Brake Caliper Design for Revolve NTNU

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***Abstract**: With the large amount of dynamic loads and heat the brake system of a Formula Student racecar experiences, the system requires resistance to both heat and external loads in several of its components. With respect to both, loading conditions have been defined and evaluated for the redesign of the brake calipers for Revolve NTNU's 2018 racecar, Atmos. Suitable production methods for manufacturing of the brake calipers have been evaluated concerning availability and impact on the final design. Topology optimization has been conducted in Tosca, subject to the evaluated loading conditions. The optimization has yielded a weight reduction of 28% and 38% for the front and rear brake calipers, respectively, compared to commercially available calipers of the same class. Verification analyses conducted in Abaqus have shown low stress levels in the final design, as well as little deformation. Fatigue life simulations conducted in fe-safe predict infinite fatigue life in nearly all areas of the brake calipers when subject to the calculated loading conditions.*

***Keywords**: Brakes, Brake Calipers, Disc Brakes, Formula Student, Race Car, Design Optimization, Fatigue, Fatigue Life, Heat Transfer, Minimum-Weight Structures, Optimization, Topology Optimization, Revolve NTNU.*

1. Introduction

The increasing performance need in student race car competitions requires students to move away from standard designs. Advanced simulation based design software is routinely used to redesign stock components, increase functionality and reduce weight. Revolve NTNU has previously bought and used off-the-shelf calipers, which have been both expensive and large, complicating the wheel packing. Reducing the unsprung mass was the main reason for deciding to redesign the brake calipers for this year's Revolve race car, Atmos. However, other reasons such as independency from external suppliers, wanting to customize several components and build a foundation for future progress have all been influencing the decision.

The brake caliper is an essential part of the disc brake system. It must hold and guide the brake pads, and with the assistance of one or several pistons it converts the hydraulic pressure in the brake system into a mechanical force, which presses the brake pads against the brake disc. The brake calipers are located near the wheels and they are subject to substantial amounts of heat, dynamic loads and space constraints. This paper summarizes the work done during redesigning of the brake caliper for higher performance and lower weight compared to off-the-shelf calipers.

1.1 Revolve NTNU

Revolve NTNU was founded as an independent student organization in 2010. It is operated by students at The Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. Since 2012, Revolve NTNU have been building a new Formula Student race car each year. The mission of Revolve NTNU is «from theory to practice», with the most important result of developing a complex Formula Student race car being students with unique knowledge and skill sets. **Figure 1** shows a render of this year's Revolve racecar, Atmos. The car features a full CFRP monocoque, additive manufactured and topology optimized uprights, optimized two-piece rims with aluminum center and CFRP shell, four motors and torque vectoring algorithms, topology optimized brake calipers and represents the with for succeeding in the organization.

Figure 1: Render of Revolve NTNU's 2018 racecar, Atmos.

2. Brake Caliper Design

In a disc brake system, the mechanism applying the brake pads to the brake rotor is the caliper. There are two main designs of calipers, fixed- and floating designsError! Reference source not found., where the difference lies in how the pads are applied to the brake disc. As a fixed design offers a better feel for the driver throughout the braking process, it is the preferred choice for Revolve.

2.1 Load Cases

By utilizing tire models, data from previous races and various simulations, load cases for the four tires were developed. In combination with preliminary parameters for Atmos, load cases for the brake system were developed.

2.1.1 Quasi Static Model

The fundamental principles lying underneath the quasi static model are derived from the tire print characteristics during braking (Milliken, 1995), i.e. the distribution of forces and sliding velocity over the contact length of a tire under the action of a braking torque M_b. Ole A. Ramsdal, who has been responsible for the suspension geometry and vehicle dynamics for Atmos developed a two-dimensional longitudinal brake model. The model calculates the resulting tire loads from braking, the brake capacity and the longitudinal friction at each wheel. A combination of the results from the longitudinal brake model, preliminary specifications for Atmos and data logs from previous years were used to calculate required braking torque, clamp pressure and resulting hydraulic pressure of the brake assemblies. A data log from 2017 showing the brake pressure during an endurance run in Spain is shown in **Figure 2**, and a selection of resulting required parameters are presented in **Table 1.**

