



School of Engineering

BEng Automotive Engineering

Major Project / Dissertation (M6X00417)

Optimisations to an Alloy Wheel through analytical and live testing methods

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.

Signed:

Date:

Acknowledgements

I would firstly like to thank my project supervisor for his continued support thought out this project. As the project supervisor he has been able to provide valuable advice and direction.

The technical staff for assisting me with my live testing in the workshop, helping with the strain gauges and for taking the time to help me create 3D printed prototypes of the proposed designs.

I would also like to thank my FEA lecturer, for his time assisting me with a methodology for the optimisation work.

Abstract

This report primarily investigates the optimisation of a Ford aluminium alloy wheel through the use of geometry and material changes. As well as discussing time management and optimisation tools used by the author, there is also various sections dedicated to the research carried out that provided a foundation for further investigation. Some of these sections include testing methods, material research and manufacturing processes.

The author also discusses the process of creating an FEA model based on the physical wheels and how this model was validated using industry standard, live testing techniques. When comparing the FEA model's accuracy to the live wheels displacement, the author found a difference of only 0.1mm. He found this acceptable to compare against an optimised proposal.

An optimised proposal was developed using mathematical techniques, to change the spoke diameter from approx. 48mm to 14.45mm. With the material changed to a recycled carbon fibre, it resulted in a wheel being 40% lighter with a displacement of half the original wheel. Torsional tests were also conducted showing similar displacements between the original and optimised wheel.

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1. Introduction

The wheel is one of the most critical components in automotive engineering with their functionality having a major impact on vehicle performance. This component is an important structural member of the vehicles suspension system that supports static and dynamic loading. Over the last few decades there has been major improvements in design and testing methods to ensure performance criteria are met. It is essential to validate any designs changes through stress analysis as (Grubisic V, Fischer G., 1984) have pointed out that testing without this will not yield an optimal design. The onus on current wheel design is focused on fuel efficiency and performance, hence why we see a lot of standard wheels being made from light aluminium alloys. (R. Muthuraj et al., 2011) (Rao et al., 2017)

This project is an investigation to examine if changes in the geometry and material selection of a Ford Softline RS7 Alloy wheel will improve the components structural rigidity and mass properties. With improvements in these properties, the vehicle will have a lower un-sprung weight resulting in an increase in overall performance and economy. By using various methodologies an optimised design can be proposed.

1.1 Project Aims

- Propose an improved design of the Ford Softline RS7 wheel by optimising its geometry and material selection.
- Use analytical and live testing methods to validate the accuracy of the original design FEA model so that comparisons can be made against the optimised design.
- Find a solution that could be considered as an aftermarket improvement.

2. Project Relevance

The energy use and travel requirements in wealthy countries are dominated by vehicles. Since that mostly all fuel is the product of either Oil or Natural Gas, vehicles account for a significant release of CO₂ that is the main gas associated with climate change. Hence, the vehicle is the primary focus of energy and environmental authorities of most countries (Schipper, 2011)

There is evidence of this consideration in the fact that the UK Government is planning to ban the sale of any new pure petrol or diesel car by 2040, in a hope to ensure none of these cars are on the road in 2050. (Steven Swinford, 2017)

The main reason of this project would be to reduce the CO₂ output of the vehicle and increase the vehicles performance. There would be many potential benefits to this:

- Environmental – Beneficial to the environment as there will be more miles/CO₂
- Economic:

Consumer – Will be saving money on whatever fuel is currently in use, as the vehicle has less overall mass, giving more Miles per Gallon

Manufacturer – When making average amount of units, how much could be saved due to material cost and processing cost?

Less Material used – Could there be less material used overall, which means less time processing raw materials – better for environment.

Renewable Materials – Is it more cost effective to use a renewable material that is relevant for the task. Could this material be processed with less raw materials that are likely to impact the environment?

- Conventional – If there is a solution, it can be implemented for any type of powertrain (Petrol, Diesel, Hybrid and Electric Vehicle) This is important as even though EV's seems to be the direction of choice of future powertrains, it will remain to be seen if the infrastructure will be able to cope with the new demand for this fuel. Also, the issues of Vehicle Range and cost of Batteries that need solutions. (Clark et al., 2017)

- Performance – With a more efficient wheel the vehicle would get a lower un-sprung mass which would give the vehicle an increase in overall acceleration. Heavier wheels are harder to accelerate and decelerate due to the higher inertia. Therefore, the shocks and springs would also have less work to do when keeping the tyres in contact with the road. (Formula1-dictionary.net, 2017)

This is because the forces generated by bumps must be overcome by the springs to keep the tyre in contact with the road. The lighter the vehicle the less compressive force is available and the easier it is for the vertical motion of the wheels to overcome the inertia of the sprung mass. (Riley, R.Q, 2017) We can see the effect of larger un-sprung masses in Figure 2.1.

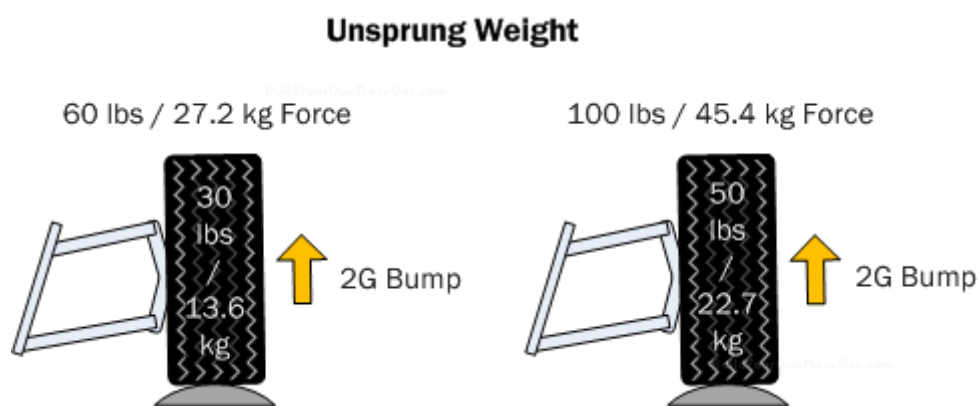


Figure 2.1 - Un-Sprung Weight is ideally kept to a minimum to avoid larger vertical forces.

(Car Suspension Basics, 2017)

A more rigid wheel also reduces wheel flex whilst cornering giving increased tire performance.

3. Project Management

There are some common factors that need to be considered to determine what a project actually is. These are:

- Unique: The project needs to have not been performed before and have a degree of novelty.
- Temporary: The project should have a beginning, a middle and an end.
- Focused: The task of the project should keep in line with the aims and objectives set out at the start.

With these factors in mind it is important for the Project Manager to implement appropriate strategies to ensure that time is optimised.

3.1 Gantt Chart

The Gantt chart is a tool which enables the user to easily create a project schedule with or without software. This method is easily understood and widely used though many industries. The user can list tasks in the order of completion and is able to set a start and end date. There are some potential limitations when using this strategy:

- Could be difficult/time consuming. to update manually where changes in the chart occur.
- It does not equate time with cost.
- Does not assist with resource allocation.
- Could lead to a false sense of certainty about the project.

The Gantt chart produced for this project is listed in Appendix 1a and 1b. The author found this tool useful in maintaining a sense of direction and time throughout the year. It served as a constant reminder on a week to week basis.

Maylor, H. (2011)

3.2 Kaizen

Kaizen originated in Japan with the word translating to mean change (*Kai*) for the good (*Zen*). It is more of a philosophy than a set project management tool. Its philosophy is based upon the approach of making continual incremental improvements. This is a versatile methodology that can be used in a number of scenarios, whether it being aimed at a corporate or personal project. Much of the focus in Kaizen is to reduce waste in several forms:

- Movement: Moving material around before additional value can be added to them (This could be applied to wastage of physical energy or mental energy)
- Time: Time spent waiting (or time wasted due to disorganised/loss of files)
- Defect: Work that needs to be re-done or fixed (re-doing work due to lack of quality/research)
- Over-Processing: Doing more than is necessary (Reading material in more detail than necessary)
- Variations: Producing a bespoke solution when a standard solution would work (Creating a new document when a modified older document would work)

Mindtools (2018)

Some companies use Kaizen to improve their manufacture process. The Toyota company use a 7-step system with a feasibility study to warrant changes in any contingency concerns they may have. The seven steps of this system are:

Step 1: Selection of Kaizen Theme

Step 2: Situation Analysis

Step 3: Root Cause Analysis

Step 4: Identification of Countermeasure

Step 5: Implementation of Countermeasure

Step 6: Checking Effectiveness of Countermeasure

Step 7: Standardisation

Jica (2018)

The author has used this system as a contingency plan to mitigate wastage in time and resources. Appendix 2a and 2b display the Root Cause Analysis and Matrix of Countermeasures conducted for this exercise.

4. Background Research

4.1 Wheel Theory

A Wheel is an assembly of the Rim (where the tyre is installed) and the Disk (where the Wheel mounts to the axle). There are various factors that make up the design of the Rim Profile and Design.

4.1.2 Rim Nomenclature

Here are some of the factors which make up the design of a wheel:

1. Wheel: Wheel is generally composed of rim and disc.
2. Rim: This is a part where the tire is installed.
3. Disk: It is a part of the rim where it is fixed to the axle hub.
4. Offset/ET: This is a space between wheel mounting surface where it is bolted to hub and centre line of rim.
5. Flange: The flange is a part of rim which holds the both beds of the tire.
6. Bead Seat: Bead seat approaches in contact with the bead face and it is a part of rim which holds the tire in a radial direction.
7. Hump: It is a bump what was put on the bed seat for the bead to prevent the tire from sliding off the rim while the vehicle is moving.
8. Well: This is a part of rim with depth and width to facilitate tire mounting and removal from the rim.
9. PCD: Pitch Circle Diameter – This is the diameter of the circle that passes through the centre of all the studs. Normally also includes the number of studs.
- 10: Rim Size is shown as the diameter in inches and the width in inches. E.g. 15 x 6.5J

See Figure 4.1 for a graphical reference. (Meghashyam, P. et al., 2013)

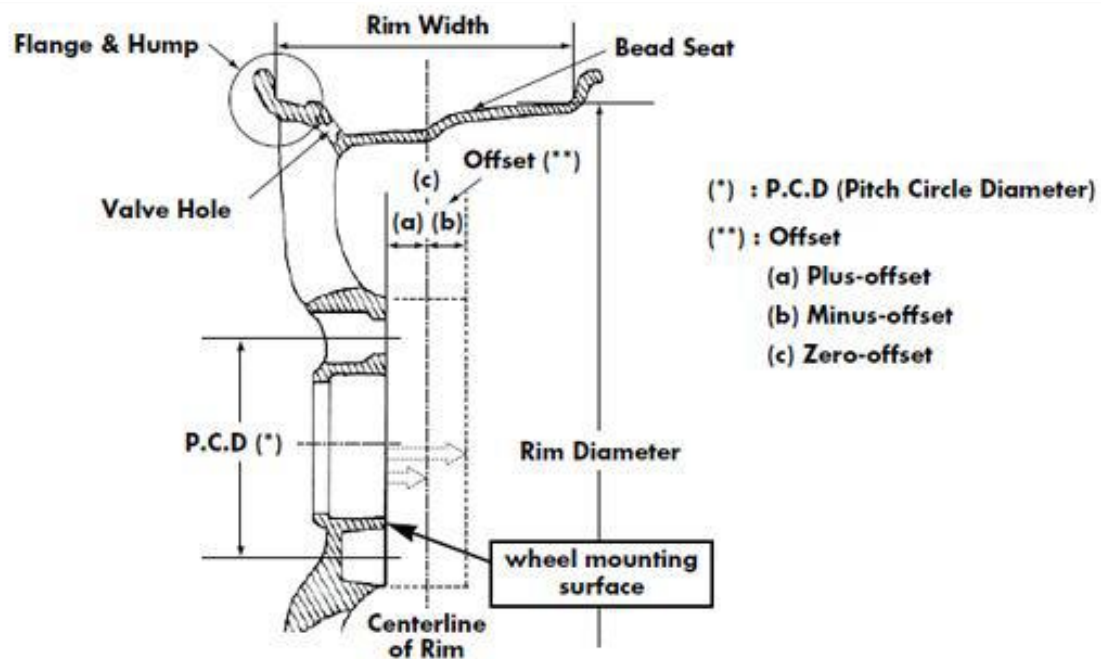


Figure 4.1 – Wheel Nomenclature (Meghashyam, P. et al., 2013)

4.2 Current Lightweight Wheel's

The majority of vehicle manufacturers, OEM suppliers and aftermarket companies still use an aluminium alloy as the material of choice for their products. Some luxury vehicle manufactures have begun using advanced materials for their wheels.

4.2.1 Koenigsegg

The Swedish supercar manufacturer Koenigsegg boasts that their 2013 Agera R feature the world's first hollow, one piece, carbon fibre wheel. This product was developed using their patented "Aircore" Technology. These wheels save close to 20kg in un-sprung mass whilst providing excellent performance and safety. Price \$42,500/Set (Koenigsegg, 2018)



Figure 4.2 – Koenigsegg's Aircore Wheel (Koenigsegg, 2018)

4.2.2 Porsche

Porsche have also created their own Carbon Fibre wheel as an option for their 911 Turbo S. These weigh around 8.5kg less than the standard wheels which is a 20% improvement. They are manufactured from a Carbon Fibre Reinforced Polymer (CFRP) Price 15,232 EUR Inc. VAT. Porsche (2018)



Figure 4.3 Porsche's Carbon Fibre Braided Wheel Porsche (2018)

4.2.3 Carbon Revolution

Carbon Revolution are an aftermarket supplier of Carbon Fibre wheels. They boast the world's only solid, one-piece wheel. They released their first wheel "CR-9" in 2008. They say the wheel has up to 40% weight saving. Price \$15,000/set (Carbon Revolution, 2018)



Figure 4.4 Carbon Revolutions CR-9 Wheel (Carbon Revolution, 2018)

4.2.4 BASF

Chemical giant BASF have recently developed injection mould plastic rims, using a new type of polyamide long glass fibre. This "Ultramid Structure" can be pelletized for the moulding process. These wheels were first seen on the Smart Concept Car (Core-77, 2018)



Figure 4.5 – BASF Wheels on Smart Concept Car (Core-77, 2018)

4.3 Testing Methods

Testing wheels is a very important practise for any automotive company. Firstly, it ensures that the product is safe to use and performs to their requirements. It also acts as a selling point to the consumer, giving peace of mind and assurance that the product will meet their expectations.

Worldwide, there are a large number of Industry bodies that provide standards. These governing bodies are:

- SAE
- SFI
- ABNT
- ASTM
- ISO

It is important to realise that these standards are not mandatory, as (BSIGroup, 2018) states:

“Standards are not mandatory but provide a distilled wisdom of people with experience in their subject matter.”

Therefore, indicating that companies looking to follow correct procedure should adhere to these standards. The largest OEM supplier in the UK is a company called Rim Stock. This company adheres to standards TS16949 (Quality management system) and ISO14001 (Environment management system) (RimStock, 2018)

As well as the standards used by Rim Stock, there are also some other more specific standards available at a price. These are ISO3006 (Testing Methods), ISO7141 (Impact test procedure) and SAEJ2530 (Aftermarket Wheels)

As well as manufacturing, Rim Stock also offer testing services using specialised equipment. Here are some of the tests they offer.

4.3.1 Compression Testing

We can see from figure 4.6 a compression test being carried out on a forged alloy wheel. This specialised equipment applies a force onto the wheel providing data such as displacements. This is important as the wheel will most certainly experience more compressive forces, rather than tensile.

