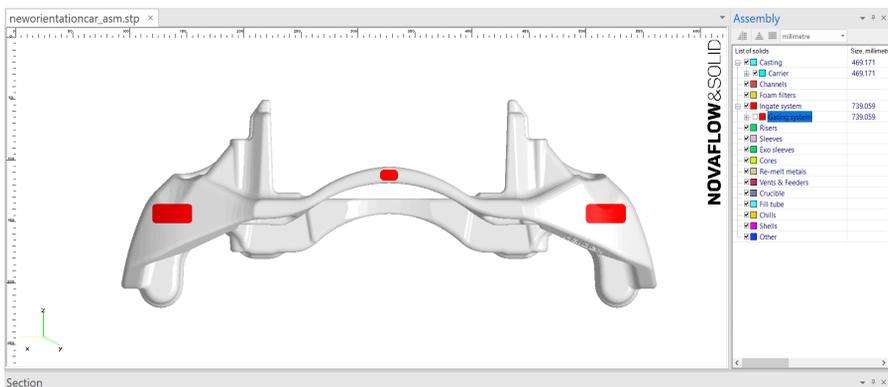


Figure 31: Contact areas – Bottom View

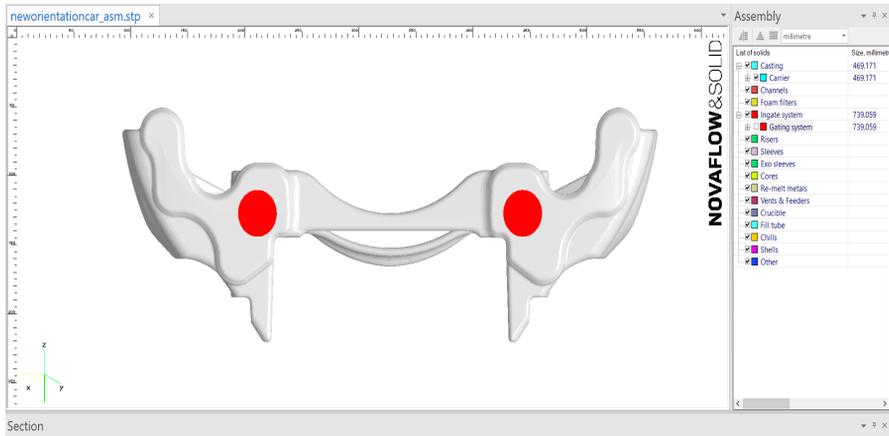


Figure 32: Contact areas – Top View

Figure 31 and Figure 32 display the contact areas between the Carrier and the gating system.

3.3. Cloud of Nodes

Creating the Cloud of Nodes: In order to map Parameters and find the safety factor, the results from Novacast need to be exported. This can be done by creating a cloud of nodes and loading the results onto them. One method of performing this process is by loading the complete setup of the Air Disc Brake with all the necessary constraints and properties onto the Mechanical Workbench software and performing a series of operations. For instance, the nodes for Caliper are obtained by hiding all the other components except for Caliper. Support and force values are provided on the surface of the Caliper (surface can be chosen freely). This makes sure that there is a condition that can be solved to get the nodes. This process may be time-consuming, and it is recommended to adjust the settings like load steps, force value, non – Linear settings to a minimum value in the solver setting window. Once this is completed, solve option is utilized to obtain the results. The Ansys solver provides results that may be Maximum or Minimum Principal stress. Right-click on one of the results gives an option – "Export to text file". Selecting

this option and saving the file in xls format gives a file with all the required node data along with coordinates.

The file is then opened using excel, and headers are provided to differentiate the Node number and X, Y, Z coordinates. It is then saved and imported back to the browser of Novacast. Now, the option to load the nodes is provided and using this, the data such as Yield strength, Maximum and Minimum Principal stress, Von-Mises stress can be loaded onto the cloud of nodes and saved individually. Stress tensors can also be loaded in the Nova Browser.

Cloud of nodes in free form and loaded onto the geometry of Component can be seen in the figures below. By observation, the cloud of nodes for both components has holes in them, but the 3D models do not have any; this is explained by the fact the nodes are created using a machined version while casting simulation is supposed to be performed on an unmachined version. From the images, one can observe perfect contact/ fit between the nodes and components, which is critical if reliable data is to be obtained from these nodes. The computational time for these nodes may be large because of the number of nodes present. The Carrier nodes have about 206489 entries, while Caliper nodes have 507638 entries in their respective Excel files. Figure 33 – Figure 41 show different views of Node Clouds with and without the component. A perfect match is visible between the body of the component and the Node clouds apart from the machine – unmachined surfaces.

