Finite element study of pressure distribution under tyre during low speed for explaining rolling resistance

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Abstract

Road transports are necessary as they are very flexible, and are essential for the logistics of today, though this requires sustainable solutions for environmentally stable transportation. Trucks are immense machines that are heavily affected by resistance, in both air and rolling resistance. In this report, the main focus will be to gain a better understanding of how the pressure distribution under a tyre influences the rolling resistance.

In order to achieve a clearer perception of this phenomena, a 2D finite element model was defined. Two separate concepts were constructed, a more advanced model in ANSYS and a more simplified, yet more controllable, model in MATLAB. A hypothesis was formulated, wherein it is described that the pressure distribution is thought to be offset in the rolling direction. This would be the driving mechanism in creating rolling resistance, and the FE-models were made in order to try and capture this behaviour. The models were created with two layers, one for the sidewall and one for the belt. The boundary conditions were different between the models, in ANSYS the force was prescribed while in MATLAB, the deformation was prescribed.

The simulations do show an offset for the pressure distribution beneath the tyre, which was thought to be the case. Though the simulation show that the offset would be in the other direction, something that was hard to explain. The two different model do however show a similar pattern, which was encouraging, though no unambiguous tendency was found. A varying vertical load, and the effects of that variation would be a desired factor to test, though since the project was short on time, this was not examined. Finally, there is more work to do in order to better understand the subject, which could be made by testing the model further or by developing a more complex model in either 2D or 3D.

Keywords: FEM, Tyre, Vehicle Dynamics, Truck, Rolling Resistance

Contents

1

Introduction

In this project a finite element study of the pressure distribution beneath a truck tyre will be made. The purpose is to gain a better understanding of how rolling resistance is affected by this pressure distribution. A hypothesis will be formulated, and the FE-model will be used to determine if the hypothesis is correct or not.

1.1 Background

Road transports are necessary as they are more flexible and scalable than most other means of transport, i.e. boat, train or air. This is an advantage and means there lies importance in creating energy efficient solutions, for sustainable logistics. However, since trucks are large and heavy machines, they are not very energy efficient. For vehicles there are two dominant factors when it comes to resistance, air and rolling resistance [1].

The first factor, air resistance, has a large impact when designing a truck, since the frontal area is quite large. Large resistance means increased fuel consumption, which leads to higher costs and more emissions. The other factor, which is the main focus of the report, is the rolling resistance, which is a loss of torque. Particularly, when the speed of the vehicle is low, up to the range of 40-60 km/h, the rolling resistance becomes the dominant factor holding the truck back [1]. Thus, there is a large area for improvement to make the vehicle more efficient.

A good estimation of the rolling resistance is also needed to make accurate range predictions, which is helpful to the driver, and also to predictive cruise control functions with speed profile optimization. This is even more crucial in electric trucks since charging takes longer than regular refueling. In a test report from Volvo Trucks [1] it has been determined that the existing way of calculating the rolling resistance is not accurate enough and therefore the way of calculating rolling resistance needs to be improved.

In this report an FE-model will therefore be created to examine the behaviour of a truck tyre, and create a model that can calculate the rolling resistance in a more accurate manner.

1.2 Goal of the project

The goal of this project is to study the pressure distribution under the tyre and investigate if there is an offset of the pressure distribution by formulating an FE-model.

1.3 Scope

The scope of the project is to create an FE-model to represent a simplified tyre. The tyre will be studied for a low and constant speed. Two different models will be made, one in ANSYS and one in MATLAB.

When the FE-model is completed, the testing of the model can be conducted. The results from these computations will be the pressure distribution under the tyre, and its influence on the rolling resistance can be determined. Based on the results, it can be concluded whether the hypothesis is correct or if further improvements should be added.

1.4 Report overview

The report is structured into three main parts. The first part consists of chapters 1 and 2. The current chapter, chapter 1, is a basic introduction to the project, followed by a introduction to the main theory behind the project in chapter 2. The second part of the report covers the set-up of the FE-model, in chapter 3, while in chapter 4 the final results of the project are presented. In the third and final part of the report, consisting of chapter 5 and 6, the results and recommendations for further work are discussed and the conclusion for the project is presented.

2

Theory

In order to lay a foundation on which the FE-model will be created upon, a hypothesis was formulated to get a better understanding of the problem. A brief introduction to tyres is also given in this chapter. In addition, the assumptions needed to create the model are presented.

2.1 The Tyre

A tyre is a complex structure and is constructed out of several different components. The main element of a tyre is rubber, which builds the outermost layer. Inside the rubber, there are steel reinforcements, to make the tyre withstand larger loads, since rubber by itself allows quite large deformations. Figure 2.1 shows a schematic view of a truck tyre and its different components.

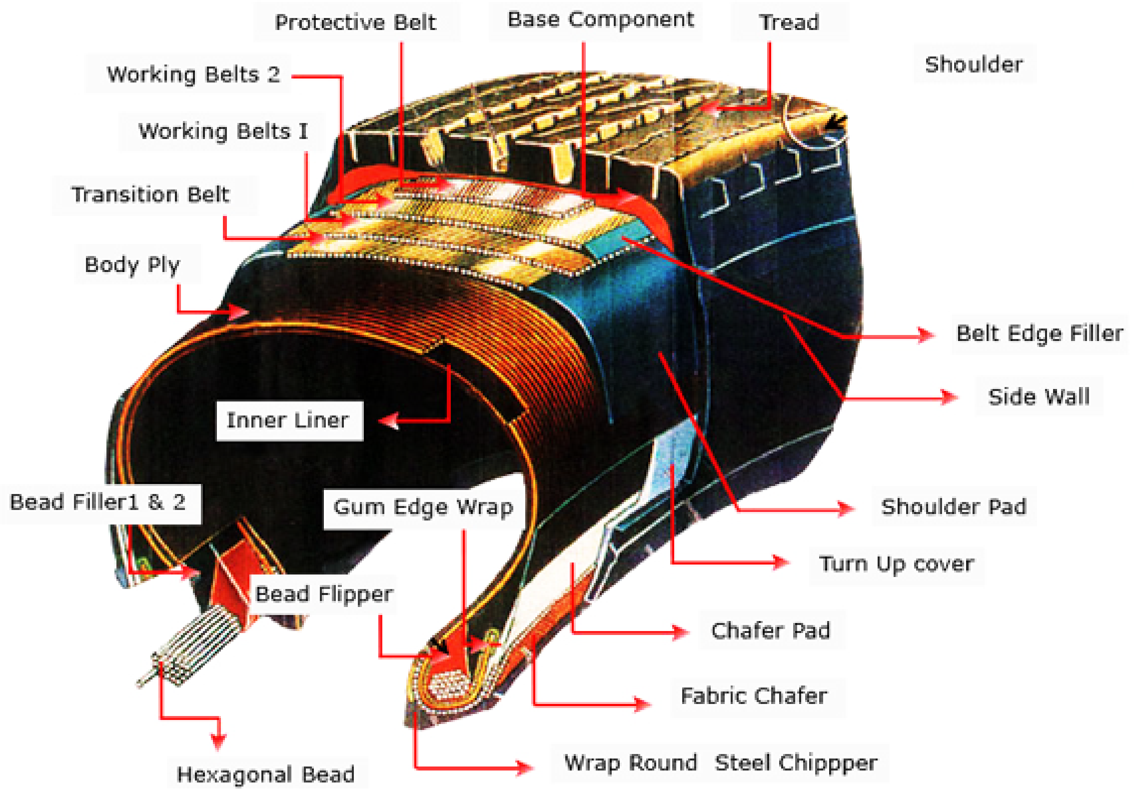

Figure 2.1: The construction of a truck tyre. [2]

The complexity of the tyre can be seen in figure 2.1 above, together with the various different components. It can be noticed that the inner liner covers the whole inside of the tyre, while the belt only reinforces the surface of the tyre. On the very surface, there are treads, designed to have sufficient grip on road surfaces. The tread is often an intricate pattern that requires a large amount of time to perfect.

