ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

FINITE ELEMENT ANALYSIS OF RAIL STRESSES AND WHEEL-RAIL DISPLACEMENTS UNDER THE EFFECT OF TRACK STIFFNESS IRREGULARITIES AND ROLLING WHEEL SPEEDS

A Thesis in Railway Engineering (Rolling Stock)

By

Venuste Masabo

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A

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Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment for the Degree of Master of Science in Railway Engineering, Rolling Stock.

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The undersigned members of the Addis Ababa Institute of Technology under the department of Railway Engineering have examined the thesis entitled '**FINITE ELEMENT ANALYSIS OF RAIL STRESSES AND WHEEL-RAIL DISPLACEMENTS UNDER THE EFFECT OF TRACK STIFFNESS IRREGULARITIES AND ROLLING WHEEL SPEEDS**' presented by **Venuste Masabo**, a candidate for the degree of **Master of Science** in **Rolling Stock Design** and hereby certify that it is worthy of acceptance.

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I, Venuste Masabo, declare that this thesis, submitted in fulfillment of the requirements for MSc in Railway Engineering, in the School of Rolling stock Engineering, University of Addis Ababa Institute of Technology, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Venuste Masabo

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Abstract

The world of today has the transportation sector growing and railway transportation system is contending all transportation modes by this time. This fact is because railway transportation system is able to carry a large number of passengers at low cost and reduced time while also being environmental friendly.

Even if the railway is booming, there are things that are still challenging and need more attention, and among those challenge, there is the track irregularities. The irregularities have many causes and in this project the main cause of irregularities is the variation of track stiffness.

Track irregularities including stiffness variation are known to accelerate the track deterioration and to affect the rail vehicle; but a little is known how this effect is correlated with train speeds, under dynamic loading conditions.

This study aims to investigate the combined effect of rail vehicle speeds and track irregularities caused by railway spatial stiffness variation on the wheel and rail stresses, deformations and vertical displacements.

Explicit dynamic finite element analysis using ABAQUS software package is used in this study. The model is composed of a train wheel rotating on a rail across several sleepers, which are fixed at their base. The equivalent average of the sleeper moduli is chosen to resemble the total average track modulus under the rail, in real situation.

The variation of track stiffness in the model is achieved by changing the statistics of the randomly distributed sleeper moduli. It is found that increase in speeds and the longitudinal variation in track stiffness for a given track stiffness mean results in increased amplitude of oscillations of rail deflections, and reduction of a corresponding oscillation frequency, and in increased level of von Mises stresses at much higher level of stiffness variations.

For the deflection of the rail as the speed changes the deflection varies as well. In this project considering the speed variation for example at standard deviation of 60 MPa, at speed of 10, 15, 20 m/s the deflection is 2.208017, 2.271236, and 2.271308 mm respectively.

As the standard deviation is changing also it causes the rail maximum deflection to vary. Taking example at speed of 10 m/s the increase of standard deviation magnitude caused the increase in maximum rail deflection magnitude as for standard deviation of 20, 40, and 60 MPa the deflections are 2.084149, 2.108914, and 2.208017 mm respectively.

For stresses as the model was considered to be perfect plastic the maximum stress was found not to exceed the maximum yield stress which is 475 MPa. To better understand the rail stress behavior, the non-linear plasticity model must be considered.

This study significance is to help railway engineers make better rail maintenance strategies.

Keywords: track irregularities, sleeper modulus, track stiffness variation, rail deflection, and rail stress.

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1 Introduction

Every mode of transportation has strengths and weaknesses. But it is remarkable that railway transportation system is the one having success compared to others. It is cheap, time saving, and environmental friendly, and lead to traffic congestion reduction. Due to its success it attracted a lot of researchers to study railway from environment infrastructure, vehicles, and population. Every nation all over the world is trying to have the railway system and pushing railway engineering community to conduct much researches related to different aspects of train passage effects in recent years.