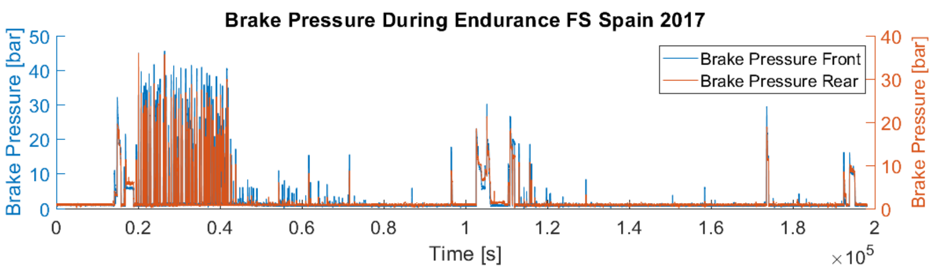

Figure 2: Brake pressure during an endurance run in Spain, 2017.

Table 1: Required parameters in the brake assemblies.

Brake Assembly	**Braking Force F_b [N]**	**Braking Torque M_b [Nm]**	**Clamping Force F_{clamp} [N]**	**Caliper Pressure P_{cal} [MPa]**
Front	3300	800	18000	5
Rear	1300	300	6800	2

2.1.2 Heat Generation Model

Based on heat generation theory during continued braking operations (Limpert, 2011), a model for heat generation in the brake calipers was made using MATLAB. Using the thermal properties for selected materials, in a combination with preliminary data for Atmos, the temperature rise in both the brake rotor and brake pads after n braking operations was calculated. The resulting plot is presented in **Figure 3**.

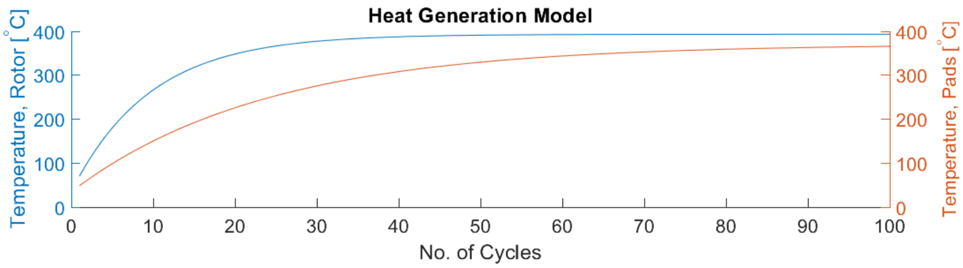

Figure 3: Theoretical temperature rise in brake rotor and -pads after n cycles.

In the heat generation model, the vehicle is assumed to decelerate from 70 km/h to 40 km/h in 0.85 s at each cycle, which represents a typical operation during runs like autocross and endurance. Although the temperature rise seems steep, Atmos utilizes regenerative braking for most of the time, which means that the mechanical brake system has time to cool down after each braking operation.

3. Brake Caliper Design for Revolve NTNU 2018

3.1 Design Domain

The geometric domain where the topology optimization algorithms can utilize the material and its density, often referred to as the design domain, was created based on two factors: (i) available design space within the wheel; and (ii) a requirement for backwards compatibility with commercially available brake calipers. The domains were modelled using SolidWorks and imported to Abaqus/CAE.

3.2 Interactions and Boundary Conditions

To represent the real-life fastening of the calipers, where they would be fastened to the upright by bolts, a fastening plate and two bolts were included in the analysis setup in Abaqus/CAE. The bolts were preloaded using bolt loads, and tied to the fastening plate. Surface contact was also defined between the caliper housing, the bolts and the fastening plate. The only boundary condition utilized in the analyses was an *encastre* condition on the bottom surface of the fastening plate, to represent the connection between the calipers and the upright. Thus, creating a load case for other components of the wheel assembly.