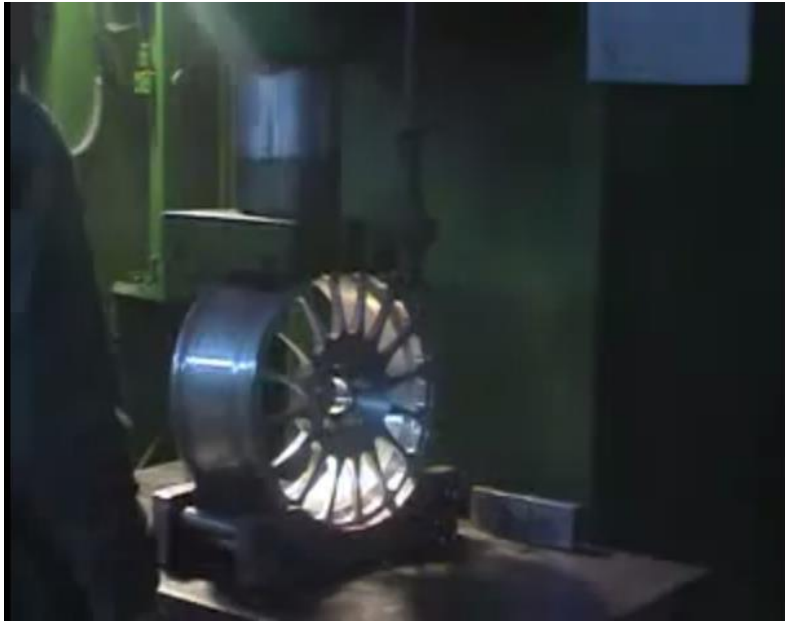


Figure 4.6 An image showing a compression test of an Alloy Wheel (YouTube, 2018)

4.3.2 Torsional Fatigue

The wheel will also experience high torsional forces under braking. Therefore, it is important that we test the torsional fatigue of the wheel. The machine in Figure 4.7 clamps the wheel in position and applies large torque forces. Again, this equipment will relay data to the user for analysis.



Figure 4.7 An image showing a torsional test (Performance Machine, 2018)

4.3.3 Impact Testing

Impact testing is useful in simulating real world, dynamic forces. For this test a specialised machine drops a weight at a set height/velocity. The damage can then be analysed by the user. Figure 4.8 shows an impact testing machine.



Figure 4.8 – An impact testing machine (CTEMag, 2018)

There are many other types of testing that could be conducted. Some are:

- Dynamic radial and cornering fatigue test
- Hydrostatic burst test
- Strain gauging
- Rim contour / dimensional checks
- Rim Flange strength test
- Metallurgical test
- Coating Analysis
- Forensic Investigations

4.4 Material Research

Almost all wheels will want to have the same mechanical characteristics:

- Structural Stiffness
- Static Strength
- Fatigue Strength
- Impact Strength

Some additional considerations include:

- Heat Dissipation
- Style
- Weight
- Geometrical Tolerances
- Corrosion Resistance

With these characteristics in mind, let us investigate some commonly/uncommonly used materials. This should indicate a selection that could be used on an optimised design.

4.4.1 Steel Alloy

Steel alloy is the cheapest material selection you will currently find when purchasing wheels. It is also the heaviest but provides good strength and durability properties. This is probably why Steel Wheels is a popular selection for cheaper vehicles, or vehicles that don't rely on a

lower un-sprung weight. Due to the nature of the material, they are more difficult to cast than the Aluminium alloy or the Magnesium Alloy.



Figure 4.9 Example of a Steel Wheel (4FreeTextures, 2018)

4.4.2 Aluminium Alloy (6000 Series)

Aluminium wheels are the most common wheels used on modern cars by manufacture's. Not only are they much lighter than steel wheels, they are also stronger and more resilient to wear. They are easily cast and have an attractive appearance. Costings are more than steel but less than Magnesium and the Carbon Fibre. Aluminium wheels can also be repaired if needed.



Figure 4.10 Example of a typical Aluminium Wheel (ChromePaint, 2018)

4.4.3 Magnesium Alloy

Magnesium alloy wheels were made as early as the 1930s. It is also the lightest metallurgical material with its density being 1.5 times less than Aluminium. With its high damping capacity and high specific strength in comparison to Aluminium, it is a popular choice in Motorsport applications. The greatest downfall of why we don't see them in commercial use is that they are very much prone to corrosion. This is a major factor as they cannot be repaired, and a wheel's aesthetics is a major priority for the consumer.



Figure 4.11 – A Magnesium Wheel (Carid, 2018)

Kale, H.N. et al. (2015)

4.4.4 Carbon Fibre

Carbon Fibre has been used in F1 and aerospace applications for some time now and has been gradually making its way into mainstream vehicle manufacture. There are many excellent benefits in using carbon fibre as a material:

- High strength to weight ratio
- High rigidity
- Corrosive resistant
- High fatigue resistance
- High thermal conductivity
- Low co-efficient of thermal expansion
- X-Ray Permeable

All these points indicate that this material would be an excellent choice for a wheel application. There are however some concerns that need to be considered. The fact is that virgin carbon fibre is very expensive and secondary that it is a brittle material, so under bending it will fail at low strain.

Therefore, an argument could be made for this material to be used if found in a cheaper form. This leaves the concerns of it being brittle.

When considering the aftermarket parts sub-culture that we have with vehicles, it is filled with products that provide reward for risk. Examples of this being producing more power in the engine by upgrading components, will most likely lower the life expectancy of the engine itself. Or changing the engine mapping so it produces more power with stock components. I believe that is why we see luxury manufacturers producing carbon fibre wheels. They believe the consumer wants the reward and is prepared to accept the risk.

I propose that it would be an acceptable material to use with the understanding that there would be an underlying risk of failure depending on the damage sustained by the wheel through an impact. It would be up to the consumer if they would be willing to risk purchasing a new wheel if damaged through careless driving, as it is only likely to bend under an impact.

4.4.4.1 ELG Carbon Fibre

ELG Carbon Fibre Ltd. produce recycled carbon fibre pellets at 10% the cost of virgin carbon fibre. Once formed into a component they confirm that there are almost no changes in characteristics compared to virgin carbon fibre. They have also confirmed to the author that these pellets could be injection moulded into a single piece wheel. Thus, eliminating some of the concern of costing whilst using this material. (ELG Carbon Fibre., 2017)

(Maserumule, L., 2015) also conducted a study where they confirmed Carbon Fibre to be a suitable material, with them gaining a 62% improvement in weight reduction.

4.5 Manufacturing Processes

4.5.1 Casting and other popular methods

The majority of alloy wheels are manufactured using a casting method (approximately 80% worldwide) This is where molten alloy metal is poured into a mold. After cooling, further work can be conducted to finalise the product.



Figure 4.12 Casting an Alloy Wheel (Wolfrace, 2018)

Some other popular methods are Forged wheels. These are wheels made from one-piece and are formed under high compressive forces.

Billeted wheels are also formed from a single piece of metal, except they are machined into the desired shape. Due to the time and material used, billeted wheels are very expensive. (Wolfrace 2018)

4.5.2 Injection Moulding

Injection moulding involves a melted pelleted material, injected into a mold at high pressure. A lot of plastic components are produced in high volume using this technique due to the accuracy able to be obtained. This technique could be used with ELG carbon fibre pellets to create an optimised design. (Rutland Plastics, 2018)

5. Development and recreation of wheel using FEA software

5.1 Preliminary Testing of FEA software

The software used for all CAD and FEA work in this project is Solidworks 2017. This software was used as it is the most familiar to the author and is also available for use at home, via a student license.

5.1.1 Creating an Example Wheel

Before purchasing a set of wheels for the project, the author decided to create an example wheel, to become familiar with the FEA software and its capabilities. This proved to be a very useful exercise as it confirmed to the author what process would be used in creating the real wheel. We can see this wheel in Figure 5.1.

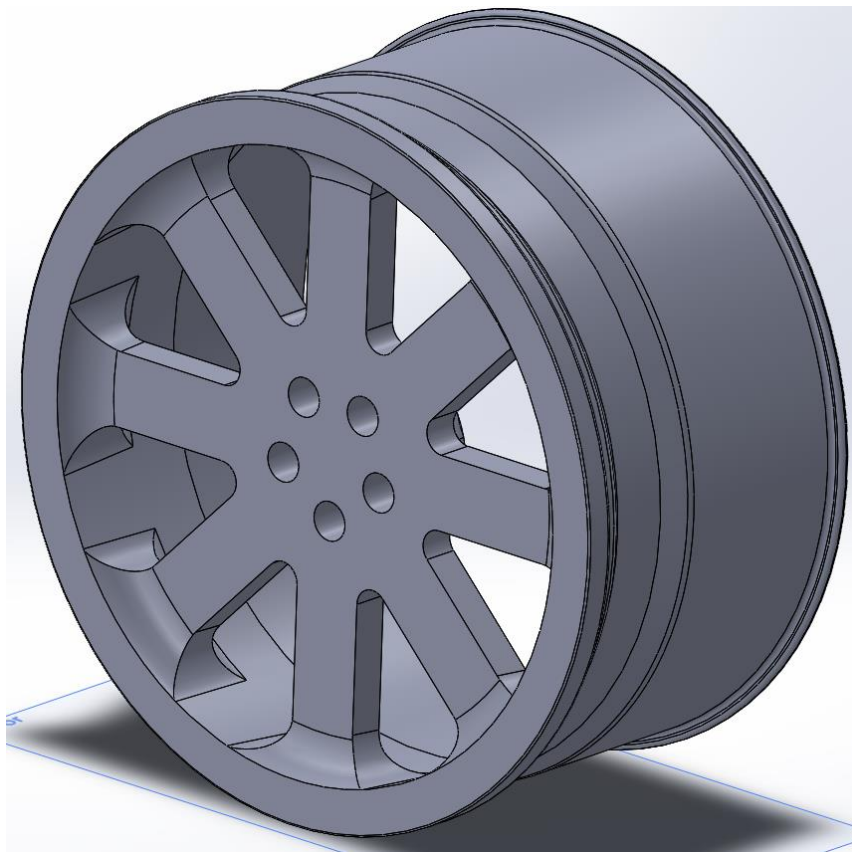


Figure 5.1 - Image illustrating Example Wheel created for FEA experimentation

5.1.2 FEA Experimentation

At the beginning of the project, the author was unaware of the correct testing procedures as discussed in 4.2 Testing Method's section. As pointed out in the Interim Viva, the following tests have little relevance to real world testing scenarios. They did however provide the author with a level of familiarity with the requirements needed for the FEA tests on the real wheel.

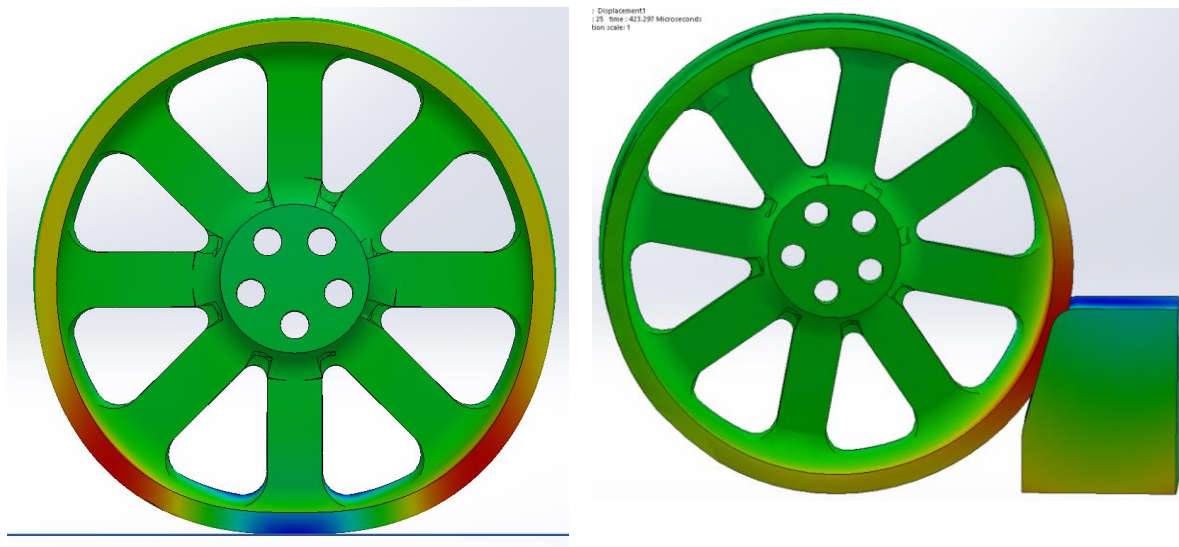


Figure 5.2 - Images illustrating FEA Experimentation

The image on the left of Figure 5.2 shows the deformation of the Experimental Wheel using the Drop Test tool. The initial thoughts behind conducting this test was that it may have been able to be recreated on a physical wheel for verification purposes. The author found this not to be possible after discussing the idea with Gareth Staddon, the workshop technician.

The image on the right of Figure 5.2 illustrates a motion study on the Experimental Wheel, also showing its deformation. In this study the wheel was accelerated into a curb along a path. At the time, the author thought this represented a real-world situation, in which he could analyse the results to see how the wheel would perform.

Another reason why these tests were not ideal is due to the types of studies they are. Motion studies and Drop Tests require much more computational time when processing the results.

5.2 Wheel Selection

The wheel that was chosen for optimisation in this project was a Ford RS7 Softline, as seen in Figure 5.3.



Figure 5.3 - One of the Ford RS7 Softline wheels purchased for model creation and live testing.

Wheel specification:

Diameter: 15 in.

PCD: 4 x 108mm

ET: 40

Centre Bore: 63.4mm

Weight: 11kg

Material: 6000 series Aluminium Alloy

(Ford Technical Information Centre, 2018)

This wheel was chosen for optimisation for several reasons: -

- Price and Availability: The set of four wheels were £50 and were collected in person locally. Important due to limited budget.
- Condition: All four wheels were in excellent condition. Critical for live testing results quality.
- Non-Complex Geometry: A simple design. A significant factor for the model creation speed and accuracy.
- Relevant: They appeared to be an Aluminium Alloy and were used on a common vehicle. Hence, representing the majority of wheels used on light motor vehicles.

These wheels were an aftermarket product of Ford and can be seen on many different models of late 90's/early 00's Ford vehicles. The wheels purchases were taken from a Ford Escort Mk6 (2000) 1.6 90HP, an example seen in Figure 5.4.



Figure 5.4 - Ford Escort Mk 6 pictured with RS7 wheels. (Gumtree, 2018)

Vehicle Specification

Curb Weight: 1000kg approx.

60/40 Front/Rear weight distribution

(Automobile Catalog, 2018)

The first step in recreating this wheel as a FEA model is to sketch the rim profile. To do this the author use a set of Venire Callipers to take the required measurements. As some of the measurements are very small or are at angles some estimations of these figures were made. Figure 5.5 shows the sketched rim profile.

[illegible]

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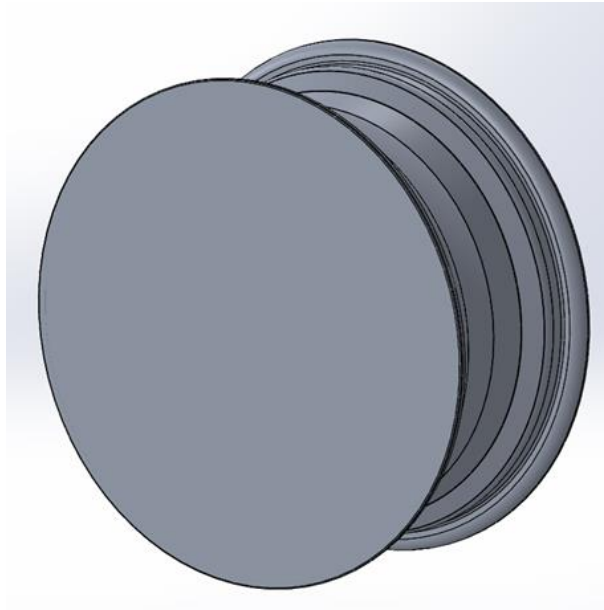


Figure 5.7 - Lofts create material that will later be spokes and hub

Figure 5.7 shows a Loft is created to add some material to create the spokes and hub and Figure 5.8 illustrates a set of extrude cuts that create the hub and bolt holes. The author decided to create the hub first as this area will help dictate the position of the spokes.

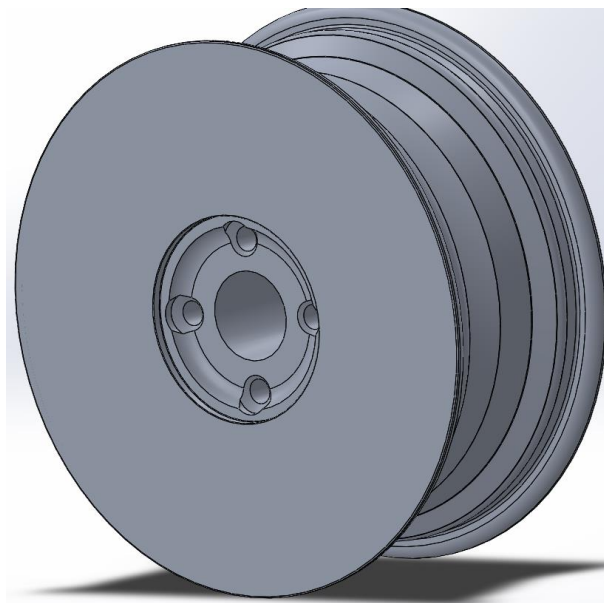


Figure 5.8 - Extrude Cuts create the hub and bolt holes.

