ANALYSIS OF A CARBON FIBRE RIM

Student Formula

Bryan Uyttersprot

TAMPEREEN AMMATTIKORKEAKOULU

Tampere University of Applied Sciences

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Electromechanical Engineering

AUTHOR : Bryan Uyttersprot
Analysis of a Carbon Fibre Rim

Master's thesis 66 pages, appendices 14 pages
May 2015

———————————————————————————————————————

This master's thesis is within the context of a formula race competition between universities. The main goal is to replace the modern rims of the TAMK Student Formula car by lighter and more efficient rims.

To achieve this goal, important topics such as general rim design, tyre forces, tyre moments, strength of materials, fatigue and mechanical properties of carbon fibre were examined. Carbon fibre was applied because of its decent strength, weight and fatigue characteristics. Two possible rims were examined. The first design was a single piece carbon fibre rim and the second model was a multiple piece carbon fibre rim of which several parts of the modern design were reused. Both wheels were drawn in a 3D Cad software called *Inventor* and their strength was calculated by simulation software called *Ansys Workbench 15.0*. After modelling the rim, a suggestion was made to manufacture the rims. A 3D print of ABS was used to create the moulds. The vacuum bag moulding method was applied to fabricate both types of rims. The modern rim, the one-piece rim and the multiple piece carbon fibre rim were compared. The parameters were deformation, different kinds of stresses, weight and cost. Technical drawings and exploded views of different assemblies were attached to the appendices.

The result was that the multiple piece carbon fibre rim could be processed on short term. The single piece rims were considered to be a possible long term solution, because new wheel hubs were required for this rim.

———————————————————————————————————————

Key words: rim, carbon fibre, finite element analysis, Student Formula

CONTENTS

PICTURES

GRAPHS

TABLES

GLOSSARY

TAMK	Tampere University of Applied Sciences
CF	Carbon fibre
SAE	Society of Automotive Engineers
F_z	Normal force
F_y	Lateral force
F_x	Tractive force
M_z	Aligning torque
$M_{z,slip}$	Aligning torque due to slip
$M_{z,chamber}$	Aligning torque due to chamber
M_y	Rolling resistance
M_x	Overturning moment
k_z	Radial stiffness tyre
d_z	Tyre penetration
c_z	Radial damping factor tyre
v_z	Rate of change of tyre penetration
γ	Chamber angle
μ_s	Friction between tyre and road at low speed
a_{dec}	Maximum deceleration sport car
g	Gravitational constant
T	Torque of the engine
T'	Torque on one wheel
R	Radius of the rim
F_f	Friction force between rim and tyre
μ_r	Friction coefficient between rim and tyre
dx	Distance between centre point and point of action in x-direction in the contact area of the tyre
dy	Distance between centre point and point of action in y-direction in the contact area of the tyre
R_u	Radius of the tyre in contact with the road
R_t	Radius of the tyre
$\sigma_{VonMises}$	Von-Mises stress
σ_{zz}	In-plane stress

τ	Shear stress
E_x	Young's modulus in x-direction
E_y	Young's modulus in y-direction
E_z	Young's modulus in z-direction
G_{xy}	Shear modulus xy-plane
G_z	Shear modulus z-plane
v_{xy}	Poisson coefficient xy-plane
v_z	Poisson coefficient z-direction
$[\sigma]$	Stress matrix
$[D]$	Compliance matrix
$[\varepsilon]$	Strain matrix
d	Deformation
V	Volume
m	Mass
ρ	Density
x	Amount of carbon fibre layers

1 INTRODUCTION

1.1 Student Formula

Student Formula is a challenge between universities worldwide. The race cars are designed and built by students and they are backed up by industry. The primary goal of the competition is to encourage youngsters to take a career in engineering.

The University of Applied Sciences in Tampere (TAMK) has a Student Formula team existing of approximately 30 students. These volunteers, from different degrees (mechanical engineering, electrical engineering, automotive engineering, etc), spend their time designing and assembling a single-seat race car.

1.2 Thesis targets

The main goal of this thesis is to design lighter rims for the Student Formula car of TAMK. A lighter sports car results in better performance. The rims are currently made of aluminium and the team of students advised to replace the old ones by carbon fibre (CF) wheels. This thesis approaches two different kinds of rims and each one has its advantages. CF weighs sixty percent less than aluminium, but both materials have different mechanical properties. The mechanical properties of CF and the production process of CF determines the shape of the rim.

1.3 Thesis structure

First a definition of the problem is given. Then background information is given on rim design, the forces and moments applying on the model, carbon fibre, strength of materials and fatigue. These are all subjects concerning the design of the Student Formula rim. The functionality and shapes of different rim designs (commercial and custom made rims) are explained. The external forces, moments and pressures which act on the rim are calculated with *Matlab* and are compared to measurements which were provided by the Formula team. Finally mechanical properties such as strength, mechanical behaviour and fatigue of carbon fibre are quantified.

The next chapter mentions the different kinds of software which were used to draw the rim. The wheel is drawn in *Inventor* (a product of *Autodesk*) and it is simulated with *Ansys Workbench 15.0* by using the finite element method.

The first design was a one-piece CF rim. The shape of this rim was a result of simulating eight different samples. Each sample had one different variable and a different result concerning deformation, Von-Mises stress and shear stress. The results of the different samples were compared and the outcome was a single piece CF rim which met with the standards. The final design was drawn in *Autodesk* and it was simulated in *Ansys Workbench 15.0*. The deformation, the Von-Mises stress, the in-plane stress and the shear stress were examined and compared with the maximal values.

The second design of the rim was almost a copy of the current one, only the loop parts were custom designed. The bolts, hubs and the spokes from the present rim assembly were reused. The different parts for this wheel were drawn and assembled in *Autodesk*. The 3D model was simulated with *Ansys*.

Besides drawing, calculations and simulations the rim needed to be manufactured and it had to be reliable in race competition. Instructions were given on how to process the rims and exploded drawings of the moulds and wheel parts were illustrated. Generally moulds for CF are made of aluminium or composite materials. TAMK has a lab where students do research on 3D printers and its models and material. The idea was to draw the moulds in *Autodesk* and to accomplish a 3D model with one of the printers.

After the simulation, the results of the current rim, the single-piece rim and the multiple piece CF rim were compared. The production price was estimated and based on this information a conclusion was drawn.

The designs of the two rims were illustrated in the appendices. Some crucial annotations and tolerances were motivated. An exploded view of the multiple piece CF rim was drawn as well and a summary of the results were presented in tabular form.

2   Definition of the problem

In this chapter the current aluminium rims were illustrated and the different parts were shown in an assembly drawing. The characteristics and functions of the parts were explained. The total mass of the modern rims was calculated and it was compared to the total mass of the car.

2.1   Current design

The loop of the current rim consist of two parts which are glued together and the adhesive serves as sealing between the two parts, so the air cannot escape. The two loop parts are bolted with twelve M6 bolts to the spokes of the rim. Washers are used between the aluminium and steel surface. The bolts made of steel would damage the soft aluminium surface if washers were not used.
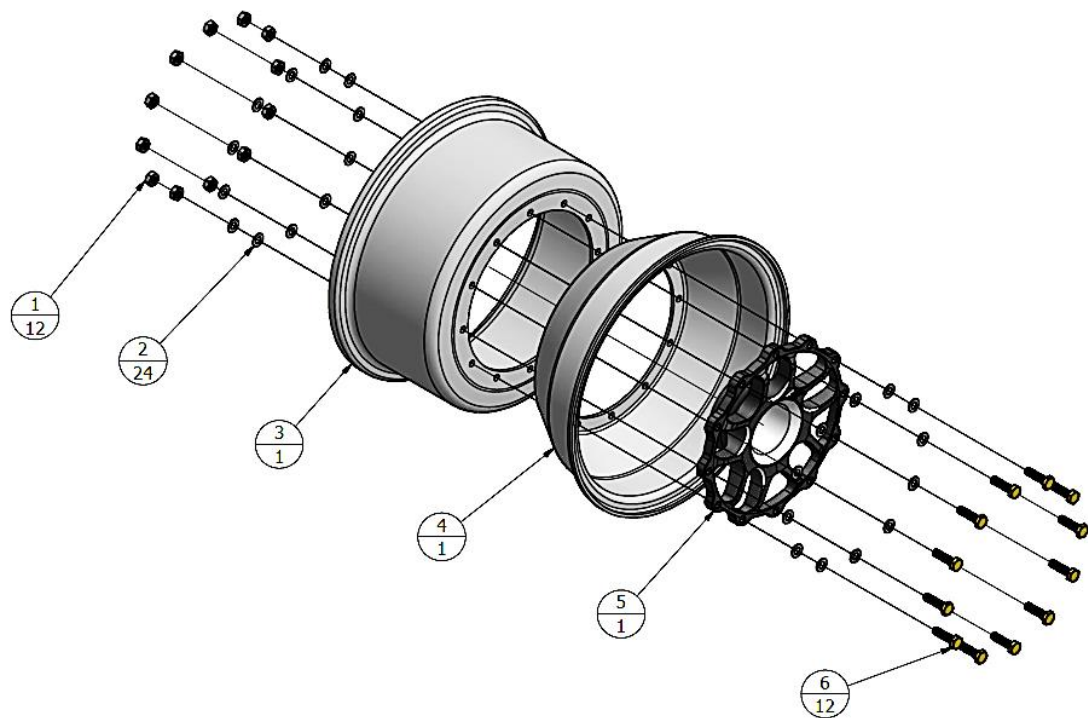
PICTURE 1. Exploded view current rim

TABLE 1. Part list aluminium rim

Number	Amount	Item	Dimension	Material
1	12	bolt	M6x25	steel
2	24	washer	ø12,7x1	steel
3	1	loop part 1	ø276x118	aluminium
4	1	loop part 2	ø276x91	aluminium
5	1	spokes	ø182x48	aluminium
6	12	nut	ø12,8x5,5	steel

2.1.1   The loop

The loop consists of two parts. They are made of an aluminium alloy and are ready made products. The rim has a diameter of 10 inches and a width of approximately 8 inches. Near the edges the loop surface makes contact with the rubber tyre. There needs to be enough friction between the aluminium wheel and the rubber otherwise the rim will spin when driven, but the tyre would not.

2.1.2   The spokes

The inner piece of the rim or the spokes are manufactured as one aluminium part. This part is connected with the loop by using bolts and it is assembled with the wheel hub. The end of the hub contains a tread that makes it possible to mount the wheel on the hub with a custom made nut. The nut makes contact with the outside surface of the spokes and prevents the rim from a longitudinal displacement. The inside surface of the inner part has a shape which creates a form-locking connection with the hub.

2.1.3   Bolts, nuts and washers

There are twelve bolts and nuts used in the current assembly. The bolts are M6 from category 8.8 and 25 mm long. The aluminium surface is softer than the steel bolts and therefore washers are used. The contact area becomes larger and this decreases wear on the aluminium surface. M6 nuts are assembled with bolts and they tighten the loop parts.

2.2   Assembly

The rim is assembled with the wheel hub which was analysed by Jesus Rincon Garcia last year. The hub is an aluminium alloy (Al 7075) and it is constructed as a hollow part to save mass. The main alloy elements are zinc, magnesium and copper, other elements are silicon, iron, titanium, chromium etc. The end of the hub is provided with a tread, so the spokes and the hub can be bolted together.
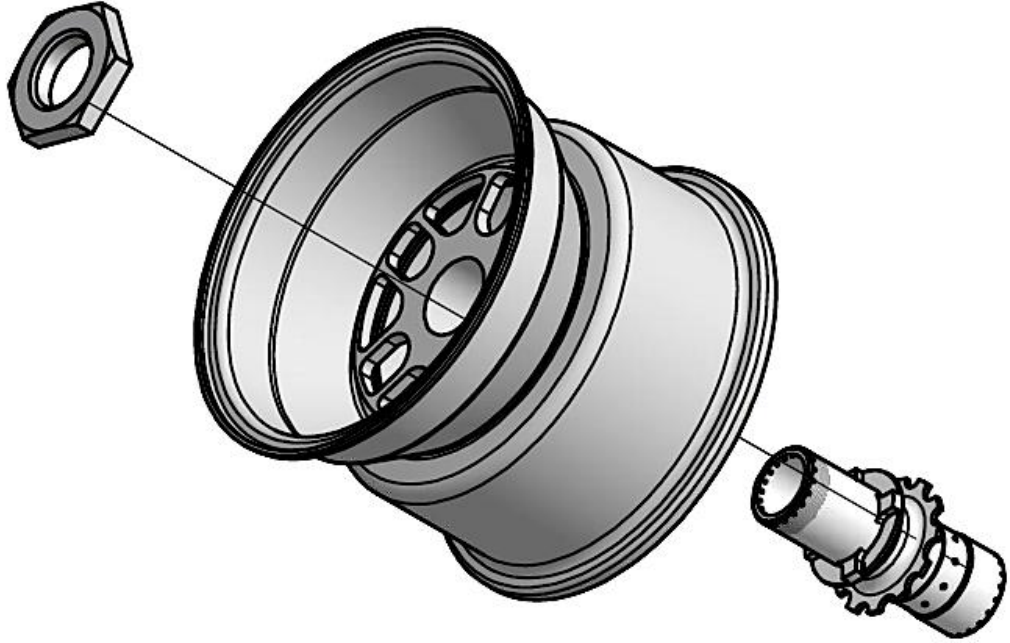
PICTURE 2. Exploded view assembly current rim

2.3 Mass

Mass is one of the deciding factors in Student Formula and motorsports in general. The main goal of the TAMK Formula Team is to design a safe and light but powerful race car.

2.3.1 Compare mass of rims to car

The mass of the rims can be easily calculated by summing up the mass of the different parts. The numbers of the parts in TABLE 2 refer to PICTURE 1.

TABLE 2. Total weight of the modern rims

Number	Title	Weight per part (g)	Amount	Total Weight (g)
1	bolt	7	12	84
2	washer	1	24	24
3	loop, part 1	1037	1	1037
4	loop, part 2	741	1	741
5	spokes	588	1	588
6	nut	1,6	12	19,2

Mass 1 rim	2493,2

Mass 4 rims	9972,8

The kerb weight is used to determine the mass of the race car. Volkswagen defines kerb weight as follows: the mass of the car, without options, with 10 litres of fuel, unloaded and the driver is not included. Volkswagen specifically calls this the 'unladen' mass (http://www.volkswagencommercial.com.au/content/vw_nfz/importers/au/brand/en/customer-care/technical-glossary/Unladen-Mass.html, last accessed 19/05/2015). The 'unladen' mass of the TAMK Student Formula car is 210 kg. This means that the rims are currently 4,7% of the kerb weight

2.3.2   Advantage of using carbon fibre

Carbon fibre is a composite material: this means that the mechanical properties and behaviour are totally different from aluminium. CF designs are often manufactured with moulds. Application of the fibre and resin on the moulds and the removal of the product from the moulds are two important issues that should be taken into consideration during the design process.

This thesis replacing the aluminium rims by custom designed and handmade CF rims. The main advantage of using this composite instead of aluminium is weight saving. The density of CF is 60% less than aluminium.

Carbon Fibre does not yield. This means there will be no plastic deformation when the stress limit is exceeded, but it takes more force than aluminium to break. It's been said that CF is as strong as steel if it is manufactured properly (Von Koenigsegg C. , https://www.youtube.com/watch?v=PGGiuaQwcd8, last accessed 19/05/2015). This statement will however be nuanced in a later chapter.

Composite materials have in general a very good fatigue resistance. The fatigue resistance is 90% of the ultimate strength and this is high compared to metals such as aluminium and steel, that do not reach 50% (Hoa, D. G. ,2007, p 10)

3   Design issues and trends

3.1   Rim design

This paragraph deals with different types of rims. First a commercial rim of a vehicle is examined, then trends are discussed of Student Formula rims.

3.1.1   Commercial rim

Very often a commercial rim is made of an aluminium or magnesium alloy. In PICTURE 2 a sketch of a ready-made vehicle rim is given. The functions of the different parts are explained:

-   The flange prevents the tyre from slipping and it provides extra stiffness.
-   The well makes an easy mounting and removal of the tyre possible.
-   The valve hole serves to pump the tyre.
-   The centre bore is assembled with the wheel hub.
-   The bolt holes are used to connect the hub with the rim.
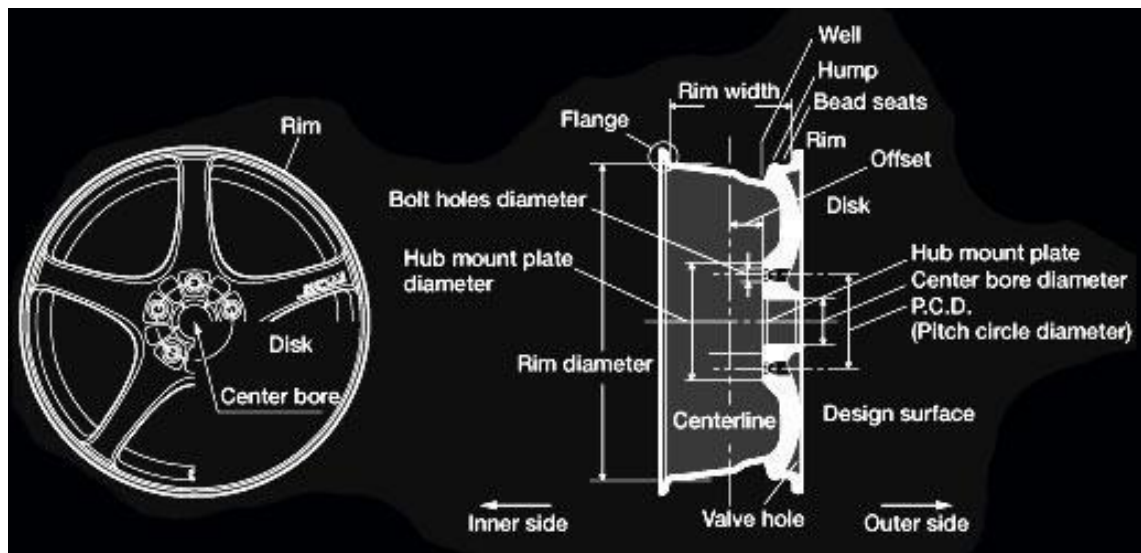
PICTURE 3. Parts of a commercial rim (http://www.garagetoolz.co.uk/blog/how-is-a-rim-built-short-article-about-the-rim-parts/, last accessed 19/05/2015)

3.1.2 Formula Student rim

The Student Formula rims differ from the commercial available wheels. Most of them are the result of a fully or partly custom design. The most popular materials which are used are aluminium and CF. Some pictures of rims from other universities are examined and three categories have been noticed:

The first category contains only aluminium parts for the rim assembly. It is manufactured as a multiple piece design: the spokes and the loop are bolted together. The current rim of TAMK Formula Student race car belongs to this category.