Compared to other systems of transportation the railway infrastructure is the most expensive and always need maintenance which is expensive. In maintenance of railway system the maintenance of track and rails consumes a large part of the budget for railway maintenance program as the main function of railway system is based on the interaction between wheels and rail. Due to that it is cost effective (in Australian freight operations, maintenance costs comprise between 25 and 35% of total train operating costs [1]) to maintain the track and rails, sometimes the maintenance is not done constantly and this will be associated to some issues that can raise and the most discussed is the track irregularities.

The track irregularities are of different types and their effects are different. Some of the researchers have stated that the irregularities don't affect the performance of the railway system. Others have shown that irregularities will affect the performance of railway system. Those researchers who show that there are effects due to track irregularities say that the track irregularities will affect the wheel-rail interaction, track deterioration, vehicle dynamic performance, and the railway vehicle-track interaction.

There can be track irregularities which can lead to discomfort of passengers inside the train. The negative effects of this vibration are numerous and it is addressed in international standards. One of these standards is ISO2631, where indoor, whole-body human exposure to vibration is evaluated in the frequency range, 1Hz to 80 Hz. The vibration evaluation is based on the root-mean-square (RMS) value of the acceleration in the three orthogonal directions.

For past researches they have identified four main types of track irregularities which are: vertical irregularities, cant irregularities, lateral irregularities, and gauge irregularities. All these irregularities are caused by the way the track is constructed and environmental changes.

This project is focused on vertical irregularities that are caused by variation of track stiffness. This variation is considered to be random along the long track. Logically when the properties of two successive sleepers, ballasts, substructure, etc. are different, the rail is subjected to varying support stiffness. Also, if there is a transition from the slab track to ballasted track the support stiffness suddenly changes. Furthermore, the rail support stiffness varies along the track when the track structural elements such as fastenings, sleepers do not mate with neighboring elements uniformly along the track. For example, loose sleepers and loose fasters at certain section of the rail. As a result, this will make the rail having different values of vertical displacements for the same applied load. This effect will induce varying stress levels and therefore altering the fatigue life of the rail. For modelling purpose, Nkundineza and Turner[2], developed a method of using equivalent sleeper modulus to solve the inherent computational complexity. They run almost a thousand of models with a rail subjected to a static load in steps and models repeated several times for various stiffness statistics. In this thesis a wheel will be rotated on the rail across fixed sleepers such that their average Young's modulus represent equivalent track stiffness. The Young's moduli of the sleepers will be generated randomly for various standard deviations

The main performance of a railway system is based on the behavior the wheel rail contact. As the vehicle is moving on an irregular track the change is not directly remarked but by time the effect will be seen.

This pushed the researcher to look into the effect of these track irregularities, which are based on stiffness variation on the rail deflection and stress variation in the rail and wheel, as the wheel is rolling on the rail. When the train is moving on the uniform track there are forces acting on contact patch of the wheel-rail interaction and their effects are different when the train is moving on an irregular track [3]. Usually the track irregularities are unavoidable due to the way the rail is supported. The sleeper spacing is one of the irregularities, apart from sleeper spacing there are source of irregularities that are discussed in this work.

In this research there will be different models; models when the track is uniform and the one that has the varying sleeper's modulii of elasticity. These sleeper's modulii of elasticity are the input variables in modeling the dynamic behavior of wheel rail contact and their effects.

This project focuses on the performance of AALRT and the input for simulation are collected at the depot and the results that are obtained in simulation are to be validated according to the international standards also by considering what others have done in the past.

1.1.Problem statement

During the construction of railway infrastructure, there are some issues related to how the components of the track system are arranged, the arrangement plays a big role in the behavior of the railway system mainly wheel rail interaction. The main issue in the track system is the track irregularities including track stiffness variations along the track. These track stiffness irregularities are caused by sleeper spacings and variation in ballast compactions along the track, substructure variations and variations in rail support elements fixation. These irregularities are the one which are responsible for the vibration. The vibration is the one which is responsible for the track problems such as misalignment and track buckle. If the track is affected this has an impact on the wheel rail interaction and the whole railway system will be affected. A lot of researches focused on the deflection of the rail as the result of track irregularities but they ignored that the track stiffness irregularities will affect the von mises and the stress concentration. These von mises and stress concentrations are responsible of the rail and wheel fatigue failure. For many times materials fail due to fatigue failure, mainly the fatigue results from the excess of stress that is fluctuating and increasing. As in this project the contact between the wheel and rail is affected the track irregularities and hence contact forces are affected. The change in contact force lead to changes in rail stresses and deflections and therefore overall fatigue life of the rail of the considered section.