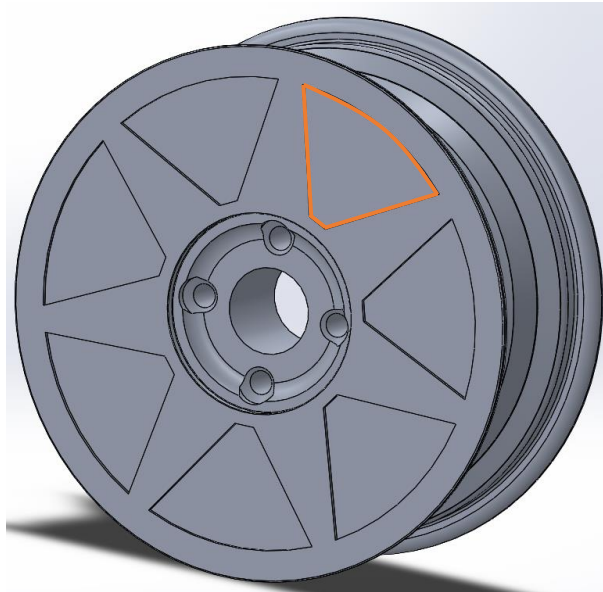


Figure 5.9 - Outer Rim and spokes are cut. Highlight shows gap used for circular sketch pattern

The outer rim was then measured with the spokes and cut. To create the spokes the minimum and maximum measurements were taken with lines connecting the two points. To create a symmetrical pattern of seven spokes, the author drew the first gap and created a circular sketch pattern to create the other 6 holes. Figure 5.10 shows that measurements were made for the minimum amount of gap between the inner and outer rim so that fillets and chamfers could be created.

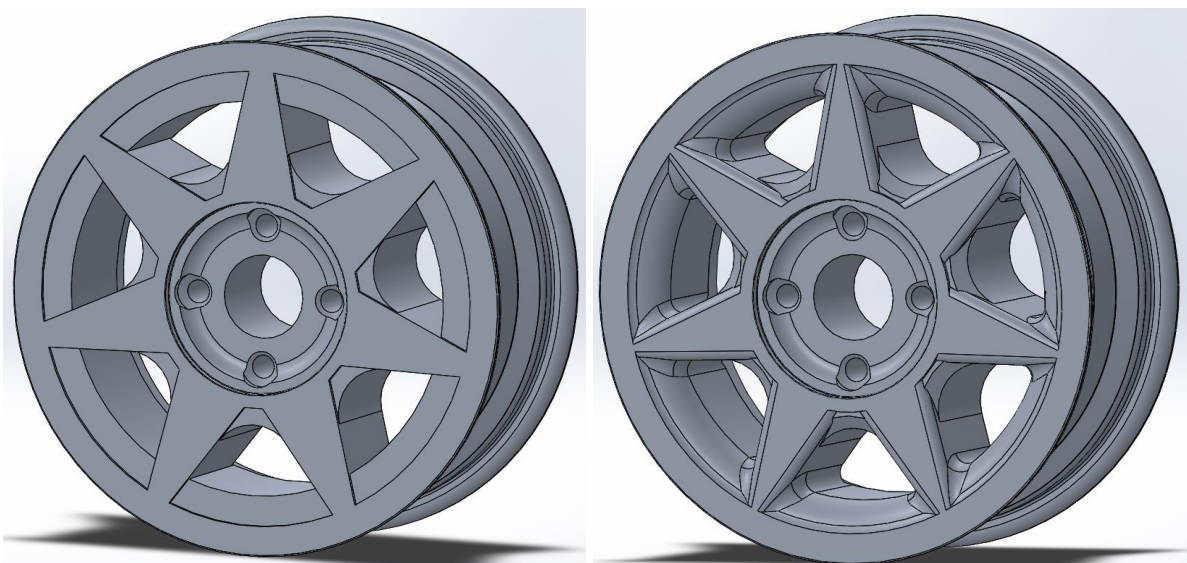


Figure 5.10 - Cut in holes made leaving some material for fillets and chamfers



Figure 5.11 - A combination of fillets and cuts for the rear

A combination of fillets and cuts create the rear part of the hub and create the rear shape and thickness of the spokes.

Throughout this process the author has made every effort to take correct measurements in a hope of recreating the physical wheels. When applying the correct material to the part and checking the models mass characteristic, the mass of the model is almost identical to the physical wheels mass of 11kg (See Figure 5.12) This check reassured the authors geometric and material selection for this model. The final render for this wheel can be seen in Appendix 3a.

Mass properties of Wheel
Configuration: Default
Coordinate system: -- default --
Density = 0.00 grams per cubic millimeter
Mass = 11005.74 grams
Volume = 4076200.75 cubic millimeters
Surface area = 641557.15 square millimeters
Center of mass: (millimeters)
X = -118.52
Y = -200.75
Z = 0.00

Figure 5.12 – Image showing mass of model wheel being 11.005kg

6. Live Testing

After consulting with workshop technician Gareth Staddon, it was decided that the author would be able to conduct a compression test using a large Denison hydraulic press (See Figure 6.1) Gareth confirmed that this press is capable of pressing with 60 tonnes of force, whilst providing electronic graphs showing Force against Displacement. This test would mimic real world testing whilst also help validating the FEA model created.



Figure 6.1 - Image showing the Denison press used for the live tests

The author also decided to attach strain gauges to one of the wheels with the hope of taking strain measurements. This would mean a double validation of results for the FEA model.

As we can see from Figure 6.2, the wheel needed to be sanded to bare metal so that the strain gauge could be glued into position. Wires were then soldered to the strain gauge, ensuring no contact was made to the wheel. The red electrical tape was used to assist this. The wires were then connected to a terminal that connected to the reading device. Unfortunately, on the day of testing, the machine showed an error message. John Kinsella, who is most familiar with the equipment confirmed that the author would not be able to use it, due to the malfunction.

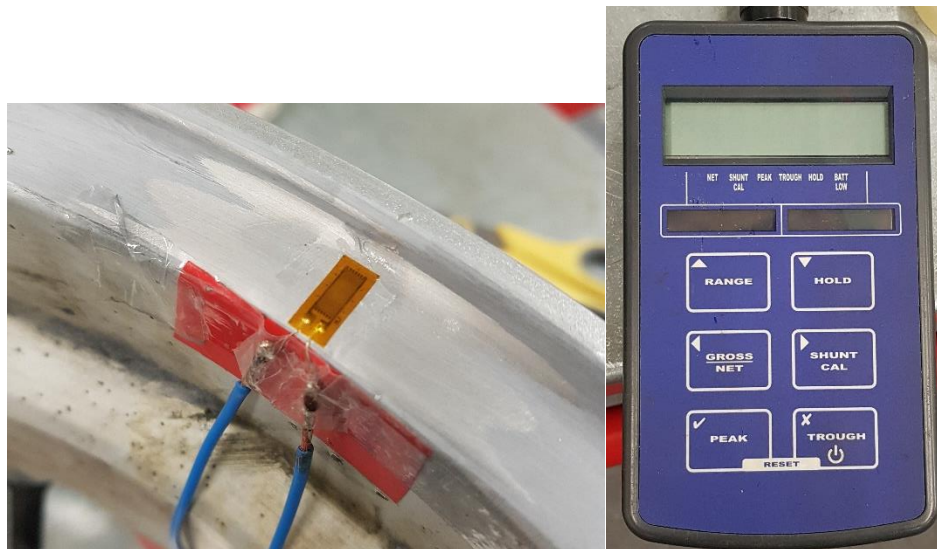


Figure 6.2 - Images showing the prepared wheel and strain gauge equipment

6.1 Week One

For this experiment, the wheel was placed in the middle of the hydraulic press. The press was operated by Gareth Staddon, as he can operate the equipment. The press was then lowered onto the wheel with the displacement measurement zeroed on the computer. The press was then started, with the force against displacement graph displayed. When the desired force was reached the press was stopped and the results were recorded. Figure 6.3 shows an example of the graphs produced by the press. Note that during Week One testing, only Wheel 1 was used.

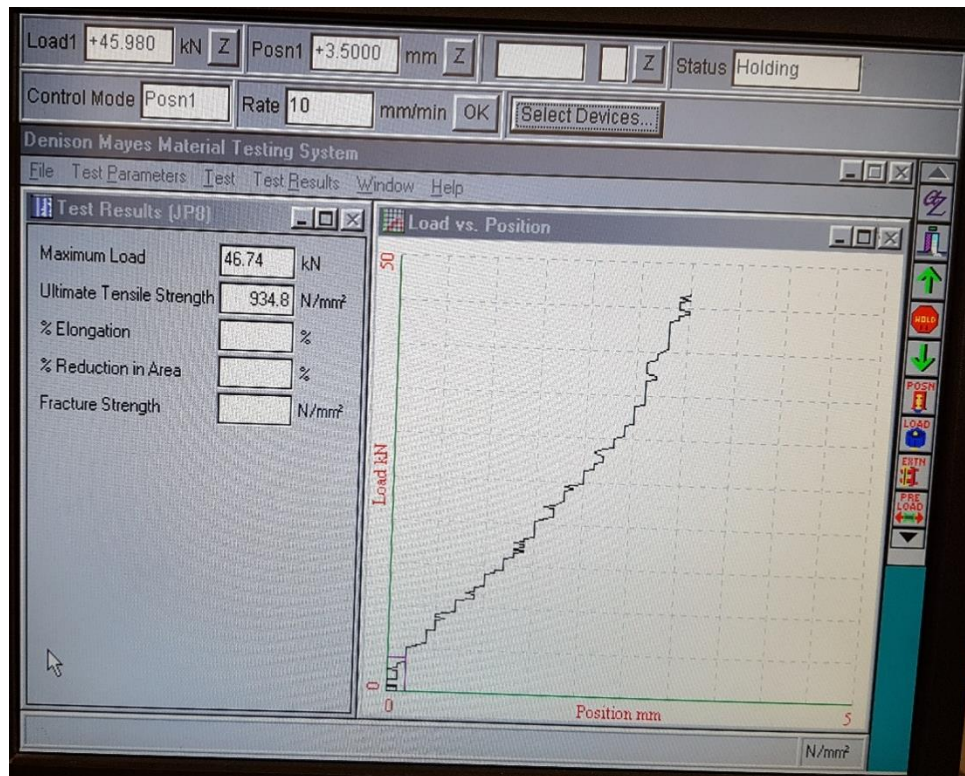


Figure 6.3 - Image showing the graphs produced by the Hydraulic Press

The main issue with the setup of this experiment was that the author didnt notice that the top press was not flush. This meant that the contact point between the top press and the wheel was not at the top of the wheel (See Figure 6.4). This resulted in the wheel being damaged from the first 3 runs and also a loss of displacement in the results. To eliminate this issue, Gareth was able to find a plate to balance on the top of the wheel.



Figure 6.4 - Images showing the recess in the top plate and the damaged caused to Wheel 1

Table 6.1 - Table showing Results from Week 1 of Testing

Run	Force (kN)	Displacement (mm)	UTS (N/mm ²)	Notes
1	8.8	19.9	176	Invalid Result due to large displacement from press not being in contact with wheel
2	9.67	0.9	193.4	No plate in between wheel and press resulting in loss of displacement
3	20.53	2.1	410.6	No plate in between wheel and press resulting in loss of displacement
4	10.44	2.2	208.8	Plate in-between wheel and press to resolve issue - Rerun of Test 1
5	20.18	2.8	436.2	Re-Run Test 3
6	31.81	2.2	636.2	Lower Displacement than previous lower force - Wheel may have fatigued at this point
7	46.74	3.5	934.8	Due to test 6 data may not be accurate due to fatigue in wheel
8	50.5	3.1	1010	Again, displacement should be higher than previous - another sign of fatigue?

Table 6.1 shows the results from Week 1 of testing. It is apparent that these results are unreliable due to the damaged sustained to the wheel from the uneven press. An example of this is that Run 6 shows a smaller displacement than Run 5, when an extra 10kN of force is applied. The same occurs with Run 7 and 8.

The first week of testing proved to be very useful in discovering flaws in the setup of the experiment. By becoming more familiar with the equipment and improving the setup, steps could be taken in Week Two to improve the accuracy of the results.

6.2 Week Two

Due to the problems encountered during Week One testing, the author arranged another session with Gareth. This time all three wheels were included in testing to ensure more testing could be done, in case more problems arose. It was decided that all runs would be conducted with a force of 10kN. The reasoning for this being that more results could be compared and that this force should be within the materials elastic limit. Being in the elastic limit should mean more runs per wheel and should increase the accuracy of comparison between FEA model and live test, as an FEA static compression test relies on the material not failing.

Although the author was confident with the new setup of the experiment, an issue was encountered on the first run. It was discovered that when the top plate was lowered onto the wheel, there was actually a massive pre-load being applied. This was because it was hard to see when the top plate and the wheel actually made contact. In hindsight, this pre-load would have had a massive effect on Week One results and the condition of the wheel.

To resolve this issue the top plate was lowered slightly above the wheel with no contact. This gave us a “Pre-Load” displacement. When this “Pre-Load” displacement was subtracted from the “Resultant” Displacement on the graph, it gives the “Actual” displacement encountered. Graph # shows the results obtained on Week 2.

Table 6.2 - Table showing results from Week 2

Wheel 2	11 kg
--------------------	-------

Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Notes
1	10.02	0	0.6	?	200.4	When attempting to put press at 0mm displacement, press was in fact applying large forces
2	10.06	?	2.7	?	201.2	This time we noticed the resultant displacement was higher than expected. We realised that we needed to monitor and subtract the pre-load displacement
3	10.21	2.5	3.7	1.2	204.2	Monitoring the pre-load displacement is giving more accurate results.

Wheel 3	11 Kg
--------------------	-------

Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Notes
1	10.23	0	1.3	1.3	204.6	
2	10.18	1.1	2.4	1.3	203.6	

Wheel 4	11 kg
--------------------	-------

Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Notes
1	10.64	0	1.3	1.3	212.8	

We can see from Table 6.2 that all the Actual displacements are around 1.3mm. It is important to note that the press gives results to 0.1mm. Ideally, we would like a higher level of accuracy as we are dealing with small displacements, but the author believes it is accurate enough to compare against the FEA model.

Due to the consistency of the results, the author is confident that the improved experimentation has yielded an accurate set of results. Figure 6.5 also shows that there was no visible damage seen on wheel 3, from the two runs it endured. This suggests that the wheel did stay within its elastic limit.



Figure 6.5 - Wheel 3 shows no sign of damage from the two runs

If this testing was carried out with Rim Stock, it would have cost approximately £2000.

7. Validation of FEA model

Finite element analysis (FEA) is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects. Finite element analysis shows whether a product will break, wear out or work the way it was designed. FEA software is a critical resource for this investigation as computers are able to calculate the FEA method much quicker than any human can. With the complex geometry of the wheel, many simplicities would need to be applied to hand calculations if they were to be used. (Autodesk, 2018)

By using Solidworks 2017 FEA software we will hope to replicate the live compression test carried out during live testing in Section 6. If the displacements correlate this confirms that the model created in Section 5 is accurate. Thus, we can do further tests on this model and compare the optimisations to it.

7.1 Mesh Considerations

Due to using only Static studies, the author found that he was able to run them with the maximum number of elements with it taking only around one minute to solve each case. Using the maximum number of elements should yield a more accurate result, as long as all the boundary conditions are acknowledged.

7.2 Compression Study

To start the compression, study the author first needed to create an assembly with two plates to replicate the press. The material used for these is Cast Iron. Figure 7.1 shows the created plate. This plate matches dimensions of plates on the hydraulic press.



*Figure 7.1 –
Plate created
for
compression
assembly*

With the wheel fixed in place in the assembly the author then used centre lines and 4 mates to ensure the plates lined up and could only move vertically. Figure 7.2 shows a picture of the completed assembly, with the blue lines being the centrelines used to help mate the parts. The author had to also cut 0.01mm from the top and bottom of the wheel, horizontally. This was so the wheel could mate at the tangent.