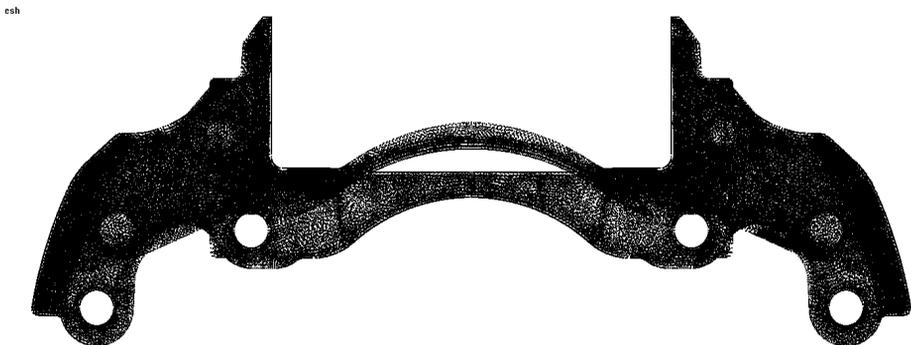


Figure 33: Cloud of Nodes for Carrier

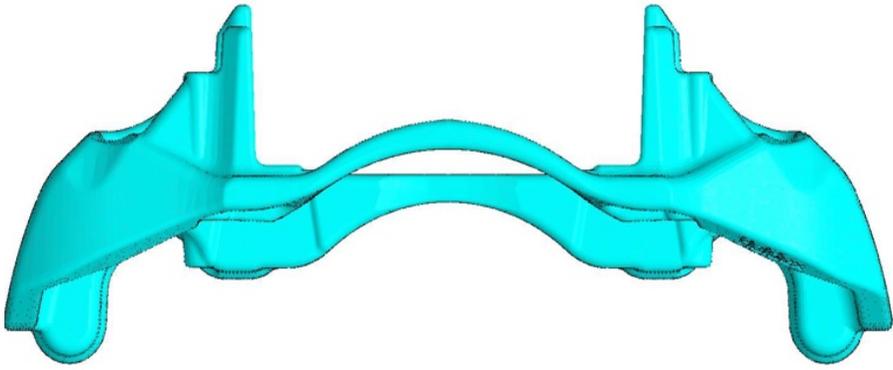


Figure 34: Loaded Carrier Cloud of Nodes

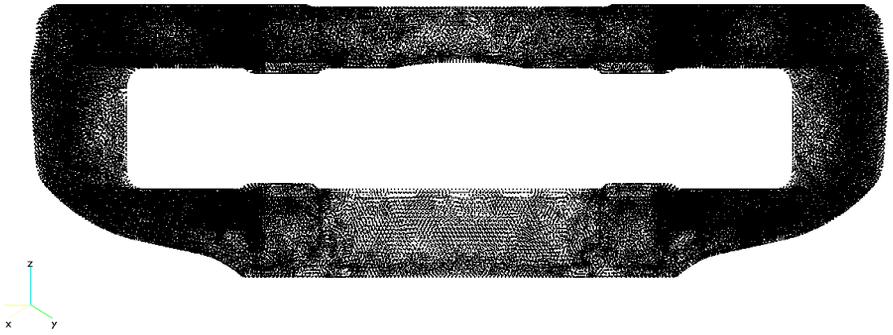


Figure 35: Side View of the Cloud of Nodes

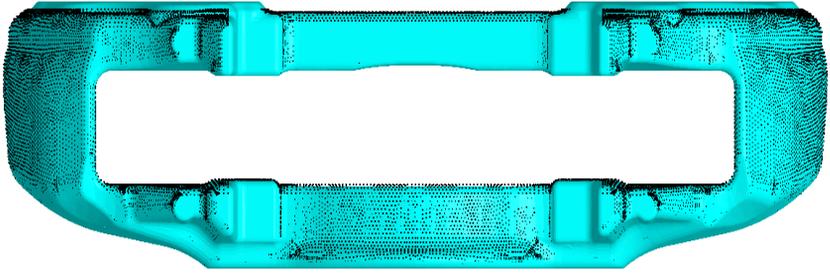


Figure 36: Side View of the nodes loaded onto the Carrier

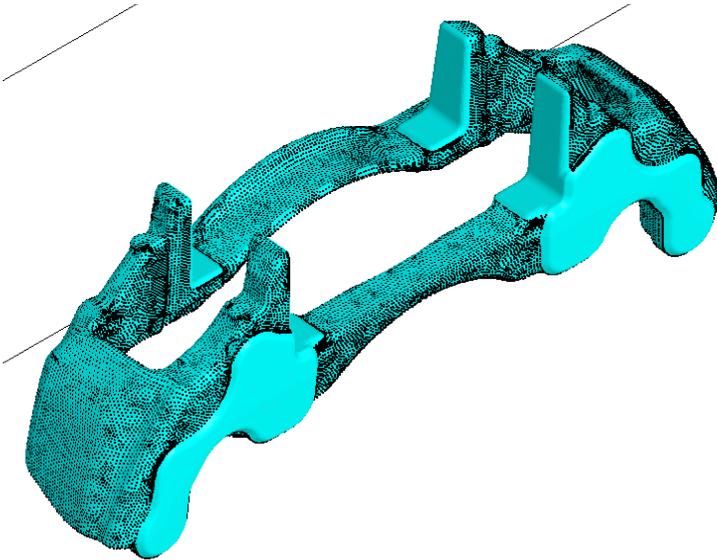


Figure 37: Isometric View of the Carrier Nodes



Figure 38: Caliper Cloud of Nodes

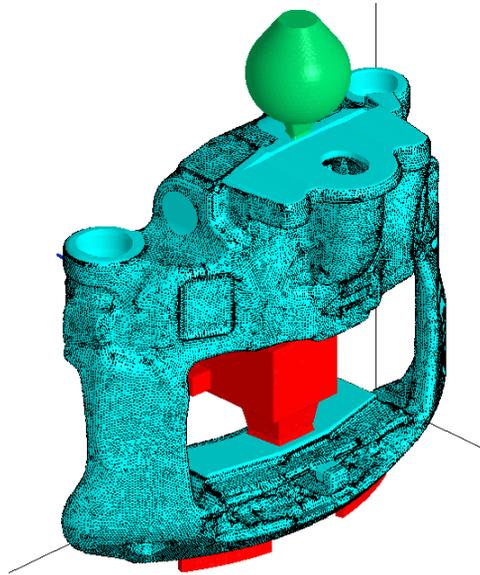


Figure 39: Loaded Caliper Cloud of nodes

lesh

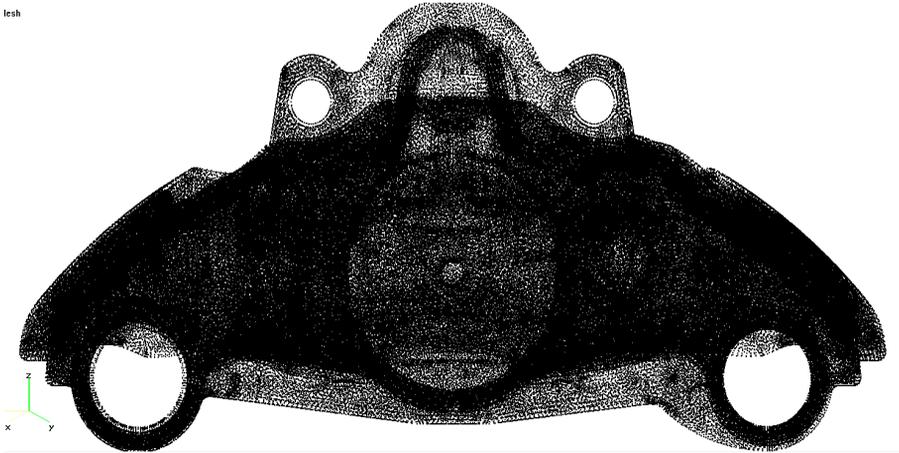


Figure 40: Bottom View of Caliper Cloud of Nodes

esh

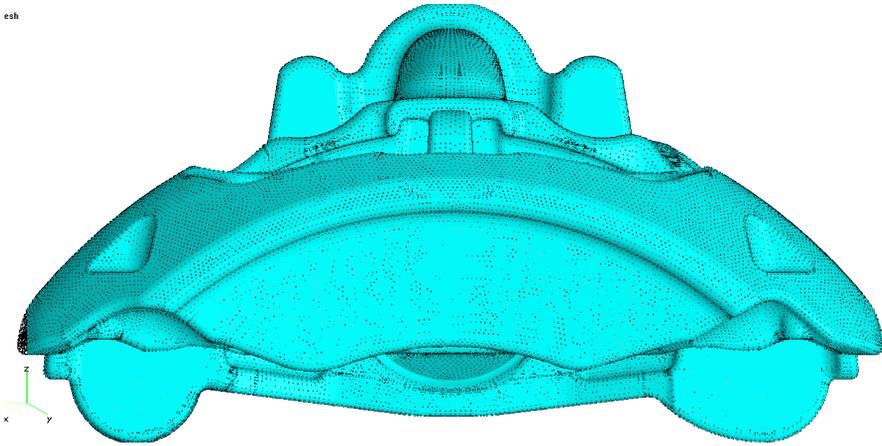


Figure 41: Bottom view of Loaded Caliper Cloud of Nodes

3.4. Creation and Utilization of Stress Tensors

The FEA performance test of the DBT22MD Air Disc Brake reveals the areas of risk in different components of the setup. Caliper and Carrier are primary components. An attempt must be made in identifying different factors that can contribute towards the generation of stresses in the components which can be analyzed early on before the production stage. A tensor is a multi-dimensional set of numerical numbers that can be used to characterize a material's physical condition or attributes. Stress is one example of a geophysical tensor [5]. Since there is no option to directly map the results from Casting simulation to FEA results in Ansys, a workaround had to be used. This required using node clouds to transfer stress tensors from Novacast to Ansys WB. After the Simulations were complete the Stress tensors were obtained from Novacast Browser using the Nodes created by following the procedure mentioned in section 3.3. The Stress tensor files are in .nodedata extension format. This format must be converted into Comma-Separated Value (CSV) file in order to make any changes in it as there is no option to edit the file within the software. The CSV file can be accessed using Microsoft Excel and checked for any need of editing. Column header are crucial in this scenario as Ansys recognizes the results through its headers. An example of the Stress tensor file is seen in Figure 42 where the column headers are Node ID, X, Y, Z Coordinates followed by Normal stress and Shear stress S11, S22, S33 and Tau11, Tau12, Tau23 respectively.

	A	B	C	D	E	F	G	H	I	J
1	Node ID	X Location in mm	Y location in mm	Z location in mm	S11	S22	S33	Tau 11	Tau12	Tau23
2	22949	-1.40E+00	2.65E+02	1.86E+02	-3.01E+01	1.31E-01	-9.27E+00	-8.19E-01	1.50E+00	-4.80E-01
3	22950	-4.11E+00	2.49E+02	1.32E+02	-2.45E+01	1.80E+00	4.23E+00	5.21E+00	2.56E+00	4.15E-01
4	22951	-1.41E+00	2.65E+02	1.82E+02	-3.06E+01	1.61E+00	-9.61E+00	-1.11E+00	-9.69E-02	3.16E-01
5	22952	-1.46E+00	2.65E+02	1.78E+02	-2.93E+01	-1.39E-03	-1.15E+01	-1.15E+00	-1.60E+00	1.21E+00
6	22953	-1.53E+00	2.64E+02	1.74E+02	-2.73E+01	2.13E+00	-1.69E+01	-8.26E-01	-2.24E+00	4.69E-01
7	22954	-1.62E+00	2.64E+02	1.70E+02	-2.89E+01	2.10E+00	-1.64E+01	-3.19E-01	-9.80E-01	-2.98E+00

Figure 42: Stress Tensor file format

These tensors were imported into Ansys Workbench (Ansys WB), which then act as Imported loads to mimic the Casting stresses. This Pre – Stressed

condition was used to calculate Maximum Principal Stress, Von-Mises Stress, Factor of Safety, Compression Factor of Safety and compare these with results obtained in the regular performance test. This process helped in identifying the areas with high risks. The results have been discussed in detail in section 4.

The image below displays the Export Data setup in Ansys WB. The Stress tensors were fed as inputs in this section of Ansys.

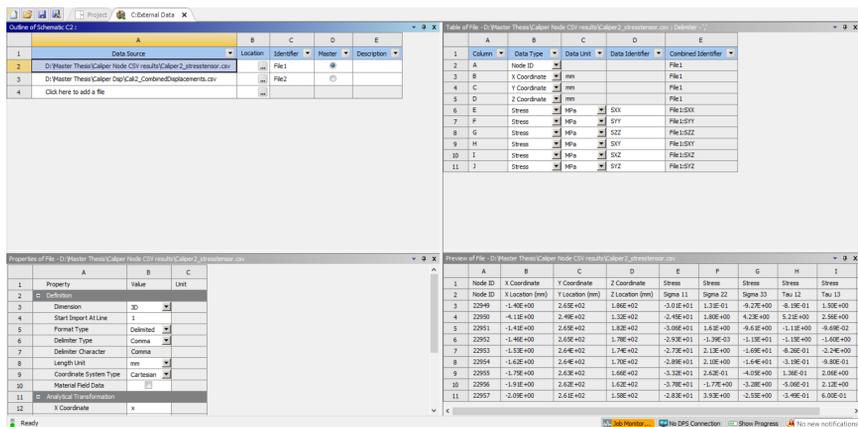


Figure 43: Stress Tensors in Export Data Setup (Ansys WB)

As seen in Figure 43, the assignment of the Data type like Node ID, Coordinates and Stress is done in “Table of File” after the file path with necessary files is provided. Preview of the file can be seen in the bottom right corner of the image.

4. Results and Discussions

This section provides the results obtained and an explanation of the same. The results obtained for Caliper and Carrier from the Simulations are: Von-Mises Stress, Minimal and Maximal Principal stress, Tensile Strength, Niyama, and Shrinkage. In addition, these results will be mapped to the results from Ansys to provide a safety factor that can be used to detect the defects in components that are not usually visible in FEA results.

4.1. Casting Simulation Results

Several results can be obtained from the Casting simulation. Right from Mechanical Properties, Temperature, Thermal Modulus, Young's modulus, Poisson's ratio to Elasto-Plastic stress results, the range of results available is vast. Some of these results are presented in this section. It is amusing to interpret the results and look at the distribution throughout the component.