1.2 Objectives

- Main objective:

The main purpose of this project is to evaluate the effect of track stiffness variations on the von Mises stresses and deflections of the rail and wheel for various train speeds using finite element analysis.

- Specific objectives:

1. To model the rolling wheel a rail track in 3D using explicit dynamic finite element analysis.

2. To investigate the effect of track stiffness variation on rail maximum stresses and wheel/rail displacements.

3. To investigate the effect of train speeds on rail maximum stresses and wheel/rail displacements

1.3. Scope and Delimitation

There are different kind of irregularities at the contact patch between the rail and wheel. In this report only irregularities due to track stiffness variation are taken into consideration. It is not easy and it is expensive to conduct experiment of measuring the track stiffness and its variation. Sleeper stiffness were generated randomly using a computer code when there is a mean value of sleeper Young's modulus that represents equivalent track stiffness parameter. Therefore effects of all track components were taken into account using only this parameter. The model used in this study is therefore an equivalent simplified model. And also the values for elastic and plastic properties of wheel, rail, and sleepers were found in some academic journals.

The study of wheel rail interaction is a huge field of study. This project focus on effect of track irregularities on the von mises stresses and deflections of the rail and wheel. Using finite element method.

For software when the processing is taking place it is taking a lot of space and time due the size of the model, mesh size, number of frames, and the number of the requested outputs. For this model the simulation is considered at the wheel when it is rolling at a distance of 1350 mm and the number of frames is 500 for each step.

1.4. Significance of the project

- As for research the main purpose of any project is to solve the existing problem or to predict any problem that can come in the future and provide strategies to overcome it or to prevent it from happening.
- This project is the reference for the future researchers who will read it.

- It is going to remind the railway companies that they must be aware of track irregularities due to track stiffness variations and their effects. They can therefore do maintenance accordingly in order to prevent any failure that can come any time due to tack irregularities.
- As the variables used in this project are from AALRT and the results obtained are similar to the results obtained in Winkler model [3], [4] , which is mainly adopted for Canadian railway, the modelling methods are reliable to use in the prediction of rail lifetime and rail deterioration rate.

1.5.Structure of the thesis

A short description of chapters is presented below to get an overview of the general structure of the thesis.

Chapter 1 has the background part, problem statement, objectives, scope and delimitation, structure of the thesis and significance of the study.

In **chapter 2,** the literature reviews are discussed, that constitute the review of the past works which are related to this thesis work. It also briefly describes dynamic properties of the railway track components, wheel-rail interaction models done by different researchers.

The well-known commercial software ABAQUS/CAE for modelling and simulation has been introduced in **chapter 3** and the procedure of creating finite element models in ABAQUS/CAE is presented in this chapter. The algorithms within ABAQUS that are used in this thesis are briefly presented and the dynamic analysis approaches were explained.

In Chapter 4, the result was analyzed and discussed, and then validated.

The chapter 5 is concluding, giving recommendation, and suggesting future works

2 Literature review

2.1 Sleeper and track stiffness variation

For many railway manufacturers, the materials used to manufacture railway sleepers are timber, concrete and in some cases steel. Timber were used due to the fact that they are adaptable and have excellent dynamic, electrical and sound-insulating properties but due to their properties and short life and that they can decompose easily this time they can't be used as the best material for sleepers. Compared to steel and concrete the wooden sleepers are not good [5]. The steel sleepers are having problems that they can deform easily and also for many time they have rust and they don't last longer. The concrete sleepers are preferred in many ways as they are not expensive and have long life. As it is shown in Figure 1 and Figure 2 the wooden and steel sleepers have problems.