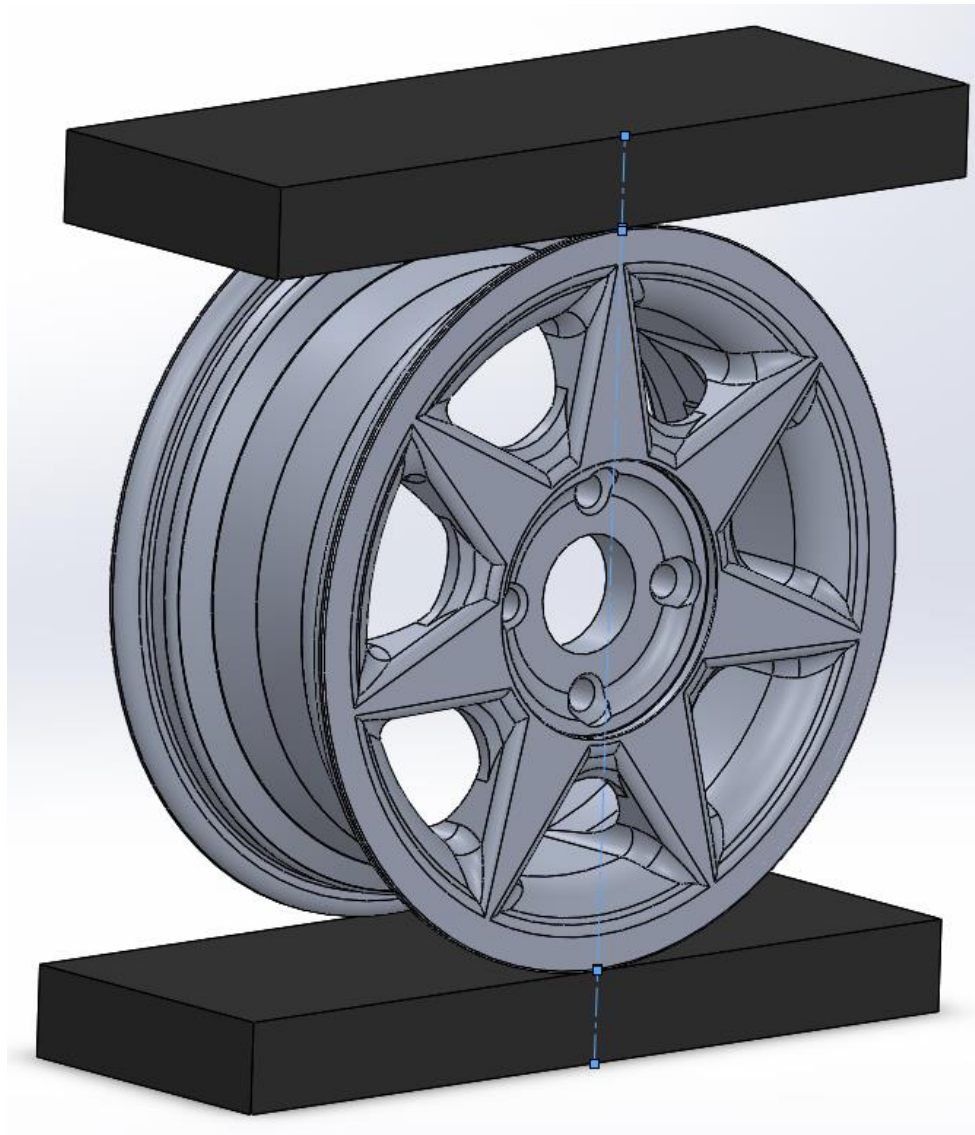


Figure 7.2 The complete assembly for the compression test

With the assembly completed the author could now setup the study. A static study was selected and meshes were applied to all the bodies (See Figure 7.3) This was the finest mesh that the software would allow.

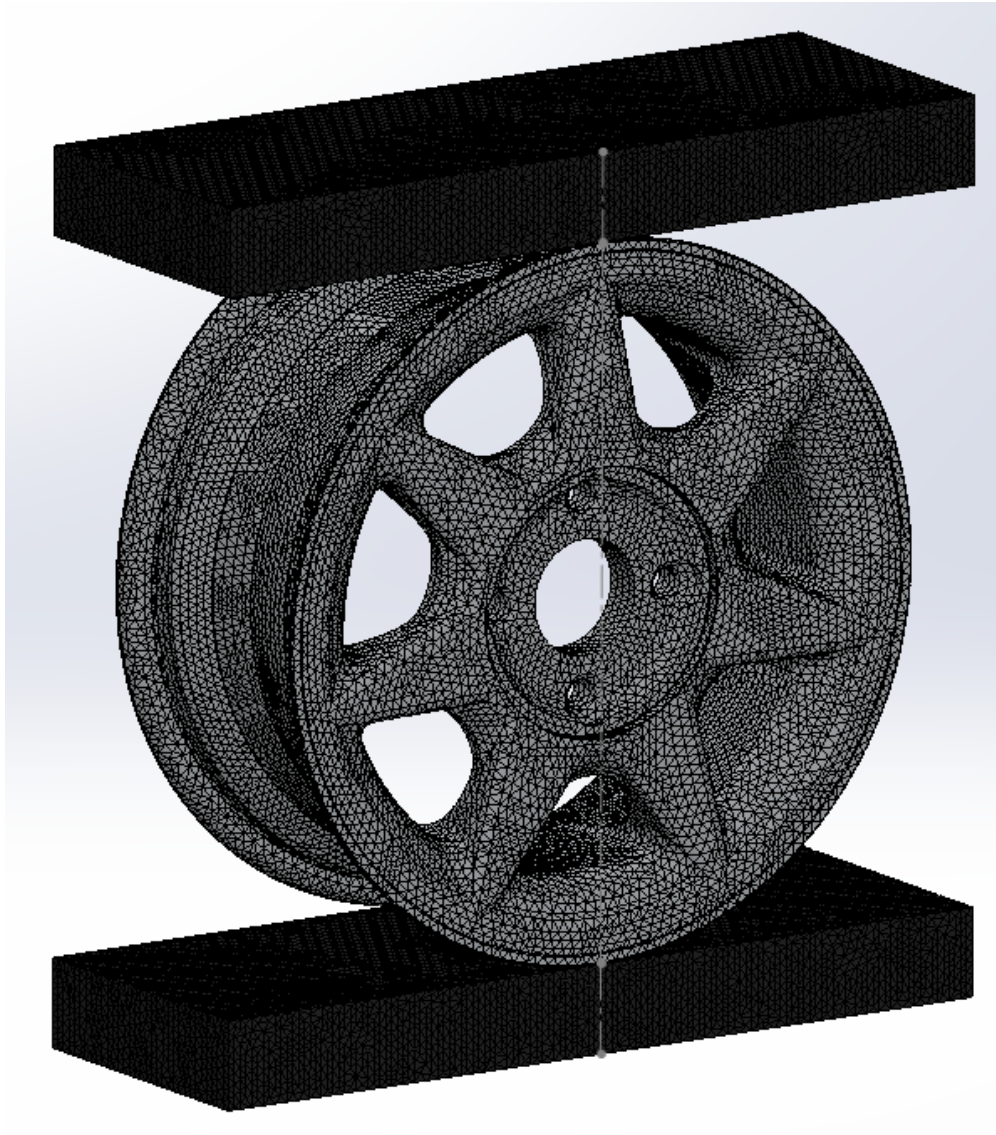


Figure 7.3 Meshes applied to all the bodies

Vertical forces were then applied to the bottom face of the top plate, in a vertical downward direction. These forces would exactly match the forces experienced during live testing. The author also used a fixture on all sides of the bottom plate to keep it in position. We can see these forces and fixtures in Figure 7.4.

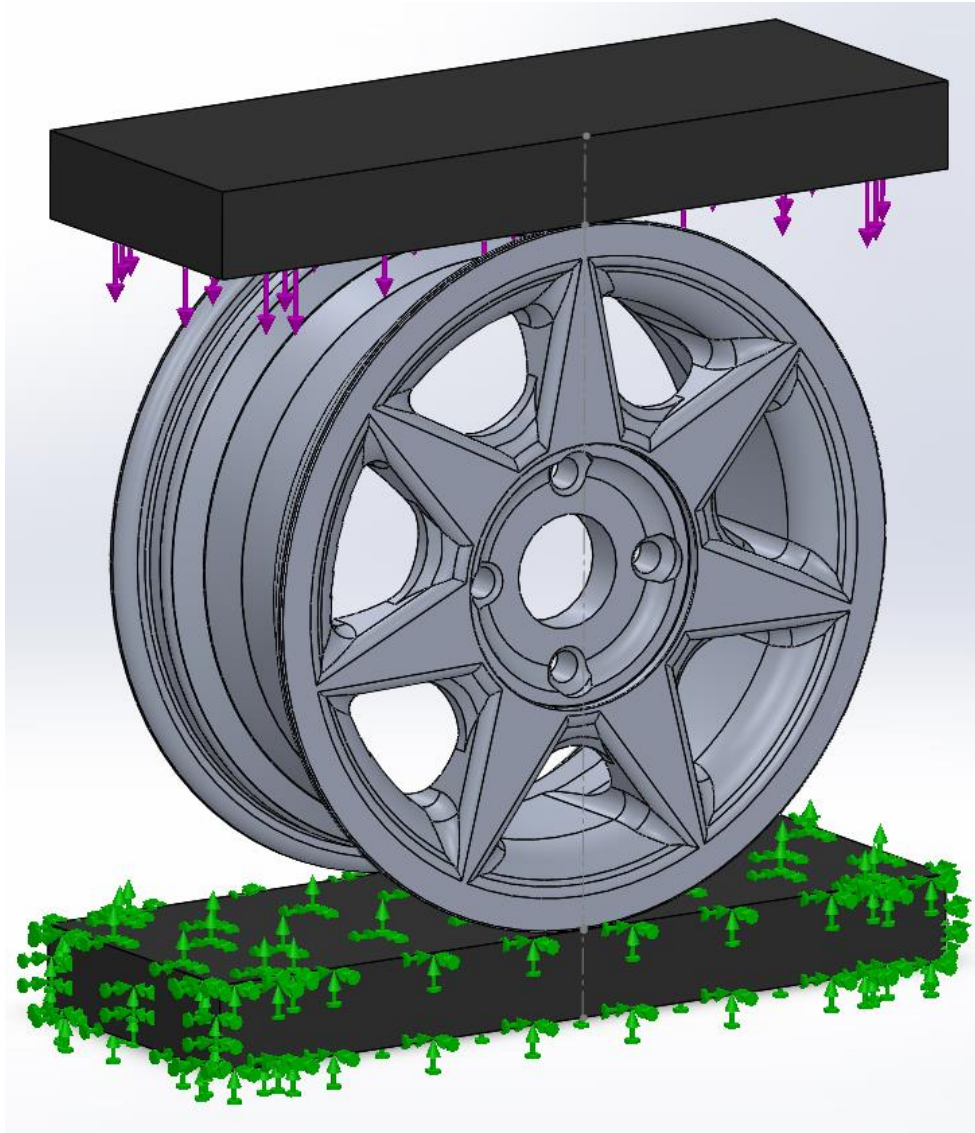


Figure 7.4 Image showing forces and fixtures acting on the assembly

This completes the setup for this study.

7.2.1 Failed Setups

When first attempting to replicate this test, the authors methods were over-complicated and failed as a result. Figure 7.5 shows an example of one of the failed methods. From this image we can see that the bottom plate does not represent the real scenario. Other problems encountered were issues setting up boundary conditions and contact conditions.

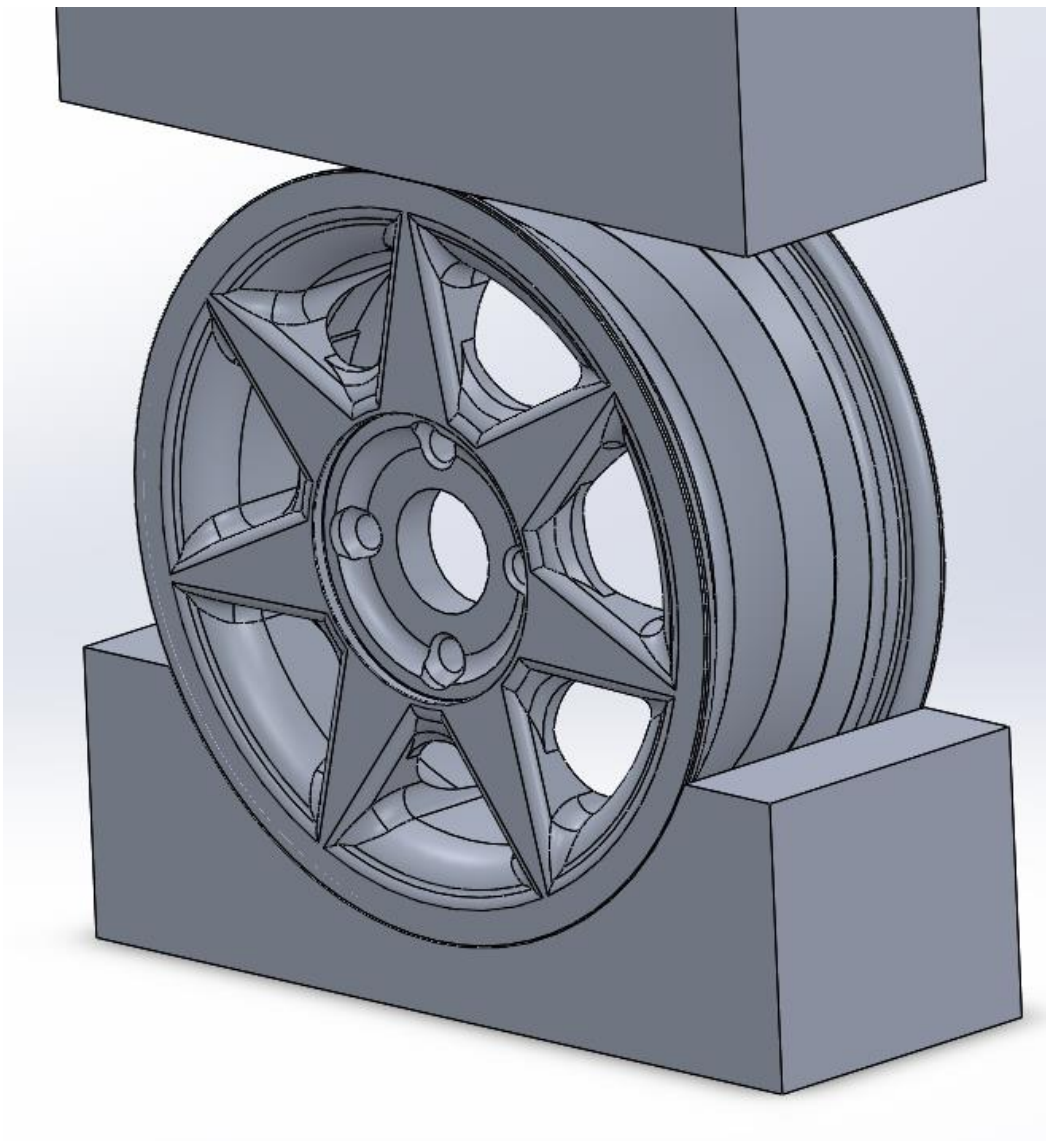


Figure 7.5 One of the failed setup attempts

7.2.2 Compression Study Results

For each of the runs the study produced results indicating displacement, stress and strain. Figures 7.6 – 7.8 shows examples of these results.