4.1.1. Carrier Results

Results and Discussions of Carrier:

The setup to obtain desired results is presented in brief below:

Table 3: Mold Information for Carrier Casting

	Box Dimension(in mm)	Casting Position	No. of cells
Along X	788	394.529	197
Along Y	220	109.749	55
Along Z	416	208.382	104

Table 4: Mesh Information for Carrier Casting

Size of cells in mm	4
Total cells	1126840
Casting cells	101047

The mold box and meshing information for the Carrier have been mentioned in Table 3 and Table 4 respectively.

The components of the Carrier Casting Assembly have been assigned their respective materials. Their initial temperature has also been mentioned in Table 5.

Table 5: Carrier Casting Setup - Components Information

Solids Name	Materials	Initial Temperature in °C
Carrier	EN-GJS-600-3	1400
Ingate System	EN-GJS-600-3	1400
Mold Material	Mold- Green Sand	20
Change condition Material	Air-Outside Mold	20
Cavity Medium	Air- In Mold	20

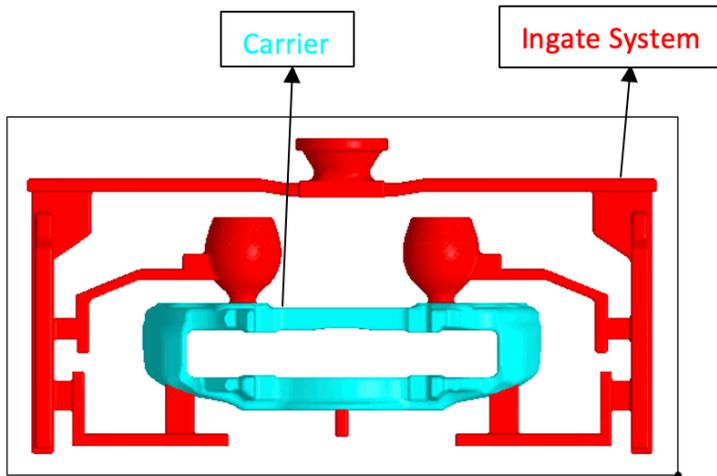


Figure 44: Carrier and Ingate /Gating System

The shrinkage calculation model is based on medium gravity influence. Convection and the gas at filling are ignored. The Gauss-Seidel method is employed. This method is used to solve the linear system equations. It is an iterative approach to solve n linear equations with unknown variables. This is an extremely simple approach that is used for computing in digital computers. It significantly decreases the number of iterations.

Pouring is done through 1 Gate with a flow rate of 7 kg/sec and a pressure height being 43.07 mm. The results summary for Shrinkage is given in Table 6. The Shrinkage in the figure determines the probabilistic distribution of defects. For instance, 5% of Shrinkage on the specified location indicates that a hollow takes on 5% of its volume in any volume sufficiently tiny near the place, and 95% is metal, but it is hard to specify how this void stands: either in solid pores or in many microscopic holes. The Shrinkage may also be connected at the specified location to the metal density. In Figure 45, we can see that the Shrinkage is mainly present in the Gating System, and only a minute fraction is present in the Carrier model. As it is less than the permissible value, the model looks good.

Table 6: Information related to Shrinkage in Carrier

Shrinkage in % :	0.285
Calculation time in (h,m,s) :	000:28:20,244
Filling time in (h,m,s) :	000:00:04,940
Solidification time in (h,m,s) :	000:29:58,628

Table 7: Important Results of Carrier

Field	Maximum	Minimum
Temperature in °C	48.807	28.36
Liquid phase %	0	0
Niyama in $\sqrt{(\text{°K} \cdot \text{s})}/\text{mm}$	1.801	0.223
Brinell Hardness	592.397	476.865
Tensile strength	702.775	549.334
Pressure, Bar	1.026	0
Velocity, m/s	0.821	0
Von Mises stress, MPa	197.247	2.023
Normal components of displacements, mm	1.181	0.009
Maximal Principal Stress, MPa	188.928	-27.478
Pressure, MPa	125.648	-82.39
Fill time, s	4.941	0
Median principal stress, MPa	134.67	-116.624
Minimal principal stress, MPa	79.921	-180.779
Solid phase, %	100	5.399

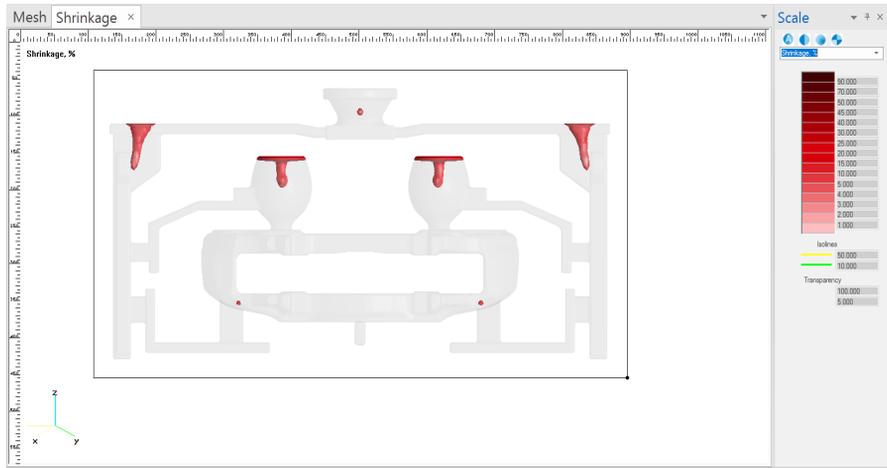


Figure 45: Shrinkage Indicator in Carrier

The Niyama criteria are used to forecast microporosity and shrinkage porosity as big as possible to be observed in x-rays. While the Niyama criteria have proved to be a valid porosity predictor for Shrinkage, caution must be taken to generalize the results to more complicated casts. In certain situations, even factors that do not take the Niyama criteria into account impact the production of shrinkage porosity. It is defined as G/v , where v is the cooling rate in K/s and G is the temperature gradient in K/mm. Both these quantities are estimated at the end of solidification.

The Niyama value 0 is a badly directed solidification wherein the higher number is a good directional consolidation. The chance of Shrinkage is largest if the Niyama value is low and vice versa. From Figure 46, we can see that the Niyama value is lowest in parts of the gating system while it is maximum uniformly throughout the Carrier. The critical value of Niyama for Iron is 0. The value of Niyama is above the critical value; hence there is very little chance of Shrinkage in the Carrier.

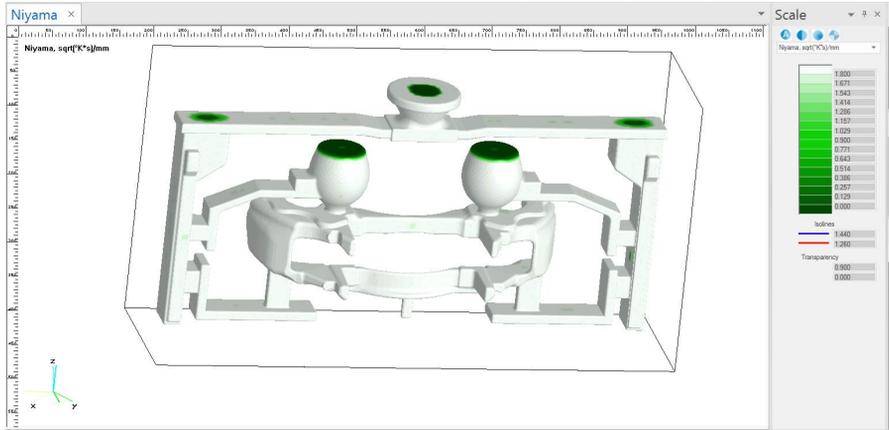


Figure 46: Niyama Indicator for Carrier

The minimum principal stress is perpendicular to the plane with zero shear stress. The kind of deformation is governed by the minimum principal stresses of the casting material. The surface of the Casting is exposed to normal compressive stress. This can be detected by the negative values obtained in Figure 48. The negative values also indicate that the respective portion is under compression.

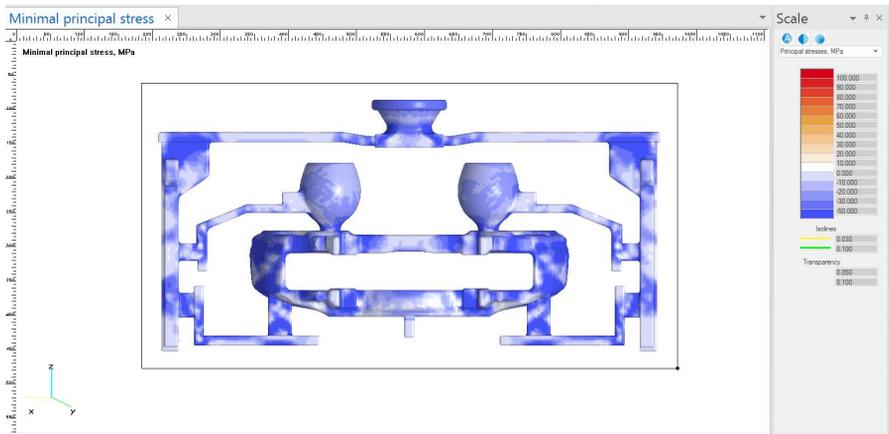


Figure 47: Minimal Principal Stress for Carrier

The maximum principal stress in the casting material (i.e., the highest tensile value) constitutes the highest stress at the site of a solid body with normal uniaxial stress. The positive value of the maximum principal casting material stress, i.e., the highest possible value, corresponds to the normal tensile stress value at the spot.