3.3 Loads and Analysis Setup

To represent the hydraulic pressure the calipers experience during braking, a pressure load was defined within the piston areas, with the magnitude defined by the calculated load cases. A surface traction was also defined on the leading edge of the calipers, to represent the generated friction force between the brake pads and -rotor.

3.4 Topology Optimization Setup

To get the lightest possible calipers, whilst still maintaining the required stiffness, topology optimization was conducted using Tosca. A general sensitivity-based optimization algorithm with a SIMP material interpolation technique was utilized. Load- and boundary condition-regions were left unfrozen, meaning they would not be restricted for the optimization algorithm.

Two design responses were requested in the topology optimization – strain energy, meaning the energy stored in the elastic body during loading, and the mass of the body. Due to uncertainties regarding the importance of stiff versus weight, weighing the two design responses against each other proved itself difficult. To avoid developing a pareto frontier, an objective function with only one design response for evaluation was defined. Minimizing the strain energy, whilst using the mass of the body to define a constraint mean that the algorithm would reduce the mass to the constraining value, then work to minimize the objective function. The mass constraint was initially based on wanted reduction of mass compared to commercially available brake calipers of the same caliber, then iteratively tuned based on deformation and stress levels in the optimization results.

3.4.1 Geometric Restrictions

Initially, one geometric restriction was defined in the optimization process – frozen areas at piston bores, and pin- and bolt holes. To investigate a machinable result, several geometric restrictions were defined – forging constraints, and symmetric constraints. Using demold control allowed the algorithm to alter the geometry in a defined pull direction, whilst the symmetrical constraints forced the algorithm to work symmetrical around a defined plane. **Figure 4** shows a comparison between an unconstrained optimization and an optimization constrained by demold control, and **Figure 5** shows a comparison between an unconstrained optimization and an optimization constrained by planar symmetry.

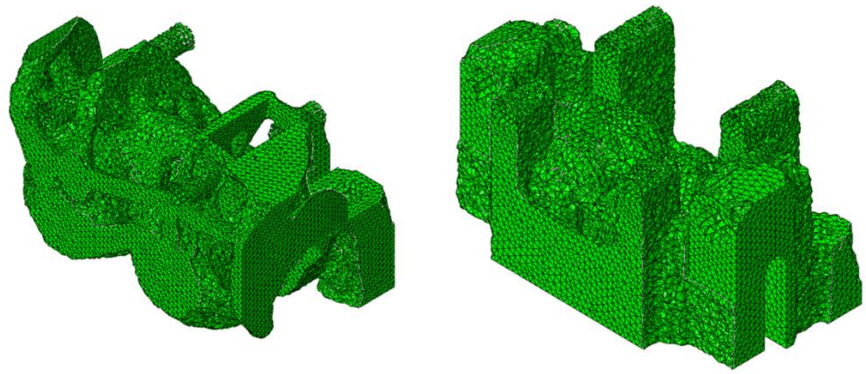

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Figure 4: Comparison between unconstrained model (left) and model constrained by demold control (right).

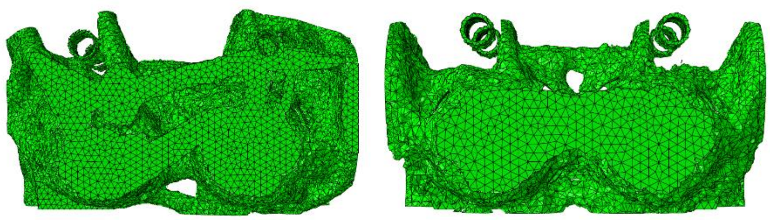

Figure 5: Comparison between unconstrained model (left) and model constrained by planar symmetry (right).

3.5 Results of Topology Optimization

3.5.1 Model for Milling

As the algorithm was subject to symmetric restriction, the result was suitable for CNC milling, as it would require one setup for several calipers, and the tool paths could be mirrored along the mid plane of the component. The resulting model for milling is presented in **Figure 6** and **Figure 7**, where the figures show the stress levels and the deformation, respectively, during expected loads.