For this project, the tyre will be simplified to a 2D-model instead of a 3D-model. This is because a 3D-model much more detailed and thereby would require significantly more time to model in comparison to a 2D model. As the only forces taken into consideration are F_z and F_x, which are both acting in the x-z-plane, it was deemed that a 2D model would be sufficient to solve this problem. A sketch of the simplified tyre can be seen in figure 2.2.

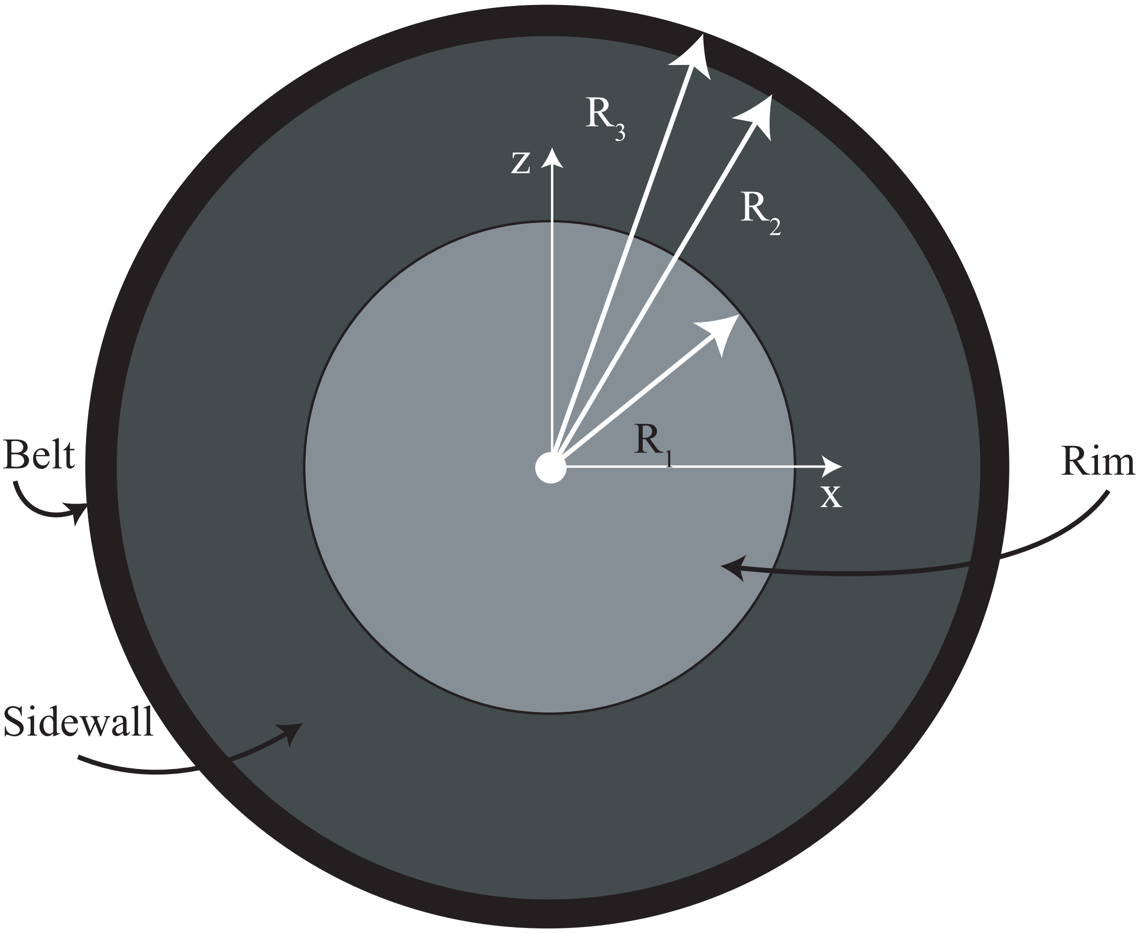

Figure 2.2: Sketch of a 2D tyre with the coordinates defined. To simplify our model the effect of the tread is neglected in our proposed 2D model.

As can be seen from figure 2.2, the wheel is simplified to three different layers. The grey middle circle is the rim, which is rigid, meaning it does not deform. However, it does translate whenever a load is applied, but it will remain in its original shape throughout. The purpose of the rim is to make sure that the inner section of the tyre remains circular. The next layer, the darker grey area, is the sidewall. This part consist primarily of rubber and closes the sides of the tyre, and connects the tyre to the rim. The outermost layer is the surface of the tyre, or the belt, which consists of a stronger mixture of materials than the sidewall. The belt is a steel reinforced rubber, which will prevent the tyre from deforming too much. On the inside of the tyre there is air pressure, which is also known as the inflation pressure, and is what keeps the tyre intact and round in shape.

2.2 Rolling Resistance Coefficient

Rolling resistance is generally defined as the force resisting the motion when a body (a tyre in our case) rolls on a surface. Rolling resistance in a pneumatic tyre is mainly caused due to hysteresis. When the tyre is stationary, normal pressure under the contact patch is distributed symmetrically about the centre of the tyre and the resultant normal force acts on the centre of the tyre. But when rolling is introduced, the distribution of the normal pressure is unsymmetrical about the centre of the tyre and this causes on offset of resultant normal force (figure 2.4). We know for a fact that an offset occurs during rolling but there is no explanation yet as to why it occurs. This project is an attempt to answer that question.

The Rolling Resistance Coefficient (RRC) for a free rolling tyre is defined as the ratio of the horizontal force F_x to the resultant normal force F_z (equation 2.2). In the test conducted by Volvo trucks, the main objective was to differentiate between the magnitude of air and rolling resistance, respectively [1]. The test was performed for different combination of trailers and the RRC was found. Ideally, our goal was to draft a hypothesis to explain the pressure distribution under the tyre and the offset of the resultant normal force and compare the results with the test data from Volvo but due to limited time period we only focused on the former task.

2.3 Material properties and tyre specifications

The tyre that is taken into consideration is a large truck tyre, with the specifications listed in table 2.1 below. The tyre that was analysed was a wide base truck tyre with dimensions 445/50R22.5. The Young's modulus for the side wall was assumed to be that of soft elastic material that should mimic the behaviour of rubber, which in reality is a viscoelastic material. The belt was stiffer, this is due to the reinforcement, which was discussed in the previous section. The inflation pressure is included as well, which simply is the air pressure inside the tyre. A normal pressure for truck tyres is approximately 8 - 9 bar [3]. Since the the tyre is reduced to a 2D-model, the width of the tyre is not included.

Table 2.1: Tyre specifications

Tyre Radius (R_3)	508 mm
Sidewall Radius (R_2)	504.25 mm
Rim Radius (R_1)	285.75 mm
Poisson's ratio Side wall	0.499
Poisson's ratio Belt	0.3
Young's Modulus Side Wall	1 GPa
Young's Modulus Belt	210 GPa

The R_1, R_2 and R_3 variables in table 2.1 are references to the arrows in Figure 2.2. It should be noted that the stiffness used could be subject to refinement, since there were no unambiguous figures for the values of the particular tyre and material combinations analysed.

2.4 Hypothesis

A contribution to make estimation of remaining travelling range more reliable would be a model of how a varied F_z influences the RRC. A model of RRC would improve the range estimation, which is desired.

"The model needs to have physical interpretation of involved variables and parameters to have large enough validity range. A mechanism sketched in Figure 2.4 is one draft hypothesis for the project. It would require a 2D model of elasticity, probably an FE-model." The hypothesis was proposed by supervisor Bengt Jacobson [4].