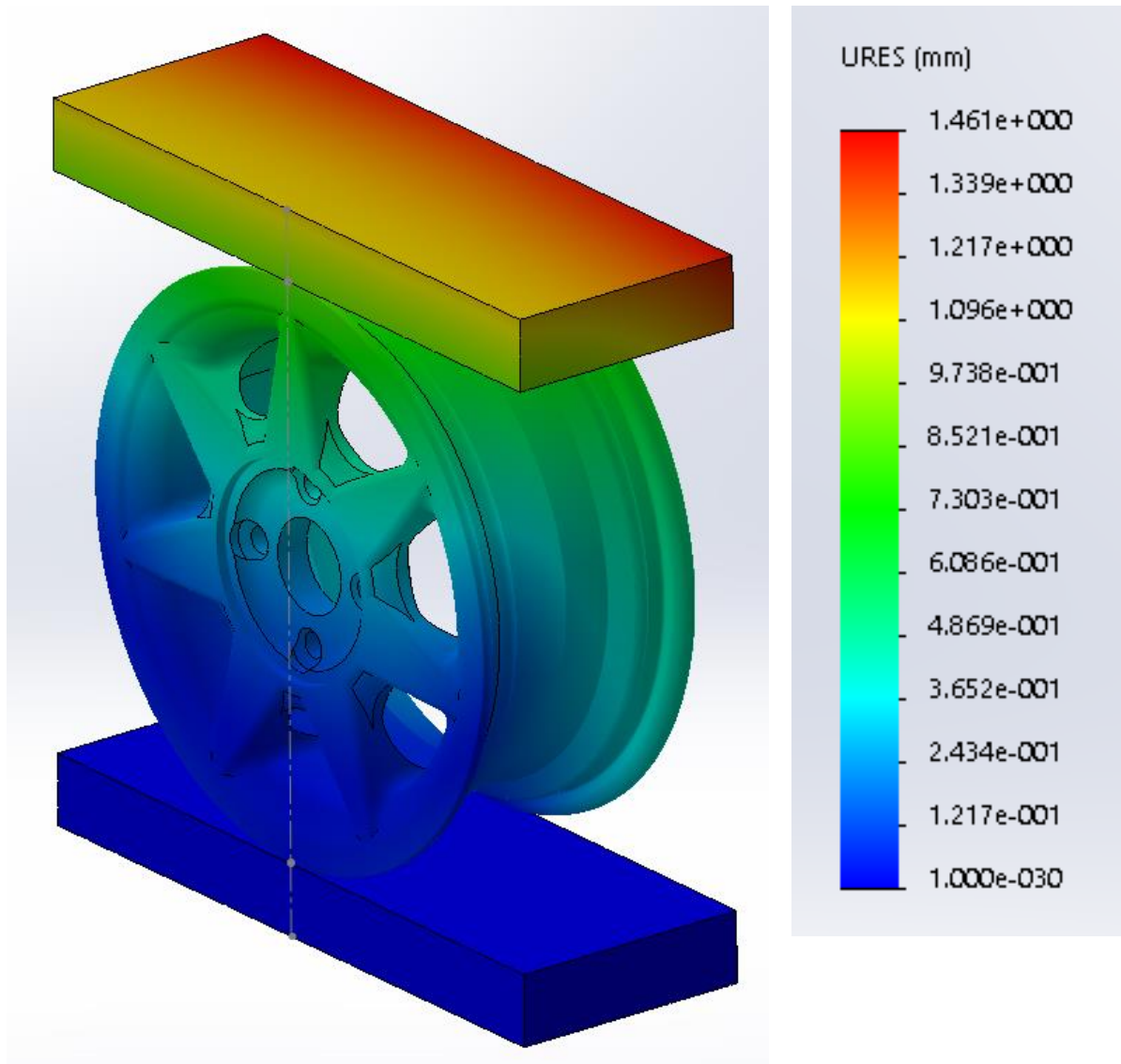


Figure 7.6 An example of the displacement results for the original model wheel

Figure 7.6 shows the displacement of the wheel. The contour scale is suggesting an accurate representation of what should be happening. We would expect to see the most displacement at the rear of the wheel where there is less support.

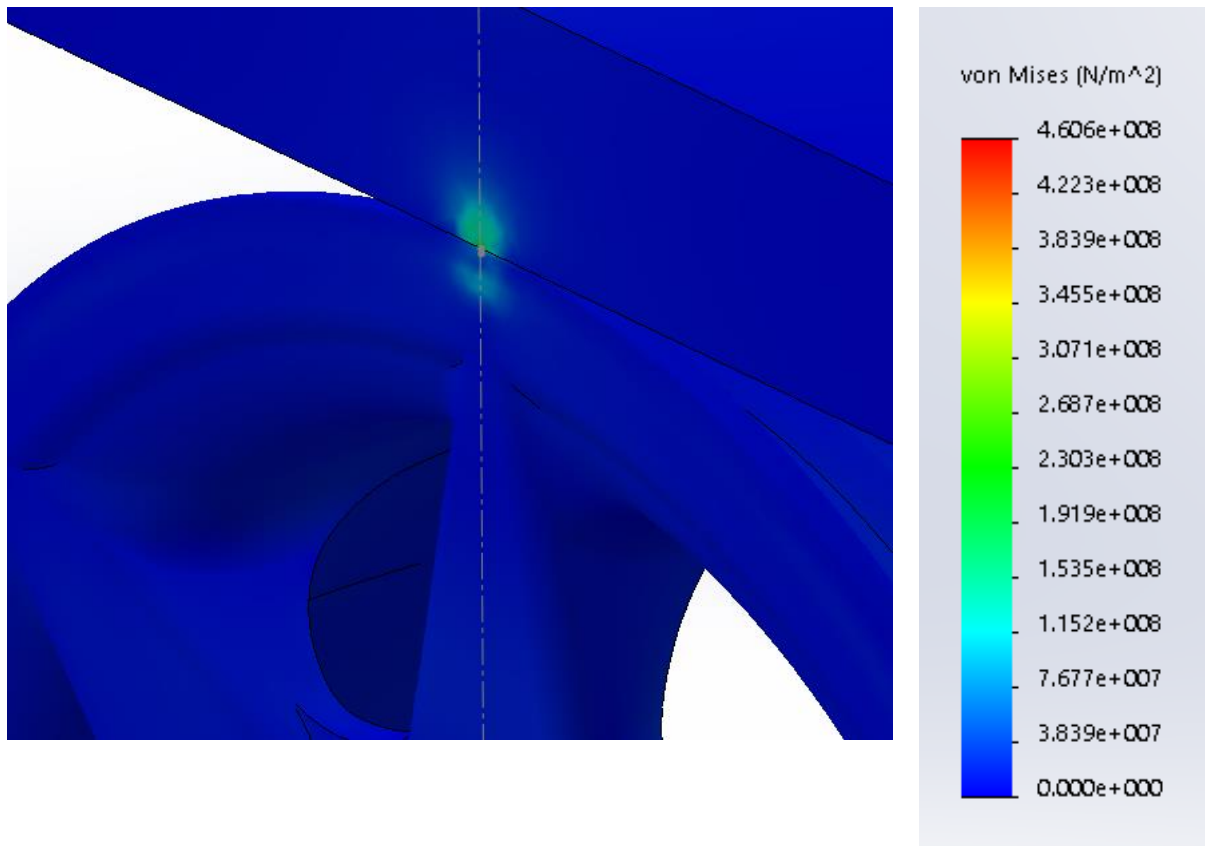


Figure 7.7 An example of the stress results

Figure 7.7 shows the stress highest concentration. This occurs, as expected, at the contact of the wheel and press. With the strain showing a similar pattern to the stress.

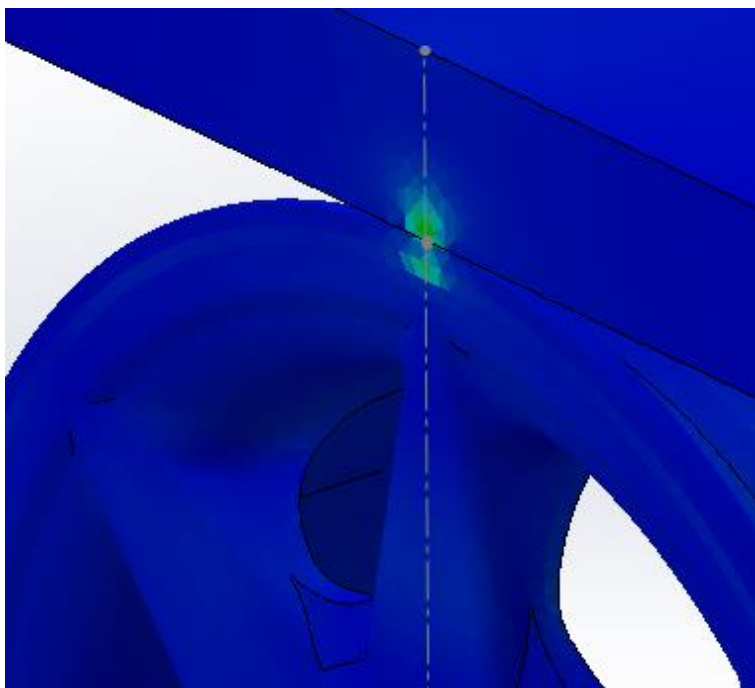


Figure 7.8 An example of the strain results

After recreating all the live tests as FEA studies, the author compiled the data for comparison. We can see this in Table 7.1

Table 7.1 – FEA displacement results in comparison to live testing results

Wheel

2 11 kg

Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Solidworks Displacement (mm)	"+"- (mm)	%
1	10.02	0	0.6	?	200.4	-	-	-
2	10.06	?	2.7	?	201.2	-	-	-
3	10.21	2.5	3.7	1.2	204.2	1.4	0.2	16.67

Wheel

3 11 Kg

Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Solidworks Displacement (mm)	"+"- (mm)	%
1	10.23	0	1.3	1.3	204.6	1.4	0.1	7.692
2	10.18	1.1	2.4	1.3	203.6	1.4	0.1	7.692

Wheel

4 11 kg

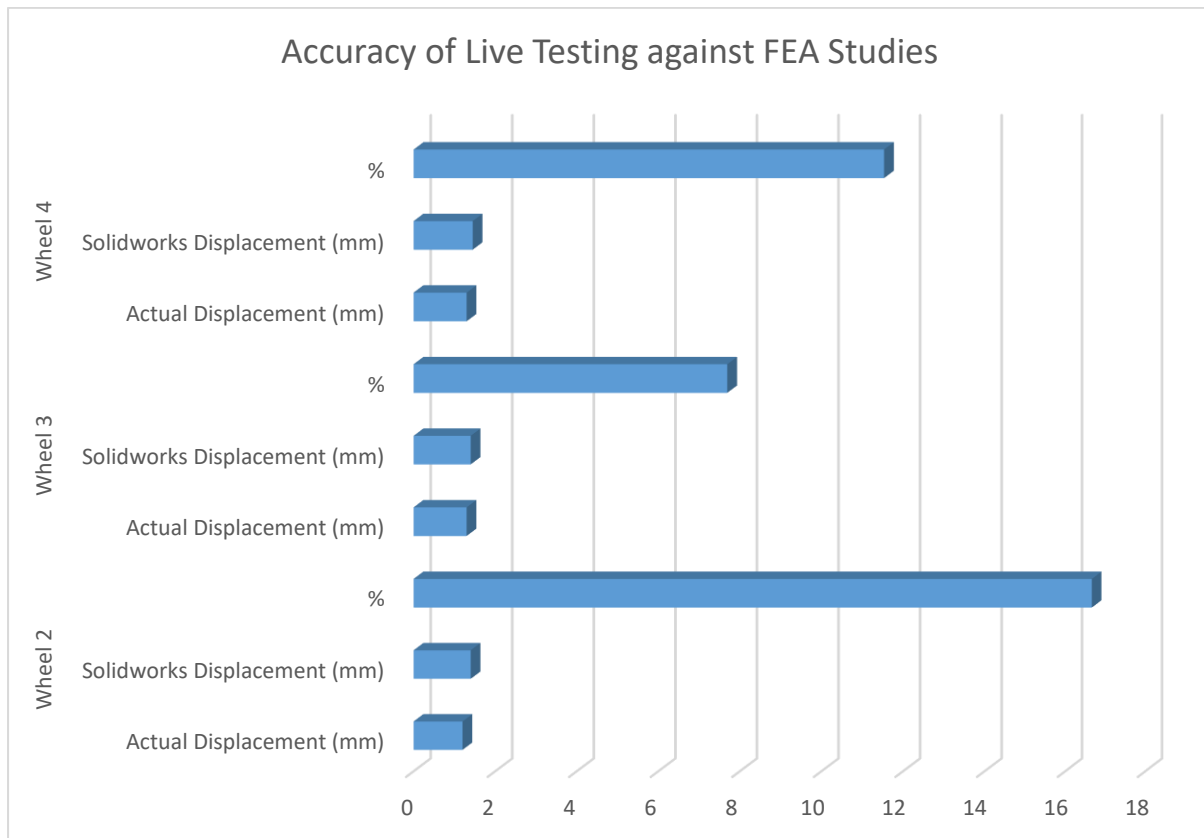
Test	Force (kN)	Pre-load Displacement (mm)	Resultant Displacement (mm)	Actual Displacement (mm)	UTS (N/mm ²)	Solidworks Displacement (mm)	"+"- (mm)	%
1	10.64	0	1.3	1.3	212.8	1.45	0.15	11.54

We can see from Table 7.1 that our Actual displacement figures from live testing are on average only 0.1mm off our FEA model. As previously stated the accuracy of the press is to 0.1mm, so there is a chance it could be more accurate. I believe the larger difference in Wheel 2 is due to the wheel being fatigued from the first two incorrectly setup tests. Wheels

3 and 4 are consistent with a 1.3mm displacement. Discounting Wheel 2 would give an accuracy of the FEA model of between 7.5-11.5%

Figure 7.9 Illustrates the accuracy of these results.

Figure 7.9 Accuracy of results for Live Testing against FEA Studies



7.3 Torsional Study

7.3.1 Calculating Wheel Torque at braking

Now we have shown how accurate the FEA model is, we can now perform a Torsional Study. Before setting up the torsional study, the author needed to calculate an approximate maximum torque the wheel would be under during braking. We will be assuming that it takes the vehicle 5 seconds to brake from its maximum speed of 44.7m/s to 0 in 5 seconds. Equation 6 on the next page, gives us the torque of one wheel under these conditions.

7.3.1.1 Nomenclature

a = acceleration (m/s²)

u = initial velocity (m/s) = 0

v = final velocity (m/s) = 44.7

t = time (s) = 5

m = vehicle mass (kg)

T = torque (Nm)

r = radius of wheel (m)

F = force (N)

7.3.1 Cont.

$$m = 1000 \text{ vehicle mass} + (4 * 80) \text{ 4 passengers} = 1320 \text{ kg} \text{ Equation 1}$$

$$r = \frac{d}{2} = 0.2005 \text{ m} \text{ Equation 2}$$

$$v = u + at$$

$$44.7 = a(5)$$

$$a = \frac{44.7}{5} = 8.94 \text{ m/s}^2 \text{ Equation 3}$$

$$F = ma$$

$$F = 1320(8.94) = 11800 \text{ N} \text{ Equation 4}$$

$$T = F * r = 11800(0.2005) = 2365.9 \text{ Nm} \text{ Equation 5}$$

$$T_{\text{front wheel}} = \frac{2365.9(0.6) \text{ front mass dist.}}{2} = 709.77 \text{ Nm} \text{ Equation 6}$$

Zammit S.J. (1987)

7.3.2 Setting up Torsional Study

Firstly, the author needed to construct a simple mount for the wheel to sit on. We can see this mount in Figure 7.10.

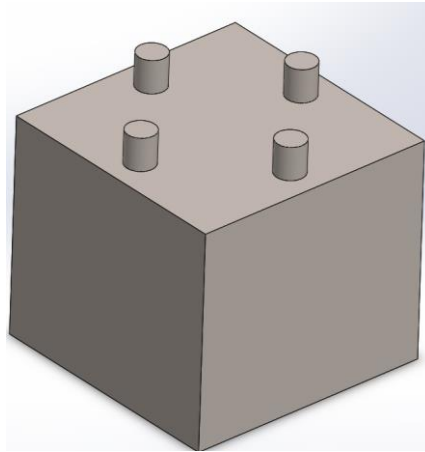


Figure 7.10 – Torsional study mount

As done with the previous compression study, we then assemble the wheel to the mount by mating the bolt holes to the mount extrusions. We see this in Figure 7.11

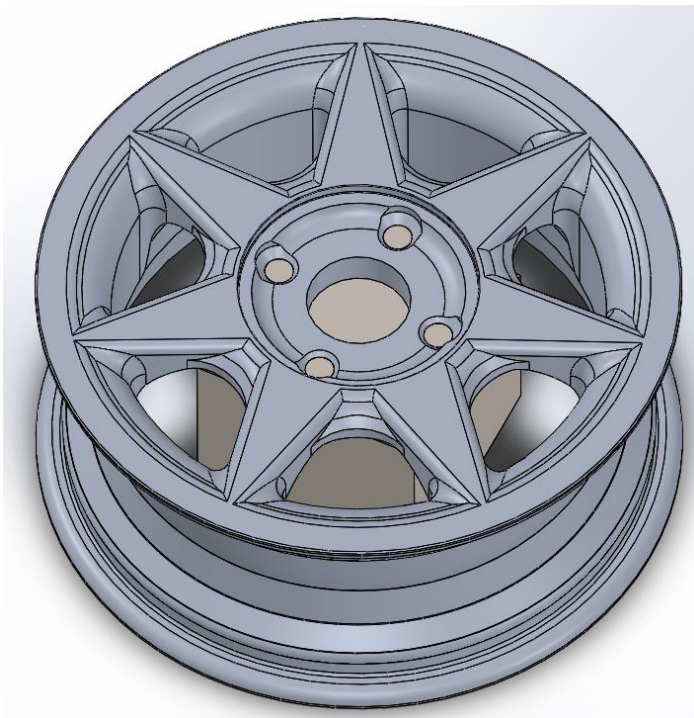


Figure 7.11 – Torsional study assembly

As before we apply the boundary conditions and mesh. The mount is fixed from all sides, but this time a torque is applied to the outside of the rim using the brake force calculated in equation 6 (See Figure 7.12) This concludes the setup of the study.