PICTURE 4. TAMK Formula Student rim

The rim of the second category contains aluminium spokes and a carbon fibre loop. As in the first category these two parts are bolted together.

PICTURE 5. Combination aluminium and CF rim

The last kind is a single piece CF rim. Only the valve is not made of a composite material.

PICTURE 6. One-piece CF rim

3.2   Forces

There are many forces that act on the rim. The forces are variable during the race and that makes it hard to determine them. The reaction forces on the tyre have been measured in the past and it was used in a previous thesis of Jesus Rincon Garcia. The available data were checked by determining the reaction forces analytical. The input of some variables was based on what could be found in literature. The results of the calculated forces were therefor not accurate, but the error was less than 20%.

According to SAE (Society of Automotive Engineers) following forces and torques act on the tyre (Harty, M. B. ,2004, p 258):

- Normal force F_z
- Lateral force F_y
- Tractive force F_x
- Aligning torque M_z
- Rolling resistance moment M_y
- Overturning moment M_x
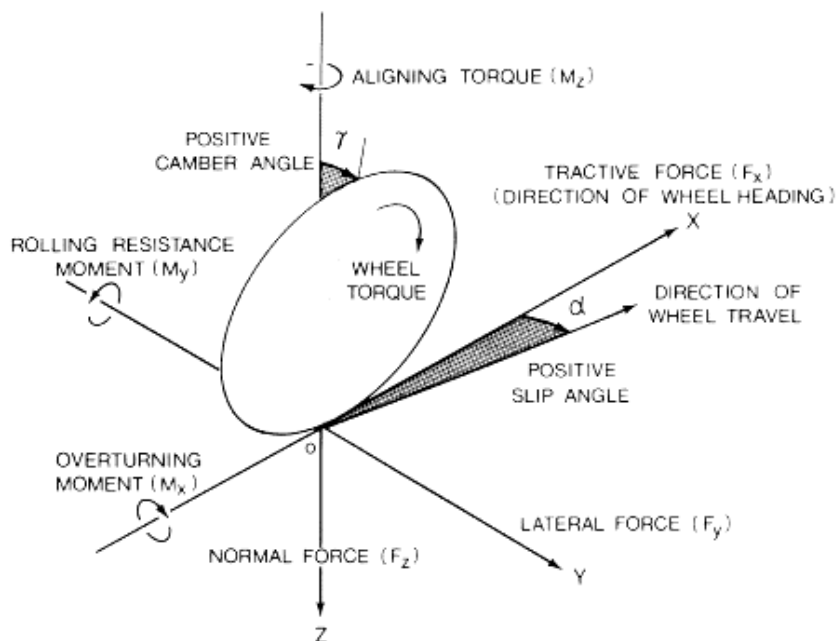
PICTURE 7. Tyre forces and torques according to SAE

(http://www.multibody.net/teaching/dissertations/2011-tomasi/, last accessed 19/05/2015)

Air pressure and pressure from the rubber on the rim also occurs besides tyre forces. In TABLE 3 a summary is given of the forces and momentums which appear on the rim is given. This will be used as input for the simulation in chapter 5.

The reaction forces are not constant during the race, but for the simulation model the worst case scenario is considered: full braking, at top speed in a turn with small radius. The front wheels are more loaded than the rear rims.

TABLE 3. Summary forces and momentums on rim

Forces	
Fx (N)	3000
Fy (N)	3300
Fz (N)	2500
Air pressure (Pa)	240000
Force rubber on rim (N)	2000
Bump (N)	4000
Torques	
Mx (Nm)	120
My (Nm)	0
Mz (Nm)	165

3.2.1   Normal force

The normal force Fz is caused by the mass of the car, by the driver, the fuel and the downforce. The latter is a result of hydrodynamic forces caused by spoilers. Downforce can be considered as a negative lift which increases the normal force while the car accelerates. This variable force causes a better grip to the road at high velocity.
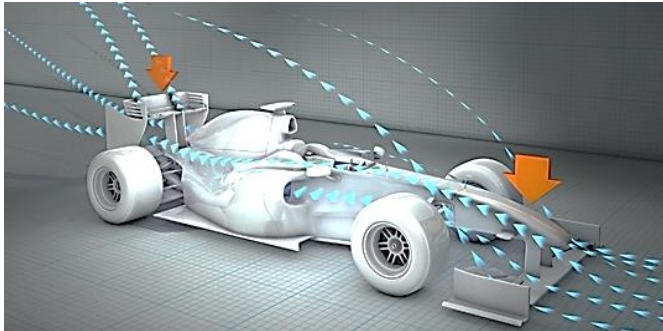
PICTURE 8. Downforce on Formula 1
(http://girlslikef1too.blogspot.fi/2011/02/diffuser-debate.html, last accessed 19/05/2015)

The normal force is not equally spread over on the four wheels. During acceleration the vertical force will be larger at the rear rims and the opposite will occur when the car decelerates.

In the analytical approach the spring damper model is used to compute the normal force (Harty, M. B. ,2004, p 259). The vertical force is given by:

$$F_z = k_z \cdot d_z + c_z \cdot v_z \qquad (1)$$

In Formula Student race cars the force caused by damping can be neglected. The stiffness and tyre penetration are variables which are almost impossible to determine accurately. Yet some orientation values were found in literature.

TABLE 4. Variables for normal force

Variables	
k_z (N/m)	168000
d_z (mm)	15

3.2.2 Lateral force

The lateral force F_y is the result of lateral slip and chamber which appears in turns. Slip occurs when the exerted force on the floor through the tyre is larger than the friction force. The chamber angle, which is illustrated in PICTURE 7, also causes a lateral force. The front wheels are more sensitive to lateral force than the rear wheels. The front left wheel is the most subjected to wear because the race circuit is driven anti-clockwise. The lateral force can be computed with following formula (Dixon, J. C. ,1996, p 105).

$$F_y = \tan(\gamma) \cdot F_z + \mu_s \cdot F_z \qquad (2)$$

TABLE 5. Variables for lateral force

Variables	
γ (°)	20
μ_s (-)	1,5
F_z (N)	2500

3.2.3 Tractive forces

The tractive or longitudinal force F_x is the result of the acceleration and deceleration of the race car. The maximum deceleration (braking) is larger than the maximum acceleration. When the vertical force is determined, the tractive force can easily be calculated using the following formula.

$$F_x = \frac{F_z}{g} \cdot a_{dec} \qquad (3)$$

TABLE 6. Variables for tractive force

Variables	
g (m/s²)	9,81
a_{dec} (m/s²)	11,5
F_z (N)	2500

3.2.4 Air pressure

There is an air pressure on the rim and on the rubber. Tubes are not used in this design, so the rims must be well sealed, otherwise the air will leak. The air pressure is estimated on 0,24 MPa and acts on almost the entire surface of the loop part.

3.2.5 Other forces

There is a radial force on the rim caused by the rubber tyre. Friction between the rim and rubber is achieved by this radial force. This is necessary, otherwise the rim will spin when driven, but the tyre will remain in rest. The minimum radial force that is acquired, depends on the torque delivered by the engine and the friction between CF and aluminium.
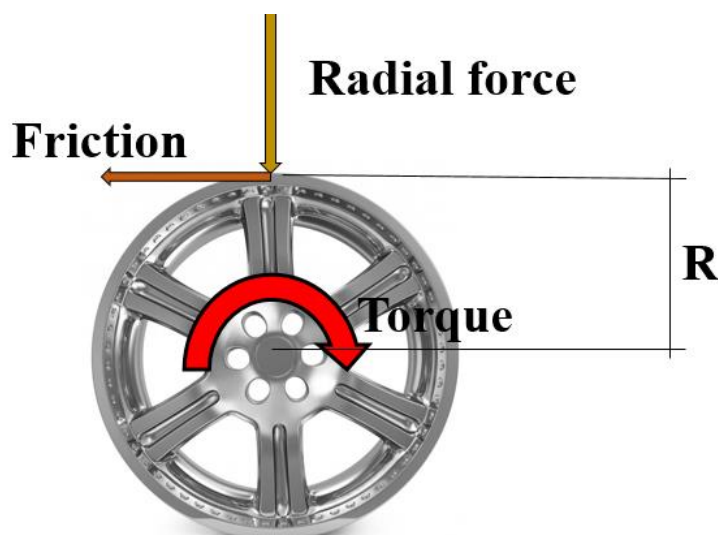
PICTURE 9. Radial force (http://www.wisegeek.org/what-is-the-difference-between-rims-and-wheels.htm, last accessed 19/05/2015)

On PICTURE 9 the radial force is reduced to a force that applies on one point. The friction moment must be larger than the torque delivered by the engine.

$$R \cdot F_f \geq T' \qquad\qquad (4)$$

And

$$F_f = \mu_r \cdot F_r \qquad\qquad (5)$$

TABLE 6. Variables radial force

Variables	
T' (Nm)	25
μ_r (-)	0,23

Another force that can be considered as a normal force, is a vertical force caused by bumps on the road. Bump forces are generated by irregularities on the road, for example: rocks, border of the road etc.

3.2.6 Contact area

When the forces are calculated, the tyre moments can be determined on condition that the point of action of the forces is known. Due to acceleration and turns the reaction force will not occur at the centre of the tyre. This causes an aligning, a rolling and an overturning moment (Harty, M. B. ,2004, p 265 and p 271).
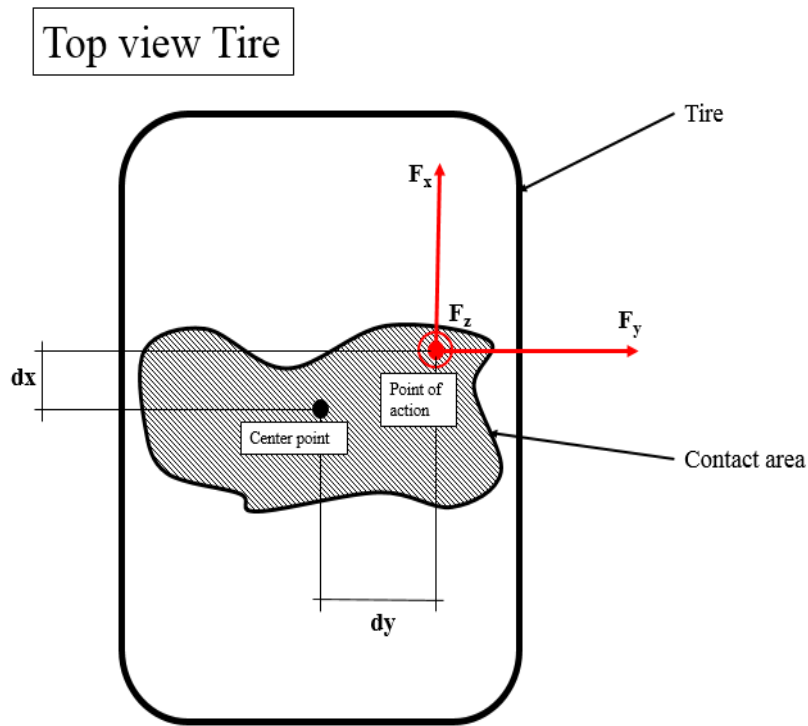
PICTURE 10. Contact area tyre

dx is illustrated in PICTURE 10 and can be determined with the following formula.

$$dx = \frac{F_x \cdot R_u}{F_z} \qquad (6)$$

R_u is the radius in contact with the road and it is given by:

$$R_u = R_t - dz \qquad (7)$$

TABLE 7. Variables radial force

Variables	
R_t (mm)	225
d_z (mm)	15
F_z (N)	2500
F_x (N)	3000

The real dy is harder to calculate analytically. The maximum value for dy is however easy to compute and is equal to the width of the tyre divided by four.

3.2.7   Tyre moments

The aligning torque can be calculated as followes:

$$M_z = M_{z,slip} + M_{z,chamber} \qquad (8)$$
or
$$M_z = F_y \cdot dy + T' \cdot \sin(\gamma) \qquad (9)$$

The overturning moment is given by:

$$M_x = F_z \cdot dy \qquad (10)$$

The rolling resistance can be neglected when its value is compared to the other moments. (Dixon, J. C. ,1996, p 110*)*

3.3   Strength of Materials

3.3.1   Deformation

As a result of the forces, the moments and the pressures applying on the rim, the design will bend. The deformation depends on the magnitude of the forces, the shape and the Young's modulus. The magnitude of the forces is in direct proportion to the bending. The thickness of the shape and the magnitude of the Young's modulus are in inverse proportion to the deformation. For simple models like a beam on two supports the bending could easily be calculated manually, but a complex model like a race car rim requires computer software.

3.3.2   Von-Mises stress

The Von-Mises stress was given by the Austrian Richard Von Mises. It is an equivalent tensile stress that takes the stresses in every direction into account. This equivalent is often compared with the yield strength of a material. The purpose is to obtain a Von-

Mises stress that is smaller than the yield strength of the material. The formula is given by:

$$\sigma_{VonMises} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6\sigma_{xy}^2 + 6\sigma_{yz}^2 + 6\sigma_{zx}^2}$$

(11)

(http://www.continuummechanics.org/cm/vonmisesstress.html, last accessed 19/05/2015)

3.3.3   In-plane stress

The in-plane stress or σ_{zz} is an important criteria in composite materials because the maximum tensile in-plane stress for CF is ten times lower than in the x and y-direction. In the next chapter in PICTURE 12 the axes of woven CF are illustrated. Low maximum tensile and compressive strength in the z-direction are a big disadvantage of composite materials. The reason for this characteristic is because CF is made of fibres and the mechanical properties are favourable in the longitudinal direction of the fibres. More information on the mechanical properties is given in the next chapter.

3.3.4   Shear stress

Shear stress occurs in a material when a force acts on a material parallel to its cross section. The maximum shear stress is one of the crucial parameters of CF. The equation for the shear stress in one dimension is given by:

$$\tau = \frac{F}{A}$$
(12)

This equation is similar to the one of stress, but for the latter the surface is along with the force, whereas for the stress the force is perpendicular to the surface.
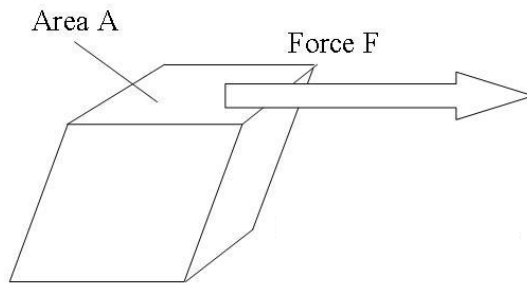
PICTURE 11. Shear stress (http://poly-mer.tripod.com/rheology2.htm, last accessed 19/05/2015)

3.4 Fatigue

Fatigue occurs in a material when forces are not constant in a period of time. Due to changing forces a material will fail after a certain time. The microstructure and other mechanical properties determine how the material will resist fatigue.

The wheel of the sports car is always subject to changing forces. Acceleration in the beginning of the race and after turns results in an increase of tractive and normal forces. Before the turn a deceleration leads to negative tractive forces and less normal force. In the turn the lateral force will appear. A Student Formula car can break from 100 to 0 kilometres an hour in less than 4 seconds. This means that the design of the rim needs to be adjusted to large variable forces.

Depending on the size of the acting forces the rim will have a certain life that can be expressed in hours or cycles.

3.5 Carbon fibre

CF was invented in the early 60's and it became very popular the last thirty years. Nowadays it is used in a lot of applications such as: road transport, building and public works, electronics, air and space transport, sports and recreation, general mechanical applications etc. CF belongs to the family of composite materials. Composite materials are characterised by strong fibres in a weaker matrix material (Hoa, D. G. ,2007, p 29 and p 30). The mechanical properties depend on the direction. This characteristic is called anisotropy. Other composite materials are Kevlar, Glass fibre, boron fibre etc.

3.5.1   Unidirectional carbon fibre

The Young's modulus is a measure for the stiffness of a material. The modulus will depend on the direction in unidirectional carbon fibre (UD CF). Composites are in general stiff in the longitudinal direction of the fibres and they are more flexible in the transverse direction. The ultimate tensile/compressive strength is higher in the longitudinal direction. This kind of carbon fibre is often used in tubes. The mechanical properties of unidirectional CF in an epoxy resin are given in TABLE 8 and are compared with S275. (Hoa, D. G. ,2007, p 40) and (Dieter Muhs, H. W. ,2012, p 1)

TABLE 8. Comparing mechanical properties UD CF – S275

	UD CF	S275
Young's modulus in longitudinal direction (Mpa)	134000	210000
Young's modulus in transverse direction (Mpa)	7000	210000
Shear modulus (Mpa)	4200	81000
Poisson ratio (-)	0,25	0,3
Ultimate tensile strength in longitudinal direction (Mpa)	1270	430
Ultimate compressive strength in longitudinal direction (Mpa)	1130	250
Ultimate tensile strength in transverse direction (Mpa)	42	430
Ultimate compressive strength in transverse direction (Mpa)	141	250
In-plane shear strength (Mpa)	63	250

Chapter 2 stated that CF is as strong as steel. TABLE 7 proves that this composite is only stronger than steel in the longitudinal direction, but it is weaker in all the other dimensions.

3.5.2   Woven fabrics

The rim will be manufactured of woven carbon fibre: Pyrofil Gewebe style 450 CF. The advantage is that the mechanical properties are the same in two directions if the fabric is balanced. The first direction is called the warp and the other is called the fill.
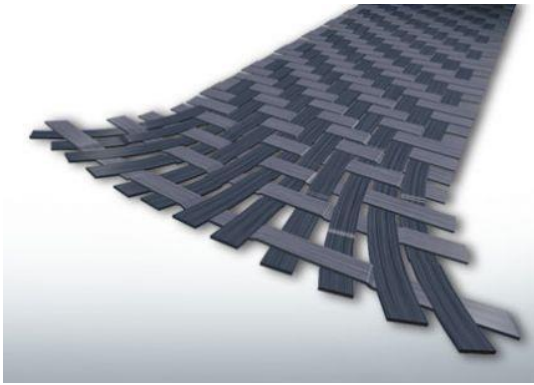
PICTURE 12. Woven CF (http://www.sniper-racing.com.au/carbon-fiber, last accessed 19/05/2015)

The mechanical properties can be calculated with TABLE 8 and with information on the thickness, number of warp and fill yarns per meter. Mechanical properties of balanced CF in an epoxy matrix have been found in literature (Hoa, D. G. ,2007, p 44) and are given in TABLE 9.