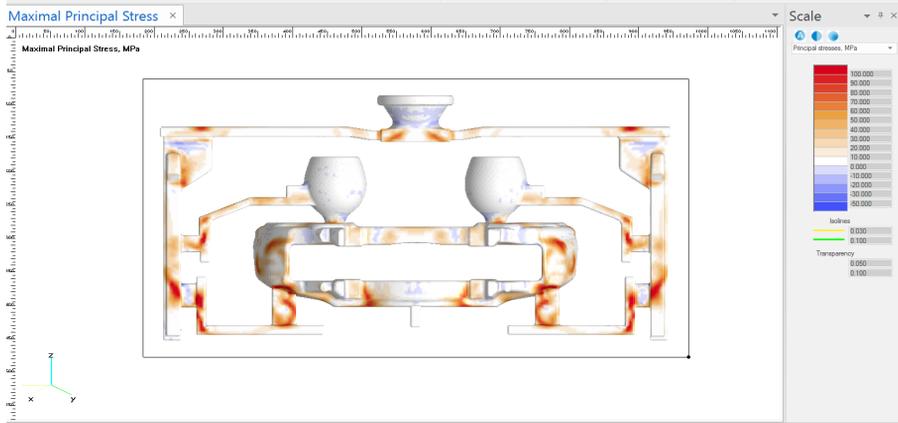


Figure 48: Maximal Principal Stress for Carrier

From Figure 49, we can see that the maximum Von Mises Stresses occur mostly at the contact points.

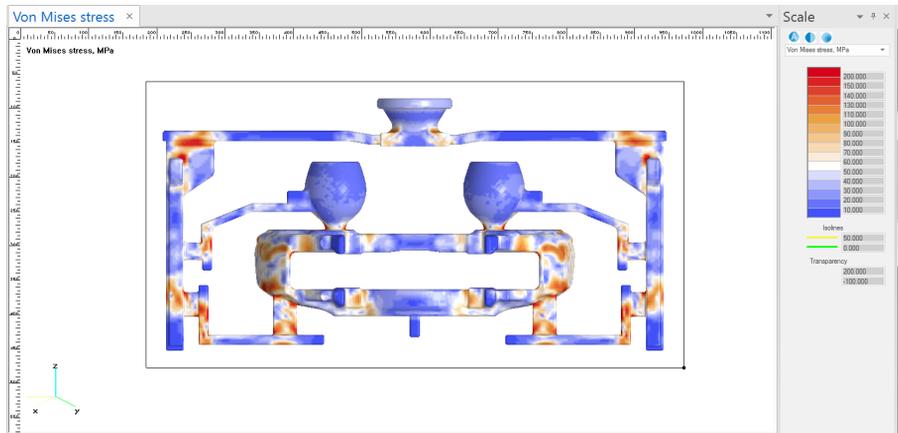


Figure 49: Von-Mises Stress for Carrier

The Tensile strength after the completion of Solidification can be seen in Figure 50.

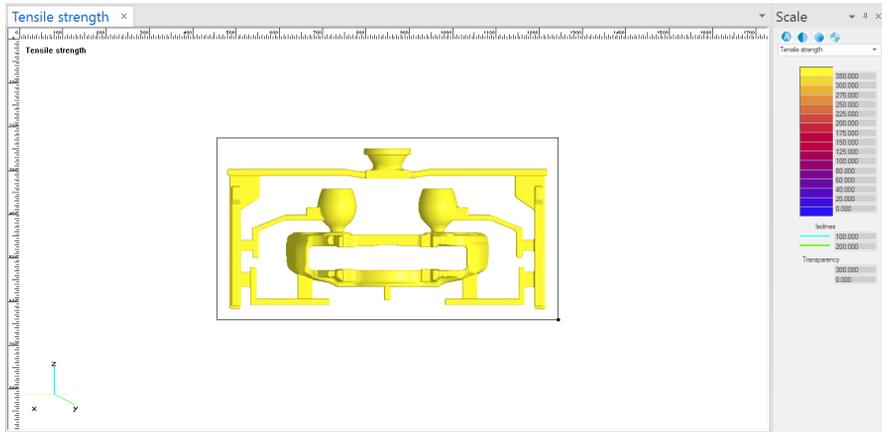


Figure 50: Tensile Strength for Carrier

4.1.2. Caliper Results

Similar to Carrier results, Caliper results were obtained after simulation. Various results achieved are presented in this section.

Table 8: Mold Information

	Box Dimension (in mm)	Casting Position	No.of cells
Along X	420	209.467	84
Along Y	245	121.596	49
Along Z	475	236.843	95

Table 9: Mesh Information

Size of cells in mm	5
Total cells	391020
Casting cells	38461

Table 10: Components Information

Solids Name	Mold Materials	Initial Temperature in °C
Caliper	EN-GJS-600-3	1500
Ingate System	EN-GJS-600-3	1500
Riser	EN-GJS-600-3	1500
Cooling Pin	EN-GJS-600-3	1500
Mold Material	Mold- Green Sand	20
Chill	Grey Iron	20
Change condition Material	Air-Outside Mold	20
Cavity Medium	Air- In Mold	20

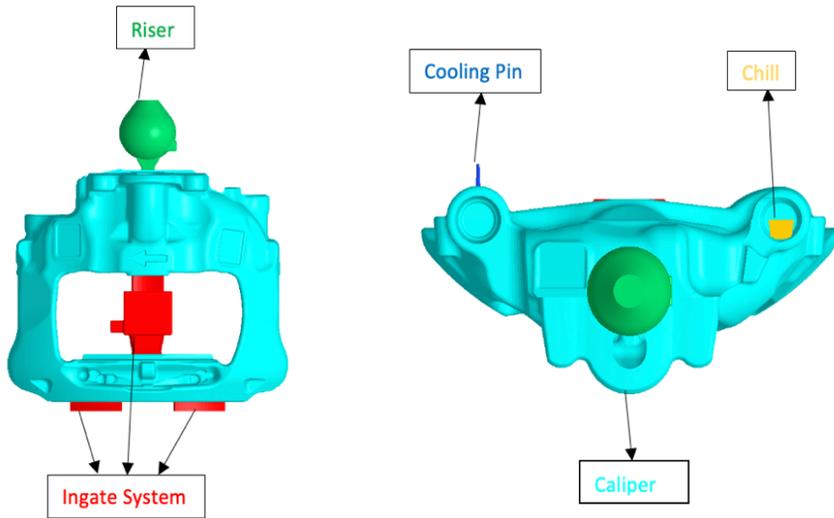


Figure 51: Right Side View (Left) and Top View (Right) of the Caliper

Table 11: Gating Information

	X in mm	Y in mm	Z in mm
Gate 1	140.93	128.01	30.05
Gate 2	278.01	128.01	30.05

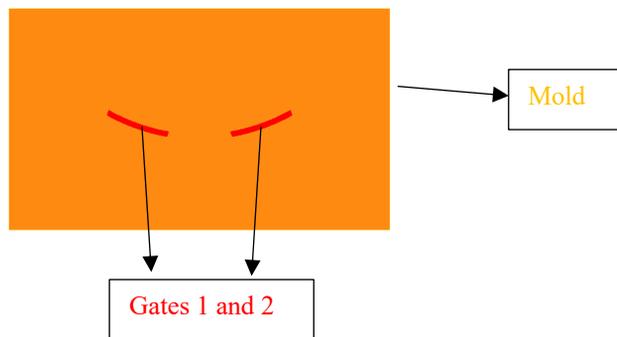


Figure 52: Gates and Mold of Caliper

Table 12: Information related to Shrinkage

Shrinkage in % :	3.889
Calculation time in (h,m,s) :	000:14:19,003
Filling time in (h,m,s) :	000:00:02,461
Solidification time in (h,m,s) :	000:21:14,364

There are two Gating points in the Caliper Casting setup, and both have a flow rate of 8 kg/s. Flow rates ranging from 2 to 12 kg/s were simulated to achieve minimum Shrinkage. Coordinates of Gating points of the selected simulation are stated in Table 11. The size of the Riser and initial temperatures played a vital role in avoiding major Shrinkage at the top end of the Component. The overall Shrinkage is provided in and is visually represented in Figure 53.

Table 13: Important Results for the Caliper

Field	Maximum	Minimum
Temperature in °C	99.99	23.41
Liquid phase %	0	0
Niyama in sqrt (°K*s)/mm	1.8	0.274
Brinell Hardness	599.685	485.118
Tensile strength	712.453	560.295
Pressure, Bar	1.32	0
Velocity, m/s	1.107	0
Von Mises stress, MPa	134.576	5.242
Normal components of displacements, mm	5.771	0.205
Maximal Principal Stress, MPa	113.906	-8.629
Pressure, MPa	64.764	-57.013
Fill time, s	2.461	0
Median principal stress, MPa	63.614	-40.116
Minimal principal stress, MPa	31.521	-143.941
Solid phase, %	100	0.015

Table 13 provides Maximum and Minimum values of different parameters that are useful in further calculations as well as parameter mapping.