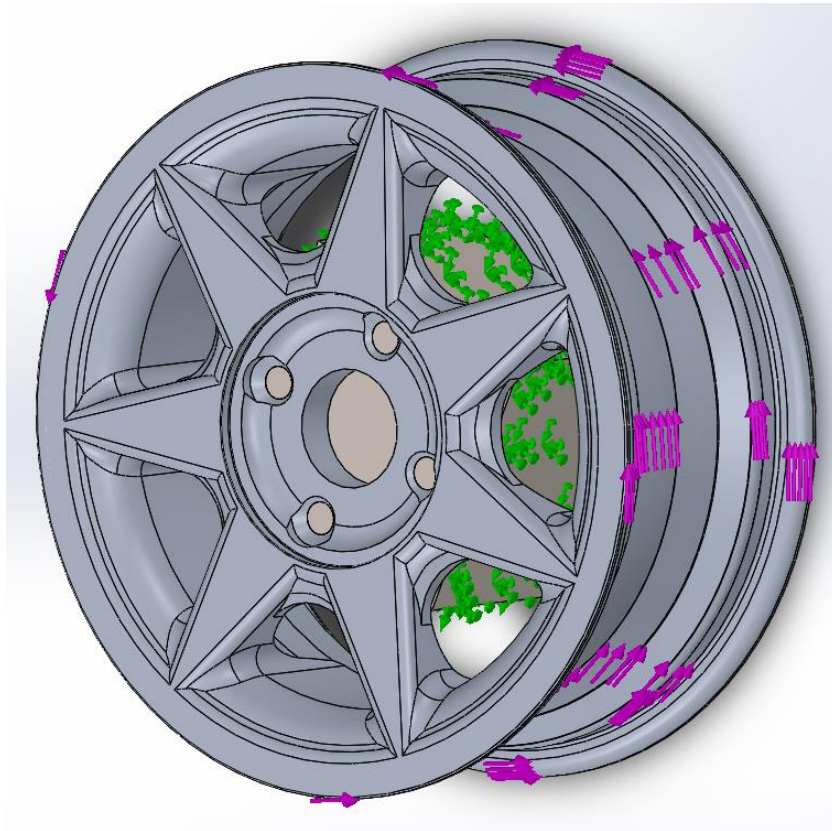


Figure 7.12 – Image showing fixtures and torque force applied to wheel

7.3.3 Torsional Study Results

As before this study produced results for displacement, stress and strain.

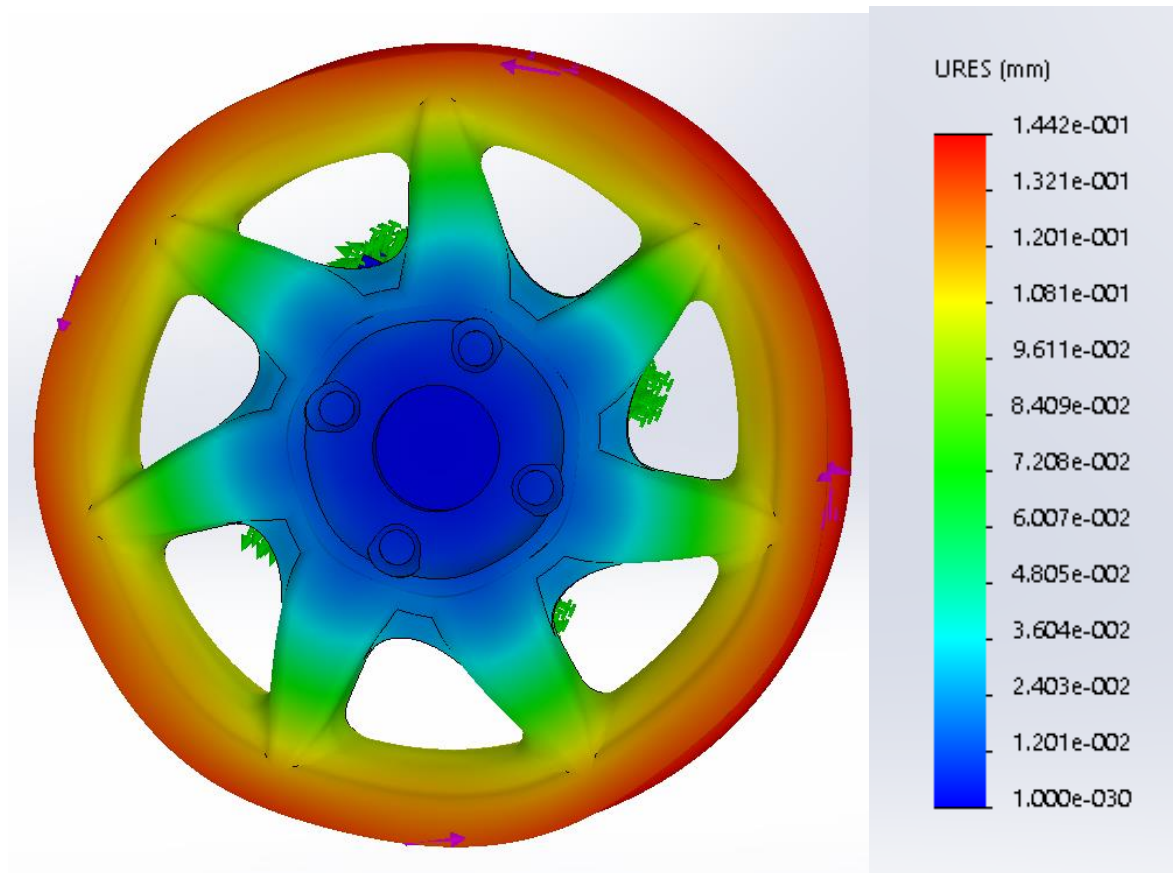


Figure 7.13 – Torsional Displacement of Wheel

We can see from Figure 7.13 a torsional displacement of 0.1442mm. Figures 7.14 and 7.15 show stress concentrations around the spokes where the geometry radius is minimal.

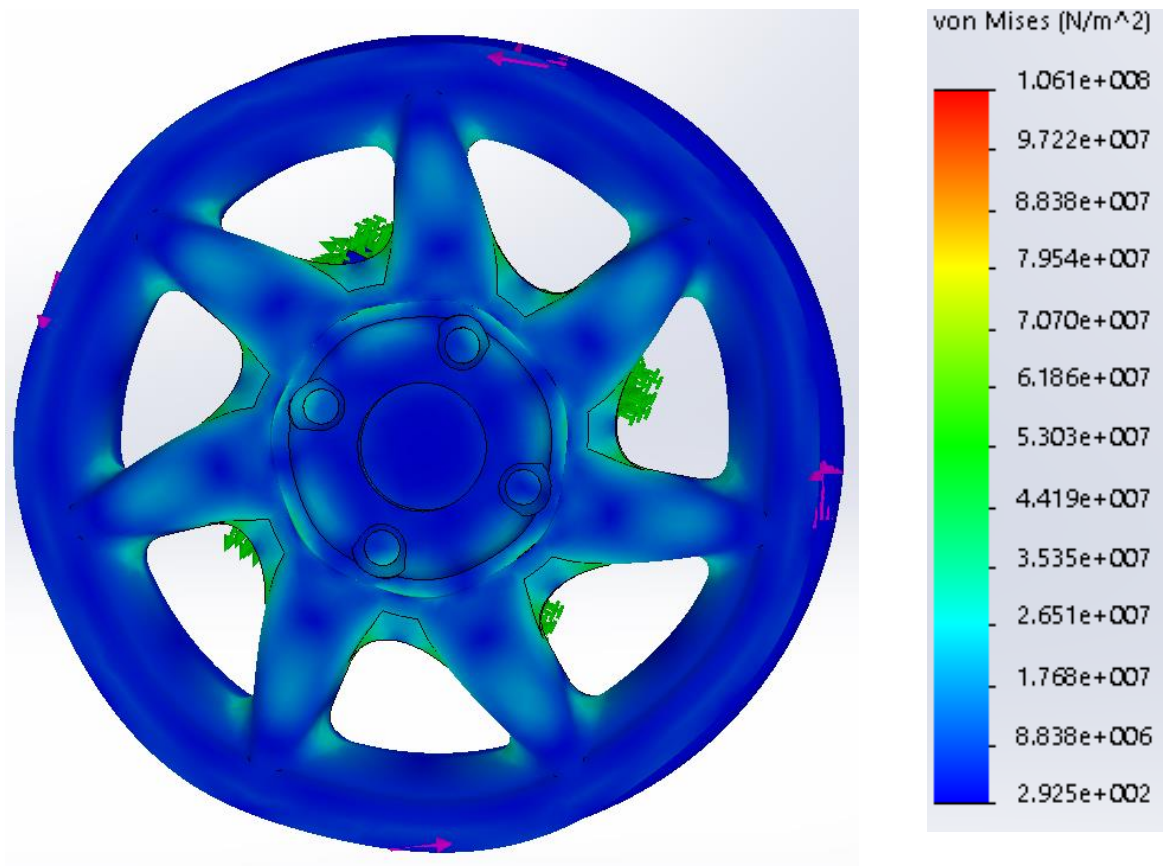


Figure 7.14 – Torsional Stress on Wheel

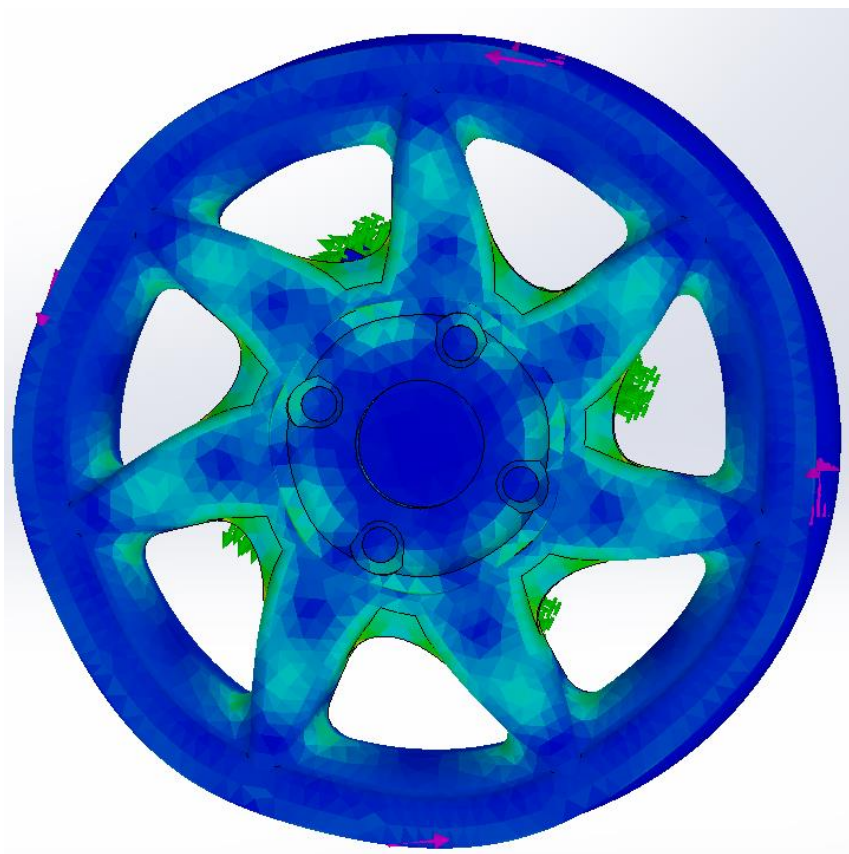


Figure 7.15 – Torsional Strain on Wheel

8. Optimisations

8.1 Material Selection

From Section 4.4 Material Research, the author decided to select the ELG Carbon Fibre pellets to base the optimisation on.

8.2 Geometry Selection

When looking to make improvements to an alloy wheel geometry the only real areas that can be influenced are the spokes and the area under the rim profile. To get an idea of the figure that we could reduce a spoke too, we will look at turning a spoke into a thin profile with rectangles. We should then be able to calculate a new breadth for the spoke.

8.2.1 Nomenclature

I_y = Moment of Inertia (y plane) (m^4)

b = breadth of spoke (m) (Original Wheel = 0.048m)

h = height of spoke (m) (Original Wheel = 0.10686m)

E = Young's Modulus (N/m^2) (Original Wheel = $6.9 \times 10^{10} N/m^2$)

y = deflection at any position



Figure 8.1 – Drawing of spoke for reference

8.2.2 Calculating new breadth of spoke

$$Iy = \frac{bh^3}{12} = \frac{0.048(0.10686)^3}{12} = 4.88 * 10^{-6}m^4 \text{ Equation 7}$$

$$EI = y = 69 * 10^9(4.88 * 10^{-6}) = 336720 \text{ Equation 8}$$

Calculate new I value (Put in E for Carbon Fibre) Matweb (2017)

$$I = \frac{y}{E} = \frac{336720}{2.28*10^{11}} = 1.47 * 10^{-6}m^4 \text{ Equation 9}$$

∴ For new breadth (h needs to stay the same)

$$Iy = \frac{bh^3}{12} \text{ Equation 7}$$

$$1.47 * 10^{-6} = \frac{b(0.10686)^3}{12} \text{ Equation 7}$$

$$b = \frac{1.47*10^{-6}(12)}{0.10686^3} = 0.01445m = 14.45mm \text{ Equation 10}$$

(Gere. J.M., 2001)

Equation 10 means I should be able to reduce the breadth of the spokes from 48mm to 14.45mm for the wheel to perform the same in that one area.

8.2.3 Modifications to Original Model

When modifying the original geometry, the first modification that took place was a reduction to the spoke breadth to 10mm. The reasoning for going lower than the calculated estimate is that only the spoke area is considered in that calculation. The rest of the wheel will also be employed in withstanding stress, strains and deflections. The reasoning for not going lower than 10mm is that the results for 10mm are in line with what increases in performance other

manufacturers are achieving. After making the reduction to 10mm the software informed me that some of the fillets and chamfers could not be produced due to the lack of area. I decided to let the spokes dictate the design and therefore removed them. Extra material was also removed from the rear recesses of the hub. (See Figure 8.2) Final render of this wheel can be seen in Appendix 3b.



Figure 8.2 – Front and Rear view of new Geometry

8.3 Compression and Tension Results

All test on the optimised wheel were carried out with the same study setup as the original model.