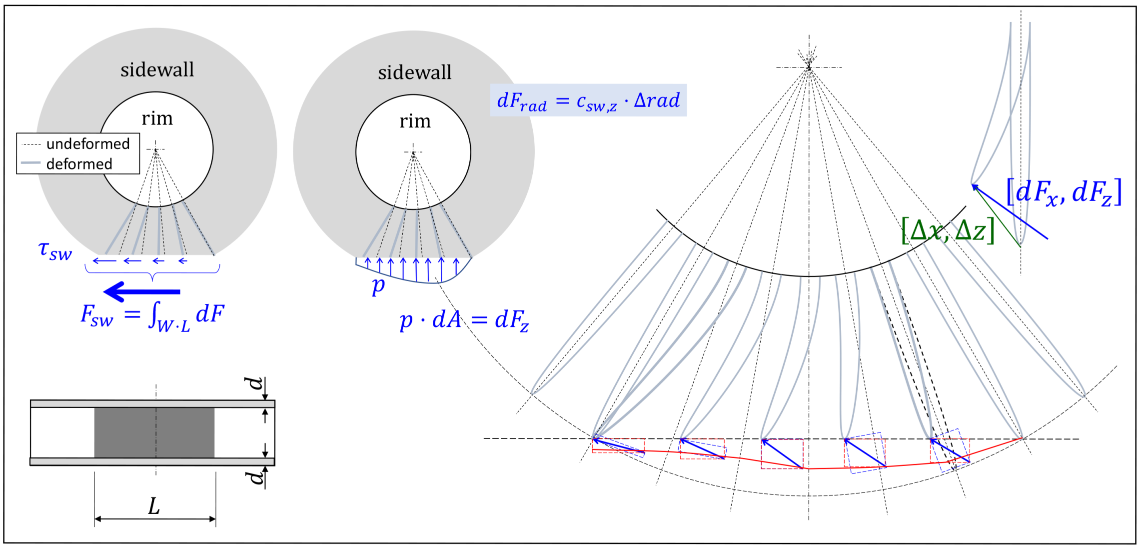

Figure 2.3: Proposed hypothesis for the project. [4]

One possible mechanism that could explain the pressure distribution which is offset towards the front end in rolling direction, can be seen to the right in figure 2.3. The mechanism is drawn as if the sidewall had beam elements, but a model implementation in 2D elasticity structure is also a possible approach. The speed of the contact surface is prescribed, which also makes the model represent direction of rotation.

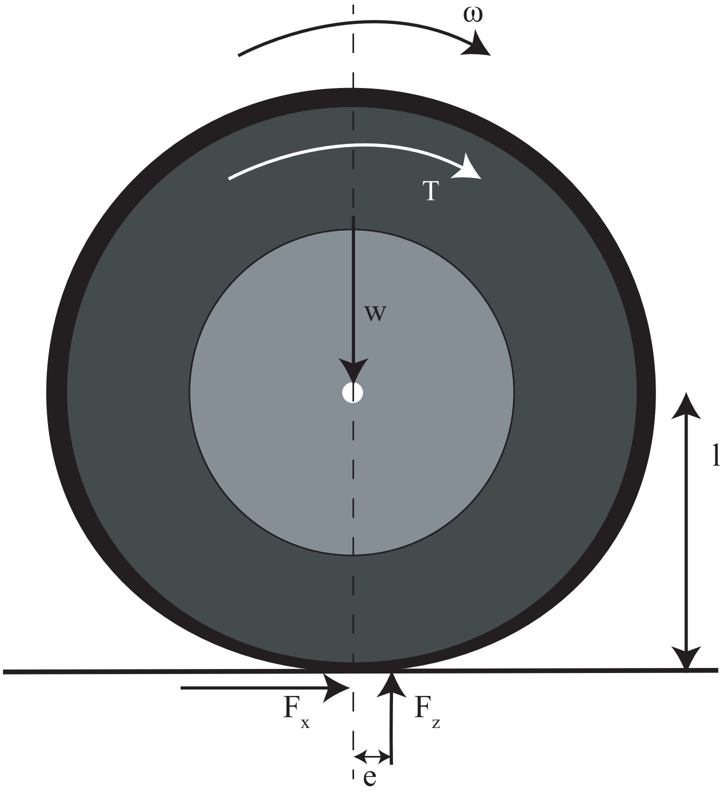

Figure 2.4: Forces acting on the wheel.

In figure 2.4 above, the variable e is introduced. This variable can be described as the distance from the center of the wheel to the position of the reaction force or center of the pressure distribution. This distance works as a lever for the moment induced by the force F_z. The other force that contributes to this moment is the force F_x, which has the deformed tyre radius, l, as its lever. w is the weight of the truck, while T is the applied torque. Note that the tyre in the figure above that the tyre is slightly deformed, i.e. the bottom part is mildly flattened out.

2.5 Assumptions

In order to create and to properly define the model in a simple manner as possible, some assumptions are made.

- Keep all parameters and variables, except F_z, numerically fixed.
- Study only low speed, no inertial effect in the tyre.

- Only constant speeds are considered, which means that viscous damping in tyre is also neglected.
- Only 2D models of tyre is considered
- Neglect the tread of the tyre.
- Free rolling tyre, i.e. no torque input on the wheel.

Some comments can be made about the limitations, all parameters are fixed, meaning that the tyre will have a fixed velocity, dimensions and material parameters. F_z is the variable that may be changed, to explore different loading conditions. The speed will be kept low, to not have inertial effects from the tyre present. Moreover, interest lies in the steady state case, when the speed is constant. These limitations are in place to make sure the model can be developed within the given time frame. Since the tyre will be modelled in 2D, there is no need to consider the tread, and in addition a tread pattern would require too much time to design.

2.6 Pressure distribution and rolling resistance

There is a normal stress acting on the road-tyre interface as the tyre is compressed and the normal force (F_z) distributed along the contact patch. The stress distribution is normally assumed to be in a parabolic shape but since F_z is offset, this shape also tends to deviate from its symmetry.

In order to describe the relation a moment balance is done about the center of the road. The equation along with the assumption that it has to be an offset of where the resulting force F_z is acting and that it is a free rolling wheel, that is no torque is applied, and can be seen in equation (2.1)

$$F_x * l + F_z * e = 0 \tag{2.1}$$

The rolling resistance could be calculated according to equation (2.2). By assuming no torque this can be simplified.

$$F_x = \frac{T}{R} - RRC * F_z = \{T = 0\} = -RRC * F_z \tag{2.2}$$

By combining equations (2.1) and (2.2) equation (2.3) can be created. From this equation is it possible to see that RRC is independent form the vertical force. However, the RRC is dependent on the height between the road and the center of the rim which is dependent on the vertical force.

$$-F_z * \frac{e}{l} = -RRC * F_z \to \frac{e}{l} = RRC \tag{2.3}$$

If there would be a symmetrical pressure distribution, e would be equal to zero since the vertical reaction force F_z would be acting along the center line of the wheel and thereby RRC must also be equal to zero. These equations are obtained by considering that the surface (ground) is a hard surface and thus does not deform. The RRC is calculated as a percentage which is the percentage of energy lost due to rolling resistance.

Another way to calculate the offset is to make a moment balance for each node around the center of the wheel and put this equal to a total load acting in the offset position, e. From this offset could be calculated according to equation (2.4).

$$\frac{\sum F_i x_i}{\sum F_i} = e \tag{2.4}$$

3

Creating the Model

The main challenge in this project was to set up FE-models to describe the problem previously presented. The FE-models were created using ANSYS and MATLAB. The reason for choosing two different software was that it would enable us to pursue two different approaches. ANSYS was chosen since it was user friendly and it was also used in previous courses. In MATLAB, the nodes in contact with the ground were prescribed with a displacement, while the force was calculated as a result. In ANSYS though, the force was prescribed and the displacement was computed. This chapter of the report will present the process of creating the models and their respective components. Firstly the geometry was transferred from the sketch in Figure 2.2 to ANSYS and MATLAB. Then, the boundary conditions are defined, along with the forces acting on the wheel. Finally the meshes for the two models are presented, which are critical for the accuracy of the computations.

3.1 Geometry

The geometry of the tyre was not made identical in the two softwares, since the ANSYS model could take on more complex constructions. Below are the different model geometries presented. A thickness of 5 mm was used in both ANSYS and MATLAB. Since only 2D deformations were considered, plane strain condition was used.

3.1.1 ANSYS-model

The model was created in ANSYS according to the tyre specifications listed in table 2.1. In essence, the model consists of three parts: the sidewall, the belt, and the ground. The belt was assumed to be made out of steel with Young's modulus 210 GPa. The ground was modeled as a rigid part. The rim was not modeled, however a frictionless support was used in the place of the rim, which allowed it to rotate freely. Figure 3.1 shows the modelled tyre in ANSYS.