Figure 1: wooden sleeper[5]

Figure 2: steel sleeper[5]

The wooden sleepers have problems of rotting and the steel has a problem of rust. For that reason, the concrete sleepers are preferred. In this project the variation of sleeper modulus implies the variation of railway track stiffness.

Railway track stiffness is an important quality that influences the comfort and passenger safety. The changes of track geometry beyond the allowable tolerances contribute in the reduction of ride comfort. The track geometry is mainly changing due to construction errors, and structural variation in track support. For railway designers, before starting up a railway system they make sure the track is regular, and that the maintenance is done consistently and keep the track in good condition all the time [6]. In many railway system it is remarked that the track properties are changing over time and this change always is affecting the performance of railway system [7]. The track stiffness must be in optimal state in order to minimize maintenance cost. The optimization of the vertical stiffness of the track and base plates has a favorable effect not only on the reduction in the vertical stresses exerted on the track by the vehicles but also on the reduction in the level of vibrations [8].

Usually the optimal track stiffness must not be high nor small. When the track stiffness is too big this is resulting in brittle behavior of the track and is contributing to track stresses and is not allowing the flexibility of the track. Due to this, any deformation that can happen is considered to be plastic. For small track stiffness this is making the track more flexible and this flexibility is the one that can contribute to the vibration of the system. This is because when the material is too ductile it deforms and returns to the normal shape as fast as possible and this is causing the track to behave as a sinusoidal function.

2.2 Track and track irregularities

In railway system the tracks are assets which will last for quite some years. The choice of a particular track system and the decision to use this system on certain lines, therefore, generally involves a decision which will hold good for 20 to 50 years.

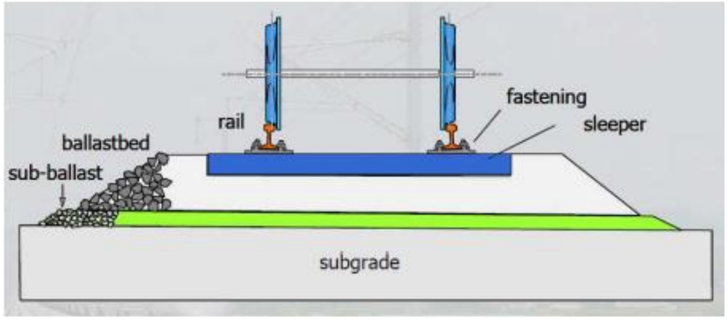

Figure 3: track structure [9]

Track engineers know that the dynamic wheel load incident on track is much greater than the static wheel load. The main concern of the field engineers in charge of mixed traffic lines is that the track deterioration caused by freight trains seriously impedes the high speed of passenger trains [10].

As a major part of a railway system it took time and money to make rails and this makes the rail one of the parts that must be cared every time. As for Indian railways industry it take a lot of time in processing rails. Figure 4 shows the steps that are required to get the rail that can be used. As it is seen the rail is manufactured with much attention and this also indicate that the rail is one of the expensive component in railway. That is the reason why the rail must be cared with higher precaution and avoid any problem that can affect its functions.