TABLE 9. Mechanical properties woven carbon fibre

	Woven Carbon Fibre
Young's modulus $E_x = E_y$ (Mpa)	54000
Young's modulus E_z (Mpa)	7000
Shear modulus G_{xy} (Mpa)	4000
Shear modulus G_z (Mpa)	25837
Poisson ratio v_{xy} (-)	0,045
Poisson ratio v_z (-)	0,25
Ultimate tensile strength in x or y direction (Mpa)	420
Ultimate compressive strength in x or y direction (Mpa)	360
Ultimate tensile strength in z direction (Mpa)	42
Ultimate compressive strength in z direction (Mpa)	141
In-plane shear strength (Mpa)	63
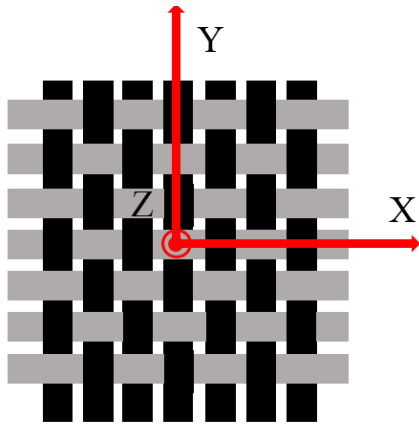
PICTURE 13. Coordinate system woven carbon fibre

3.5.3 Anisotropic approach

First the difference between isotropic and anisotropic material is explained. Than the stiffness matrix of anisotropic CF is given.

An isotropic material has the same mechanical properties in every direction whereas in anisotropic material the properties vary along the direction. Examples of isotropic materials are steel, aluminium and other metals. Carbon fibre and composites as Kevlar and glass fibre in epoxy resin show an anisotropic behaviour. Woven CF is however not completely anisotropic, because according to TABLE 9 the mechanical properties are the same in the x and y-direction. This special case of anisotropy is called transversely isotropy. The compliance matrix was found in literature (Hoa, D. G. ,2007, p 319) and is given as follows.

$$[D] = \begin{bmatrix} \dfrac{1}{E_{xy}} & -\dfrac{v_{xy}}{E_{xy}} & -\dfrac{v_z}{E_z} & 0 & 0 & 0 \\[2ex] -\dfrac{v_{xy}}{E_{xy}} & \dfrac{1}{E_{xy}} & -\dfrac{v_z}{E_z} & 0 & 0 & 0 \\[2ex] -\dfrac{v_z}{E_{xy}} & -\dfrac{v_z}{E_{xy}} & \dfrac{1}{E_z} & 0 & 0 & 0 \\[2ex] 0 & 0 & 0 & \dfrac{1}{2 \cdot G_z} & 0 & 0 \\[2ex] 0 & 0 & 0 & 0 & \dfrac{1}{2 \cdot G_z} & 0 \\[2ex] 0 & 0 & 0 & 0 & 0 & \dfrac{1 + v_{xy}}{E_{xy}} \end{bmatrix} \qquad (13)$$

This matrix can be completed with the values of TABLE 8.

The compliance matrix [D] is the relation between the stress and the strain (Bekaert, G. ,2014, p 9).

$$[\sigma] = [D] \cdot [\varepsilon] \qquad (14)$$

It is possible to insert an anisotropic stiffness matrix in Ansys Workbench, but calculations with this kind of matrix are only accurate with simple shapes like plates and tubes. The shape of the rim is too complex for the software to be approached as an anisotropic material.

Instead of using the transversely isotropic model another approach is used. The simulation of the transversely isotropy is replaced by an isotropic model. More details on this methodology are explained in a later chapter.

3.5.4 Rupture

Otherwise than metals like aluminium and steel, CF does not yield. The most crucial strength characteristic for a metal is the yield strength. If the stress is higher than the yield strength of the material, plastic deformation occurs. After plastic deformation a metal does not return to its original shape when the force disappears. Carbon fibre and other composite materials only have an elastic deformation. This means that rupture appears abruptly when the ultimate strength is exceeded (Hoa, D. G. ,2007, p 38).
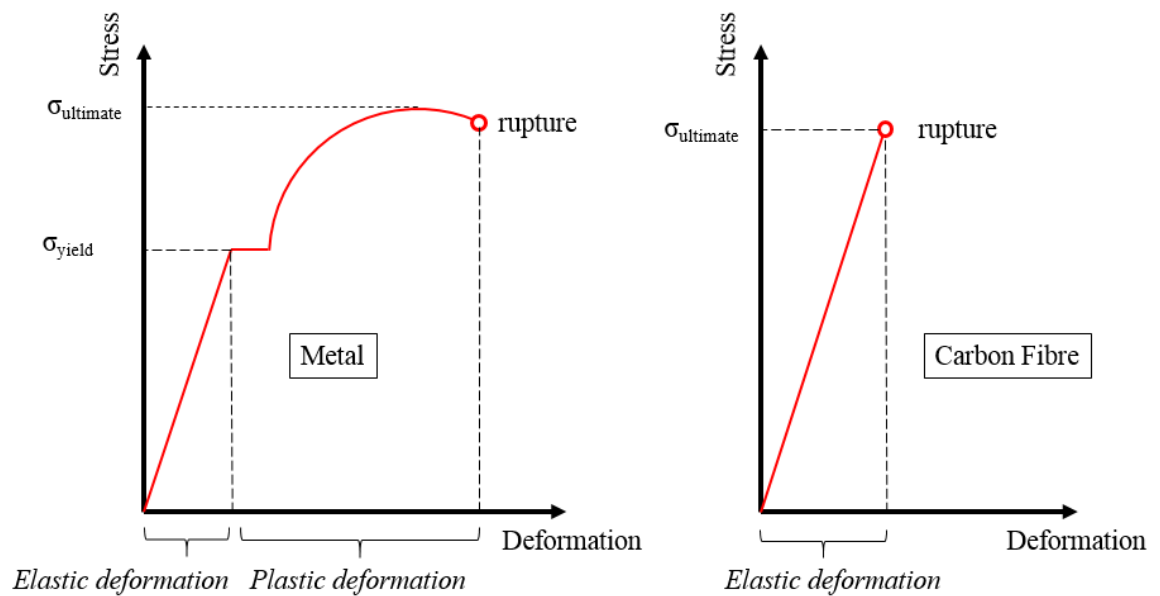
GRAPH 1. Loading curves metal and CF

3.5.5 Fatigue in carbon fibre

The combination of woven carbon fibre with epoxy resin endures fatigue remarkably. The reason is shown in FIGURE 13. When a crack occurs in CF the initial stress concentration leads to resin failure between the CF layers. When the damage gets through a few layers the fibres experience a relaxation. This prevents the carbon fibre from further fatigue damage. In a homogeneous material the stress concentration remains and this leads to a deeper crack (Hoa, D. G. ,2007, p 112). Because of the favourable properties of CF qua fatigue, this characteristic was not simulated by computer software.

Crack

Stress concentration

Crack

Carbon Fibre
Resin

Resin failure
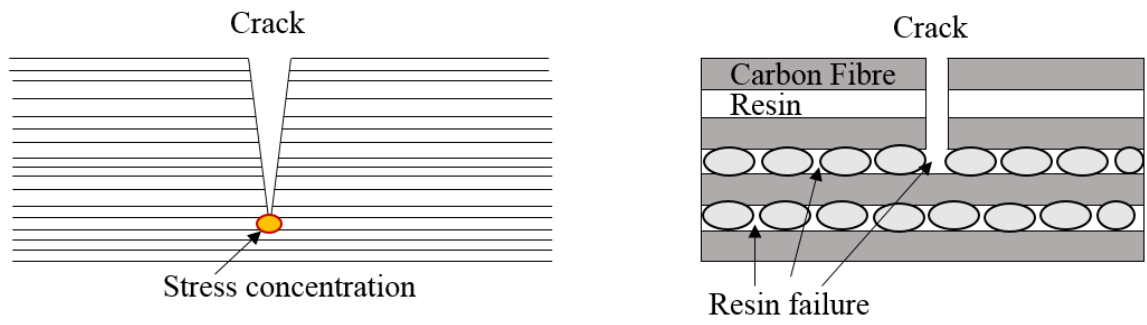
PICTURE 14. Comparison of fatigue failure between CF and a homogeneous material
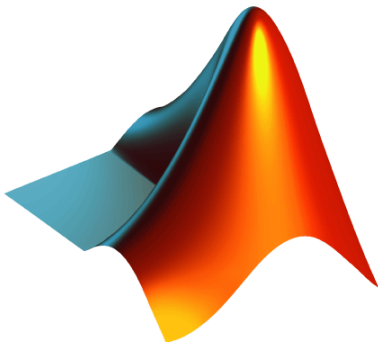
4 Software

During the design process a couple of software tools were used to analyse the rim. The reaction forces and momentums were calculated with *Matlab*. The 3D rim was drawn with *Inventor* which is a product from Autodesk and the simulation happened in *Ansys Workbench 15.0*.

4.1 Matlab

Matlab is a software package developed by *MathWorks*. It is a software tool that is popular with engineers and it is used for mathematical applications. The m-code is used in *Matlab*. This is a high-level programming language which means that there is more abstraction with the machine language and as a result the software is more user-friendly.

The tyre forces and moments were calculated with *Matlab*. The advantage of calculating forces with this computing software is that the variables can be modified any time. It also gives a structured overview on the results, so they could easily be compared with the measurement of the forces which were provided by the Formula team.

PICTURE 15. *Matlab* logo (http://se.mathworks.com/company/newsletters/articles/the-mathworks-logo-is-an-eigenfunction-of-the-wave-equation.html, last accessed 19/05/2015)

4.2 Inventor

Inventor is a 3D CAD software that is easy to use and simple static simulations can be performed too. The software is available at school and can be downloaded for free on the

website of *Autodesk* on condition that the software is downloaded by a student for educational purposes.

This software was used to draw all the rims and their assemblies. Even in an early stage of the design process 3D sketches were made with *Inventor*. The mould parts could be exported to an STL file and drawings with this file extension could be read by a 3D printer.

4.3   Ansys Workbench 15.0

Ansys Workbench 15.0 is a simulation software that is provided by *Ansys*. It can perform different kinds of simulations such as: heat transfer, fluid, magnetism, static etc. The static simulation is used to model the rim, but the license at TAMK can only apply a mesh of maximum 30.000 nodes.

This simulation software was used to calculate crucial parameters of the rim. After inserting a mesh, applying forces, moments, pressures and entering the boundary conditions, the deformation and different kinds of stresses were calculated.

5   One-piece carbon fibre rim

This thesis deals with the analysis of two types of rims. The first design is a single piece CF rim. The design was based on a study of samples which were all drawn with *Inventor* and they simulated with *Ansys*. The wheel hub needs to be redesigned for a successful assembly with this kind of rim. The moulds for this rim are manufactured as a 3D print made of ABS.

5.1   One piece carbon fibre rim

In the following paragraphs the analysis of a CF rim made of one piece is discussed. First, the method to reach a reliable design is explained, next the rim is simulated with *Ansys Workbench 15.0*. Finally the moulds and an approach on manufacturing the composite rims are illustrated and explained.

5.2 Method

Different possible designs of one piece carbon rims were designed. After a discussion with some team members the most promising rim was chosen. Manufacturability and general strength were the most important criteria.

In the next step certain variables of the design were changed. The different samples were simulated by *Ansys Workbench* and the influence of the changing variables was examined. The samples that had a positive influence on deformation, Von-Mises stress, shear stress and in-plane stress could be determined. The aim was to have a bending, stress and mass that were as low as possible.

In the next step the different positive variables were combined into one final design. This rim was than examined in detail.

5.3   Samples and design

In this paragraph different models were already simulated. More information on modelling the rim follows in paragraph 5.4 where the final design is simulated.

More detailed sketches on the samples can be found in the appendix 1. The first sample served as a reference for the comparison of the other samples. The samples had only one main difference with the reference and this makes it possible to examine the influence of that particular variable. A short description of the samples is given:

- Sample 1   : The first sample was the reference.
- Sample 2   : The holes in the inner part were larger.
- Sample 3   : The holes of the spokes had a different shape.
- Sample 4   : Larger radiuses were applied.
- Sample 5   : The width of the horizontal ribs was smaller.
- Sample 6   : The rim had four holes in the inner part instead of three.
- Sample 7   : This sample was based on a design that was used in the Student Formula race car of Metropolia in Helsinki.
- Sample 8   : Samples one through seven had a constant thickness of three millimetres, sample 8 had a thickness of six millimetres.
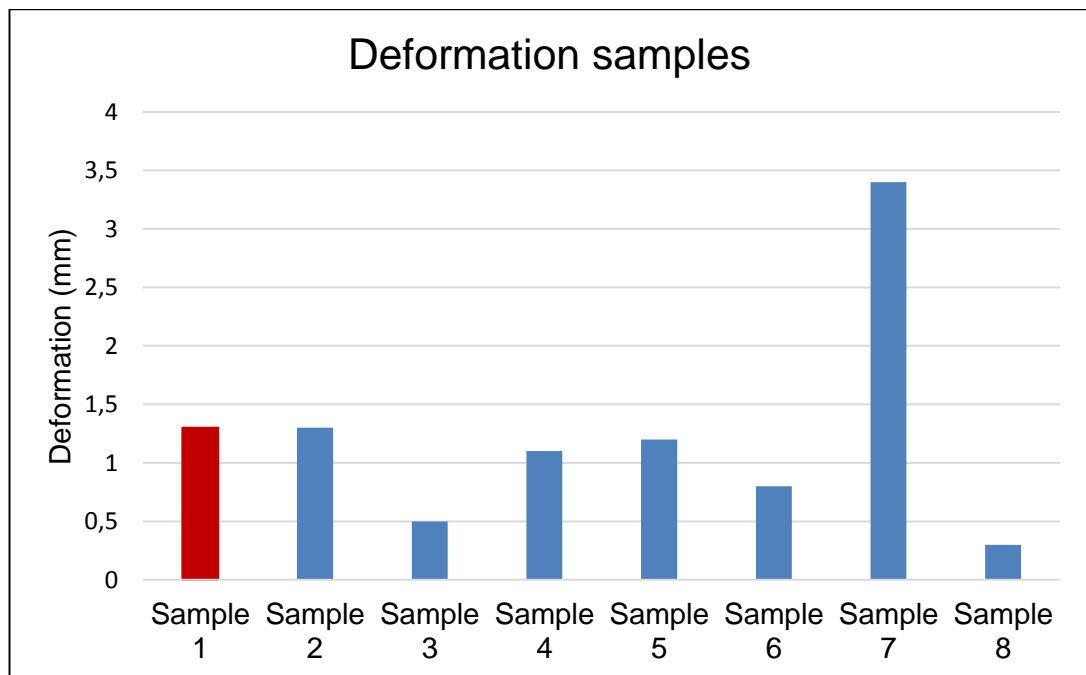
GRAPH 2. Deformation of the different samples
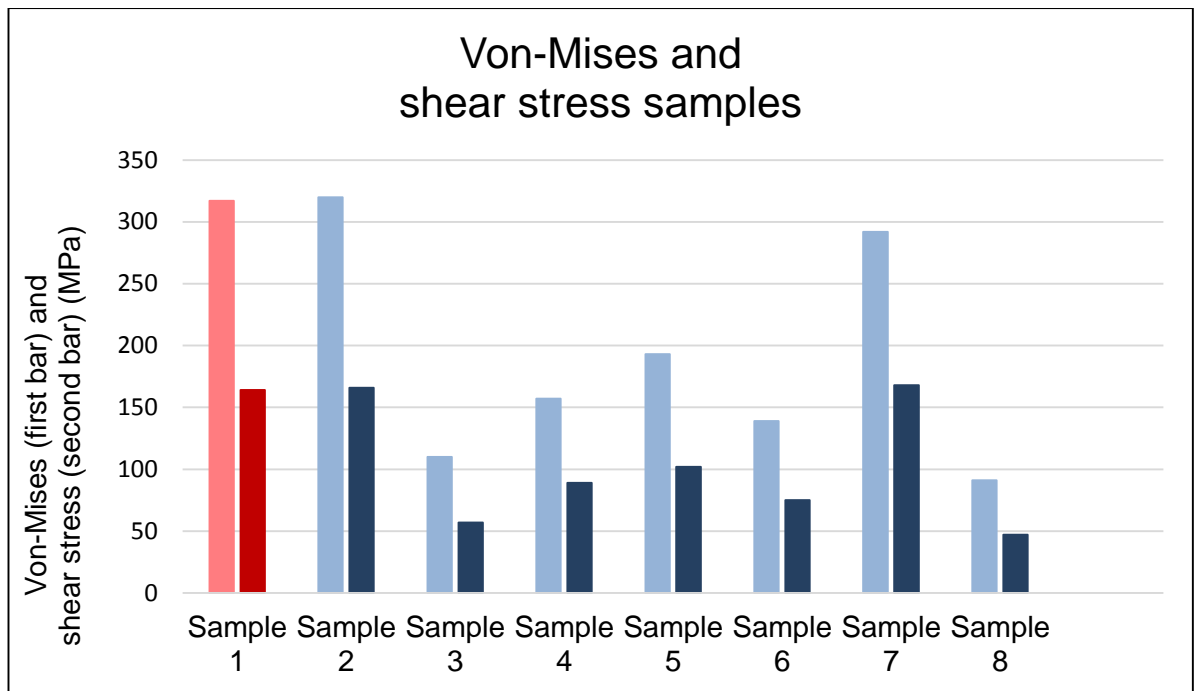
GRAPH 3. Von-Mises and shear stress of the different samples

The variables in samples 3, 4, 5, 6 and 8 had a positive influence on the deformation. All samples apart from 7 have a lower stress than sample 1 (the reference). In sample 8 the weight was doubled because the thickness was multiplied by two and in sample 6 the weight was increased, because more material was applied.