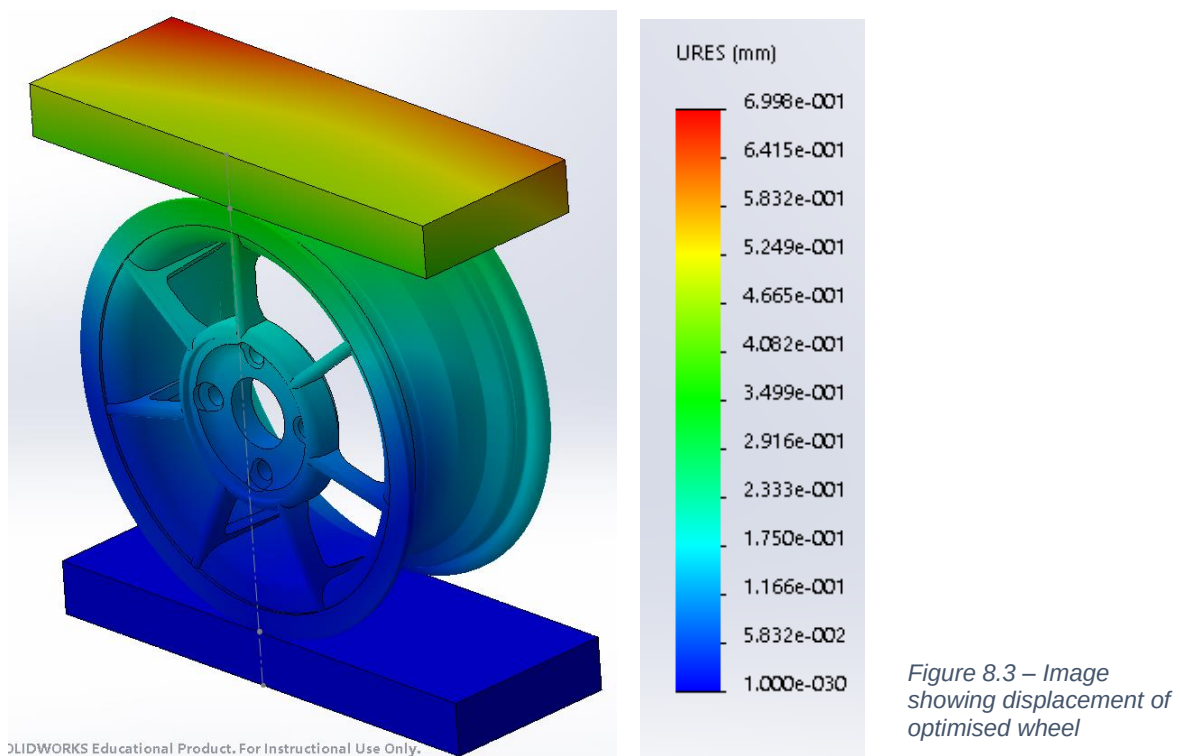
8.3.1 Compression Study

Table 8.1 – Table of results for compression test of optimised design

New Wheel Design 2
- Carbon Fibre
Against Original
Wheel 3 Test 1

Force (kN)	Original Wheel 3 Displacement (mm)	Design 1 Displacement (mm)	"+" "-" (mm)	%	Original Wheel Mass (kg)	Design 1 Mass (kg)	"+" "-" (kg)	%
10.23	1.4	0.7	-0.7	-50.00	11	6.42	-4.58	-41.63636364

We can see from these results that the wheel was only displaced 0.7mm which was half of the original design. This weight also weights 41% less than the original wheel. Figure 8.3 – 8.5 shows images of the displacement, stress and strain.



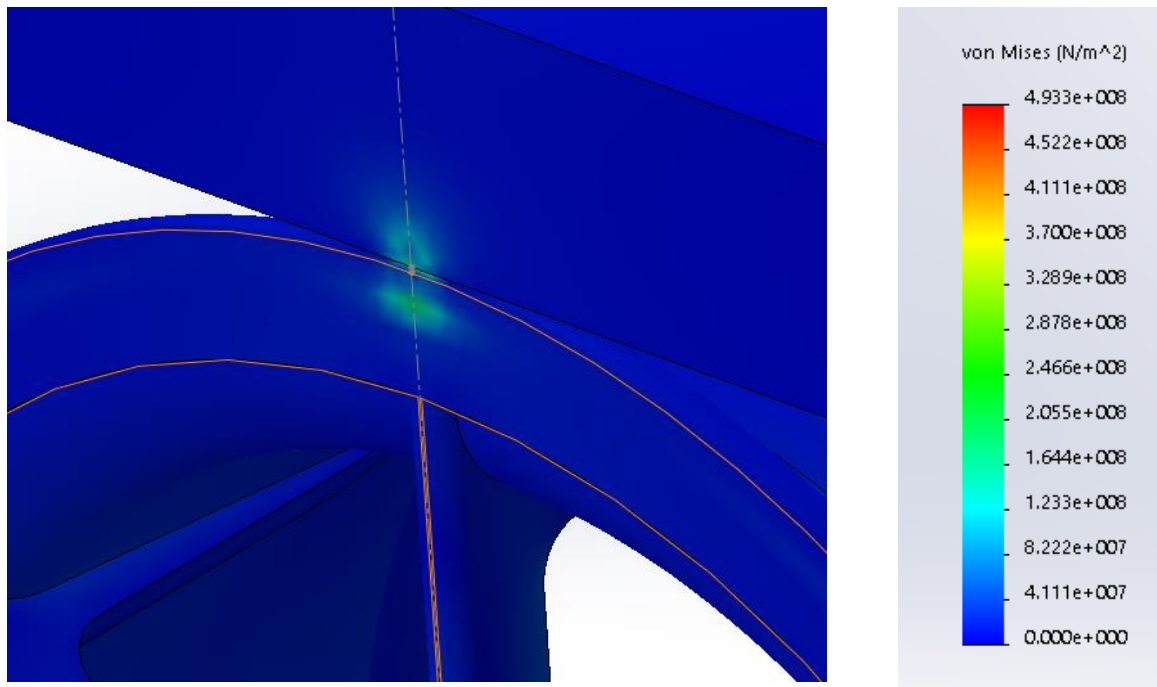


Figure 8.4 – Image of stress concentration for optimised wheel

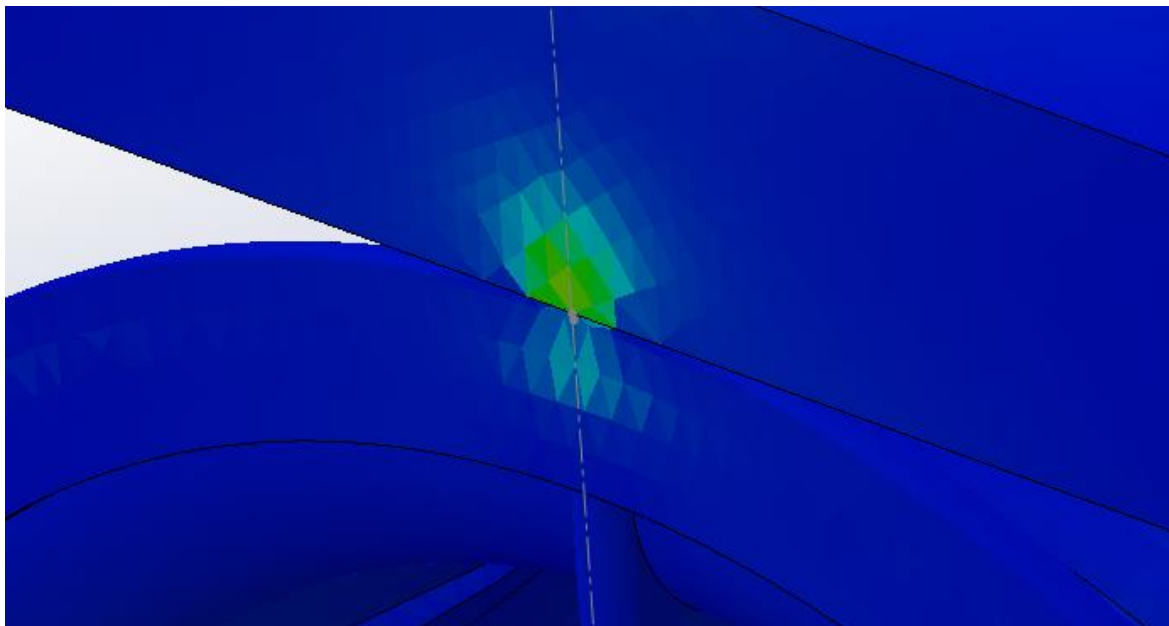


Figure 8.5 – Image of strain concentration on optimised wheel

8.3.2 Torsional Study

Table 8.2 Table of results for torsional study for the optimised wheel

Torsional Test		Displacement (mm)	+/- (mm)	%
Original Wheel		0.144	-	-
Wheel Design 2		0.155	0.011	7.638889

We can see from this table that the optimized design is approximately 7% worse than the original design. Even though this is the case this is only a difference of 0.011mm. The author theorises that this is due to the thinner spoke and lose of fillets at the ends of the spokes, leading to higher stress concentrations. Images 8.6 – 8.8 show the displacement, stress and strain of the wheel.