In ANSYS all the different sections were assigned different material properties. In ANSYS there is the option to create materials with properties defined by the user. Two such materials were made for the belt section and the sidewall with material properties according to table 2.1. These new materials were then assigned to their respective part. The road was created out of material a thousand times stiffer that steel, this to prevent any deformations of the ground.

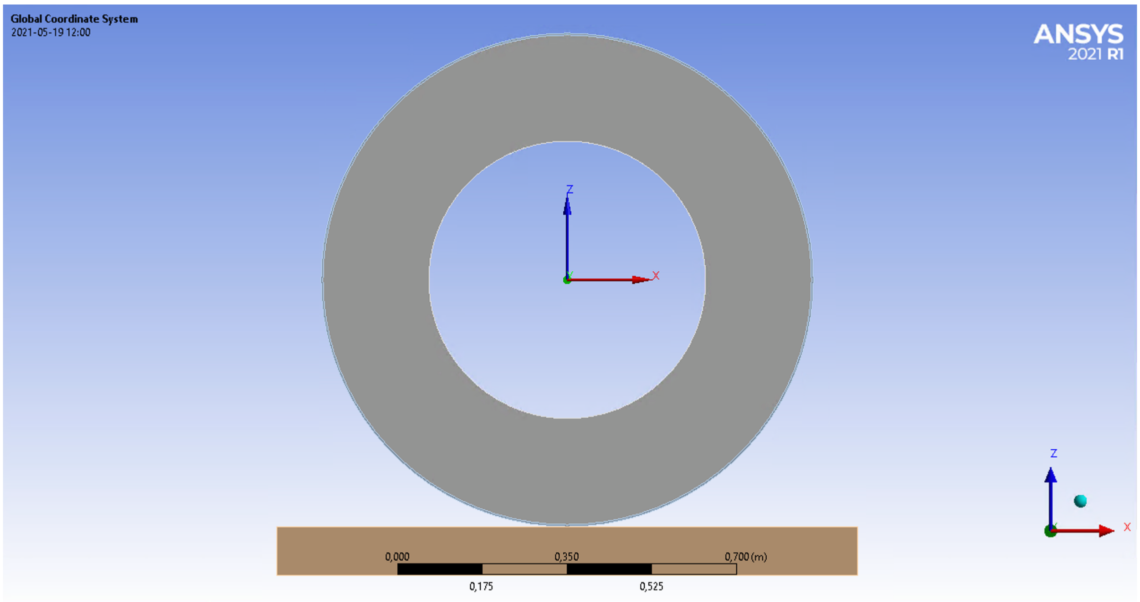

Figure 3.1: The model of the tyre in ANSYS.

3.1.2 MATLAB-model

The geometry in MATLAB was modeled very similarly to the one in ANSYS. However, there were three differences compared to the the geometry in the ANSYS; the first one is that the rim was modeled as completely fixed instead of with a friction less support. The second difference is that the ground was not modeled in MATLAB. The last difference is how the belt was modeled. Instead of a separate part, the material properties of the outermost elements along the outer radius were changed from the sidewall's to the belt's material properties. The material properties for the sidewall and the belt are given in table 2.1.

3.2 Boundary Conditions

As mentions previously the approach to the MATLAB model was different to the one used in the ANSYS model. The different loading conditions will be presented in the following subsections.

3.2.1 ANSYS-model

In order to properly define the model, boundary conditions were needed. The approach that was implemented in ANSYS was that the tyre was fixed in position during the entire simulation. However it was allowed to rotate freely the Y-axis, mimicking the behavior of a free rolling wheel.

The belt of the tyre and the sidewall was set to be bonded together, meaning that there was no separation allowed or sliding between them. Furthermore, the contact between the belt and the ground was set as a frictional contact with a friction coefficient of $\mu = 0.8$.

The simulation was carried out over two time steps, each of them one second long. In the first time step, the vertical load F_z, which represents the trucks weight, was applied with a magnitude of 30 000 N. The load was applied from the ground up. In the second time step, the ground was displaced 5 cm in the negative x direction, corresponding to a velocity of 0.05 m/s, leading to the wheel spinning clockwise around the y-axis.
Furthermore, all the components in the system was set to have zero displacement in the y direction, to essentially make the case a 2D plane strain simulation. The ground was also restrained even further to not allow any rotations, which means that it was only allowed to move straight in the x and z directions. These loads and boundary conditions can also be seen in Figure 3.2.

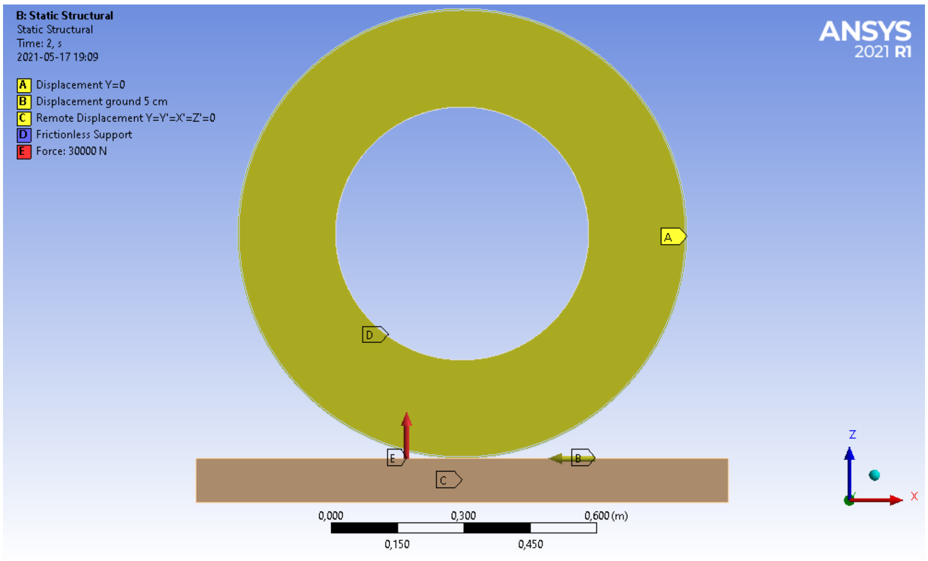

Figure 3.2: Schematic figure of the tyre and the applied loads.

As mentioned previously, the speed of the ground was low to not have any inertial effect from the tyre. ω is induced by the moving ground, i.e. not prescribed.

3.2.2 MATLAB-model

The setup was done differently in MATLAB when compared to ANSYS. While the forces were prescribed and the deformation was the targeted measurement in ANSYS, it was done the other way around in MATLAB. Another difference is that MATLAB was only looking into the last time step and therefore everything happened at once, there is no difference between static and rolling case.

The part of the tyre that would be in contact with the ground was given a deflection and the force was calculated as a result of this displacement. The displacements can be divided into three different section. The first section is the part of the tyre that is in contact with the road, the second section is the nodes located at the inner radius and the third section is the part of the tyre that is not in contact with the road. In Figure 3.3, the different sections are shown. The deformation to be given on the nodes which are in contact with the road are calculated using the fact that the circumference has to be the same before and after deformation and the angle at the centre of the tyre can be found.

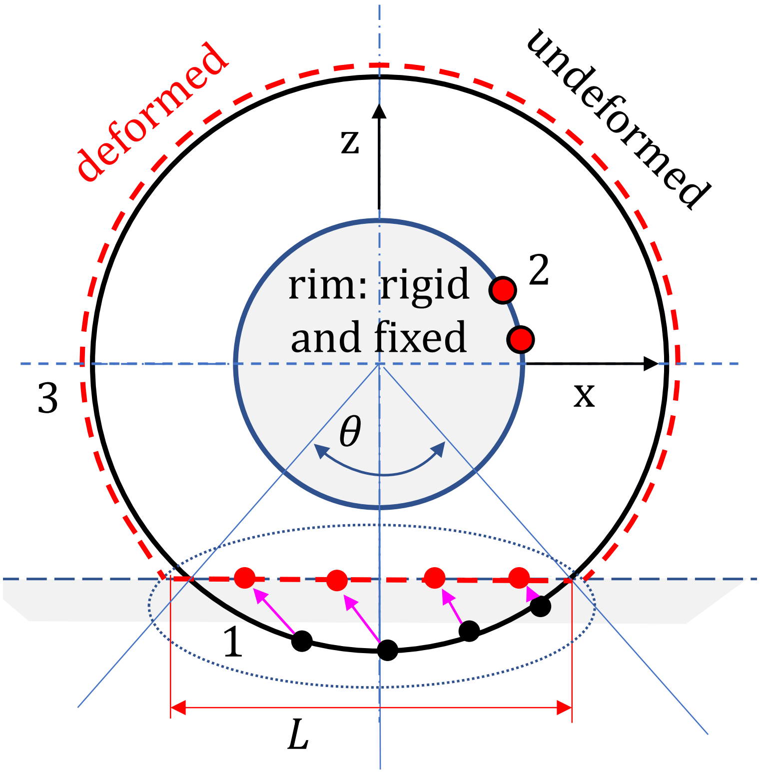

Figure 3.3: Figure showing the sections where different boundary conditions were used. Black is node before deformation, red is after deformation.