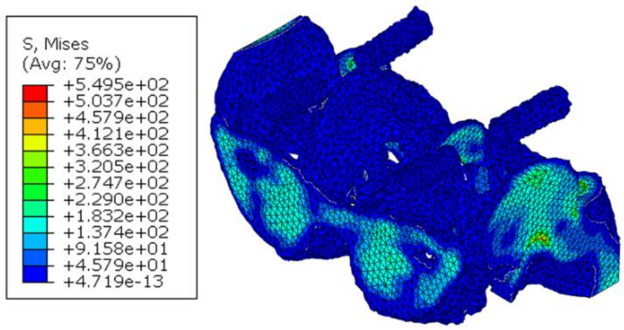

Figure 6: Stress levels, front caliper (restricted by planar symmetry).

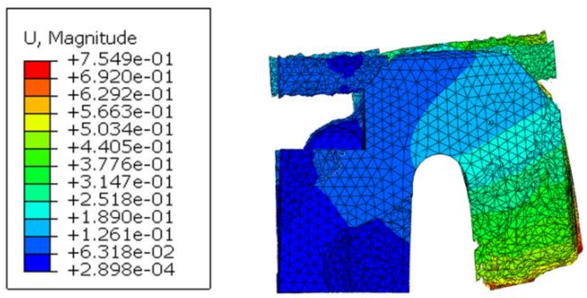

Figure 7: Deformation, front caliper (scaled by 10, restricted by planar symmetry).

3.5.2 Model for Additive Manufacturing

When looking at a design for additive manufacturing, the algorithm was allowed to work freely within the geometrical domain. It yielded lower stress levels and deformations compared to the model for milling, as evident by **Figure 8** and **Figure 9** respectively.

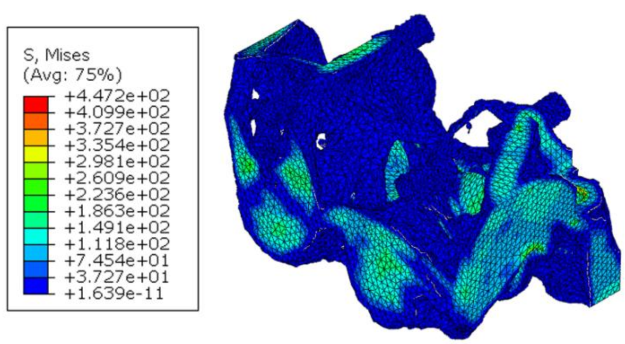

Figure 8: Stress levels, front caliper (non-restricted).

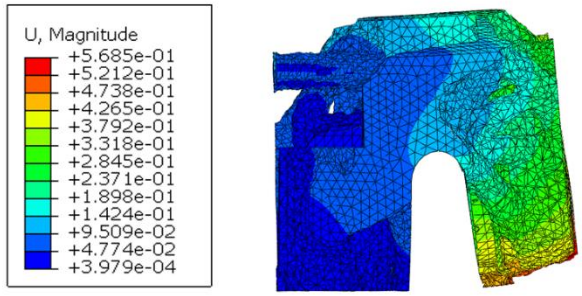

Figure 9: Deformation, front caliper (scaled by 10, non-restricted).

3.6 Regeneration of CAD-models

Although the 3DEXPERIENCE platform was initially planned to regenerate the CAD-models after optimization, as it offers great tools for regenerative processes, a more conventional approach was chosen. The geometrical representations were imported from Abaqus to SolidWorks, and used as guiding domains while rebuilding the geometry from scratch, with a goal of designing for manufacturing.

3.7 Final Design

Although designs for both milling and additive manufacturing were investigated, only the design for milling was finalized. Fatigue life analyses were conducted using Abaqus/CAE in combination with fe-safe, where the calipers were subject to the loads previously described. When investigating fatigue, however, both the mid-stresses and the amplitudes are of interest. For the calipers, the mid-stresses were defined by the pretension of bolts, and the amplitudes were defined by the hydraulic pressure. These loads were setup in Abaqus/CAE, and the resulting stresses were imported into
fe-safe, where they were defined by two curves – a sine curve and its inverse.