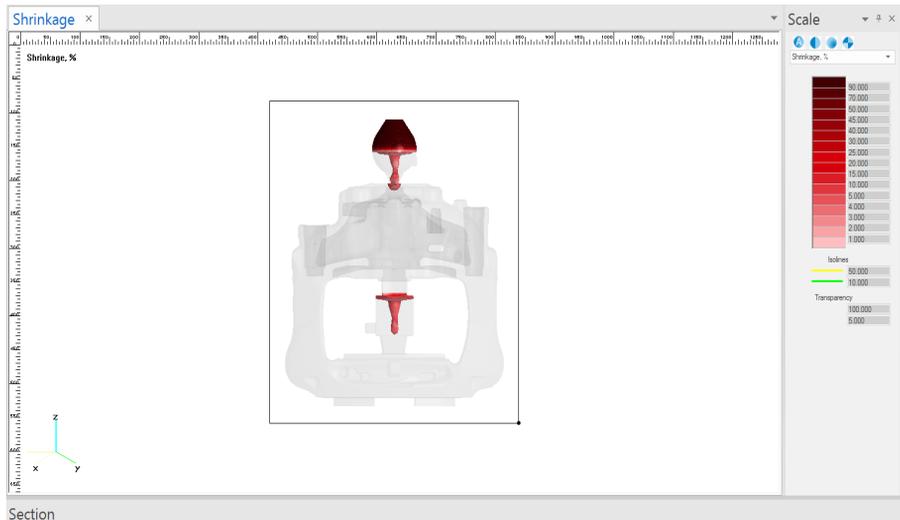


Figure 53: Shrinkage Indicator in Caliper

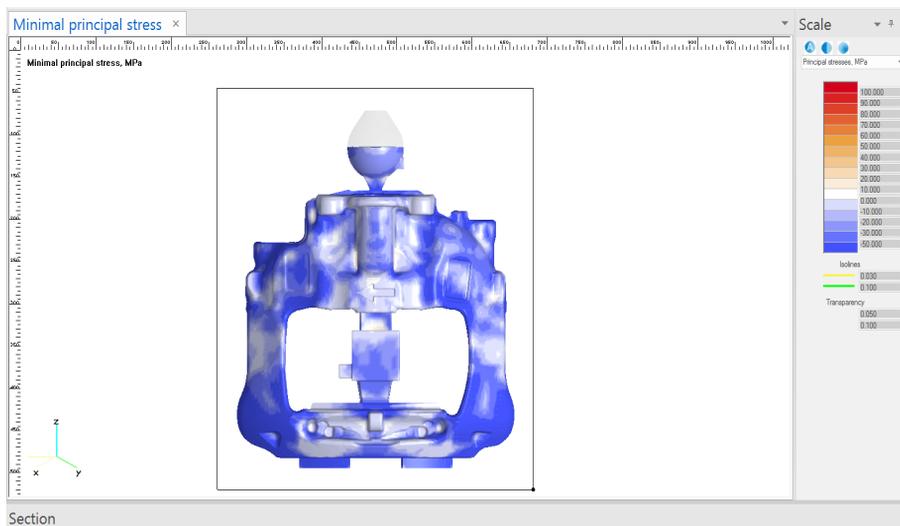


Figure 54: Minimal Principal Stress for Caliper

Figure 53 and Figure 54 display Shrinkage and Minimal Principal Stress for Caliper. The Shrinkage is majorly present in the gating system in the mid-section and a tad bit at the top surface which is acceptable.

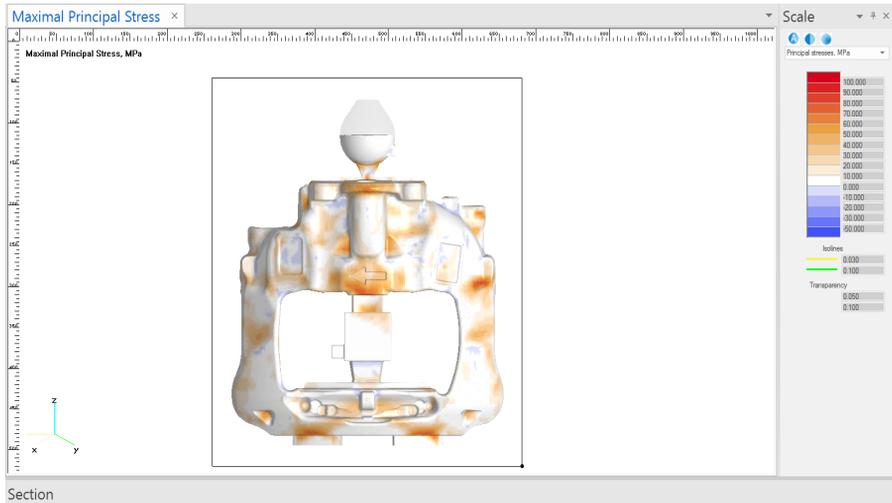


Figure 55: Maximal Principal Stress for Caliper

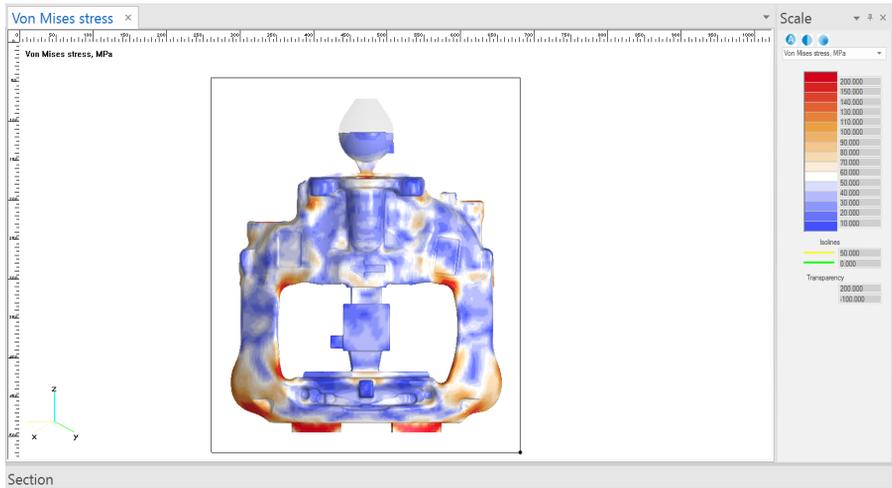


Figure 56: Von-Mises Stress Distribution for Caliper

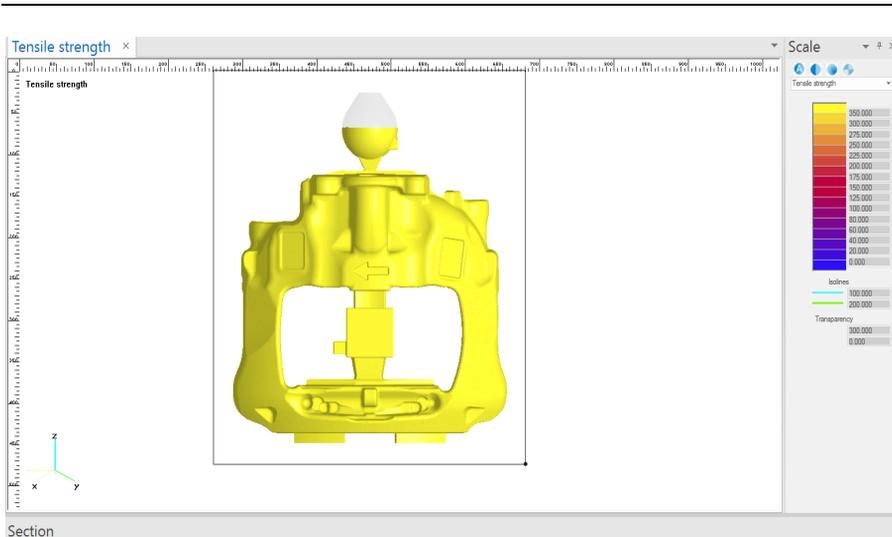


Figure 57: Tensile Strength for Caliper

The stress distribution in Caliper can be seen in Figure 55, Figure 56, and Figure 57. The slider in the Scale tab can be used to observe and compare different results at varying parameter values such as volume filled, temperature, etc.

4.2. Parameter Mapping

The Performance test conditions can be seen in the table below. The type of results obtained from both these conditions are listed in Table 15.

Table 14: Test Conditions in Ansys WB

Performance Test Conditions in Ansys	
Test 1	Test 2
Moment and Force Loads	Moment and Force Loads
Bolt Pretension (6*Bolt Pretension, Leading and Trailing Screw Pretension)	Bolt Pretension (6*Bolt Pretension, Leading and Trailing Screw Pretension)
Fixed Support	Fixed Support
	Imported Loads (Stress Tensors from Novacast)

Table 15: Results Obtained

Available Results in Ansys Mechanical	
Test 1	Test 2 (Pre-Stressed Condition)
Maximum Principal Stress	Maximum Principal Stress
Von-Mises Stress	Von-Mises Stress
Factor of Safety	Factor of Safety (Using CSV Plot)
Compression Factor of Safety	Compression Factor of Safety(Using CSV Plot)

The Tensile strength of 661 Mpa is used for test 1 while test 2 has tensile strength from Casting simulation. The differences in the test conditions being the introduction of the Casting Stresses in test 2 makes it convenient to analyze the influence of the introduced factor and make the results much more evident.

ANSYS Remote Solve Management (RSM) is used to send computer jobs directly to the desktop in HPC clusters from Workbench using ANSYS Workbench. This enables to benefit from the substantially higher computational power the desktop or laptop is likely to have [15]. The RSM Job Monitoring system also helps us to keep a track of the status of the jobs that are being tested.

The tensile strength of the Caliper and the Carrier that was imported from the Casting Model have been used to calculate the Yield Strength. This was done in the software called Compose. Compose allows users to conduct a wide range of mathematical operations including the manipulation of the linear algebra and matrix, statistics, differential equations, signal processing, control systems, and polynomial fitting [16].