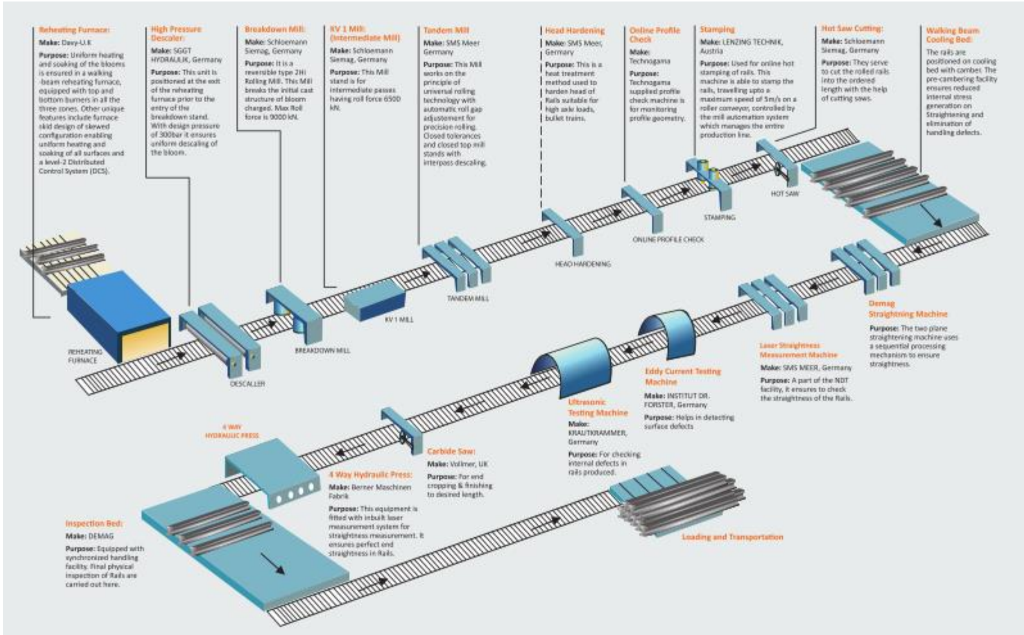

Figure 4: Process route for rail production [11]

Since rail is the first component of track to face the brunt of loads and since rail failures have disastrous effect on safety, efficiency of train operation and public opinion, any problem on the rail will affect the performance of the whole railway system. Rail fatigue is a problem of major economic importance for heavily-loaded railway lines [12].

As it has been seen in many research papers, many researchers have specified that the main problem in the contact between wheel and rail are wear, fatigue, and contamination. Also another problem that is attracting the attention of many other researchers at this time is the track irregularities.

Track stiffness is an important factor influencing the safety and reliability of train operation, the vibration and deformation of track structures, and the dynamic response of substructures like subgrades and bridges.

The track stiffness measurement is of great theoretical and practical significance to the design of new railway lines and especially the railway maintenance works. The measurement of track stiffness for maintenance relates to four stiffness problems: low stiffness, variable stiffness, virtual stiffness, and assortative stiffness problems [13]. As the track stiffness is measured this is of great importance as it helps in modelling and computations of wheel rail interaction.

Zakeri1 et al. [14] said that the track and rail imperfections which may be investigated are: rail corrugation, track irregularities, single imperfections such as bad welded joint, existence of unsupported sleeper, existence of rail joint, damaged fastenings, and existence of primary clearance in sleeper support. The following conditions were used in the program:

- The effects of shear and rotational inertia is considered in the rail model by using Timoshenko beam theory;
- Non-linear contact behavior for wheel-Rail interface (loss of contact) was used;
- The sleeper is modeled as a non-uniform Timoshenko beam on visco-elastic foundation by using finite elements model;
- For these systems an in-core variable band solver was included as an equation-solving option;
- Symmetric loading of track
- New boundary conditions are introduced by using two infinite boundary elements;
- Considering track imperfections such as the above mentioned cases;
- Accounting the shearing continuity of the interlocking ballast particles.

As a potential threat to safety of operation and comfort of passengers, surveillance of train-track vibration remains an important work for the railway management [15]. Rail irregularity, with its random nature, is a critical factor that causes the vibration in the train-track interaction system [16]. And this pushed many researchers to study the track irregularities.

According to Tingting [17] the deep groove ball bearing used in the traction motor is a key component that ensures the safe operation of a high-speed train; however, it is one of the most vulnerable parts of the motor. The operating temperature rise of the deep groove bearing induced by the frictional heat at high rotating speed greatly affects its service reliability, especially for the deep groove ball bearing operating in a high-speed vehicle that vibrates more due to track irregularities which accelerates the temperature rising of the bearing. The track irregularities affect the temperature of the bearing and this imply higher energy losses when there are irregularities.