The Factor of Strength (FOS) is a factor which, when applied to the elastic stresses from FEA at a node, will produce the corresponding design life at the node. The fatigue life is compared with the design life or target life specified by the user and the elastic stresses at the node are scaled by a factor either lass than- or greater than one, if the calculated life is lower or greater than the design life, respectively. Results from analyses conducted on the front caliper are summarized in **Table F**.

Table 2: Effects of surface roughness on fatigue life, front caliper.

R_a [μm]	Worst Life-Repeats	Worst FOS@Life-Infinite	Largest Damage

$\mathbf{40 < R_a \leq 75}$	23633	0.5	4.29E-5
$\mathbf{16 < R_a \leq 40}$	62225	0.538	1.61E-5
$\mathbf{4 < R_a \leq 16}$	195289	0.613	5.12E-6
$\mathbf{1.6 < R_a \leq 4}$	261071	0.613	3.83E-6
$\mathbf{0.6 < R_a \leq 1.6}$	565250	0.669	1.77E-6

The final designs for the caliper housings were produced by Semcon Devotek, and are shown in **Figure 10**.

Figure 10: Caliper housings, produced by Semcon Devotek.

4. Production of Calipers

Based on a combination of the availability of machining processes within sponsors and a wish for combining topology optimization and traditional machine processes, CNC-milling was chosen to be the main process used for creating the calipers. More specifically, the caliper housings are made through 5-axis CNC milling, while their pistons are made through turning.

Utilizing CNC-milling made it possible to get a close-to-finished product from one sponsor, with the specified dimensions and tolerances. Other benefits include freedom of choice with regards to materials and organizational knowledge about the prerequisites for a successful process. However, the chosen production methods have their drawbacks. Choosing CNC-milling over for example additive manufacturing meant that the fluid channels needed to be drilled and sealed, and that the geometry was more restricted.

4.1 Influencing Factors

The quality of the produced components is governed by several influencing factors, such as tolerances between moving parts, surface roughness, residual stresses, individual positioning of co-working features relative to one another, need for post-machining processes, and many more. Some of the easily controllable factors are for instance tolerances and surface roughness.

4.1.1 Surface Roughness

The specified tolerances do not only specify dimensions of feathers and their positions relative to one another, but also the surface roughness of specified areas of a component. Recommendations provided by Seal Engineering gave ranges of surface roughness in areas surrounding a seal.

Since the caliper pistons translate along the axial direction of the seals, their surface roughness had to be within the recommended range. Although the pistons were specified with a surface roughness $R_a = 0.4$ mm, possibilities of surface treatment after machining were explored. A potential surface treatment was utilizing a diffusion method that converts the surface of the metallic titanium in the pistons into a ceramic titanium nitride. A test specimen of a titanium plate that had undergone TiSurf (the aforementioned diffusion method) was provided by SentinaBay AB. Features specified by the company were a hard surface, excellent tribological properties, resistance against wear and heat, as well as extremely low friction. Although the process is not for improving the surface roughness of a component, the test specimen's surface roughness was investigated and compared to the surface roughness of two caliper pistons straight from turning. The investigation was conducted using a Mahr Perthometer, with a setup shown in **Figure 11.** The results are summarized in **Table 3.**

Figure 11: Perthometer setup. Investigated specimen in the left field of the picture.

Table 3: Surface roughness of caliper pistons and TiSurf test specimen.

Object	**Maximum height of the profile, R_t[μm]**	**Mean deviation of the profile, R_a [μm]**
Caliper Piston A	2.99	0.216
Caliper Piston B	1.82	0.167

TiSurf Plate A, Longitudinal	9.51	1.238
TiSurf Plate B, Longitudinal	10.9	1.278
TiSurf Plate A, Lateral	11.5	1.331
TiSurf Plate B, Lateral	11.2	1.209

5. Mechanical Testing of Calipers

To be able to defend the caliper design, the design has to be backed up by in-lab tests and on-track validation. When the testing was planned, three things were subject to study – static- and dynamic behavior, as well as heat sensitivity. Thus, both peak loads, cyclic behavior and changes during rising temperatures were of interest.