The first section contains the nodes along the road. These nodes were first pushed upwards in order to be located at the road. Next, the calculated deformation was applied to the left. For every node is the deformation becomes bigger and bigger since the first node affects all nodes after itself. The difference in x- and y-coordinates between the black and the red was then prescribed as the deformation of the node. The second section is prescribed with zero deformation since the rim was assumed to be fixed. The third and last section containing the nodes that is at the outer radius but not in contact with the road, these nodes were assumed to be free.

3.3 Mesh

For the problem to be solved a mesh had to be created, splitting up the surface in smaller regions for the solver to compute the results in. A fine mesh yields better results while it requires more time for the computer to solve. While a coarse mesh can be used to speed up the calculations, a too rough mesh can result in the solver not capturing the correct deformations. The differences between the two meshes for the different models are explained in this chapter

3.3.1 ANSYS-model

An auto-generated mesh was an option in ANSYS, which was used during most of the simulations. This setting produced a mesh good enough while not using too much computational time. Though, for final results a finer mesh was desired and for this an element size of 7.5 mm was used for all elements. The final mesh used in ANSYS can be seen in Figure 3.4.

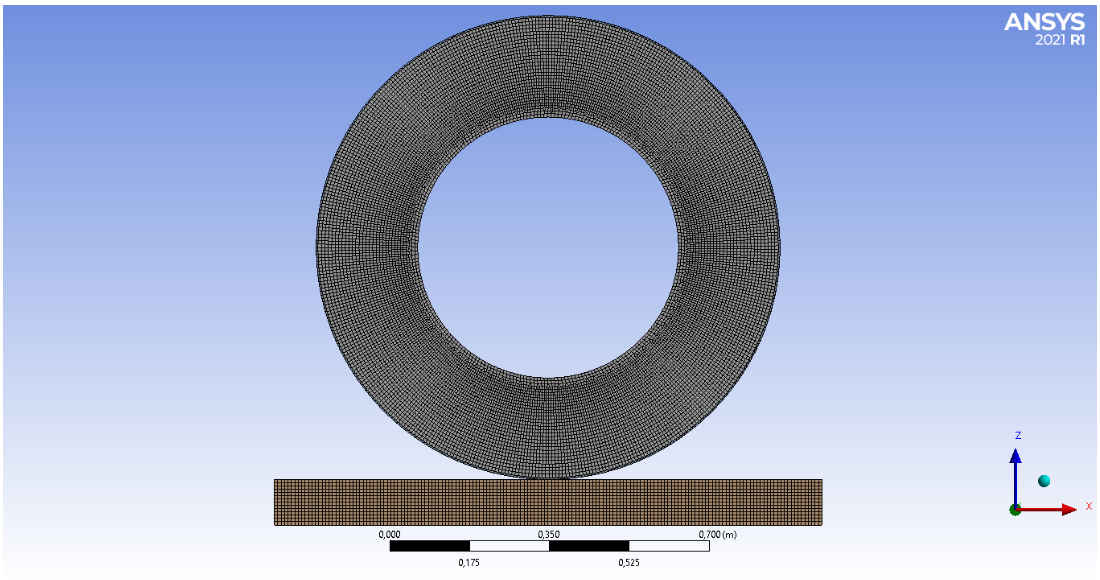

Figure 3.4: The mesh for the whole system in ANSYS.

A zoomed view of the contact between tyre and ground can be seen in Figure 3.5. The belt is also visible, the thin outermost layer of the tyre.

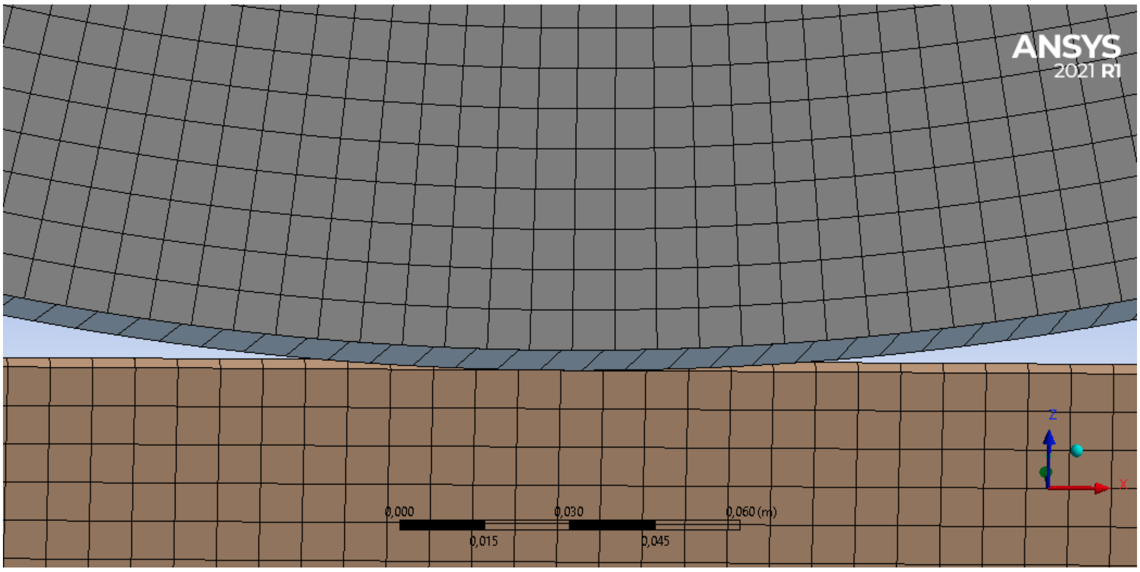

Figure 3.5: The mesh for the whole system in ANSYS along with zoomed view of contact region.

3.3.2 MATLAB-model

The tyre was divided into two parts when creating the mesh, one fine mesh, and one coarse mesh. The difference between the meshes was the number of elements used along the circumference, in the radial direction the same amount of elements were used for both the fine and the coarse mesh. The fine mesh was used around the region in contact with the road, since this was the most important area of consideration. The coarse mesh was used for the remaining regions of the tyre. This differentiation in meshing was done to minimize computational time without Influencing the result.

A schematic representation of the partitioned mesh can be seen in figure 3.6. This is not the mesh used since the number of elements made the figure completely black and therefore a coarser mesh was used to show the partitioning of the mesh. The coarser mesh was using the 33 number of element along the circumference close to the contact patch and 37 for the rest of the tyre. In radial direction were 15 elements. For the fine mesh that actually was used was instead 135 elements used because this would result in a belt thickness of 3.76 mm which was almost the same belt thickness as in the ANSYS model. The number of elements used in the circumferential direction close to the contact patch was 75 and for the remaining tyre only 84 elements. A mesh sensitivity study is shown in detail in sub-section 4.2.2

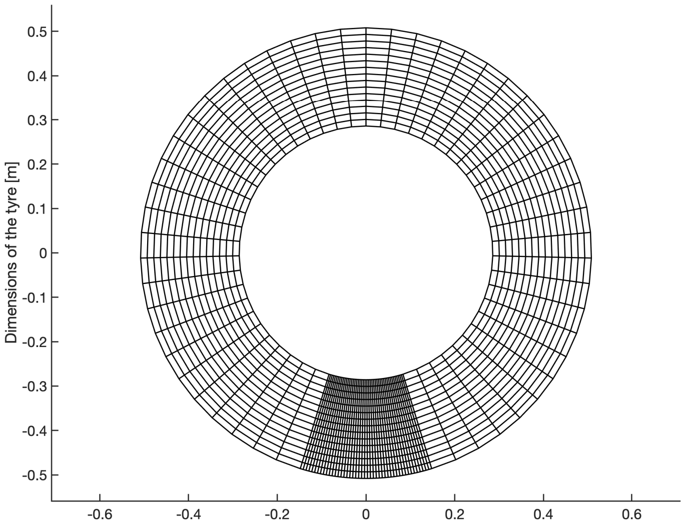

Figure 3.6: A schematic figure of the mesh for the whole system in MATLAB.