As it is seen in the figure 5 when there is irregular track this cause the vibration of the wheel which leads to increase of temperature of the bearing.

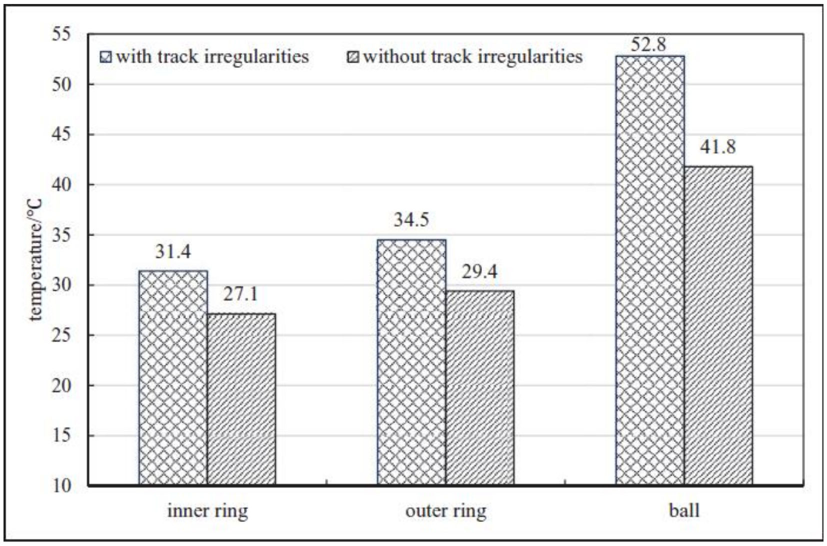

Figure 5: Comparisons of temperature on bearings considering track irregularity and without considering track irregularity

As the bearings are not fail safe materials, their failure will cause severe accident on the system.

In recent years, many researches have based on predicting the track geometry irregularities through measurements of vehicle dynamics behavior. Most of these studies analyze the vertical irregularity and the vertical vehicle dynamics since the lateral direction is much more challenging due to the non-linearities caused by the contact between the wheels and the rails as it is shown in the Figure 6.

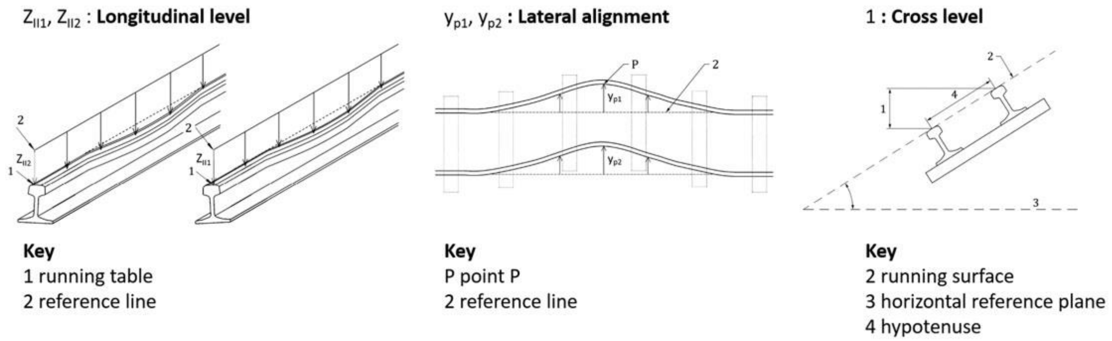

Figure 6: the main types of track irregularities [18]

Special attention should be paid to the short wavelength in range of 3 to 25m because irregularities in this range could affect the running safety, whereas irregularities in range of 70 to 200 m wavelength are mainly linked with ride comfort. According to the UIC 518:200919 and EN14363:200520 standards [19], three quality levels are defined for track geometry irregularities:

- QN1: requires keeping a track section under observation or taking maintenance measures within the frame of normal operations scheduling.
- QN2: requires taking short-term maintenance measures.
- QN3: leads to the track section being excluded from the analysis, in case of assessment tests, because the track geometry quality encountered is not representative of usual quality standards. At this stage, this value is not as poor as the value reflecting the most unfavorable maintenance condition but remains acceptable.