5.1 Test Setup and Procedure

To test the feasibility of the brake caliper, a test jig was designed and produced. The setup is shown schematically in **Figure 12**. The master cylinder was mounted to a universal test machine, whilst the calipers were fully assembled on a stationary bracket, representing the brake disc. To log internal strain energy, and derive the internal stress levels of the calipers, they were equipped with one-axis strain gauges, as shown in **Figure 13** and **Figure 14.**

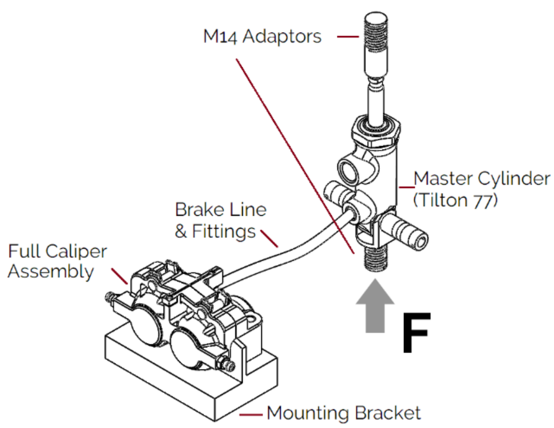

Figure 12: Schematic drawing of the test jig setup.

Figure 13: Strain gauges mounted on front caliper.

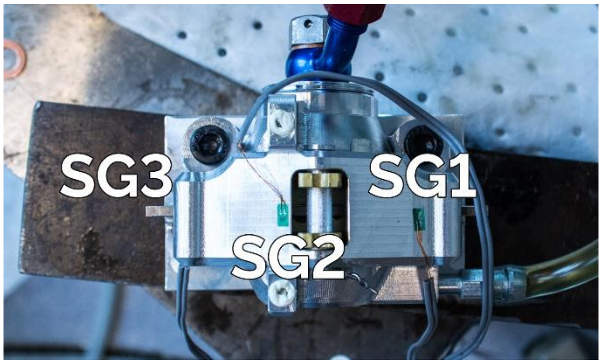

Figure 14: Strain gauges mounted on rear caliper.

The mechanical testing was carried out as listed:

1. The closed system was filled with brake fluid
2. The calipers were bled, to avoid formation of internal air bubbles during actuation
3. The universal test machine was actuated manually, to inspect for leaks in the calipers
   a. If leaks were discovered, measures were taken (e.g. re-applying PTFE tape or re-tightening fittings)
   b. If there were no leaks during investigation, the actuation was continued
4. Peak loads were defined and carried out. Simultaneously, data was logged
5. Cycles were defined and carried out. Simultaneously, data was logged
6. Heating of the calipers were conducted, and peak loads carried out. Simultaneously, data was logged

5.2 Mechanical Test Results

The testing took both cycles and peak loads into account. Some of the results with the highest resulting stresses are graphically represented in **Figure 15** to **Figure 18**. Selected numbers from the results are listed in **Table 4**.

Table 4: Summarized results from mechanical testing of calipers.

Caliper	Type	No. of Cycles	Surface Temp.[°C]	Speed of machine [mm/s]	Peak Load [kN]	Max. resulting stress [MPa]
Front	Peak	-	Ambient	48	3.77	130
Front	Peak	-	Ambient	48	3.84	133
Front	Peak	-	Ambient	48	3.91	136
Front	Peak	-	Ambient	24	3.98	139
Front	Peak	-	Ambient	24	4.05	142
Front	Cycle	50	Ambient	24	2.53	114
Front	Cycle	8	100	24	2.55	94.0
Front	Cycle	3	100	48	2.66	101
Front	Cycle	25	100	48	3.42	128
Front	Cycle	25	100	24	3.99	157
Rear	Peak	-	Ambient	30	2.49	293
Rear	Cycle	25	Ambient	30	1.83	214
Rear	Cycle	25	Ambient	30	2.09	225