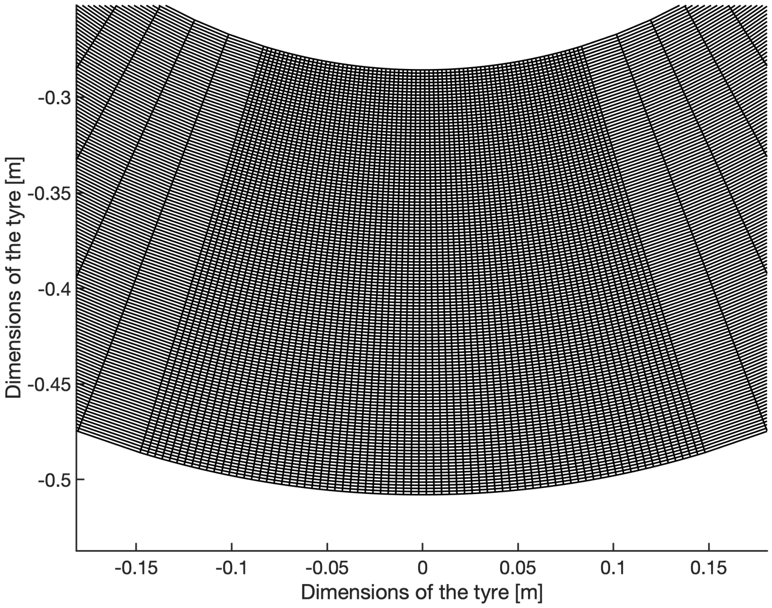

Figure 3.7: The mesh close to the contact area.

Figure 3.7 above shows the zoomed in picture of the contact area between the road and the tyre. It can be seen that the element size used for close to the contact area were much finer than the mesh used for the remaining section of the tyre.

4

Results

In this chapter the results from the testing of the two different FE-models will be presented. The main focus is on the pressure distribution and rolling resistance, although some additional results are also presented.

4.1 ANSYS-model

The pressure distribution between the belt of the tyre and the road was determined for two cases: while the wheel was only loaded with a vertical force F_z and while the force was both loaded with a vertical force F_z and rolling.

The pressure distribution for the static case can be seen in figure 4.1 and the pressure distribution for the rolling case can be seen in figure 4.2.

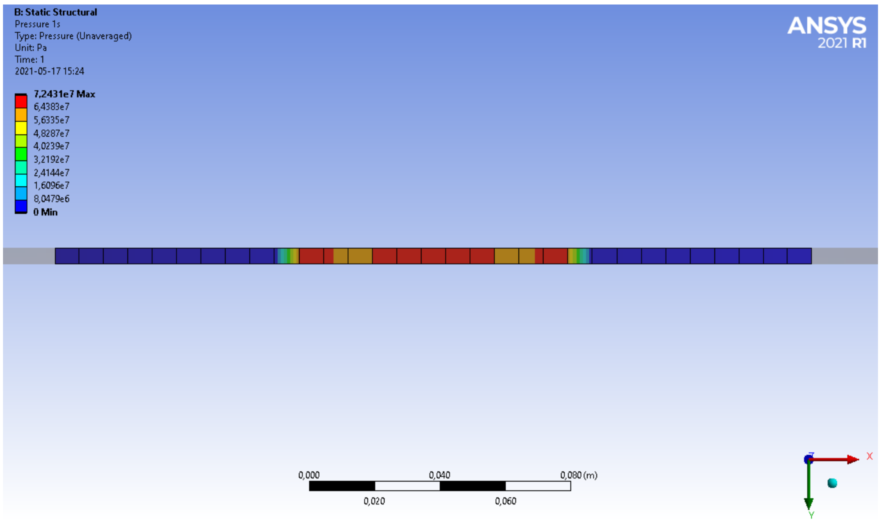

Figure 4.1: Pressure distribution while static.

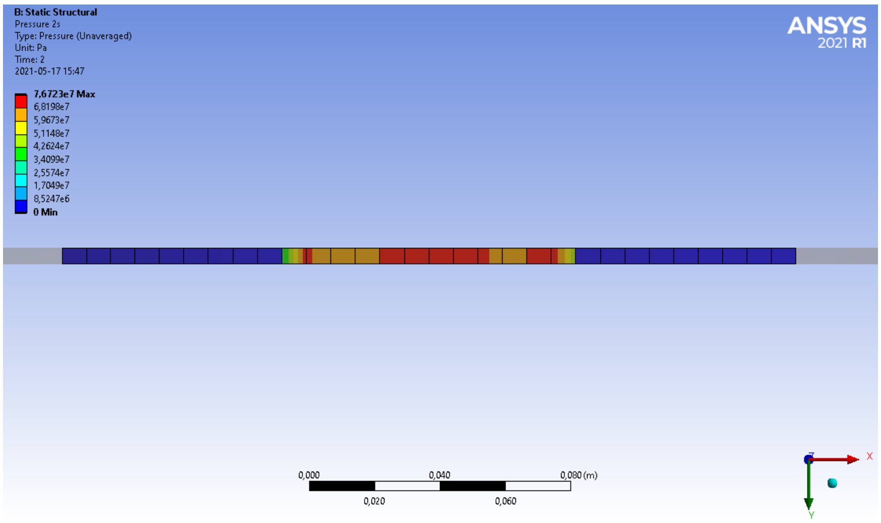

Figure 4.2: Pressure distribution while rolling.

From figure 4.1 and 4.2 it can be observed that until the force is applied vertically (F_z) the distribution is almost symmetrical from the center and once its starts to roll the pressure distribution starts to get unsymmetrical and offset slightly in the negative x-direction.

The values for the pressure distribution are also plotted in figure 4.3. In this plot the position of e, which is the position of the resulting force or "center" of the pressure distribution, is also shown for both the static and the rolling case. The value for e in static case was -1.25 mm and in the rolling case -2.5 mm, which gives the values for the RRC as -0.25% and -0.49% respectively. These values for e were calculated by taking the integral of the values in 4.3 and finding the center of the distribution.

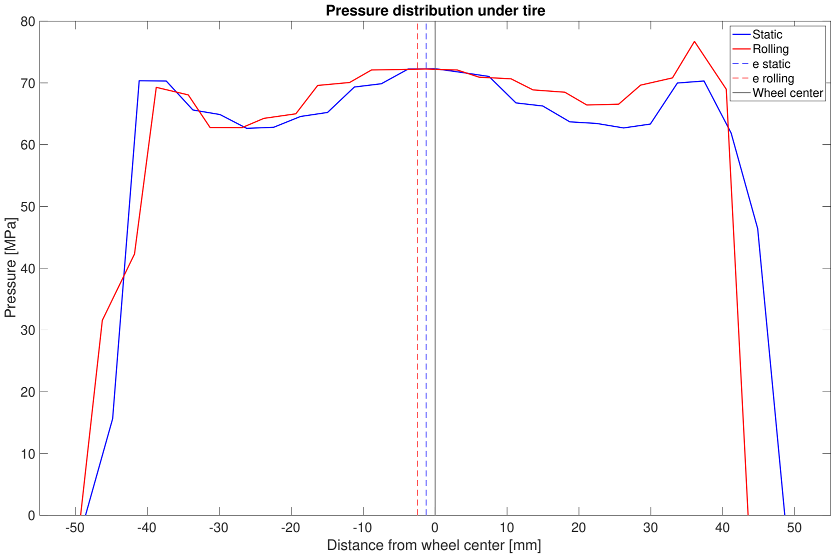

Figure 4.3: Pressure distribution from ANSYS.