From the study of the different samples a couple of conclusions could be made. More thickness, large radiuses and an appropriate design of the spokes could decrease both deformation and stress.

The parameters that decreased stress and deformation were combined into one final design. The critical areas of the design where large values of the stress appeared, were further examined. The maximum Von-Mises and shear stress always occurred on the same place of the different samples. The critical places were around the horizontal spoke ribs and in the contact area with the wheel hubs. Those areas needed more attention during the design process. According to the analysis more thickness and larger radiuses were a good solution for reducing the stress.

The basic thickness was three millimetres and in the crucial areas, more material was applied. It was not necessary to increase the weight by applying thickness on places where

it was not needed. Based on the research results the final rim was given a variable thickness. A detailed drawing is attached in the appendix 2.
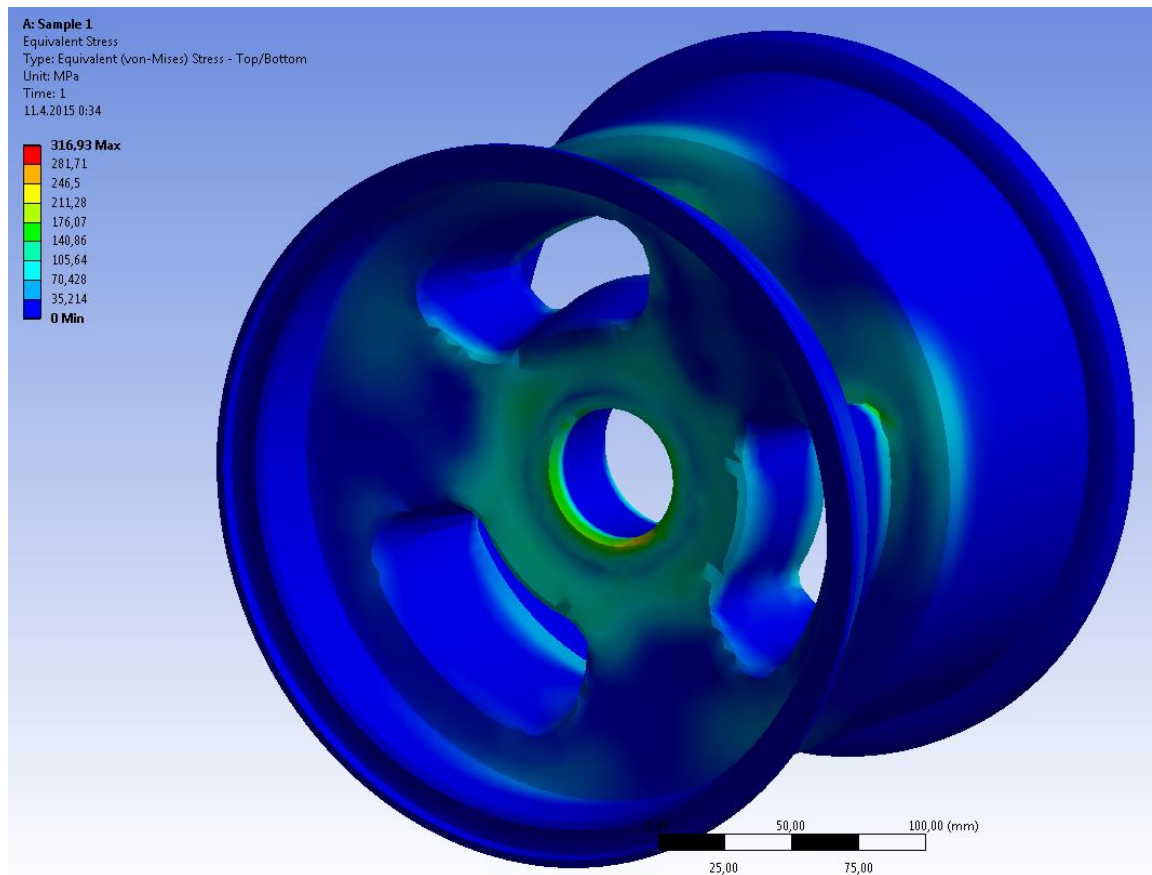
PICTURE 16. Von-Mises stress in the reference sample

5.4   Simulation

5.4.1   Material

The first step was to define the material in *Ansys Workbench 15.0*. Carbon fibre is a transversely isotropic material and its stiffness matrix has already been calculated in a previous chapter. Other characteristics could be found in TABLE 9. Anisotropic materials could only be simulated for simple shapes with the licence that the school provided. The form of the single piece CF rim was too complex to be simulated as a transversely isotropic material. Another possibility was to use the ACP tool which was developed for simulating composite materials, but this upgrade was only possible with a full license.

5.4.2 Mesh

The samples could be meshed with a shell element because of their constant thickness. The one-piece CF rim however had a variable thickness and neither *Ansys* nor *Inventor* could generate an accurate mid-surface. The rim was meshed with solid elements. Due to the license, the maximum amount of nodes is thirty thousand.

### 5.4.3 Applying forces, pressure, moments and support

The forces, pressures and moments were introduced, after having determined material and having applied a mesh. The magnitudes were already calculated in a previous chapter. The normal, lateral and tractive forces act through the tyre on the rim. The forces occur on the contact area between the tyre and the rim. The overturning moment, the aligning torque and the radial force of the rubber on the rim appear on the same place as the tyre forces. The air pressure occurs on the surface that captures the inflated air. This surface includes the inside surface of the tyre and a part of the outside of the rim. An additional pressure appears on a surface perpendicular to the axis of the hub. This pressure is needed to assemble the wheel hub and the rim as a conical connection. The surface of the hub is considered as a support.

5.4.4 Notice

Due to material limitations as mentioned in 5.4.1 another technique of simulating stress and deformation was considered.

The mechanical properties in x and y-direction of woven CF are very stiff in comparison with the properties in the z-direction. The Young's modulus in the xy-plane is eight times larger in the z-direction and the Poisson coefficient in the xy-plane is ten times smaller than in the z-direction. The properties in the z-direction cause the largest deformation. For this reason the rim was simulated as an isotropic material with the properties of the weakest direction. The maximum deformation in the z-direction of the isotropic approach is a good approximation for the total bending. This statement was modelled in *Matlab* for a triangle shell element with different inputs. Equation (13) was used in the model and

one could prove that there is a linear relation between the deformation and the strain. As result the real strain was only 5% larger than the approximation according to the approached model.
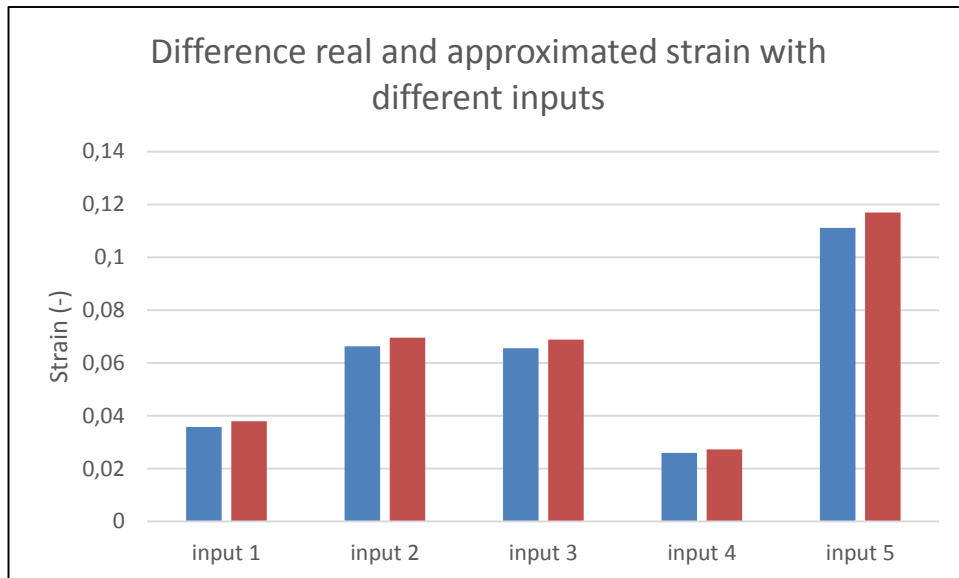

GRAPH 4. Difference between real approximated strain with different inputs

The stress that appears in the rim is however not dependant on the material properties if considered in its elastic region. Stress is only associated with the forces, moments, pressures and shape on which they apply.

$$\sigma = \frac{F}{A} \qquad\qquad (14)$$

5.4.5   Results

On PICTURE 17 the deformation of the rim is illustrated. The area with the largest deformation was on the inside edge of the rim. The element in the mesh with the most bending was selected and the deformation in the z-direction was determined as described in paragraph 5.4.4.
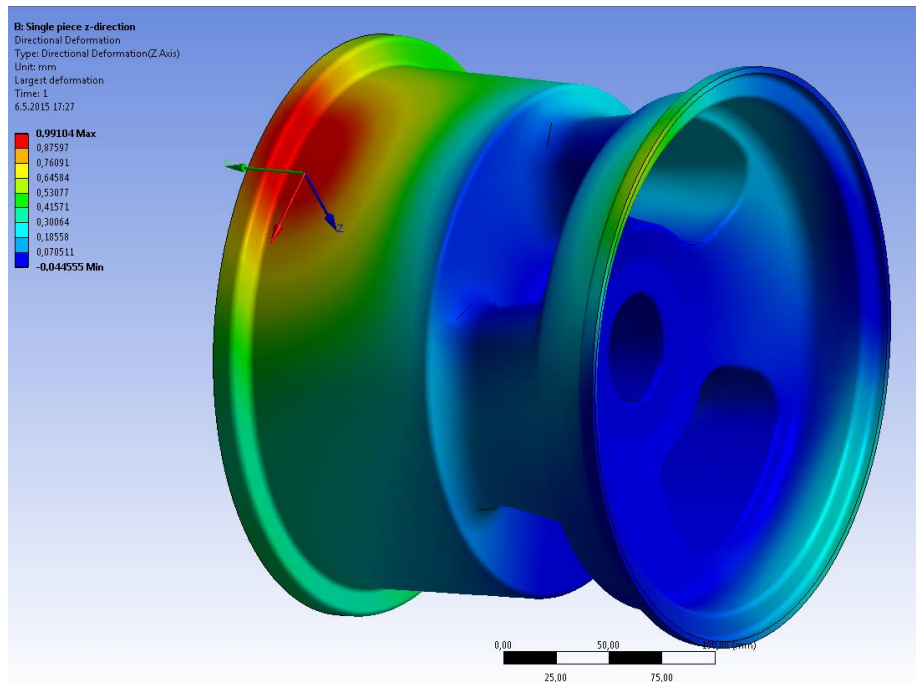
PICTURE 17. Deformation single piece CF rim

$$d_{tot} = 0,991 \ mm$$

The distribution of the Von-Mises stress is illustrated in PICTURE 18. The shear stress
and in-plane stress were calculated as well.
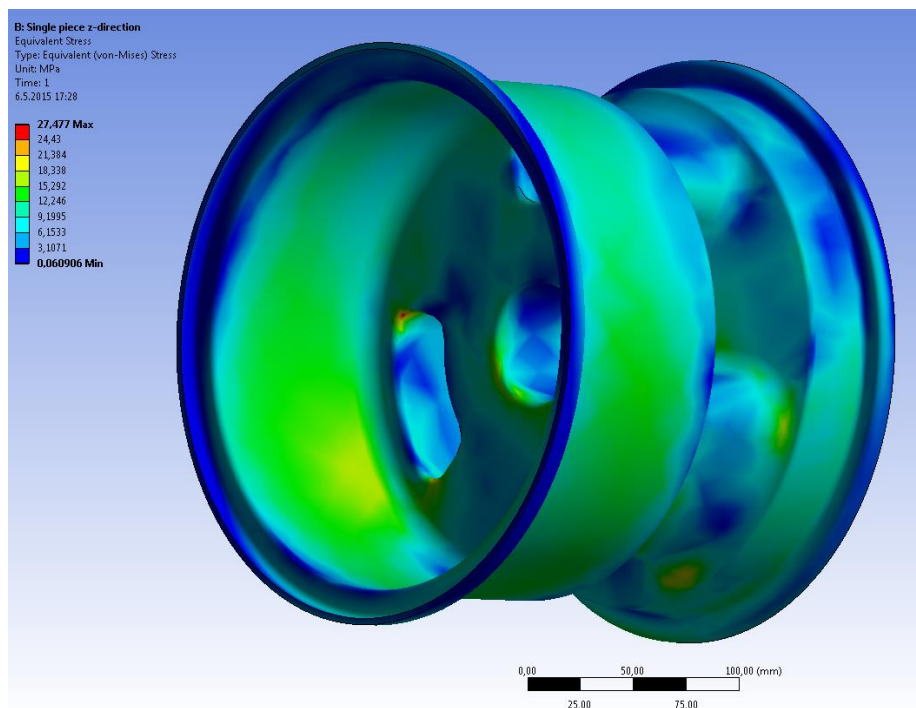
PICTURE 18. Von-Mises stress single piece CF rim

$$\sigma_{max,Von-Mises} = 27,48 \; MPa$$

$$\tau_{max,shear} = 14,10 \; MPa$$

$$\sigma_{max,zz} = 20,46 MPa$$

5.5 Moulding

5.5.1 Vacuum bag moulding

Vacuum bag moulding or vacuum bagging is an open mould technique that is often used for manufacturing CF shapes. This paragraph deals with the different steps of the procedure.

The first step is to put a gel coat on the mould. This provides the rim with a better surface quality. When the coat is dry, the CF layers are applied around the mould. Each layer of CF is provided with epoxy resin and special attention is needed in the corners of the shape.
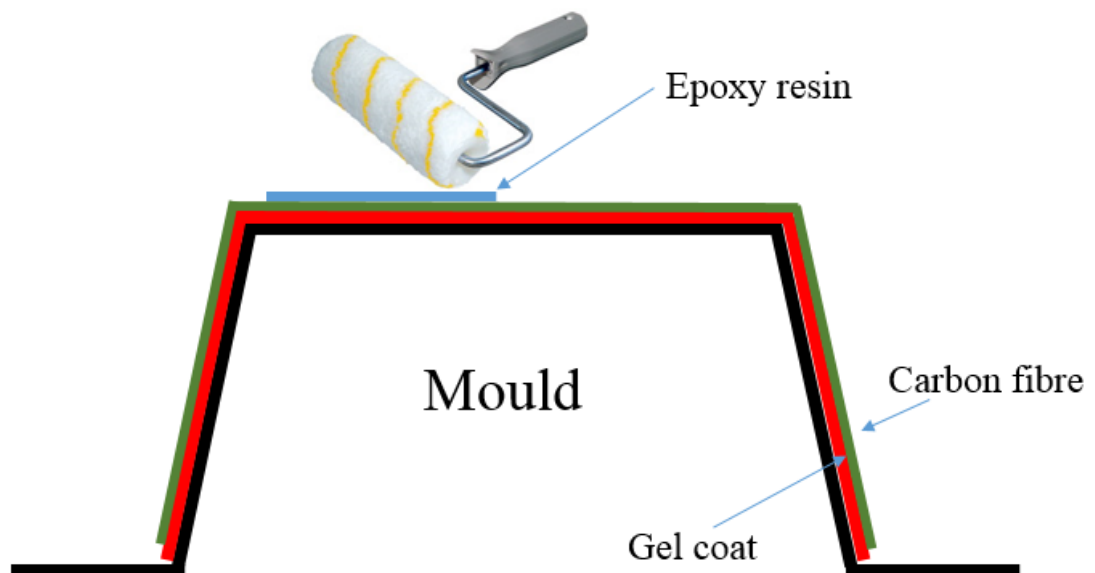
PICTURE 19. Applying CF and epoxy resin on a mould

When the desired thickness is achieved by adding multiple layers, the mould is wrapped up in a couple of plastics. Each of them has its own function. First the rim is wrapped up with a release film. This layer is not stuck to the epoxy resin and it is used to separate the breather from the laminate. Then the mould is coated in a porous breather material that

makes it possible to suck the air from every place in the shape. In the next step a vacuum bag that is larger than the mould is put around the whole. The vacuum bag is provided with a plumbing system that makes it possible to make connection with a vacuum pump. The pump sucks the air out of the plastic bag.
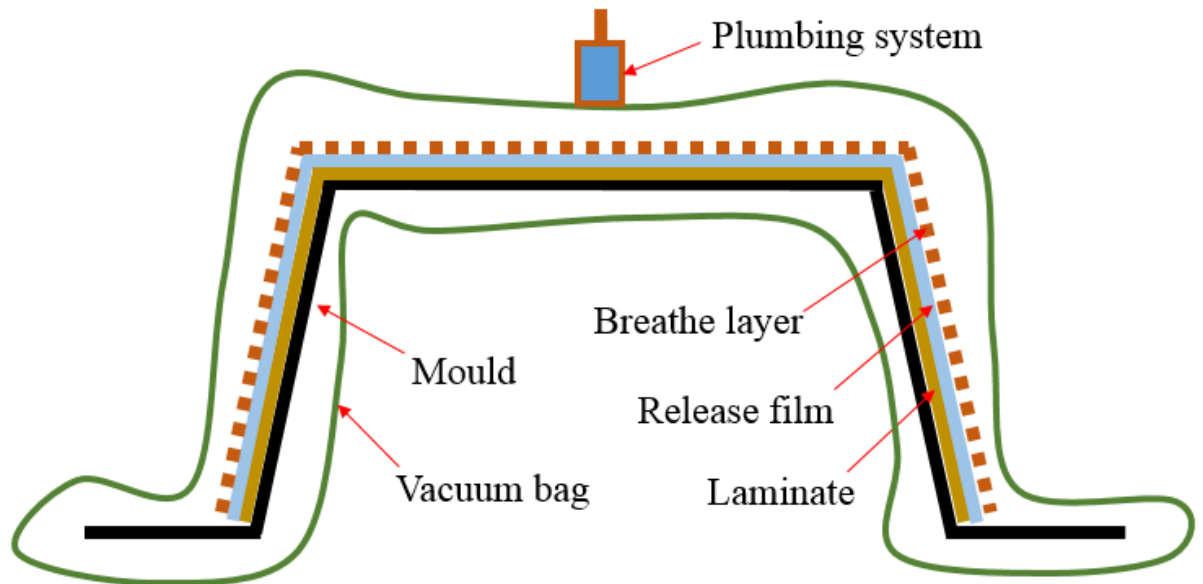
PICTURE 20. Different layers for CF moulding

The vacuumed mould is put in an oven of 100°C for eight hours and the final step is to remove the mould (demoulding) from the CF shape.