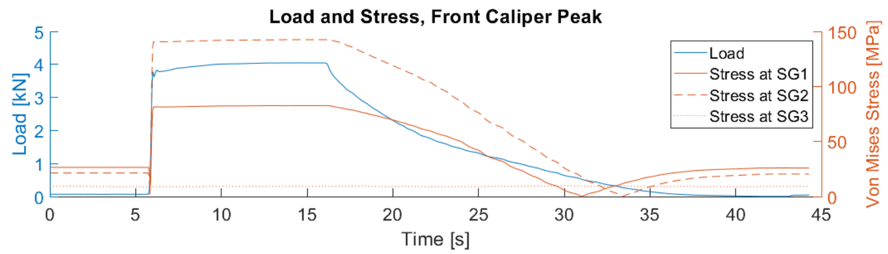

Figure 15: Peak load testing of the front caliper, resulting in $\sigma_{max} = 142$ MPa at $F_{peak} = 4.05$ kN.

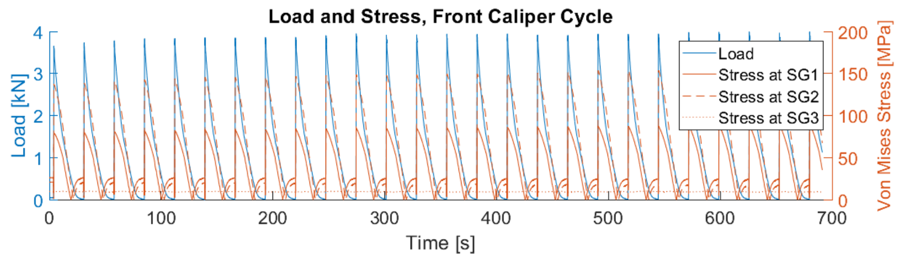

Figure 16: Cycle testing of the front caliper, resulting in $\sigma_{max} = 157$ MPa at $F_{peak} = 3.99$ kN.

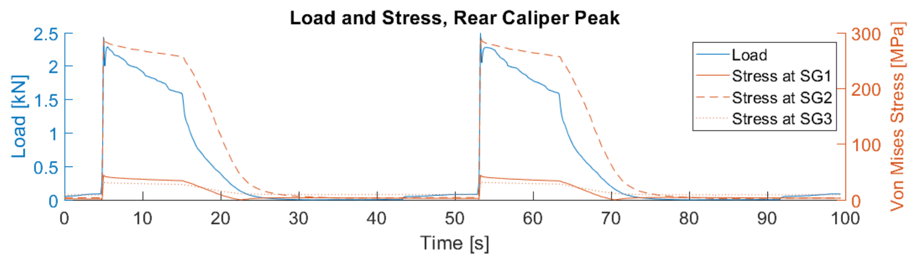

Figure 17: Peak load testing of the rear caliper, resulting in $\sigma_{max} = 293$ MPa at $F_{peak} = 2.49$ kN.

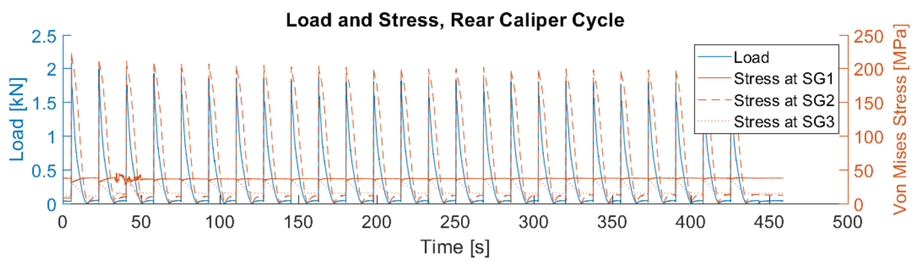

Figure 18: Cycle testing of the rear caliper, resulting in $\sigma_{max} = 225$ MPa at $F_{peak} = 2.09$ kN.