One of the Compose script used and user menu can be seen in the Figure 58. Different scripts were used for obtaining Yield Strength, Patching Node IDs and values when the files were out of sync and to calculate Factor of Safety, Compression Factor of Safety.

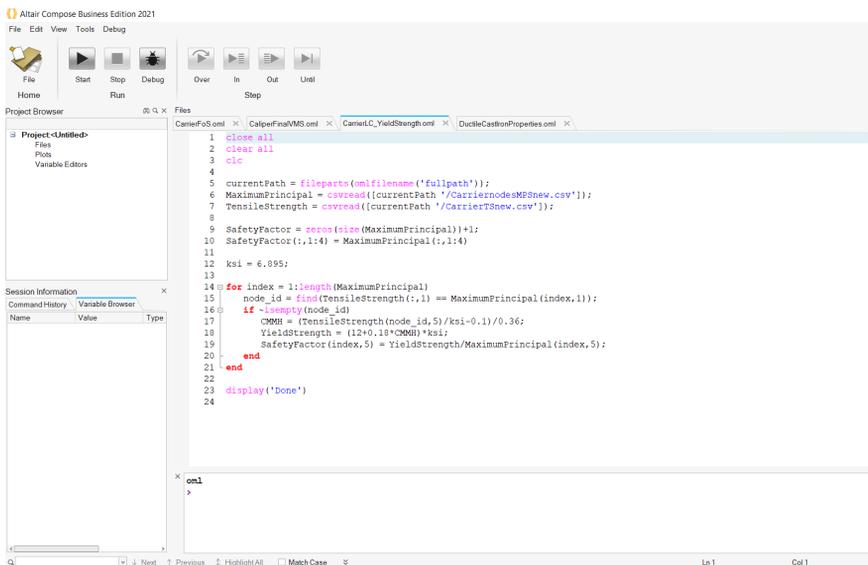


Figure 58: Compose script and User Menu

Using Compose, Yield Strength was calculated, and the formulas utilized for the same are presented in Table 16. CMMH is a composite matrix microhardness and is given by the formula in the table below. HF and %F, HP and %P are respective hardness and volume functions of Ferrite and Pearlite. The Tensile Strength is considered as 661 MPA in the calculations as recommended by the company supervisor. This feeds as input for the program written in the software. After obtaining the values, the files are saved in CSV format and these files are plot on the components using CSV Plot extension in Ansys WB giving us FoS and CFoS.

Table 16: Formulas Used [17]

$\text{CMMH} = \frac{((\text{HF} * \%F) + (\text{HP} * \%P))}{100}$
$\text{Tensile Strength (ksi)} = 0.10 + 0.36 * \text{CMMH}$
$\text{Yield Strength (ksi)} = 12 + 0.18 * \text{CMMH}$
$\text{Elongation (\%)} = 37.85 - 0.093 * \text{CMMH}$
$\text{Factor of Safety (FoS)} = \frac{\text{Yield Strength}}{\text{Maximum Principal Stress}}$
$\text{Compression Factor of Safety} = \frac{\text{Compressional Yield Strength}}{\text{Von-Mises Stress}}$

Note: The Images shown henceforth have the color scheme set to reverse rainbow except for the Maximum Principal stress and Von – Mises Stress distribution images. The color scheme can be recognized by the ruler/ legend on the left side of the images. The range is set to 10 for all Factor of Safety and Compression Factor of Safety images to improve the display of results and obtain better images.