5.5.2   Type of mould

The first idea was to manufacture the moulds from aluminium by turning and milling. This process could not be done at school so the Formula Team might have given this task to an external local company. The disadvantage of turning and milling aluminium of considerable size is the high cost.

After manufacturing a 3D print of a one-piece rim on scale 1/2 in an early design stage, the idea came to accomplish the mould as a 3D print made of acrylonitrile butadiene styrene or ABS. Some students are currently working on a new 3D print machine that would be large enough to prepare the mould for the single piece CF rim.

The mould (orange) which consists of two parts and the CF rim are illustrated in PICTURE 21.
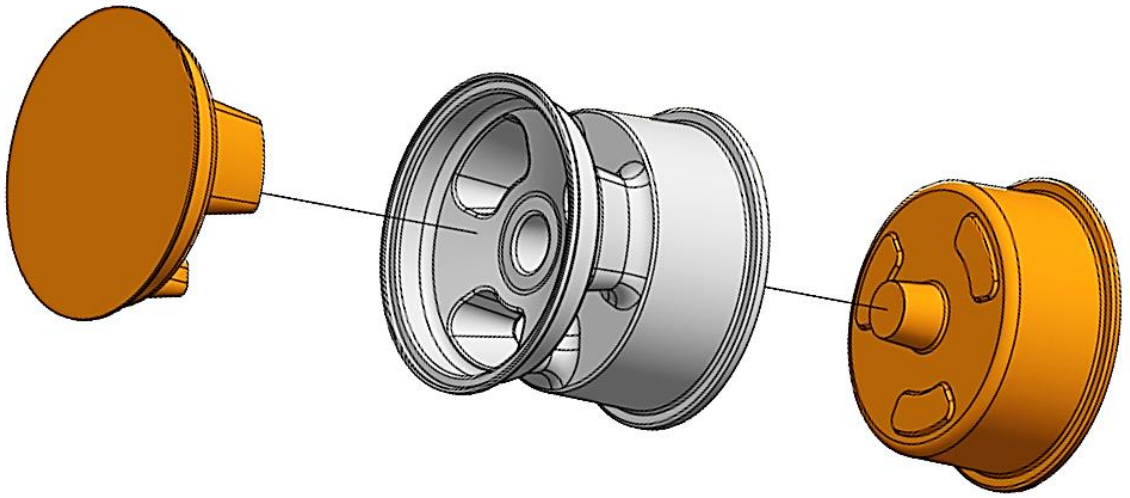
PICTURE 21. Assembly moulds and CF rim

6 Multiple piece carbon fibre rim

The second rim is a multiple piece rim of which the loop part is made of CF and the spokes are reused from the current design. The biggest advantage of this design is that the wheel hubs do not need to be redesigned as in the one-piece CF design. The shell parts were almost an exact copy of the modern aluminium ones. Only a few smaller modifications made in order to facilitate demoulding. The moulds could be the result of turning aluminium or a 3D print into a single piece CF rim. A technical drawing of the loop is attached with appendix 3.

6.1 Method

The shape was based on the current rim. The assembly consisted of an aluminium inner part and two CF shells. They were joined together with bolts, washers and nuts. The first idea was to make a mould from the current aluminium rim, but this was not possible. There is no angle in the modern design so demoulding would be impossible.
A small modification was made in comparison with the current design that allowed to manufacture the mould, and to demould the CF shell.

The simulation happened almost in the same way as the model in chapter 5. The current rim made of aluminium was calculated and compared with the multiple piece CF rim and the single piece rim in chapter 7.

6.2 Simulation

6.2.1 Material

The shells of the current rim are made of aluminium alloy 6061 (Dieter Muhs, H. W. ,2012, p) and the spokes are the same alloy. The bolts, washers and nuts are made of steel, but they were not simulated. The parts have proven to be strong enough because they have not failed in the past. The shells of the new rim are manufactured of woven CF, the same material as mentioned in the previous chapter. The mechanical properties of the aluminium alloys are given in TABLE 10. Unlike CF aluminium behaves like an isotropic material which is easier to simulate.

TABLE 10. Properties Al 6061

|	**Aluminium 6061**
Young's modulus E (Mpa)	68900
Shear modulus G (Mpa)	26000
Poisson ratio ν (-)	0,33
Ultimate tensile strength (Mpa)	310
Tensile yield strength (Mpa)	280
Maximum shear strength (Mpa)	207
Density (kg/m³)	2700

6.2.2 Mesh

The inner part and the loop of the rim were meshed with solid elements. Due to the variable thickness of the rim it was not possible to apply a proper mid-surface.

6.2.3 Applying forces, moments, pressures and support

This step was almost the same as in paragraph 5.4.3, only the additional pressure on the surface perpendicular to the axis of the hub was removed. In the one-piece design this pressure was needed to assemble the wheel hub and the rim as a conical connection. That pressure is not necessary anymore because the inner piece of the rim and the wheel hub are assembled cylindrically.

6.2.4 Results

On PICTURE 22 the deformation of the rim is illustrated. The area where the deformation is the largest is on the inner edge of the rim. The element in the mesh with most of the bending is selected and the deformation in the z-direction is determined as described in paragraph 5.4.4.
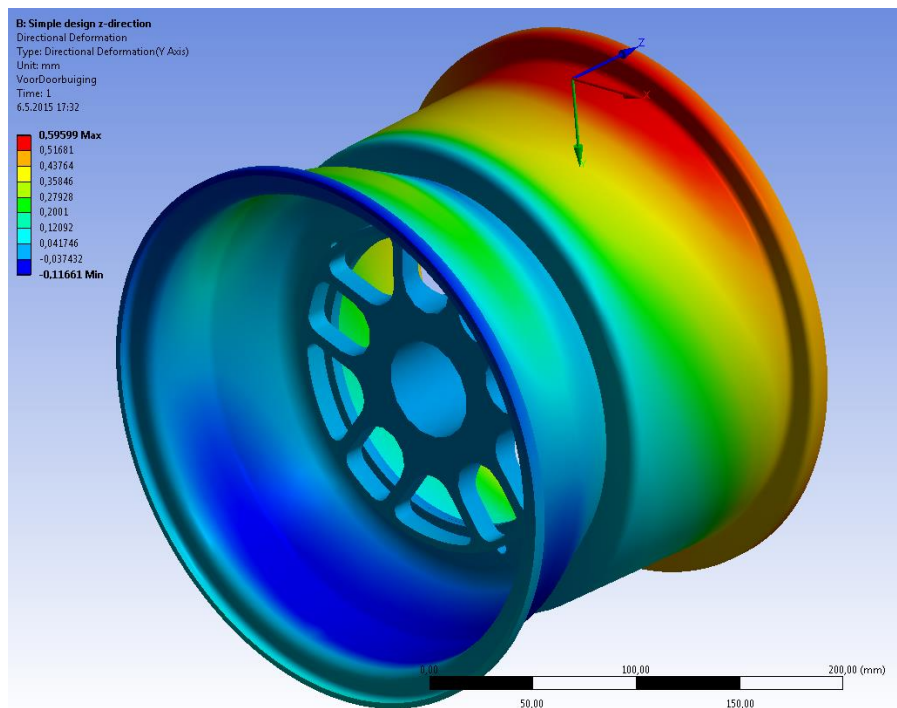
PICTURE 22. Deformation multiple piece CF rim

$$d_{tot} = 0,600 \ mm$$

The distribution of the Von-Mises stress is illustrated in PICTURE 23. The shear stress and in-plane stress were calculated as well.
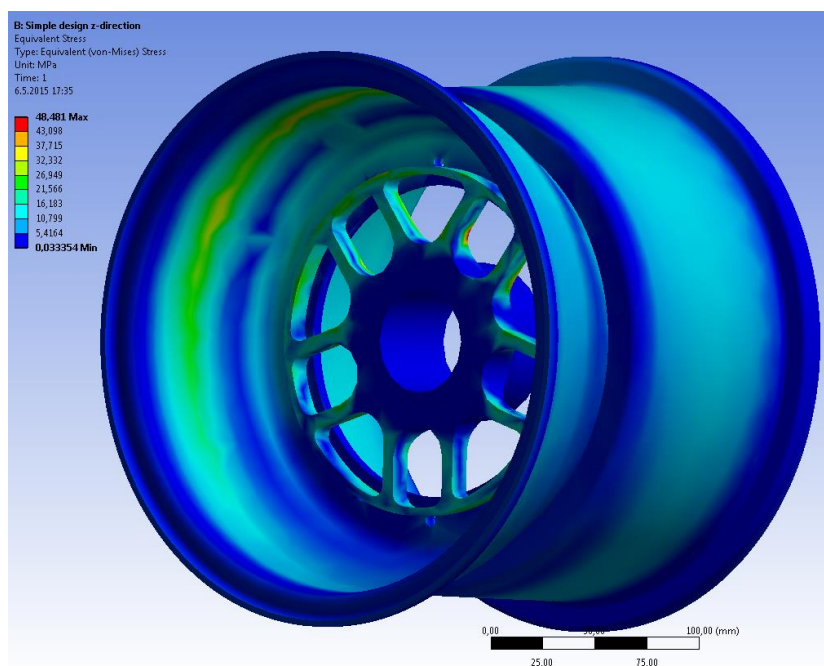
PICTURE 23. Von-Mises stress multiple piece CF rim

$$\sigma_{max,Von-Mises} = 40,45 \ MPa$$

$$\sigma_{max,shear} = 22,73 \ MPa$$

$$\sigma_{zz} = 7,55 \ MPa$$

This design is an assembly of two materials: CF and aluminium. That is why the largest values for deformation and stress in the aluminium spokes must be calculated as well:
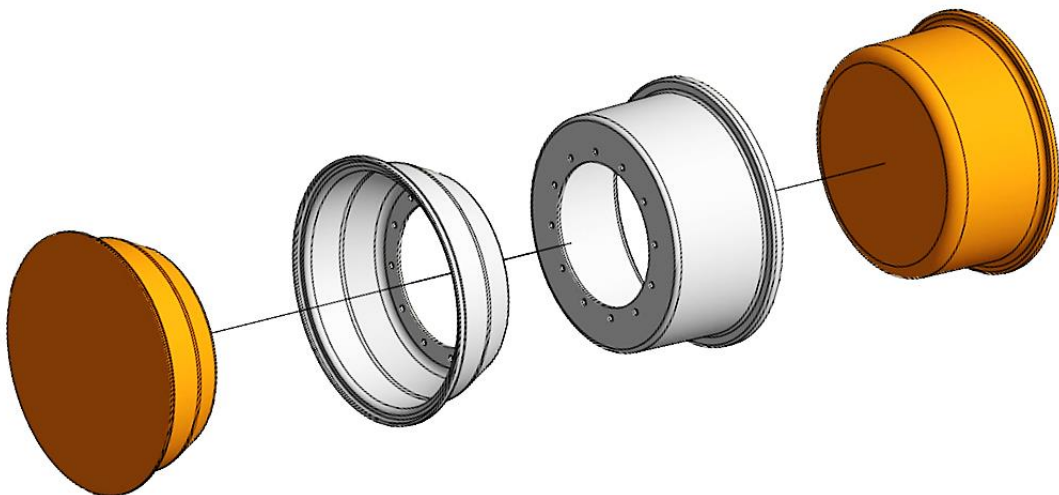
$$d_{tot} \approx 0 \ mm$$

$$\sigma_{max,Von-Mises} = 48,48 \ MPa$$

$$\sigma_{max,shear} = 24,37 \ MPa$$

6.2.5   Moulding

The method of manufacturing the mould for the two loop parts is identical to the process of the single piece rim. In PICTURE 24 an assembly of the mould (orange) and the two loop parts are illustrated.


PICTURE 24. Assembly moulds and CF loop parts

7 Compare the rims

In this chapter the results of the three rims (current rim, multiple piece with CF loop parts and one-piece CF rim) were compared to each other. The deformation, different kinds of stresses, weight and manufacturability were discussed. A summary of the results could be found in the appendix 4.

7.1 Result Deformation

Only the largest deformation was given. It occurred on the inner side on the edge of the rim because there was no radial support on that place. Woven CF in an epoxy resin has a large Young's modulus in the x and y-direction, but in the z-direction the modulus is eight times smaller. Due to this reason certain areas have a larger thickness; the technical drawings are attached to the appendices. The exact values of the deformation can be found in the summary that is attached with the appendices as well.
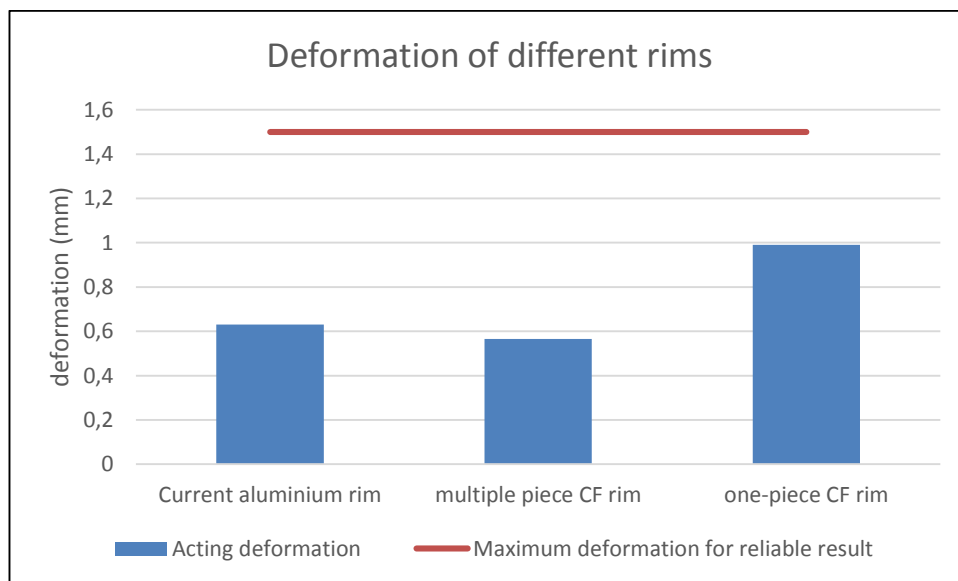
GRAPH 5. Deformation of different rims

For a good quality of the results, the bending must be less than the average thickness (3 mm) divided by two. In GRAPH 5 the results are given for the deformation of the three kinds of rims. All the values are smaller than 1,5 mm which is one of the factors that indicates a trustworthy simulation.

The single piece CF rim has the largest deformation. The main reason was because the support for the shell was made of woven CF which is less stiff in the z-direction than the

aluminium alloy. The transitions from one surface to another were smooth and the model contains more material in crucial areas. Thanks to these modifications the deformation is still acceptable.

The modern rim has a constant thickness of three millimetres. The multiple piece CF rim has a smaller deflection even though the Young's modulus is smaller than the modulus of aluminium. The reason herefore is because more material in important areas is applied.

7.2 Result stresses

7.2.1 Result Von-Mises stress

The Von-Mises stresses should be compared to the yield strength. In CF the yield strength is equal to the maximum strength because plastic deformation does not occur in this composite. In the multiple piece CF rim the maximum stress occurred in the spokes which are made of aluminium.
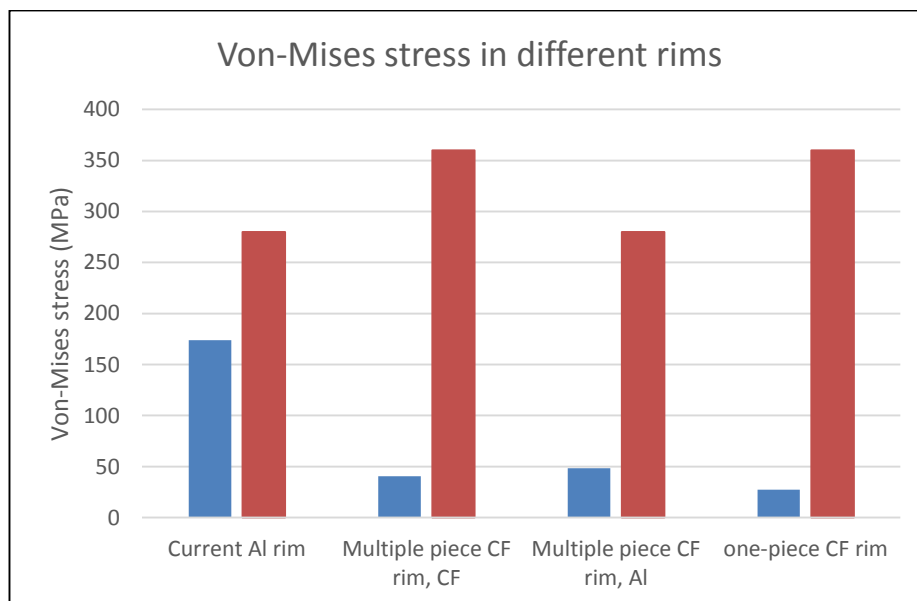

GRAPH 6. Von-Mises stress in different rims

All the calculated Von-Mises stresses were lower than the yield strength. At first sight the acting Von-Mises stress is only a fraction of the maximum strength. The reason is because this kind of stress is not determined for the shape.

7.2.2 Result In-plane stress

The in-plane stress or σ_{zz} is the most crucial parameter for composite materials because the mechanical properties in the z-direction are low. Aluminium is an isotropic material which means that the properties in every direction are equal. Verifying the in-plane stress for metals is not useful if the Von-Mises stress has been checked.
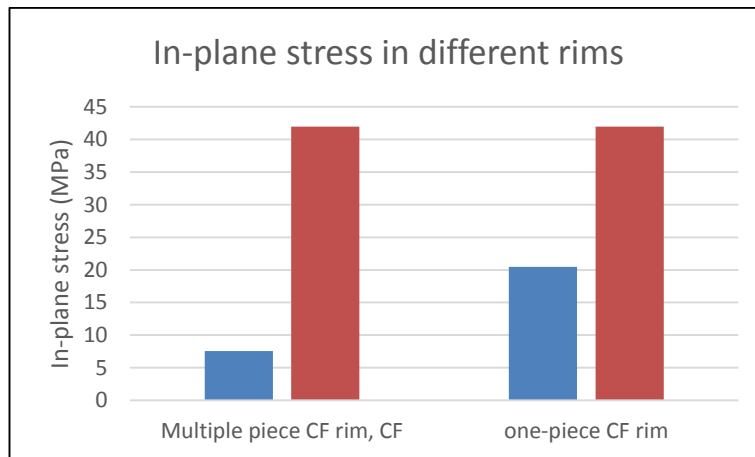

GRAPH 7. In-plane stress in different CF parts

The maximum stress in the z-direction is only 42 MPa and this is almost ten times less than the maximum compressive strength of CF. This is the weakest dimension of woven carbon fibre and the reason for this can be found in physical composition of CF. There were made a lot of modifications during the design process to keep this stress as low as possible. The exact values for the in-plane stresses are given in the appendices.