In figure 4.4 the contact status between the ground and the tyre is shown. In this figure three different contact statuses can be seen: ”sticking”, ”sliding”, and ”near”. The yellow parts in the figure which represents ”near” are where the road and the tyre are not in contact, but are very close to each other. The light orange regions represents slipping, and are located at the inlet and outlet of the true contact patch. In this region the tyre and the road are making contact, but the tyre is slipping due to the low normal force in these regions. The red region in the center of the contact patch represents sticking, which means that the tyre rolls over the ground in an ideal way i.e. without any slipping.

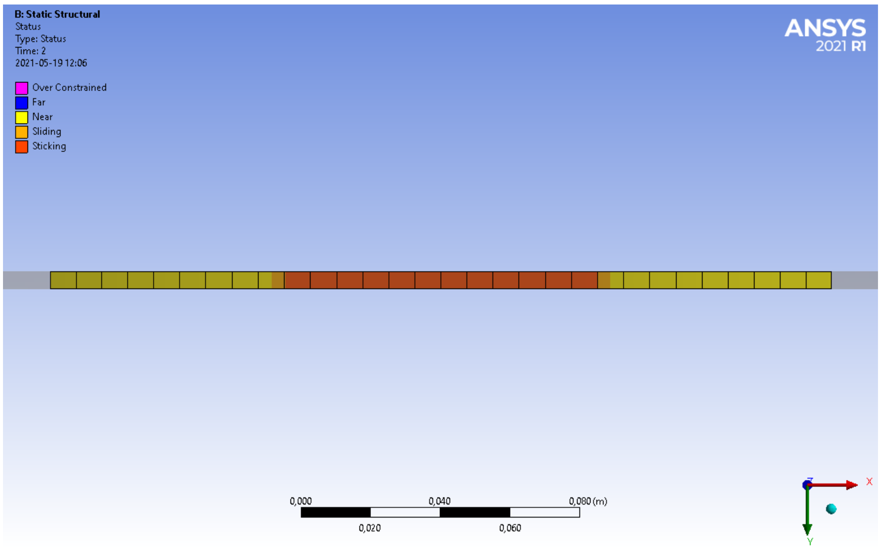

Figure 4.4: Contact status under the tyre

Furthermore, the reaction forces acting on the wheel at the contact patch were determined to be $F_z = 30007$ N and $F_x = -74.8$ N in ANSYS. Inputting these forces into equation (2.1), it gives a value of e = -1.28 mm. This in turn gives an RRC of -0.25%.

4.2 MATLAB-model

In this chapter the result from MATLAB is presented, beyond the pressure plots, a mesh sensitivity study was preformed in order to investigate how the offset was depending on the amount of elements along the contact patch that were used.

4.2.1 Pressure distribution and reaction forces

The pressure distribution perpendicular to the road can be seen in Figure 4.5 below, since the deformation was applied simultaneously for both direction a pressure distribution for the static case was not calculated. The reaction forces in MATLAB was calculated to F_z = 6.44 kN in vertical direction, and in the horizontal direction the reaction force was F_x = -394.27 N where the minus sign means that the force is heading to the left. With this forces inserted in equation (2.1) the offset be calculated to e = 31 mm which would give a RRC value of 6.13%.

The offset was also calculated according to equation (2.4), which resulted in an offset of e = -0.067 mm, which would give a RRC value of -0.013 %. In figure 4.5, there is two different offsets plotted together with the pressure distribution.

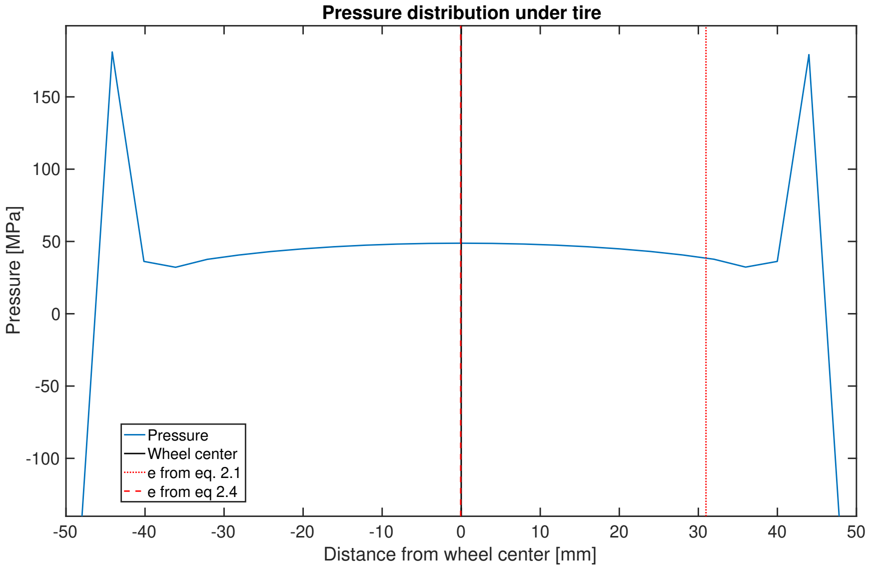

Figure 4.5: Pressure distribution calculated in MATLAB

Beyond the pressure distribution perpendicular to the road was also the traction, i.e. the pressure along the road, plotted which can be seen in figure 4.6.

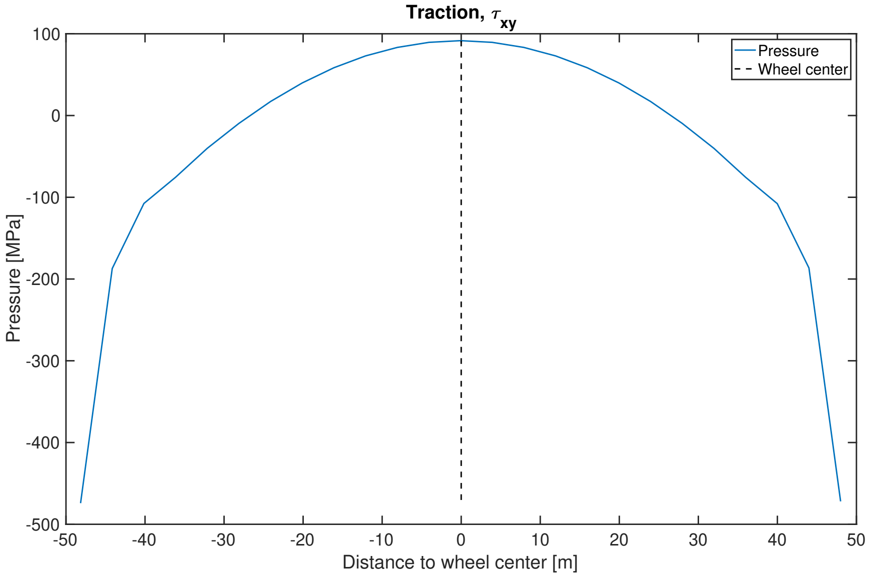

Figure 4.6: Traction between road and belt calculated in MATLAB

4.2.2 Mesh sensitivity study

A mesh sensitivity study was done in order to see how the results were affected by the number of elements along the contact patch. The result that of interest to investigate was the offset of the pressure distribution, e. In figure 4.7 and 4.8 the offset of the pressure distribution was plotted against the number of elements close to the contact patch. As seen in the figure, the plot starts to converge at 75 elements close to the contact patch. At number of elements more than 75, the convergence would be better but since it would take up a lot of computational time, it was decided that 75 elements would be sufficient.