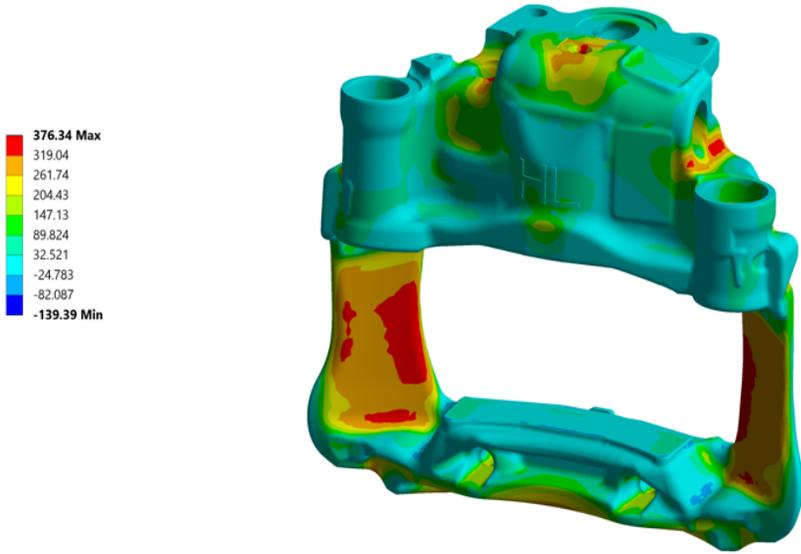


Figure 59: Caliper Test 1 - Maximum Principal Stress Distribution

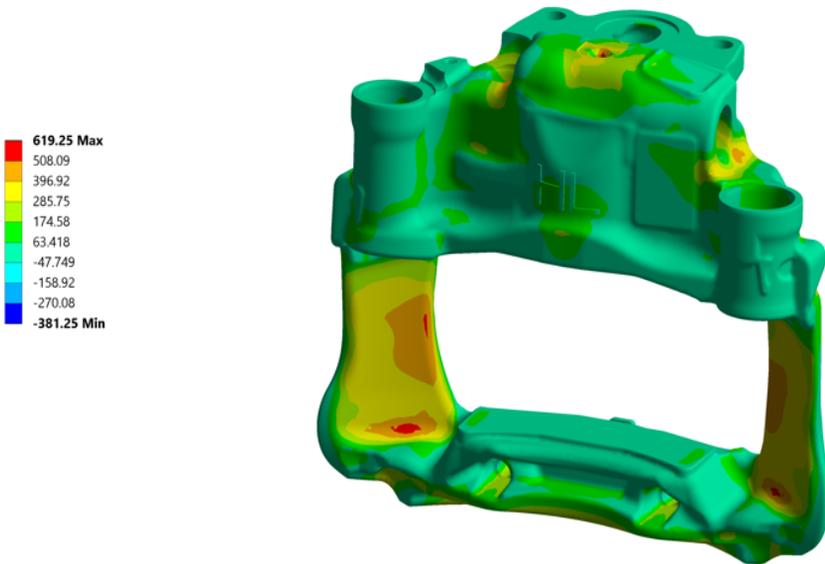


Figure 60: Caliper Test 2 - Maximum Principal Stress Distribution

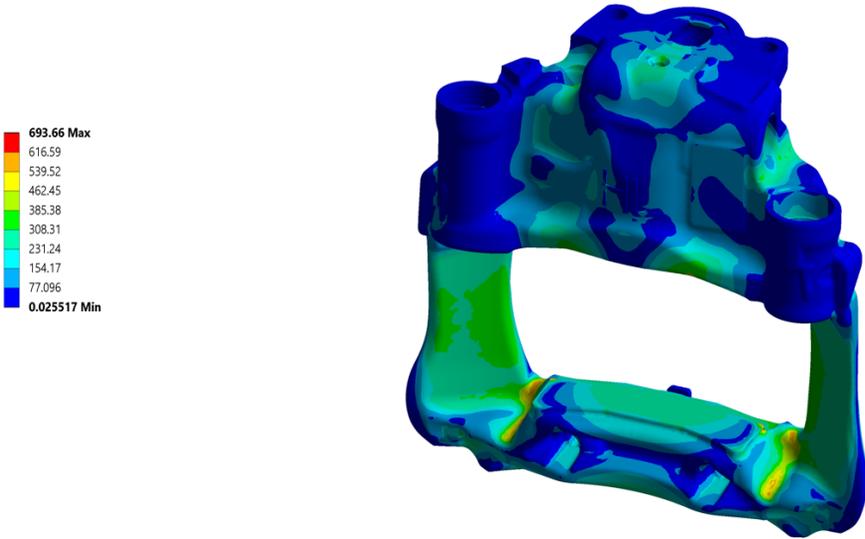


Figure 61: Caliper Test 1 - Von-Mises Stress Distribution

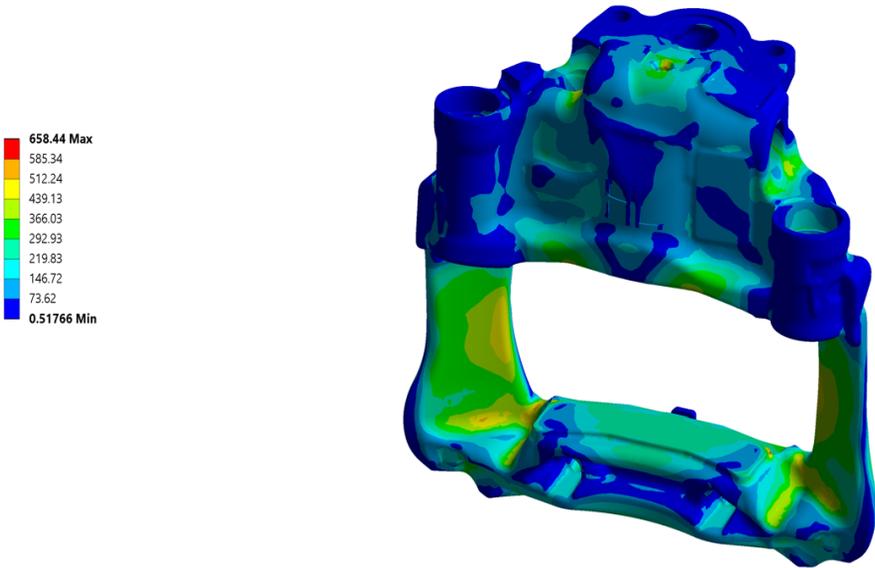


Figure 62: Caliper Test 2 - Von-Mises Stress Distribution

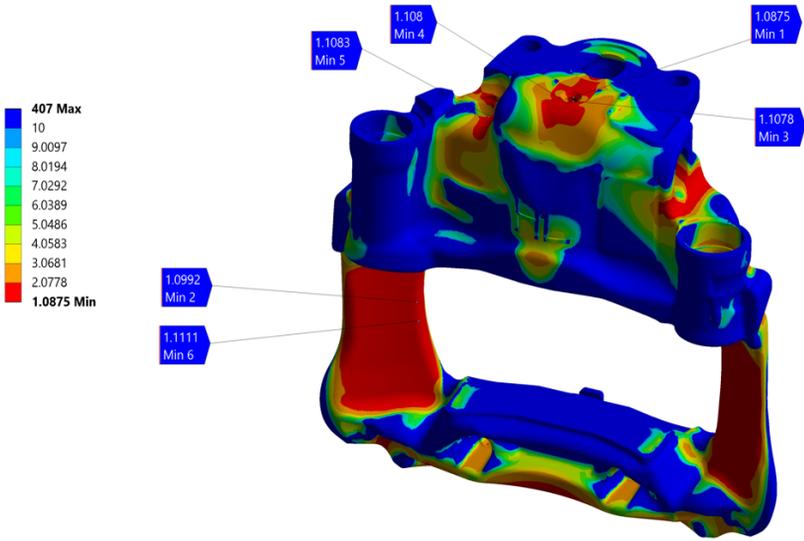


Figure 63: Caliper Test 1 - Factor of Safety (FoS)

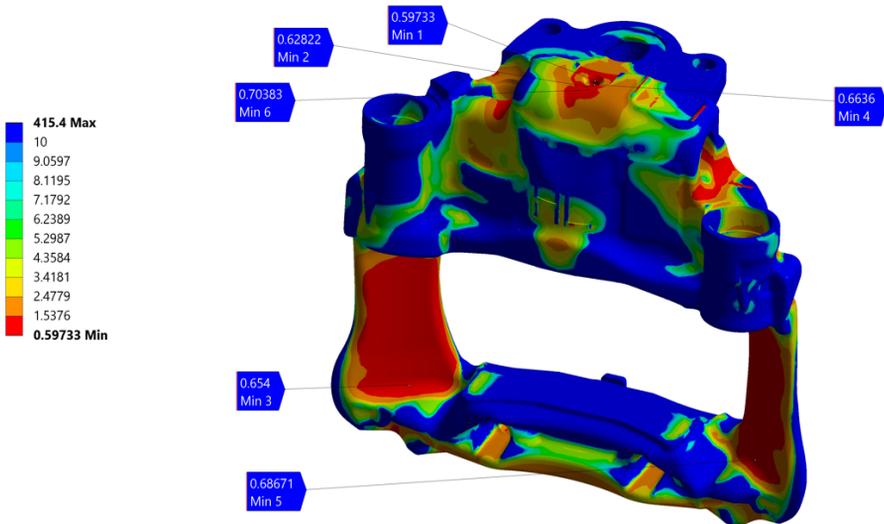


Figure 64: Caliper Test 2 - Factor of Safety (FoS)

The Von – Mises Stress distribution images 61 and 62, show a significant increase in the distribution throughout the component when Tests 1 and 2 are compared. While most of the stresses may be induced during the breakout of the mold during casting in this case too, the actual Casting stresses may not be spread out to this extent. Refinement in the results can be done by setting values of the Mold sand rigidity to a lower number during Casting Simulation similar to all other cases [18].

Factor of safety distribution in case 2 have an interesting outcome where certain areas have less stress concentrations while the other areas experience an increment. The probes in Figure 64 show that the FoS for Test 2 has dropped below 1 with the lowest being 0.59733 which is unacceptable. Compare it with the lowest FoS of Test 1 which is 1.0875 and it can be observed how drastic the changes are. This in plain term means that the component will not sustain up to the standards under the pre-stressed load conditions in test 2 and may experience unexpected failure.

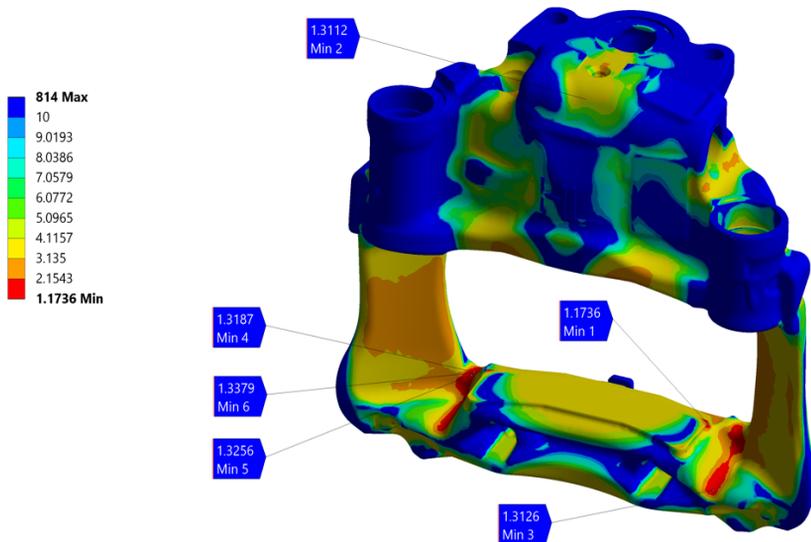


Figure 65: Caliper Test 1 - Compression Factor of Safety (CFoS)

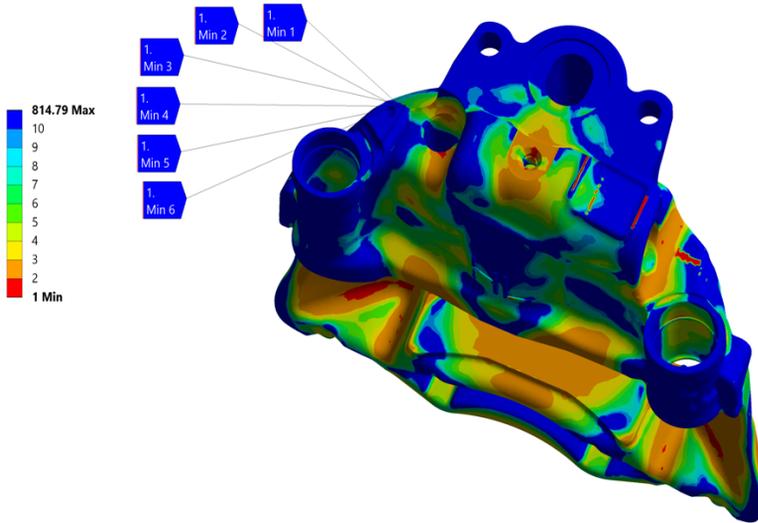


Figure 66: *Caliper Test 2 - Compression Factor of Safety (CFoS)*

The Compression Factor of Safety for all cases is obtained by Compressional Yield Strength / Von – Mises Stress. It can be seen in Figure 65 and Figure 66 that it follows the trend of increased and decreased areas of stress distribution similar to FoS result of Caliper test 1. It was confirmed that the area where there was an unexpected crack in the Caliper during physical testing but no major trace of it was found in FEA results has high level of stress distribution in Test 2 performance conditions.

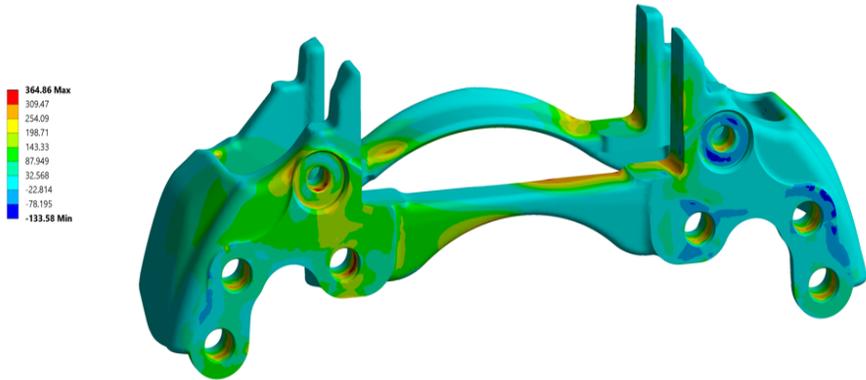


Figure 67: Carrier Test 1 - Maximum Principal Stress Distribution



Figure 68: Carrier Test 2 - Maximum Principal Stress Distribution

Figure 67 and Figure 68 comparison yields that the Maximum Principal stress has increased in Test 2 significantly. This follows the trend of increased stress distribution in all results obtained from Test 2.