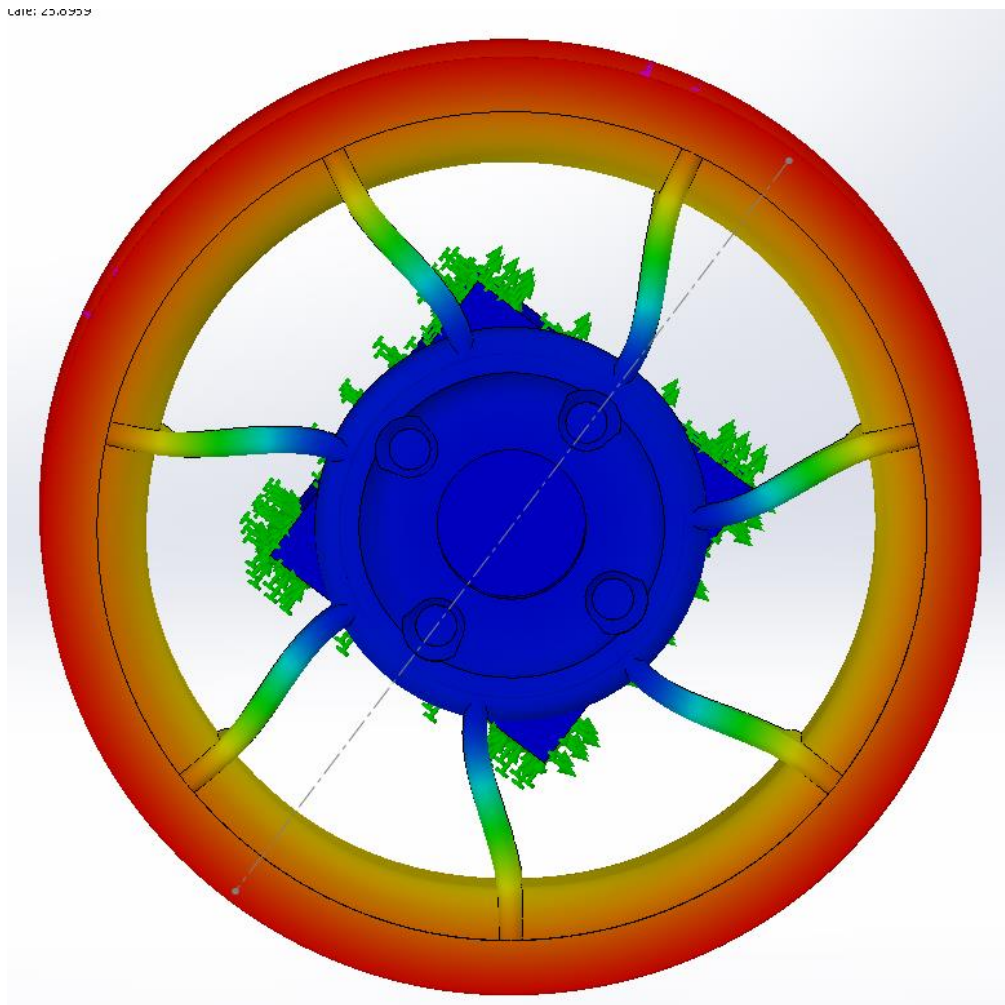


Figure 8.6 – Torsional displacement of optimised design

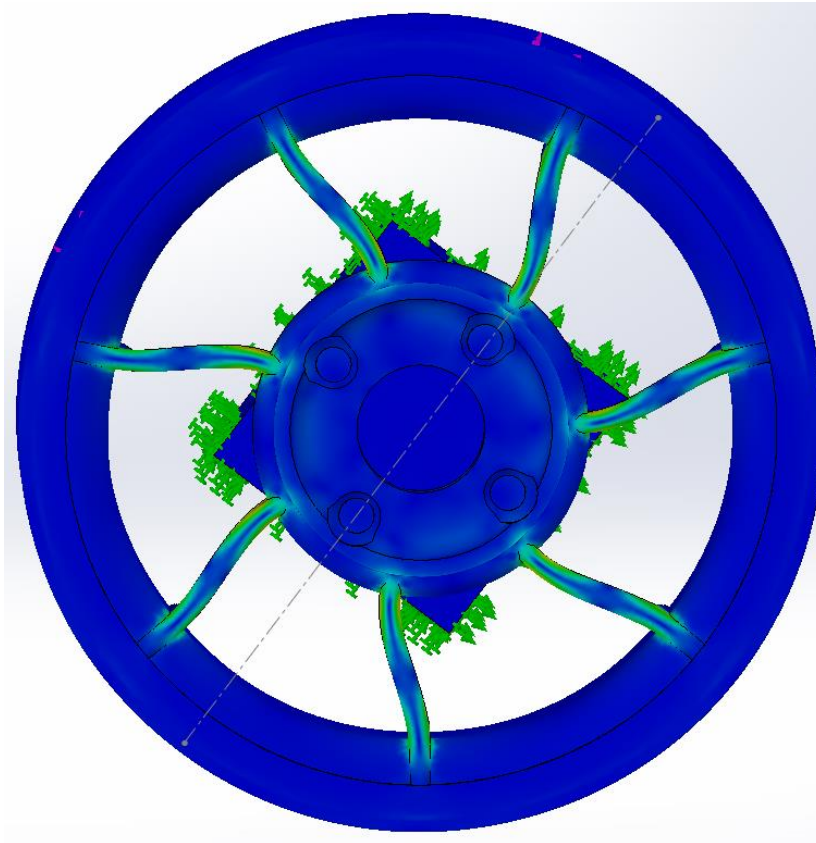


Figure 8.7 Torsional stresses in optimised design

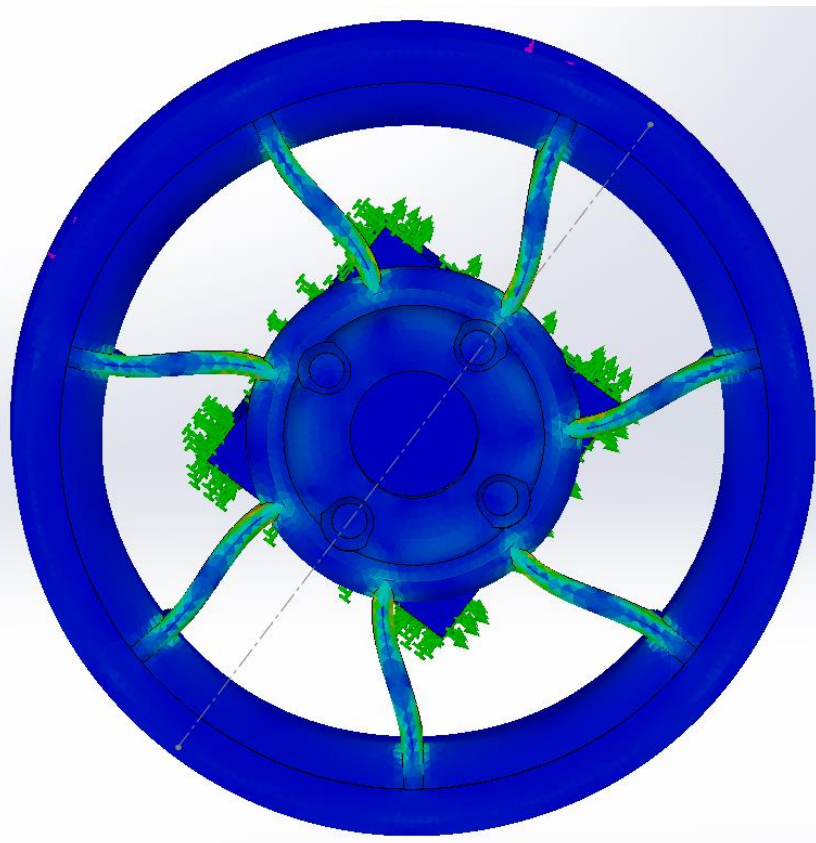


Figure 8.8 Torsional strains in optimised design

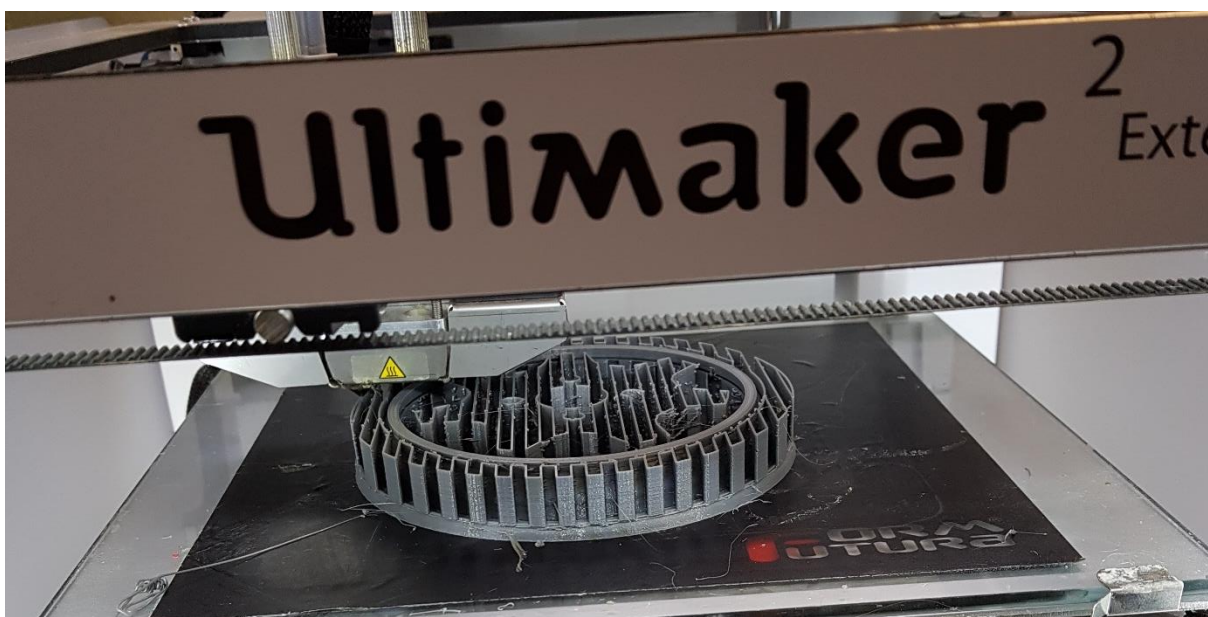
9. Prototyping designs via 3D Printer

The author decided to get both the original wheel and the optimised wheel 3D printed. He decided to do this as he believed it would give him a greater sense of the shape of the new optimisation. Also, another comparison of how accurate the original model was in comparison to the physical wheel.

After speaking to David Cooper, a technician at the university, the author found that it would only require a small investment of £50 to buy the material. He would not need to spend any time monitoring the build as only David would be authorised to use the 3D printer. Therefore, the author found this to be a worthwhile investment. Figure 9.1 shows the finished models.



Figure 9.1 – Image showing 3D printed models and Ultimaker2 creating original model



10. Future work to be considered

The author feels that this project has the potential to be an ongoing investigation. With the content in this report, a metaphorical line was drawn to give the project a conclusive result. This section will discuss the work that has been missed in this report and that the author would have liked to investigate, if more time was available.

10.1 Optimisation

Quite late on in the project the author had discovered that he had developed his initial optimisations using a CAD methodology, rather than an FEA methodology. There is topology software available that can analyse models and with a set of conditions provide a graphical view of what material should be left. This would have given the user a greater indication of what material could have been removed from the areas underneath the rim profile. This would have given a more accurate figure for spoke reduction as it takes the wheel into consideration. Could there have been a hollow section here, filled with a composite material?

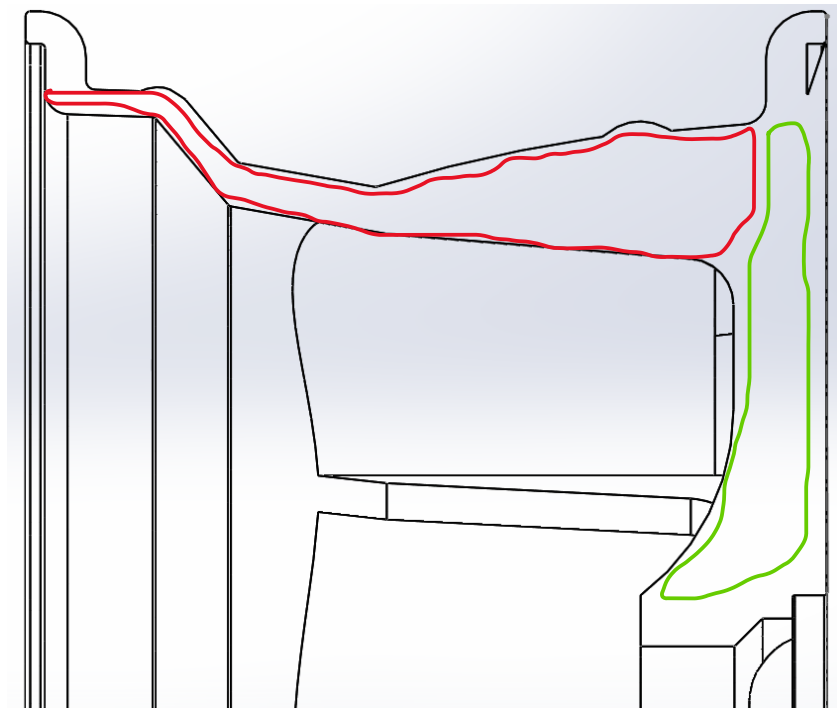


Figure 10.1 – A diagram showing the wheels cross section. The Red area highlights the possible reduction in material for the rim profile and the Green area shows the area for the spoke.

10.2 Further Testing

There could be more validation on the optimised wheel. The main argument against the use of carbon fibre is the question of its durability. The author would have liked to have conducted a fatigue analysis on the optimised model, with the hope in further justifying its choice. If this model presented good results, an ideal scenario would have been to create a physical prototype of the optimisation and take it to a testing facility to validate the results.

Without a budget of this magnitude, other tests as previously discussed could also be carried out on the FEA software. One of these tests would be an impact test. A 3D scanner would have also been more accurate in creating the original 3D model.

10.3 Materials

There is a vast supply of new materials and techniques that could be applied to this project. The author would have liked to study plastic composites and how they may be used in this function.

10.4 Costings

The author believes a costing section would have helped percept the performance increase against cost. When considering an economical view of the product, it would have been interesting to know what fuel savings would be achieved or how much could be saved/lost when manufacturing.

10.5 Performance

It would be interesting to know what the optimisations have made to the performance of the vehicle. The author could apply the weight changes to a vehicle model and conduct a vehicle dynamic analysis to see differences in performance. Telemetry software would be useful in comparing new wheel accelerations/speeds.

11. Conclusions

From conducting live testing on the original wheel and comparing the results against an FEA compression test, we found the FEA model to be within approximately 7.5-11.5% accurate. This enable us to compare the original model with an optimised wheel with changes in material and geometry. Comparing the optimised wheel against the original, we found the wheel to be 4.5kg lighter (41% decrease) with the optimised wheel only weighing 6.4kg. In compression the wheel was twice as resistant. In torsion the optimised wheel performed 7% worse than the original, this worked out to be only 0.01mm.

The optimisation is promising but requires further validation to see how the wheel performs under a fatigue analysis. This exercise however shows this wheel should perform as well as the original in scenarios in which it does not sustain impacts. The author admits the optimisation carried out may not be its optimal design due to the methodology carried practised. Although he is confident that there appears to be large improvements made to the weight reduction of the wheel, that would indicate a clear performance increase of the vehicle.

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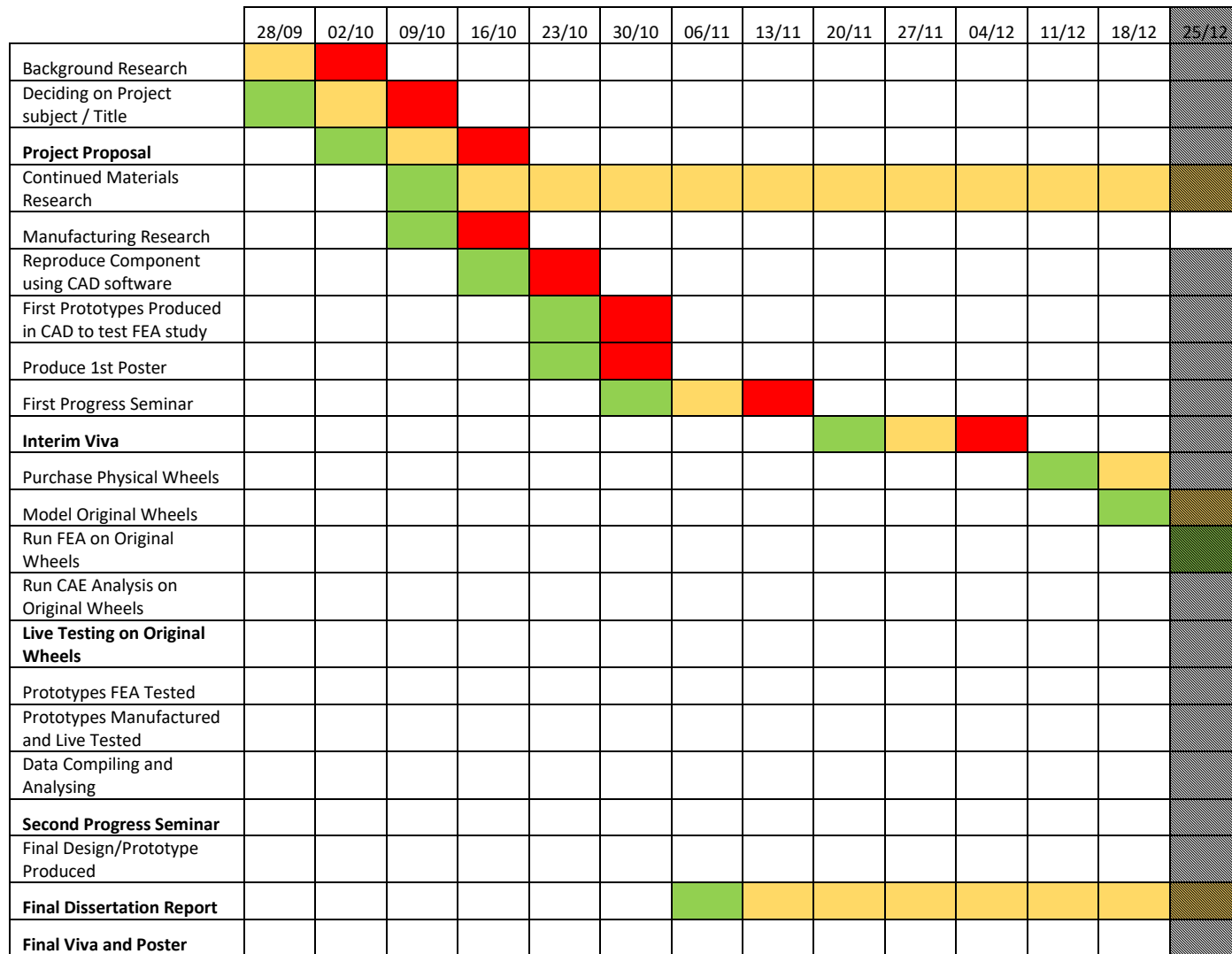
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Appendices

Appendix 1a - Gantt Chart (Sept – Dec '17)



Appendix 1b – Gantt Chart (Dec – May '18)

01/01	08/01	15/01	22/01	29/01	05/02	12/02	19/02	26/02	05/03	12/03	19/03	26/03	02/04	09/04	16/04	23/04	30/04	
																		Background Research
																		Deciding on Project subject / Title
																		Project Proposal
																		Continued Materials Research
																		Manufacturing Research
																		Reproduce Component using CAD software
																		First Prototypes Produced in CAD to test FEA study
																		Produce 1st Poster
																		First Progress Seminar
																		Interim Viva
																		Purchase Physical Wheels
																		Model Original Wheels
																		Run FEA on Original Wheels
																		Run CAE Analysis on Original Wheels
																		Live Testing on Original Wheels
																		Prototypes FEA Tested
																		Prototypes Manufactured and Live Tested
																		Data Compiling and Analysing
																		Second Progress Seminar
																		Final Design/Prototype Produced
																		Final Dissertation Report
																		Final Viva and Poster

Appendix 2a – Kaizen, Root cause analysis

Cause			Effect
People	Method	Measurement	Diminished Project
Family commitments	Poor prioritisation	Not tracking progress	
Friends	Poorly defined goals	No short-term goals	
Project supervisor unavailable	Poor time planning	Lack of accountability	
Lack of communication to Supervisor	Wasting time by repeating bad work	Not updating progress	
Possibility of being let down on meetings	Dealing with unforeseen/errors in work	Not tracking meeting/minutes	
Transportation breaks down	Electronic distractions	Lack of stationary equipment/Paper	
University equipment broken/not booked	Noisy Family/Children	Materials not ordered in time	
USB stick failure	Noisy Environment	Correct amount of material ordered	
Internet connection	Uncomfortable (Hot/Cold/Seating)	Save materials where possible (e.g. meeting templates)	
PC breaks down	Food and Drink availability	Defected material received	
Machine	Environment	Materials	

Appendix 2bi – Kaizen countermeasure matrix

	Countermeasures	Importance	Urgency	Difficulty	Time Consumption	Resource Availability	Feasibility
People	Plan family events in advance, prioritise work	2	3	3	3	3	14
	Plan time with friends in advance, prioritise work	2	3	3	3	3	14
	Use various methods of contact. Have backup supervisor	1	2	2	2	2	9
	Set up a set weekly meeting to maintain contact	3	3	3	3	3	15
	Make use of time - Backup Supervisor, time for other work	3	3	2	2	2	12
Machine	Make arrangements for colleague to provide transport / funds for repairs/taxi	1	2	2	2	1	8
	Find alternative backup equipment. Book time for equipment.	2	2	2	1	1	8
	Make daily backup of work on other devices.	3	3	3	3	3	15
	Make sure travel is available from home to university if internet cannot be fixed that day	2	1	1	1	2	7
	Backup Funds available for repairs. Use university computers for in interim	1	1	2	3	1	8
Method	Create time management strategies to prioritise workload	3	3	1	1	3	11
	Collaborate with supervisor and spend time assessing the quality of the goals	3	3	1	2	2	11
	Create and maintain a schedule that accommodates workload	3	3	2	2	3	13
	Learn from mistakes to prevent repeat problems - Saihatsu boshi	2	1	3	3	3	12
	Stop process. Evaluate mistake with supervisor and make adjustments	2	3	1	2	3	11

Scale	Meaning
3	High Priority, Easy to do
2	Moderate
1	Low Priority, Hard to do

Appendix 2bii – Kaizen countermeasure matrix

	Countermeasures	Importance	Urgency	Difficulty	Time Consumption	Resource Availability	Feasibility
Environment	Make myself accountable for distractions - use study, close doors, ear plugs	2	1	3	3	3	12
	Communicate importance of work with family. Arrange another workspace.	2	1	3	2	2	10
	Uni. can be noisy environment. Work from home study where possible	2	1	3	3	3	12
	Purchase comfortable/supportive: desk, chair, lamp	1	1	2	2	2	8
	Make sure workspace has food and drink availability	1	1	3	3	3	11
Measurement	Create/Update Gantt Chart with progress	3	2	2	2	3	12
	Create daily (shower) / weekly short-term goals	3	3	1	2	3	12
	Tell supervisor/family/colleagues about progress and what short term goals that will be done that day/week	1	1	3	3	3	11
	Create alarm reminders to ensure progress is updated	1	1	3	3	3	11
	Ensure meeting materials are available (Pen and Paper always in bag) and meeting forms are copied weekly	2	3	3	1	2	11
Materials	Purchase supplies when needed	2	3	2	2	2	11
	Plan what materials needed ahead of time and order early	3	2	2	2	3	12
	Communicate with technician how much material is needed. If some is remaining, sell onto other students	2	1	2	2	3	10
	Ask supervisor what materials have been left over from other projects. Ask supervisor for any spare meeting forms	2	1	3	2	3	11
	Plan material to be ordered early enough for replacement to be sent	2	1	3	3	3	12

Scale	Meaning
3	High Priority, Easy to do
2	Moderate
1	Low Priority, Hard to do

Appendix 3a – Original wheel final render



Appendix 3b – Optimised wheel final render