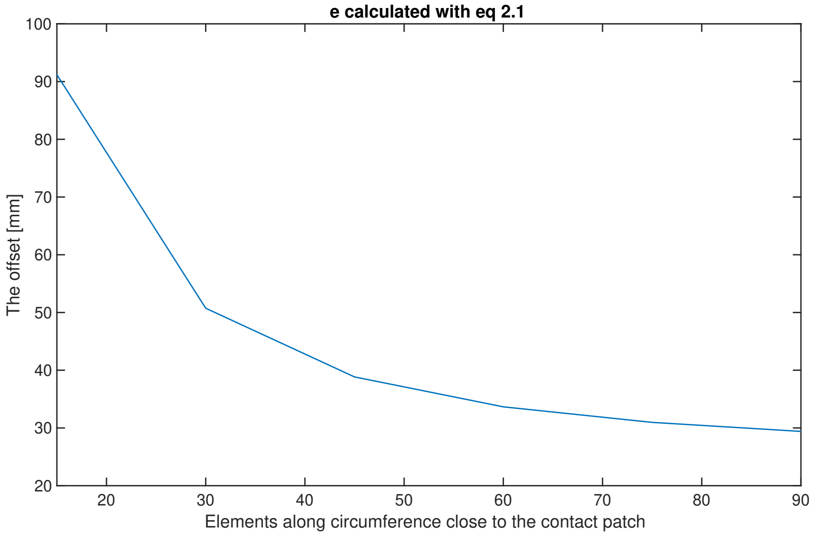

Figure 4.7: Mesh sensitivity study from equation 2.4

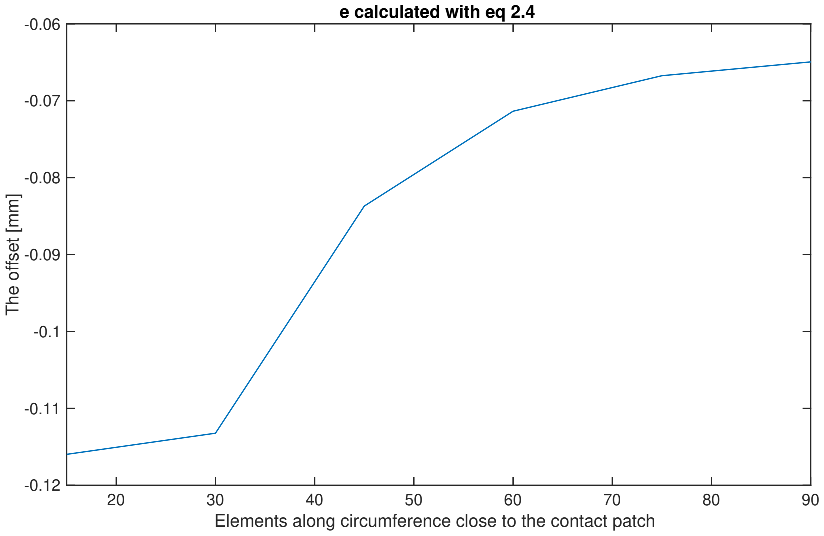

Figure 4.8: Mesh sensitivity study from equation 2.4

5

Discussion

In this chapter the results from the simulations are discussed in order to evaluate and draw conclusions about how accurate the FE-models was. Moreover, the flaws and limitations in the developed model is also discussed. Finally, recommendations for further development of what has been created is presented.

5.1 Comparison between ANSYS and MATLAB models

When looking at the results from ANSYS, one can see in figure 4.3 that the pressure distribution is unsymmetrical, and that there is an offset of it. In the same figure, a dotted line for e is also seen, and it indicates that the offset would be towards the negative x-direction. This result was not anticipated, and was something yet to be explained.

The two different approaches to calculate the offset e in MATLAB was very different, one was suggesting the there would be a large offset to the right while the other solution would say that the offset would be almost zero. By just looking at the pressure distribution in figure 4.5 is it possible to assume that the offset should be somewhere around zero. One explanation to why the offset is very large for the approach based on equation (2.1) is that the reaction force is very low when comparing with ANSYS. An explanation to that is that the first and last node has a negative reaction force and thereby reduce the total reaction force. Why this is negative is uncertain yet but one explanation might be that the nodes is being pulled towards the ground since the material in the tyre want to lift the node up from the road. This would cause the offset to become very large when using equation (2.1).

When calculating the *RRC* for the models, one can note that the value was found to be negative, i.e. the tyres are adding energy to the truck meaning the truck could in theory propel itself. This seems like an unreasonable result and further questions the values of e computed. Moreover, the fact that there was an offset of e for the static ANSYS case, i.e. there will be rolling resistance, should be an indication that the model might not be entirely reliable.

Finally, the approach by taking on the problem with two different softwares, proved to be a valuable one. While they may not agree with each other, there is a clear indication that the sought after mechanism is at work, and that more knowledge of it has been acquired.

5.2 Review of the hypothesis

From figures 4.3 and 4.5 it can be seen that the graph show an offset e. Though, the two different models do not show the offset in the same direction. These offsets of the pressure distribution would be the desired or predicted result, as discussed in Section 2.4. However, none of the presented offsets are shown to be located in the same direction, which was not in accordance with the hypothesis. A revised hypothesis might be needed to better describe the behaviour seen in the simulations, though the result from ANSYS and MATLAB are difficult to explain.

5.3 Model accuracy

The accuracy of the models are very much dependant on the size of mesh used. As can be seen in figure 3.6 the mesh in MATLAB was created with a varying sized mesh, meaning the mesh was made finer in the particular area of interest. This was made in order to better capture the pressure distribution. In figure 3.4, one can see the meshed system in ANSYS, where the mesh was created more symmetrically across the surface. The mesh can always be made finer, though it will increase the computational time by a significant amount. In figures 4.3 and 4.5, one can note that the curves are quite uneven or not in a particularly parabolic shape, and this could possibly be due to the mesh size used. If even better results are wanted, a finer mesh can definitely be of use.

Another part of the model accuracy to take into consideration is if the model describes reality in a satisfactory manner. As mentioned previously, a tyre is very complicated, consisting of a lot of parts and different layers. In this project, there was an effort to simplify the problem as much as possible. But with simplifying, there is always a risk of the model not accurately describing the actual behavior.

5.4 Further improvements to the model

Since the project was quite short on time, all aspects of the problem could not be examined. The effects of a varying vertical load, F_z, was to be tested, though this test could not be conducted. So, a next step for the model presented in this report would be to vary the load, and analyse the response, how it influences the force location distance e, and how the rolling resistance would be affected. Another thing that could be of interest, would be to analyse a driven wheel, i.e. a torque is applied on the wheel. In this report, a free rolling wheel was analysed.

In order to further increase the accuracy of the model one could increase the complexity of the material composition. This could be done by splitting up the surface of the wheel and including more elements from figure 2.1. As can be seen from that figure, there are a significant number of layers not taken into consideration, which could be done in future work to increase the accuracy. The tread of the tyre could also be created, a simplified version for instance, in 2D. However, it should be mentioned that adding too much complexity might lead to a loss of understanding. Therefore one should be somewhat careful before making a too complex model.

Lastly, if an even more accurate model is to be created, a 3D model could be implemented. In 3D, there would be the possibility to include all layers seen in Figure 2.1. A model like that would require more time and more detailed creation, which could potentially produce a very accurate model. In her thesis Zeinab El-Sayegh [5] describes an approach on how to model a tyre in 3D, with the different material parameters and layers, which could be a good way to go about the modelling.

6

Conclusion

The overall conclusion of the project is that a better understanding of the tyre behaviour has been achieved. Moreover, the result seen from the simulations means there is an offset of the pressure distribution, thus the result is relevant and something to continue building on. Though, the hypothesis can be update or revised to better match the phenomena seen in the report. However, not enough testing has been conducted to determine whether the hypothesis is wrong, meaning there is a cautiousness surrounding the acceptance or rejection of the hypothesis.

The two models created in ANSYS and MATLAB, was a good approach, to tackle the problem for different perspectives and including different levels of complexity. Moreover, the two methods yielded quite similar results. Further testing of the model is recommended, in order to examine the effects of a varying load, for instance. The current model in 2D could be expanded to include more layers and material decompositions. To take another step, a 3D model may be created, to have an even more realistic tyre representation. Though, since time was a dominant factor to the extent of the project, the subject has to be investigated further and new models to be created.

While there is definitely more to do, there is a strong argument to be made that the understanding of the tyre behaviour has been increased. Although the end result does not ambiguously show what was drafted in the hypothesis, the outcome of the project could serve as a strong starting point for further development, and to a larger extent generate knowledge of the pressure distribution and rolling resistance, in order to maximize the efficiency of road transports.

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