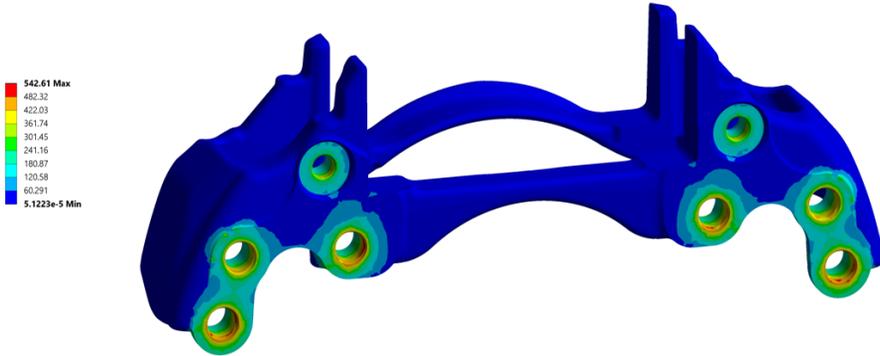


Figure 69: Carrier Test 1 - Von - Mises Stress Distribution

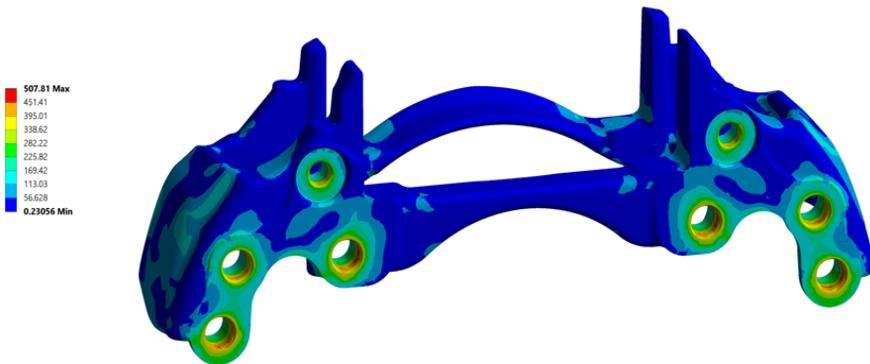


Figure 70: Carrier Test 2 - Von - Mises Stress Distribution

The Von-Mises stress distribution here is spread out quite widely and is more concentrated towards the holes and curved edges. The difference in Test 1 and Test 2 results are clearly visible and are significant.

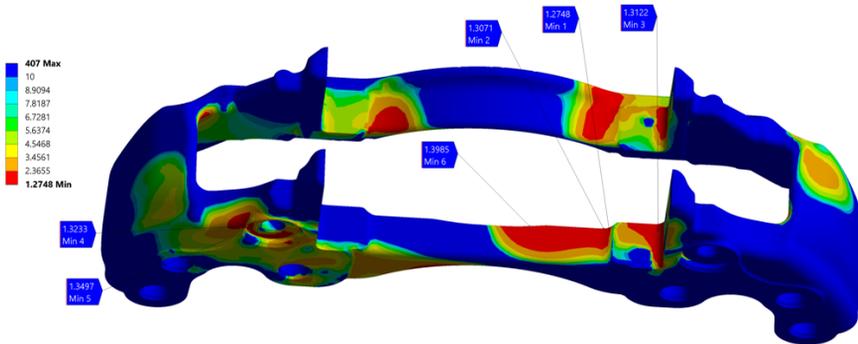


Figure 71: Carrier Test 1 - Factor of Safety (FoS)

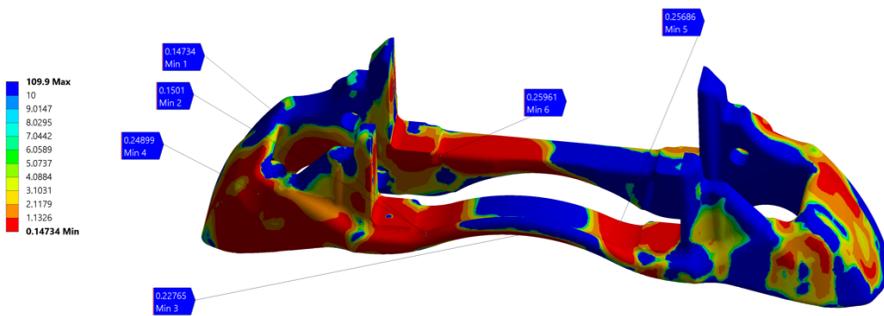


Figure 72: Carrier Test 2 - Factor of Safety (FoS)

The stresses seen in case 2 seem to be high and erratic. Apart from high Mold sand rigidity at the breakout of mold in casting simulation, temperature can also be a reason for these stresses. This can also be rectified by setting the rigidity of sand to a value lower than 1 and setting the mold temperature around 400° C at breakout in Novacast.

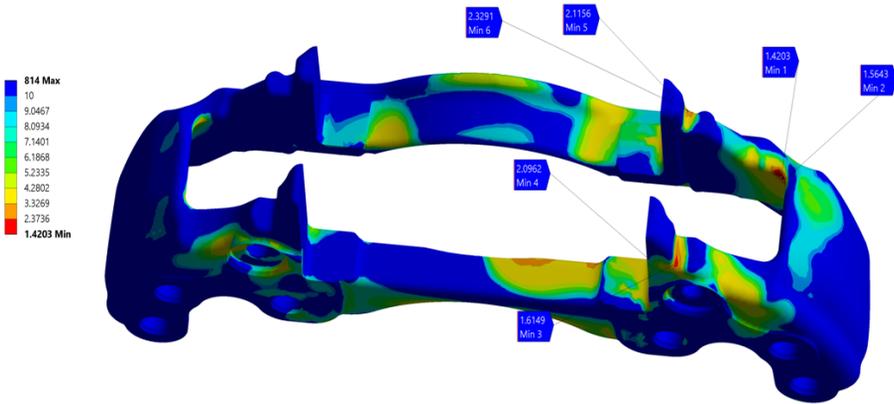


Figure 73: Carrier Test 1 - Compression Factor of Safety (CFoS)

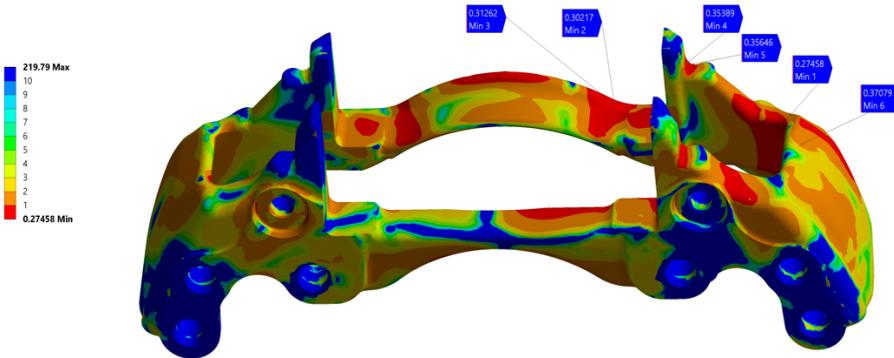


Figure 74: Carrier Test 2 - Compression Factor of Safety (CFoS)

The Compression Factor of Safety probe values in Figure 73 and Figure 74 have a drastic difference with the Minimum CFoS value in Test 1 being 1.4203 and 0.27458 in Test 2. This difference is significant enough to take it into consideration while conducting analysis before production.

5. Conclusion

Casting simulations may investigate the impacts of several casting factors (e.g., melt temperature, velocity, design of the gate and runner system, riser design, mold design (single or multi-cavity)) in sound casting. The simulation of casting solidification can efficiently be utilized to reduce casting defects. With the use of software like NovaCast, cast Shrinkage along with other defects may be anticipated correctly. The results achieved, allow for optimization of the parameters and reduction of the Shrinkage. In connection with sites of contact and a rapid shift in the cross-section of the Casting, the maximum residual stress may be determined. It can be observed that the highest residual stresses of material occur in joining sites and in abruptly changing cross-section of the Casting. These were observed in the results especially near the holes and cavities in both Caliper and Carrier.

After analyzing the results obtained in both the performance tests, it is also observed that there is a significant increase in stress distribution. While it may be debated that the increase in the stress is obvious as another load condition was introduced, this can be refuted by the fact that the load condition was derived from stress tensors from Casting simulation results. Also, as mentioned in section 1, FEA does not take variable material quality or casting defects into account, which may be an omnidirectional or restricted approach. There is a strong possibility that residual stresses induced during Casting can also contribute to the structural integrity of products or components in the performance test. For instance, the areas with intermediate stress distribution in one of the FEA outputs, which were not decisive, resulted in cracks during physical testing. However, the same performance test conducted with the pre-stressed condition from casting resulted in stress distribution in that very area to be fatal. Therefore, adding residual stresses from casting during Finite Element Analysis to create a pre-stressed state can act as a heads-up, contributing to possibly more informative analytical results.

The theory can be checked for different load conditions, combinations, and there is a high possibility of obtaining results that display a similar trend. Therefore, it can be concluded that the theory speculated in this thesis topic has a good chance of being corroborated and implemented.

6. Limitations and Future Scope

Every study has limitations, and this is no exception. There are a few limitations that can possibly be overcome by repeated and incremental updates to the procedure. For instance, the nodes were created using machined part and casting simulation stresses were captured on unmachined part which results in a loss of stresses developed at the holes/ machined area, including all the parameters of Casting process in a way that can be imported into FEA process seems challenging due to the nature of the process itself. Another major point to be noted which isn't a limitation but is a crucial factor is that the mapping procedure is highly interlinked and error in any one of the steps can stimulate a chain of errors. It is of utmost importance that one keeps record of the data, procedure and tracks the results as closely as possible.

This Thesis work can act as a foundation for similar studies which are unexplored and opens new doors to possibilities in improving the FEA tests and results which will help in increasing the Factor of Safety for a product significantly. For instance, fatigue properties of the material can be studied for their effects on unexpected defects and check if those can be included in the simulation. This can further refine the process of improving safety factor.

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