7.2.3 Result Shear stress

An important stress that also needs to be examined is the shear stress. According to the simulation the maximum shear stress occurred on almost the same place as where the maximum Von-Mises stress appeared.
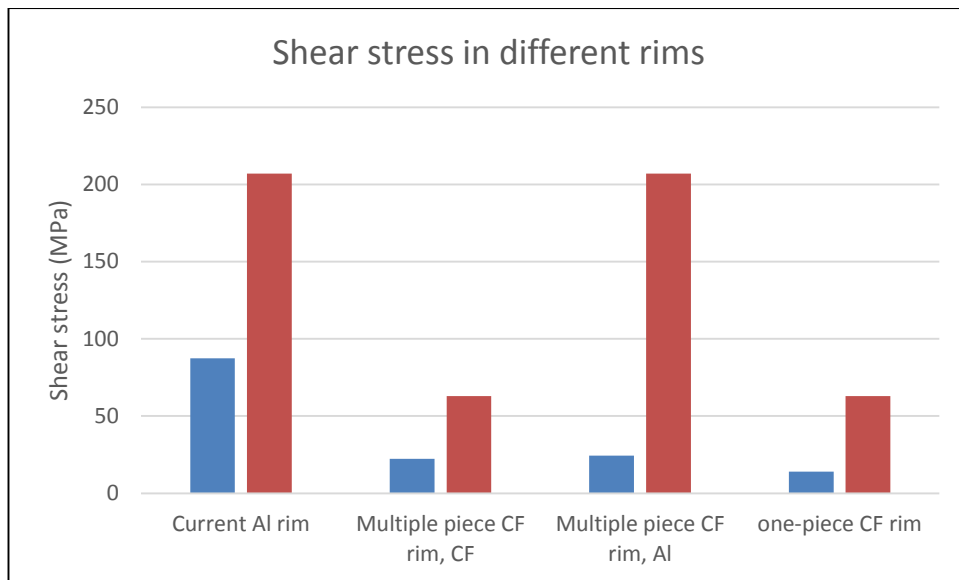
GRAPH 8. Shear stress in different rims

7.3 Weight

The weight of the current rim was already calculated in one of the first chapters. It included all parts: two loops, all bolts, washers, nuts and the inner part. The total weight of the four rims was 10 kg. The main goal of this thesis is to reduce the mass.

7.3.1 Comparison

The mass of the multiple piece CF rim was calculated in the same way as the modern rim. The mass of the spokes bolts, washers and nuts was not changed. The loop parts of the composite material were lighter than the aluminium parts. The total mass of the four rims (7 kg) was compared to the present rims and the mass was reduced with 30%.

TABLE 11. Total weight of the multiple piece CF rims

Number	Title	Weight per part (g)	Amount	Total Weight (g)
1	bolt	7	12	84
2	washer	1	24	24
3	loop, part 1	620	1	620
4	loop, part 2	416	1	416
5	spokes	588	1	588
6	nut	1,6	12	19,2

Mass 1 rim	1751,2

Mass 4 rims	7004,8

The volume of the one-piece rim could be determined with Inventor and this was multiplied by the density of woven CF in an epoxy resin. The mass for a single piece CF rim was 1,500 kg and the total mass of the four rims was 5.991 kg. This meant a reduction of almost 40% compared to the modern wheel.
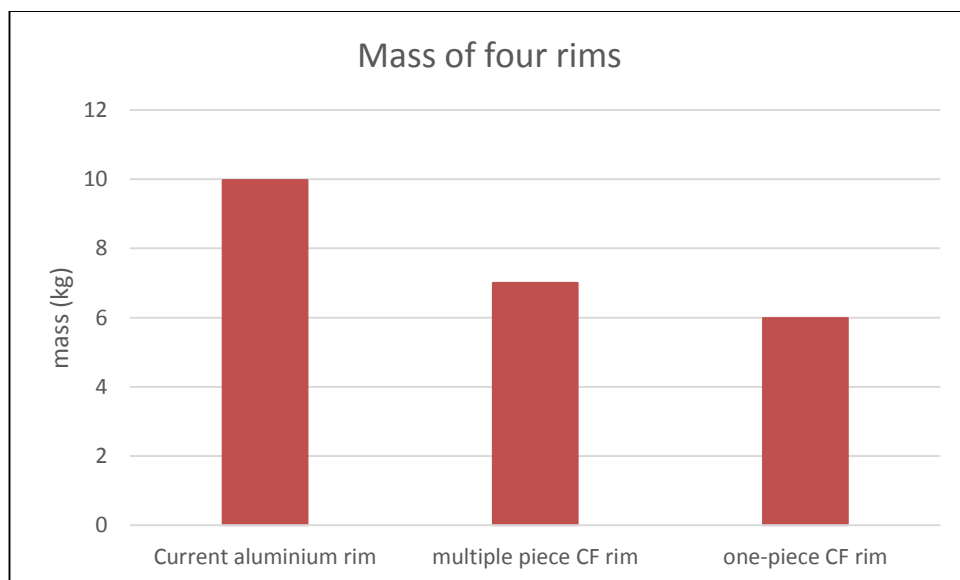
GRAPH 9. Mass of four rims

7.3.2 Compare to car

GRAPH 10 illustrates how the weight of the current race car is distributed. It only deals with the major parts without going into detail.
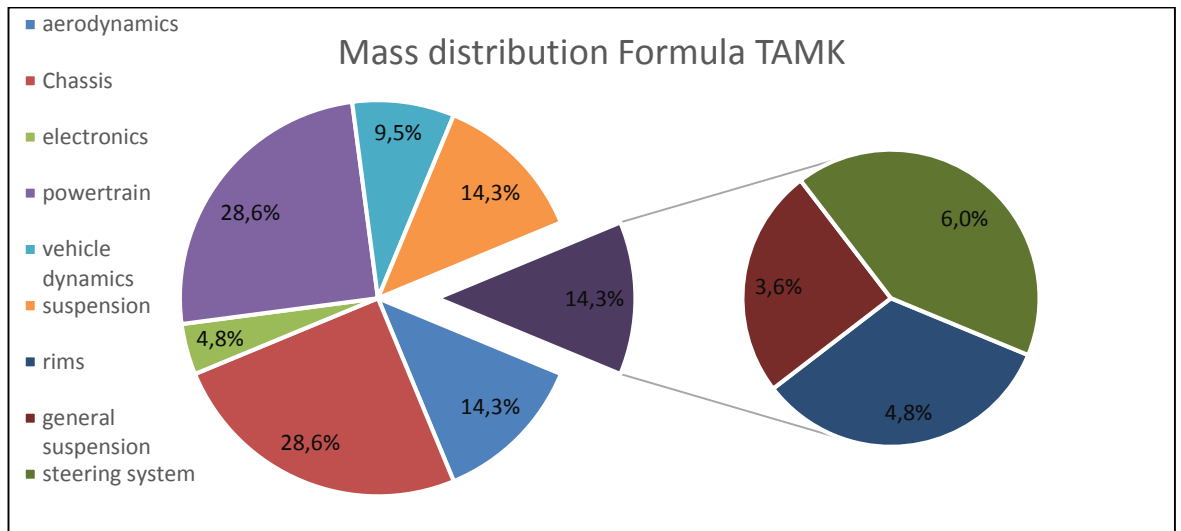
GRAPH 10. Mass distribution Student Formula TAMK

A lighter car accelerates faster than a heavy car and Student Formula is all about weight and power. In paragraph 7.3.1 the weight reduction was compared to the current rim, but it did not give an idea of the performance. The kerb weight of the sports car is 210 kg and in TABLE 11, the reduction of the two types of rims is compared to the 'unladen' mass of the car. The reduction of the different rims compared with the total mass of the car is given in TABLE 11.

TABLE 12. Weight reduction compared to the 'unladen' mass

	Reduction (%)
Current aluminium rim	0
multiple piece CF rim	1,4
one-piece CF rim	1,9

GRAPH 10 illustrates that the mass of the rims is 4,8% of the total mass. That's the main reason why a reduction of 1,4% or 1,9% does not seem much compared to the total mass. However in Student Formula, these reductions are quite large, but this statement depends on the cost of the production of the wheels.

7.4   Cost

The cost for the three different models were estimated and compared. The work hours were not mentioned because the purpose is to fabricate everything by students in TAMK.

7.4.1   Current rim

The information on the actual cost of the parts that were used in the current rim, was found on online-shops or it was given by the Formula Team.

TABLE 13. Price modern rim

Number	Item	Price per part (Eur)	Amount	Total price (Eur)
1	bolt	0,20	12	2,40
2	washer	0,02	24	0,48
3	loop, part 1	50,00	1	20,00
4	loop, part 2	50,00	1	20,00
5	spokes	350,00	1	200,00
6	nut	0,20	12	2,40

Total cost	€ 245,28

7.4.2   Multiple piece carbon fibre rim

The carbon fibre loop parts could be manufactured with the following materials: moulds, CF, epoxy resin, release film, breathe film, vacuum bag, plumbing system, vacuum pump, oven and electricity.

The cost of the 3D printed moulds could be calculated with the software that makes part of the 3D printer. *Pyrofil Gewebe style 450 CF* is the composite that is used to create the rims. The price of CF could be found per square meter and is about 50 Eur/m².

The volume of the first CF loop part could be determined with *Inventor* and is 281.000 mm³. The second part has a volume of 419.000 mm³.

$$V_{tot} = V_{part\ 1} + V_{part\ 2} \qquad\qquad (15)$$

$$V_{tot} = 281000\ mm^3 + 419000 mm^3 = 700000\ mm^3$$

Approximately 65 % of that volume consists of woven CF and the rest is epoxy resin.

Cost Carbon fibre

The total surface of the first part is 0,094 m² and the second part is 0,131 m². The average thickness of the woven CF is 0,2 mm. The amount of woven CF layers that was needed could be calculated.

$$\left(V_{part\ 1} + V_{part\ 2}\right) \cdot 0{,}65 = x \cdot \left(A_{part\ 1} + A_{part\ 2}\right) \cdot 0{,}02$$

$$x = \frac{\left(V_{part\ 1} + V_{part\ 2}\right) \cdot 0{,}65}{\left(A_{part\ 1} + A_{part\ 2}\right) \cdot 0{,}02} \qquad\qquad (16)$$

$$x = 10\ layers$$

The amount of CF for one rim could be calculated:

$$A_{multiple\ piece} = 2{,}25\ m^2$$

The price could be calculated:

$$PRICE = 2{,}25\ m^2 \cdot 50\,\frac{Eur}{m^2} = 112{,}5\ Eur$$

Cost epoxy resin

The price of epoxy resin is 5 Eur/l, so the cost could be calculated:

$$Cost = 0{,}35 \cdot 0{,}7l \cdot 5\,\frac{Eur}{l} = 1{,}23\ Eur$$

Cost of Moulds

The price of the moulds was calculated by computer software. The price of the moulds must be divided by the amount of rims that would be manufactured. The number of sets that would be produced was estimated at 25. This means that the moulds should last for the production of 100 rims.

$$Cost = \frac{Cost_{mould}}{100} \qquad\qquad (17)$$

$$Cost = \frac{1500\ EUR}{100} = 15\ EUR$$

Summary

TABLE 14. Cost multiple piece CF rim

Number	Item	Price	Amount	Total price (Eur)
1	bolt	0,20	12	2,40
2	washer	0,02	24	0,48
5	spokes	350,00	1	200,00
6	nut	0,20	12	2,40
3	Carbon fibre	112,50	1	112,50
4	epoxy resin	1,22	1	1,22
7	moulds	15,00	1	15,00
8	release film	10,00	1	10,00
9	breathe film	10,00	1	10,00
10	vacuum bag	15,00	1	15,00
11	electricity	5,00	1	5,00

Total cost	374,00

Estimated cost	168,72

The total cost for the multiple piece rim is shown in TABLE 13 and amounts 374,00 Eur. The topics marked in yellow are costs that are not made yet. The estimated cost that has to be made to manufacture a multiple piece CF rim is 170,00 Eur.

7.4.3   Cost one-piece carbon fibre rim

The cost for the one-piece CF rim was calculated on the same way as the multiple piece design. The main difference was that the parts of the modern rim were not reused in the design. The cost of CF is higher because the entire rim is made this composite.

TABLE 15. Cost one-piece CF rim

Number	Item	Price	Amount	Total price (Eur)
3	Carbon fibre	163,00	1	163,00
4	epoxy resin	1,77	1	1,77
7	moulds	20,00	1	20,00
8	release film	15,00	1	15,00
9	breathe film	15,00	1	15,00
10	vacuum bag	20,00	1	20,00
11	electricity	5,00	1	5,00

Total Cost	239,77

Estimated cost	239,77

7.4.4   Comparison costs

In TABLE 13 and TABLE 14 there is a difference made between the total price and the estimated cost. The current rim only had a total price because all parts were already bought and the cost of the single piece rim is equal to the total price because there were no parts reused from the modern rim.
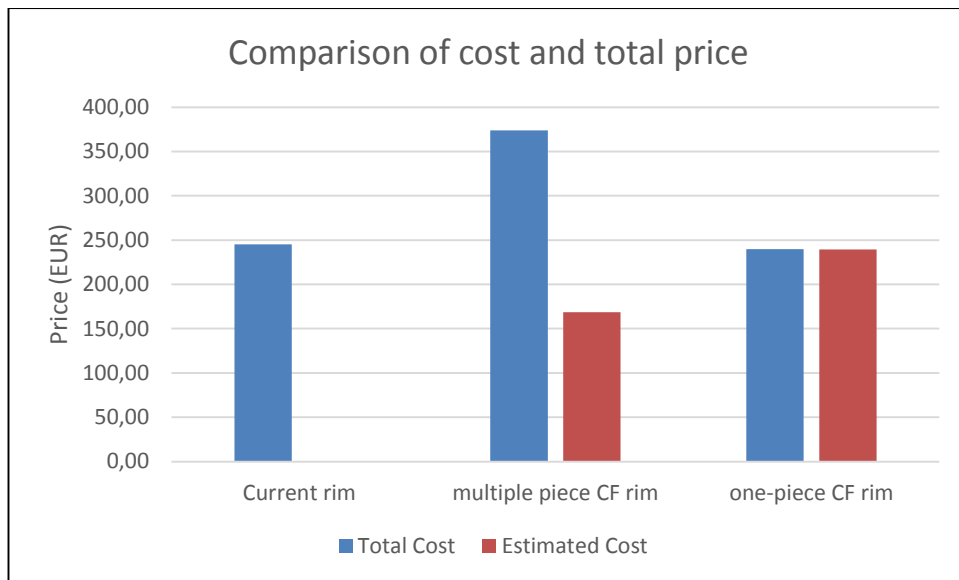
GRAPH 11. Comparison of total cost and estimated cost

8   Conclusion

Three different kinds of rims (modern rim, single piece CF rim, multiple piece CF rim) were compared to each other in chapter 7. Variables such as deformation, different kinds of stresses, weight and cost were determined and this chapter takes the results into account to formulate a conclusion.

GRAPH 5 illustrated the deformation of the three rims and none of them exceeded the maximum bending of the thickness divided by two (1,5 mm). The in-plane stress was the most critical one and the shapes were modified till the real in plane stress was smaller than the maximum stress in the z-direction. The largest stress of this kind occurred in the one-piece CF rim, but was still two times less than the allowable stress.

The crucial factor in race competition is mass, because the lighter the race vehicle, the greater the performance. The multiple piece rim reduced the mass with 30% and the single piece rim reduced the mass with almost 40% in comparison with the modern rim. This seemed like a lot, but if the decrement was matched with the 'unladen' mass of the car, the weight reduction was only 1,4% and 1,9%. This was normal because the total mass of the modern rims are only 4,8% of the car.

The cost to produce one multiple piece CF rim was 170,00 Eur and the cost of a single piece CF rim was estimated on 240 Eur.

The multiple piece rims are the best solution on short term. The moulds can easily made at TAMK with a 3D printer and the manufacturing process of the CF parts can be performed at TAMK as well.

The single piece rim is not dramatically more expensive and its weight is a big advantage. This might be easily manufactured at school as well, but the problem is that the rim does not fit on the current wheel hub. A new wheel hub must be designed to make an assembly possible between hub and rim. This also means a simulation and a study on manufacturability. Another advantage is that a custom design of the hubs can lead to weight saving. The one-piece CF rim might be the solution on a long term.

9 Discussion

The model of the applying forces and moments was the first step in this thesis. It was not possible to determine them exactly because some of the variables in the analytical approach were almost impossible to find out. That's why the force and moment calculations were compared to measurements that were provided by the Student Formula team. In reality the forces and moments alternate during the race and it was hard to figure out how they would alternate because the racetrack is different in every competition. That's why the forces were calculated in the worst case scenario.

The exact mechanical properties of *Pyrofil Gewebe style 450 CF* were not available. The characteristics were found in literature. The tables and charts were compared to datasheets of similar woven carbon fibres that could be found on internet.

Due to software limitation the rim could not be calculated thoroughly. The main issue was that the school license allowed a simulation with maximum 30.000 nodes. The variable thicknesses and complex shapes of the two CF designs made it impossible to take an accurate mid-surface. Instead of applying a shell element mesh which was appropriate for thin surface shapes, less accurate solid elements were applied. The simulation can however easily be recalculated by *Ansys* software that is equipped with a full license. If the solid element mesh can be modelled smaller (at least three elements in the thickness), a more accurate result would be the outcome.

Despite these errors that might occur, the model its most crucial factor qua strength (the in-plane stress) was still two times less than the maximum, so safety is ensured.