5.3 Comparison of Test Results and Simulation Results

To validate the simulation models, a comparison of the results from mechanical testing and simulation was conducted. As the loads were known from the mechanical testing, dividing the loads on the master cylinder boring yielded the theoretical pressure within the brake system, which was used in the verification simulations. Simulations were carried out using Abaqus/CAE, where a pressure load was applied at the piston bores within the caliper housing, and controlled by a ramping amplitude. **Figure 19** and **Figure 20** show plots of the resulting (and measured) strains for the front and rear calipers, respectively.

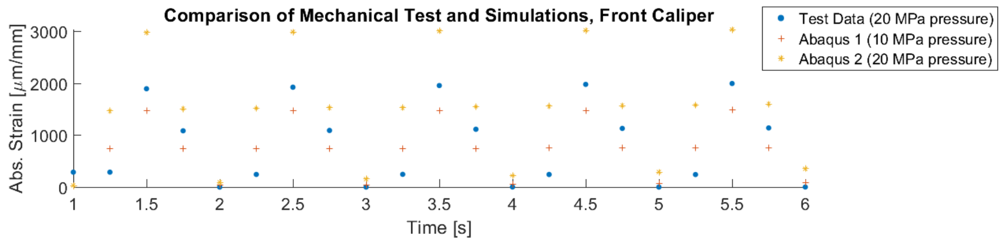

Figure 19: Strains measured and simulated in the front caliper.

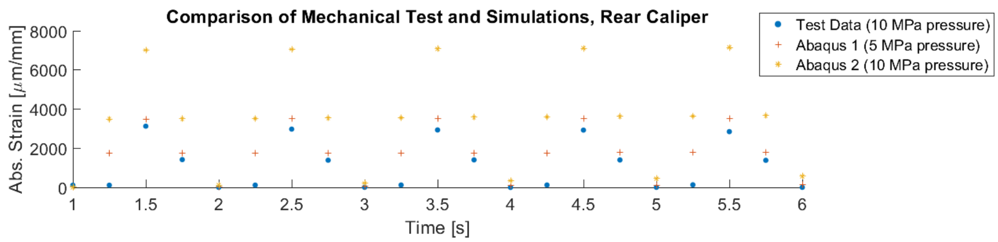

Figure 20: Strains measured and simulated in the rear caliper.

6. Conclusions, Discussion and Future Work

Based on the work presented in this paper, it has been concluded that:

- Front- and rear brake calipers for Revolve NTNU's race car, Atmos, have been developed, designed, produced and verified. Unsprung mass reductions have been approximated to a total of 500 g by redesigning the brake calipers, whilst fulfilling the requirements defined during calculations of load cases.
- Mechanical testing of the calipers has been conducted, and results have been compared to equivalent models in Abaqus/CAE.
- The backwards compatibility has been successful, although it has constrained the caliper design.

The comparison of test results and simulation results raised a concern based on the large deviations, as it means that either (i) despite not being visible, leaking occurred during testing; or (ii) bleeding of the brake system was not sufficient. As the calipers were sealed by PFTE tape which has a lower rating than needed, mechanical testing will be re-done when new thread sealants are available.

As of now, no comparison between the models for milling and additive manufacturing has been conducted, although it will be during the spring of 2018. The comparison will include verification analyses in Abaqus/CAE, as well as fatigue life analyses in fe-safe. This will give an indication for future steps in caliper design for Revolve NTNU, as this year's calipers are the first of their kind within the organization.

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Several areas are recommended as future areas of interest:

- High temperature loads during cycling testing of calipers.
- Deeper investigation of additive manufactured brake calipers, both theoretical and practical applications.
- Better integration between calipers and e.g. uprights for improving in-wheel packing.
- Improving producibility of calipers by looking at tolerances and geometry.

7. References

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