The single piece rim was more expensive than the multiple piece CF rim, but the latter was more efficient. If the Formula team would decide to use a one-piece rim, the wheel hubs need to be redesigned. There needs to be more research on the wheel hubs in the future because the one-piece rim requires adapted wheel hubs. Jesus Garcia already simulated the current hubs last year and his study could be the first step to new hubs.

In the future a different simulation software would be opted, because of the software problems with *Ansys*. *NX Siemens* is a simulation software that has more possibilities than *Ansys*. The parameters of woven CF in an epoxy matrix would be measured to check the

values that were given in literature. The maximum tyre forces could be measured as well if a proper lab was available.

10 References

Bekaert, G. (n.d.). *Composieten: Technologie en Productietechnieken.* Oostende: KULAB.

Bekaert, G. (n.d.). *Eindige Elementen Methode ing4EMEM.* Oostende: KHBO, IW&T.

Bekaert, G. (n.d.). powerpoint, Eindige Elementen Methode. Oostende: KHBO, IW&T.

Dieter Muhs, H. W. (2012). *Roloff/Matek Machine-onderdelen tabellenboek.* Den Haag: Academic Service.

Dieter Muhs, H. W. (2012). *Roloff/Matek Machine-onderdelen theorieboek.* Den Haag: Academic Service.

Dixon, J. C. (1996). *Tires, Suspension and handling.* 338 Euston Road London NW1 3BH: SAE.

eFunda. (2015). *eFunda.* Retrieved from Transverse isotropic: http://www.efunda.com/formulae/solid_mechanics/mat_mechanics/hooke_iso_transverse.cfm

García, J. F. (2014, May). Analysis of Wheel Hubs. Tampere, Finland: TAMK.

Harty, M. B. (2004). *The Multibody Systems Approach to Vehicle Dynamics.* Linacre House, Jordan Hill, Oxford OX2 8DP: Elsevier.

Hoa, D. G. (2007). *Composite Materials.* 6000 Broken Sound Parkway NW, Suite 300: CRC Press.

Ketonen, M. (2014, May). Formula SAE -kilpa-auton alumiini- ja kompo-siittivanteiden suunnittelu. Helsinki, Finland: Metropolia.

Khennane, A. (2013). *Introduction to finite element analysis using Matlab and Abaqus.* New York: Taylor and Francis Group.

Ressa, A. (2013). Development of a Carbon Fiber Wheel Rim. Ohio, USA: The Ohio State University.

Schöm, J. (2004). Coefficient of friction for aluminum in contact with a carbon fiber epoxy composite. *Elsevier*, 395-404.

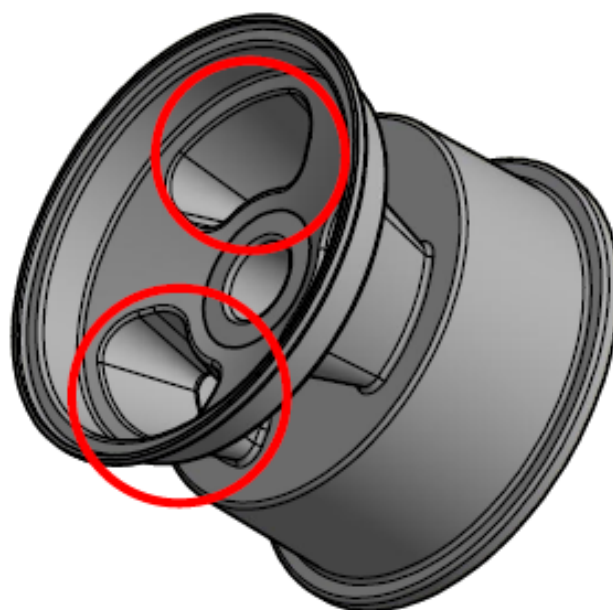TAMK, S. F. (2015). Retrieved from Tampere UAS motorsport: http://formula.tamk.fi/

Volkswagen. (2015). *Technical glossay*. Retrieved from VW Commercial vehicles: http://www.volkswagen-commercial.com.au/content/vw_nfz/importers/au/brand/en/customer-care/technical-glossary/Unladen-Mass.html

APPENDICES

Appendix 1. 3D drawings of samples

Sample 1: Reference

Sample 2: Larger holes
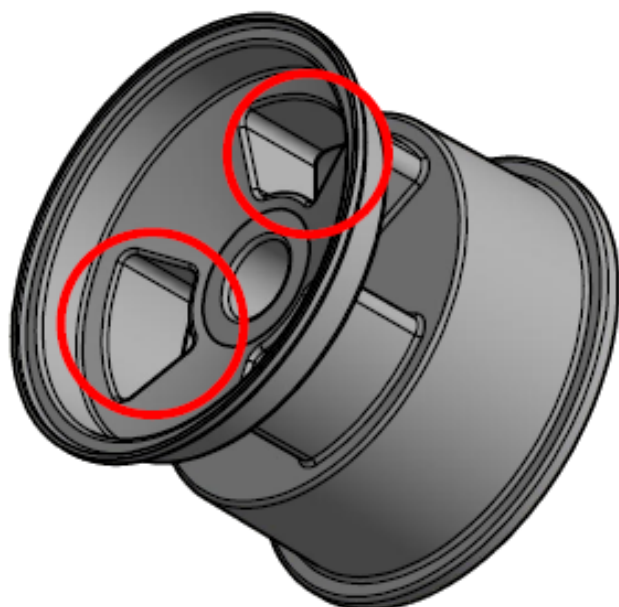
Sample 3: Different shape of holes
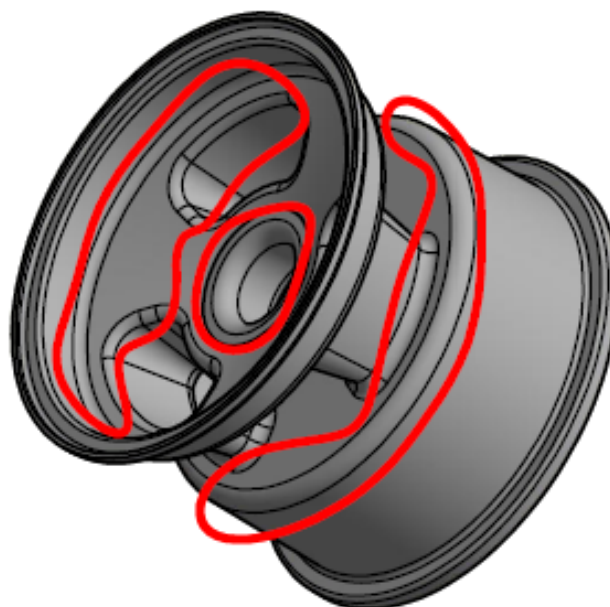
Sample 4: Larger radiuses

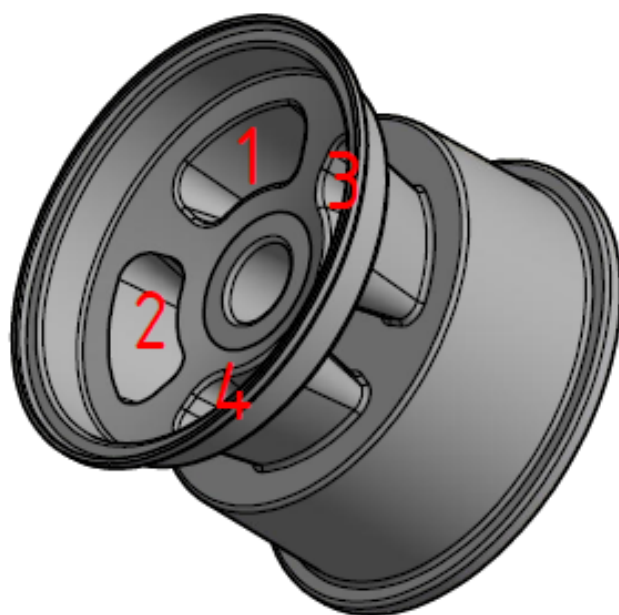|	NAME	DATE		
DRAWN	UYTTERSPROT Bryan	05/05/2015		
CHECKED				
APPROVED				

TAMK TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

Title: Samples 1,2,3 and 4

Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)

Size: A4	File Number: SA 1
Scale: 1/4	Sheet: 1 of 2

69

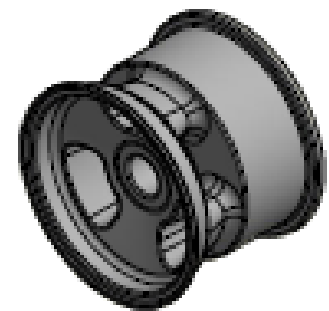Sample 5: Smaller horizontal ribs

Sample 6: Four holes
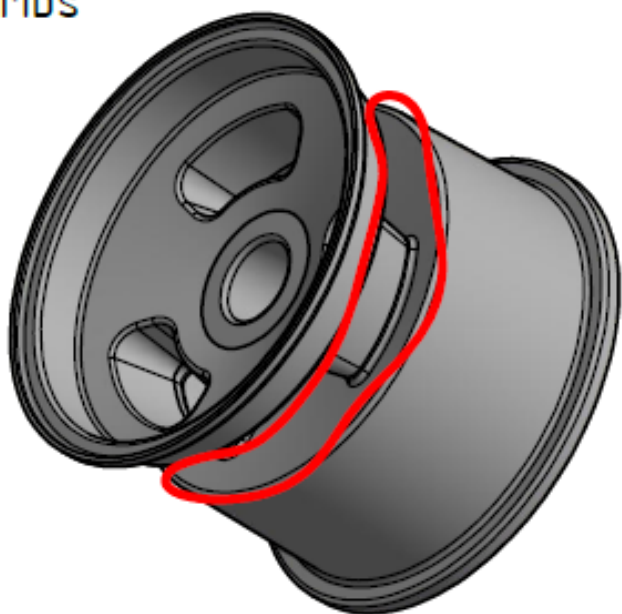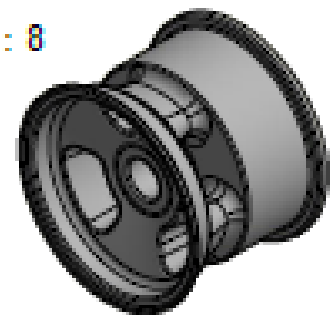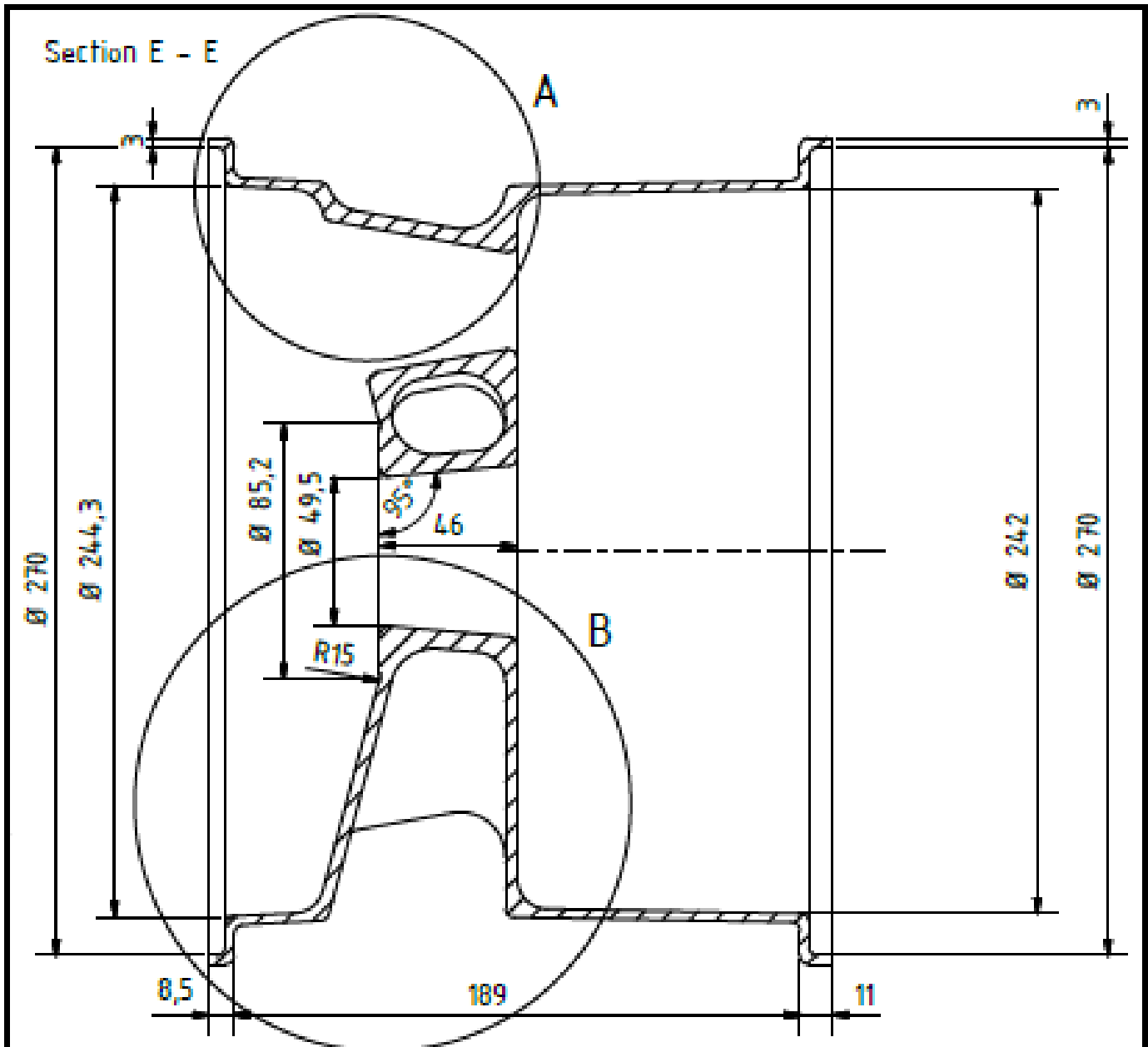

Sample 7: Metropolia design

Sample 8: Double thickness

	NAME	DATE
DRAWN	UYTTERSPROT Bryan	05/05/2015
CHECKED		
APPROVED		

TAMK TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

Title: Samples 5,6,7 and 8

Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)

Size: A4

File Number: SA 2

Scale: 1/4

Sheet: 2 of 2

Appendix 2. Technical drawing one-piece CF rim

E

Hole x3 every 120°
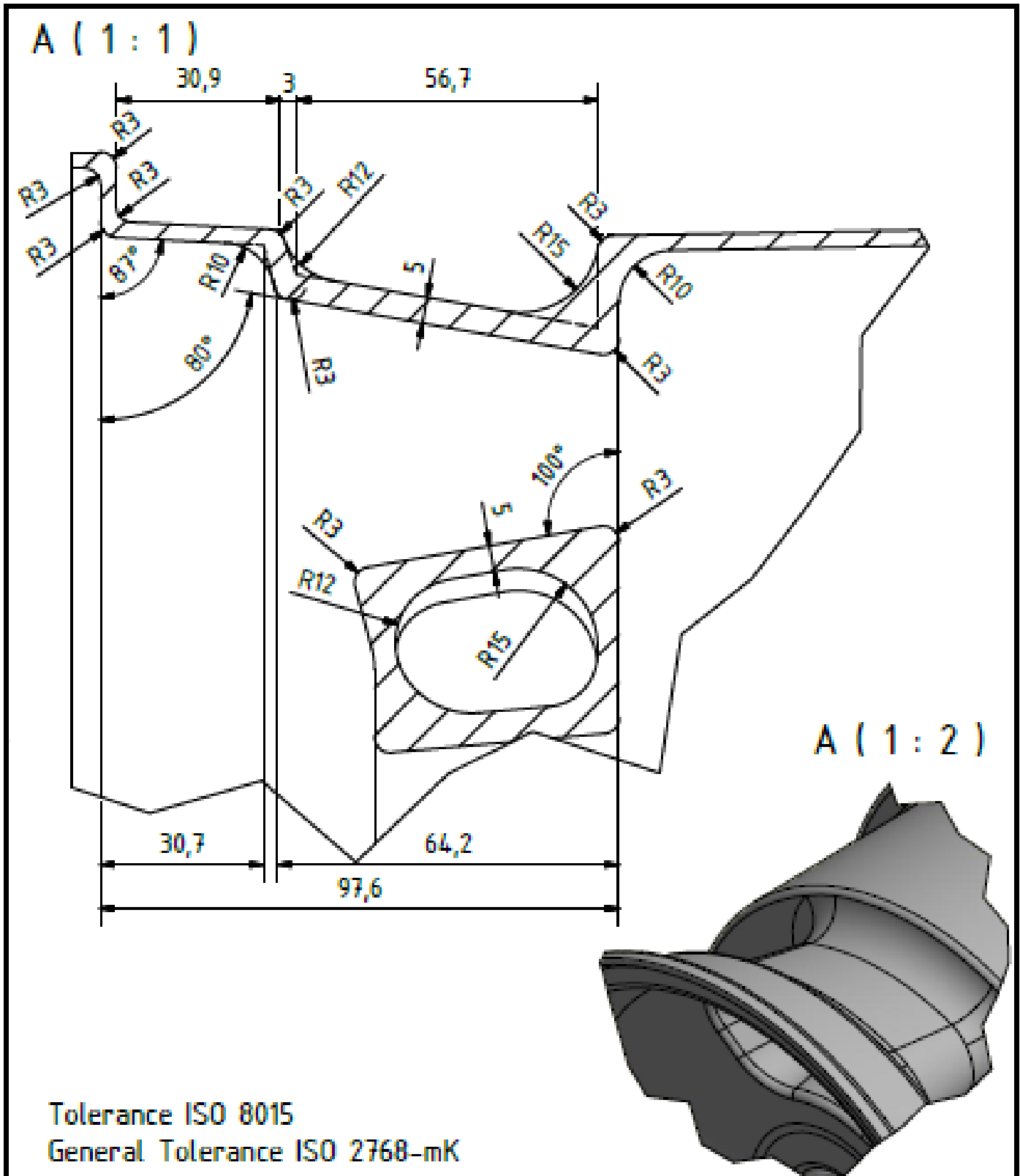
60°

R10

R10

R100

R68

E

Scale 1 : 8

Tolerance ISO 8015
General Tolerance ISO 2768-mK

	NAME	DATE	TAMK TAMPEREEN AMMATTIKORKEAKOULU *Tampere University of Applied Sciences*	
DRAWN	UYTTERSPROT Bryan	05/05/2015		
CHECKED			**Title: One-piece rim**	
APPROVED				
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4	File Number: OP 1
			Scale: 1/2	Sheet: 1 of 4

Section E – E

A

3

B

Ø 270
Ø 244,3
Ø 85,2
Ø 49,5
95°
L6
R15

Ø 242
Ø 270
3

8,5
189
11

Scale 1 : 8

Tolerance ISO 8015
General Tolerance ISO 2768-mK

	NAME	DATE		
DRAWN	UYTTERSPROT Bryan	05/05/2015	TAMK TAMPEREEN AMMATTIKORKEAKOULU Tampere University of Applied Sciences	
CHECKED			Title: One-piece rim	
APPROVED				
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4	File Number: OP 2
			Scale: 1/2	Sheet: 2 of 4

A (1 : 1)

30,9   3   56,7

R3
R3
R3
R3
81°
80°
R10
R12
R3
R12
R3
5
R10
R15
R3
R3
R3
R12
R3
R15
5
100°
R3

30,7   64,2

97,6

A (1 : 2)
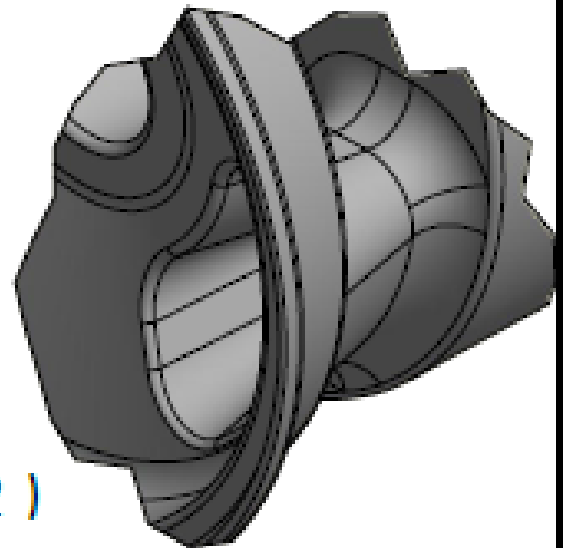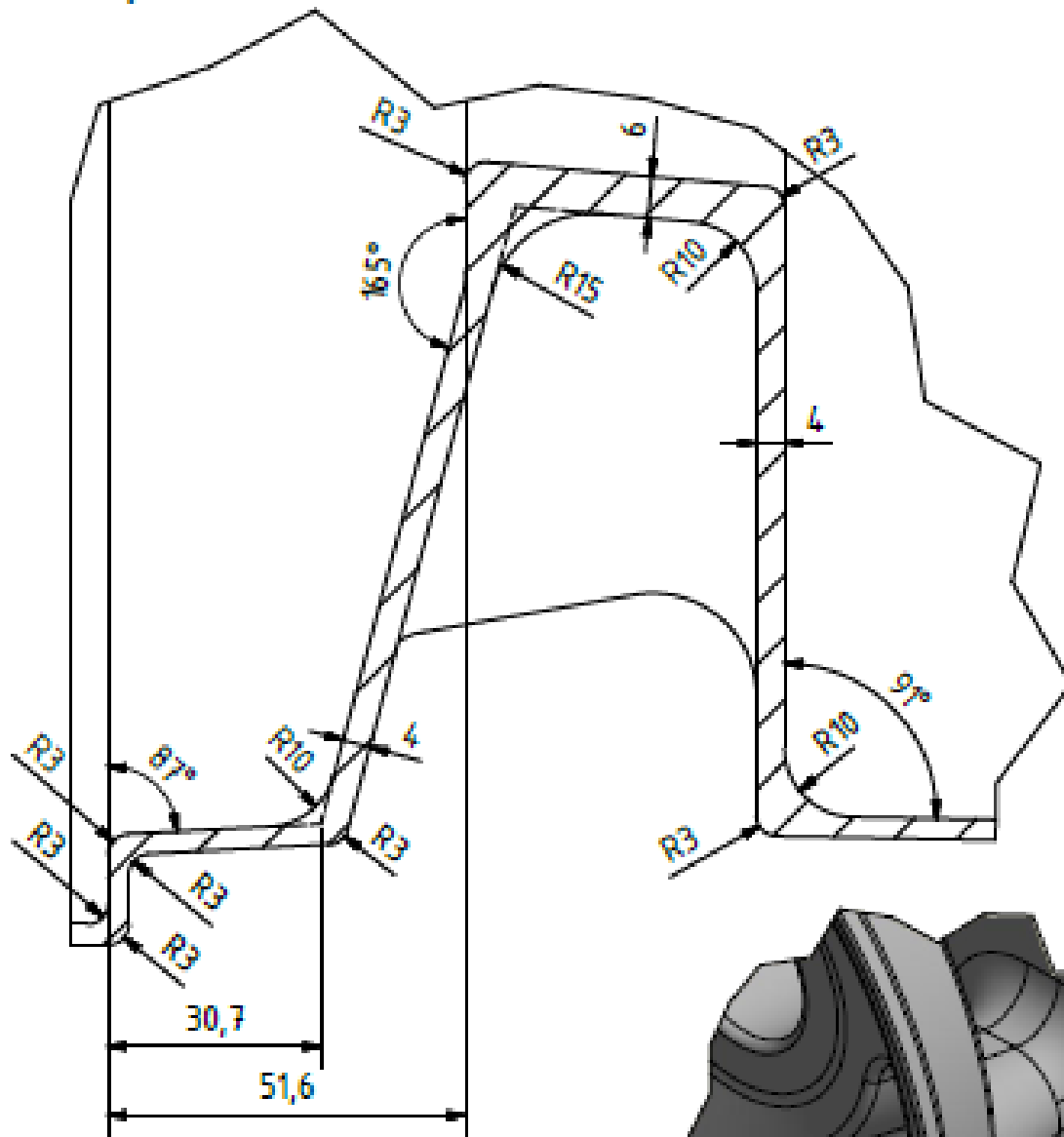
Tolerance ISO 8015
General Tolerance ISO 2768-mK

	NAME	DATE	TAMPEREEN AMMATTIKORKEAKOULU *Tampere University of Applied Sciences*	
DRAWN	UYTTERSPROT Bryan	05/05/2015		
CHECKED			Title: One-piece rim	
APPROVED				
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4	File Number: OP 3
			Scale: 1/2	Sheet: 3 of 4

B (1 : 1)

R3

6

R3

165°

R15

R10

4

R3

R3

8T°

R10

4

R3

R3

R3

R3

R3

9T°

R10

R3

30,7

51,6

Tolerance ISO 8015
General Tolerance ISO 2768-mK

B (1 : 2)

	NAME	DATE	
DRAWN	UYTTERSPROT Bryan	05/05/2015	
CHECKED			Title: One-piece rim
APPROVED			

TAMPEREEN
AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

Unless otherwise mentioned
Dimensions are in mm
and angles in degrees (°)

Size: A4	File Number: OP 4
Scale: 1/2	Sheet: 4 of 4

Appendix 3. Technical drawing multiple piece CF rim

A

STC Ø171,45

Ø6,35 $^{+0,5}_{-0,0}$ ×12 for M6

⌖ | ⌀ 0,15 Ⓜ | A | B
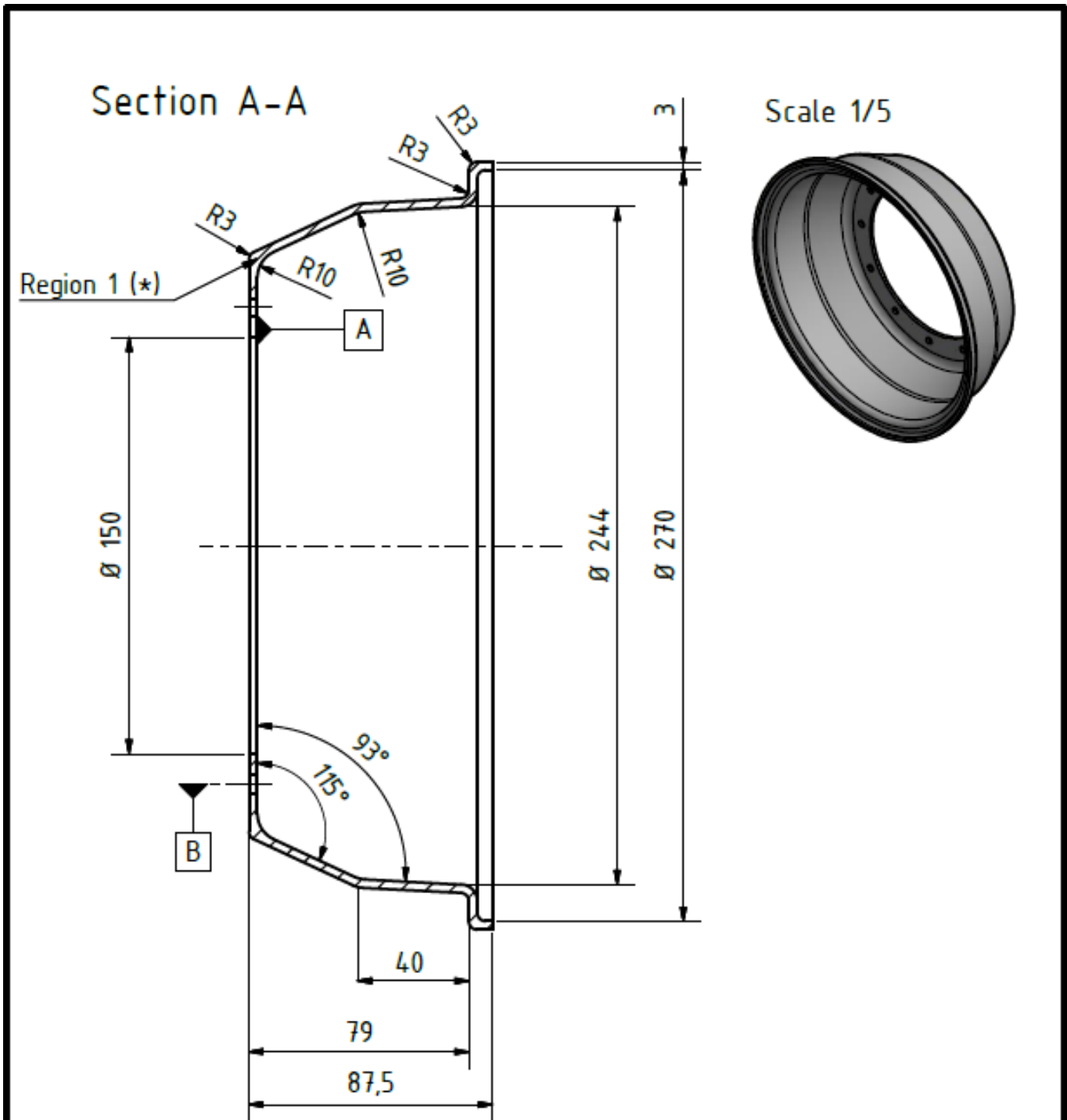
A

Scale 1/5

Tolerance ISO 8015
General Tolerance ISO 2768-mK

	NAME	DATE			
DRAWN	UYTTERSPROT Bryan	05/05/2015	TAMK TAMPEREEN AMMATTIKORKEAKOULU Tampere University of Applied Sciences		
CHECKED			Title: Part 1 Multiple piece CF rim		
APPROVED					
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4		File Number: MP 1
			Scale: 1/2		Sheet: 1 of 4

Section A-A

Scale 1/5

R3

R3

R3

R10

R10

R3

Region 1 (*)

A

Ø 150

Ø 244

Ø 270

3

93°

115°

B

40

79

87,5

Tolerance ISO 8015
General Tolerance ISO 2768-mK

(*) The constant thickness is 3 mm,
only in region 1 the maximum
thickness is 5 mm.

	NAME	DATE		TAMPEREEN AMMATTIKORKEAKOULU Tampere University of Applied Sciences
DRAWN	UYTTERSPROT Bryan	05/05/2015		
CHECKED			Title: Part 1 Multiple piece CF rim	
APPROVED				
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4	File Number: MP 2
			Scale: 1/2	Sheet: 2 of 4

B

STC Ø171,45

Ø6,35 $^{+0,5}_{-0,0}$ x12 for M6

$\oplus$ | $\emptyset$ 0,15 Ⓜ | C | D

B

Tolerance ISO 8015
General Tolerance ISO 2768-mK

	NAME	DATE
DRAWN	UYTTERSPROT Bryan	05/05/2015
CHECKED		
APPROVED		

TAMK TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

Title: Part 2 Multiple piece CF rim

Unless otherwise mentioned
Dimensions are in mm
and angles in degrees (°)

Size: A4	File Number: MP 3
Scale: 1/2	Sheet: 3 of 4

Section B-B

Scale 1/5

R3
R3
R5
R15

C

Ø 270
Ø 242
Ø 150

91°

D

Region 2 (**)

3

110

121

Tolerance ISO 8015
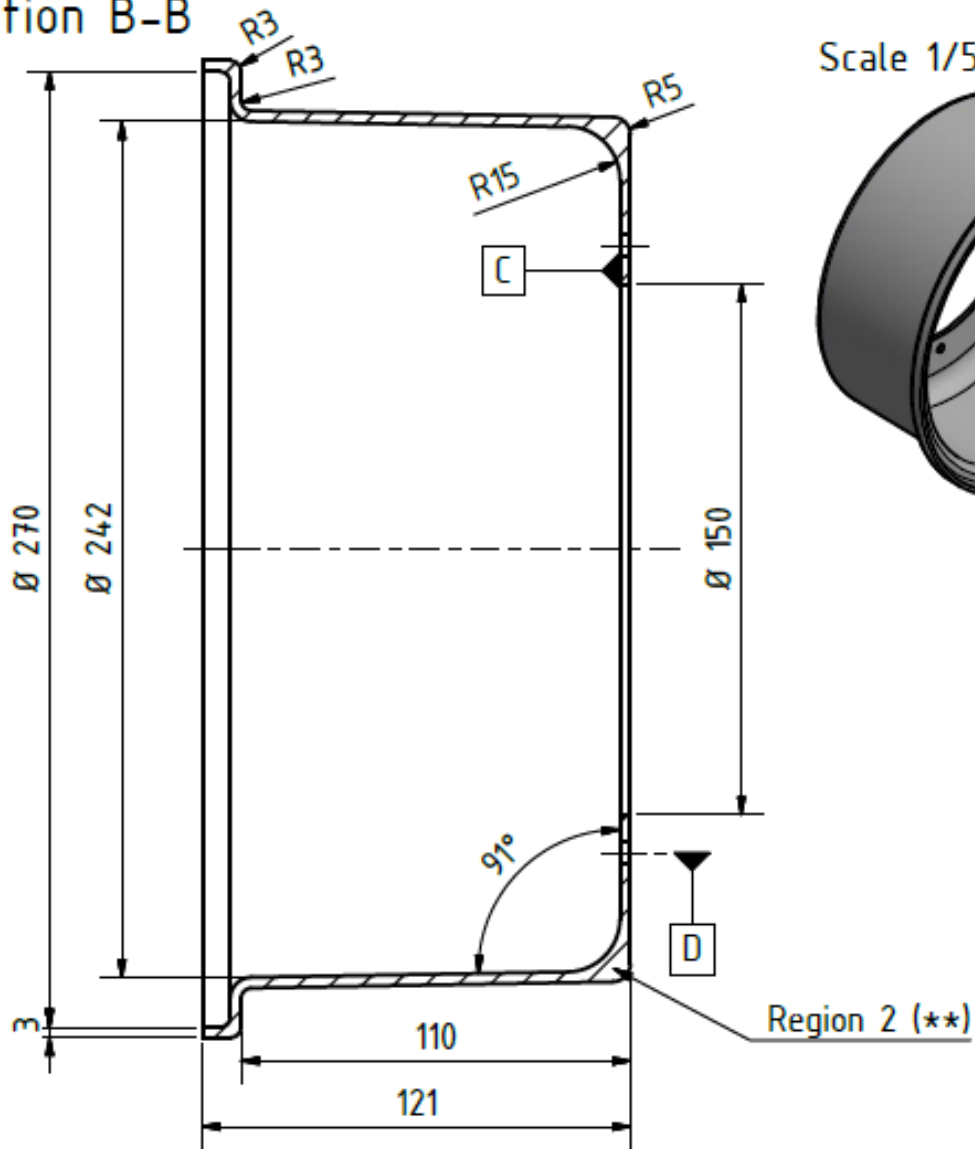General Tolerance ISO 2768-mK

(**) The constant thickness is 3 mm, only in region 2 the maximum thickness is 10 mm.

	NAME	DATE	TAMPEREEN AMMATTIKORKEAKOULU Tampere University of Applied Sciences	
DRAWN	UYTTERSPROT Bryan	05/05/2015		
CHECKED			Title: Part 2 Multiple piece CF rim	
APPROVED				
Unless otherwise mentioned Dimensions are in mm and angles in degrees (°)			Size: A4	File Number: MP 4
			Scale: 1/2	Sheet: 4 of 4

Appendix 4. Summary of all results

		Current design	multiple piece CF rim, CF loop	multiple piece CF rim, Al spokes	one-piece CF rim
deformation	real deformation (mm)	0,631	0,566	0	0,991
	max deformation (mm)	1,5	1,5	1,5	1,5
stress	Real Von-Mises stress (Mpa)	173,8	40,4	48,5	27,5
	Max Von-Mises stress (Mpa)	280,0	360,0	280,0	360,0
	Real shear stress (Mpa)	82,3	22,3	24,4	14,1
	Max shear stress (Mpa)	125,0	63,0	125,0	63,0
	Real in-plane stress (Mpa)		7,6		20,5
	Max in-plane stress (Mpa)		42,0		42,0
			Multiple piece CF rim		
mass	Mass of one rim (g)	2493		1751	1500
	Mass of four rims (g)	9973		7005	5991
	reduction compared to modern rim (%)	0		29,8	39,9
	reduction compared to 'unladen' mass (%)	0		1,4	1,9
cost	Total price (EUR)	245.28		374,00	239,80
	Extra cost (EUR)	0,00		168,70	239,80