The limits are given as a function of vehicle speed and they are normally based on SD over a defined length, and 100 m was considered in [18].

SD is one of the most commonly used indexes for track irregularities of the European railway network. It represents the dispersion of the signal in a specific track section. The standards UIC 518:200919 and EN14363:200520 define the threshold levels for SD of longitudinal level and lateral alignment, but not for the cross level irregularity. Therefore, the cross level limits are chosen equal to the most restrictive ones (lateral alignment).

Hunting monitoring is very important for high-speed trains to achieve safe operation. But all the monitoring systems are designed to detect hunting only after hunting has developed sufficiently. Under these circumstances, some damage may be caused to the railway track and train wheels. In many researches they were using single-sensor fusion framework to detect the hunting amplitude. But the results were not accurate, Ning et al [20] proposed the use of multi-sensor fusion framework.

A track irregularity is either a dynamic irregularity or a static irregularity, depending on whether or not there are loads imposed on the track [21].

Understanding the relationship between the static and dynamic track geometry irregularities is crucial for the proper maintenance of rail infrastructures and the reduction of on-site workload. Gao et al [22] has focused on the analysis of the dynamic and static track irregularities on simply-supported beam bridges for high-speed railways. It can be said that the static track geometry irregularities are the ones that are due to natural phenomena and it cannot be prevented as they occur without any human intervention. For dynamic irregularities they are cause by the destruction of the infrastructure as the act of human being and this can be prevented in scheduling the maintenance and also regulating the amount of loads and forces that are being applied.

The track stiffness irregularity on the simply-supported beam bridge due to dynamic load of vehicles can result in cyclical effects on the dynamic longitudinal level. The static track irregularities are due to temperature, humidity, and the creep of the concrete.

Azizi, et al [23] said that when the track has irregularities due to unsupported sleepers this will lead to severe issues like derailment and said that the variation of speed will not affect the maximum displacement of the rail if they are few sleepers which are not supported. Also irregularities are frequently created due to erosion, clearances, subsidence, and inappropriate maintenance.

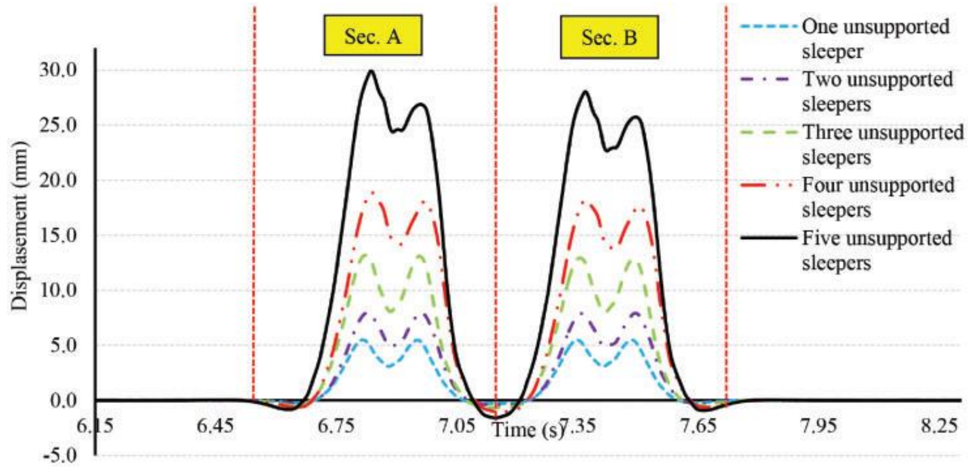

Figure 7: Track displacement with unsupported sleepers at the velocity of 70 km/h [23]

As it is shown in the Figure 7 it is now clear that when the sleepers are not supported it will affect highly the displacement of the rail. When the rail is supported between two sleepers it is considered as a simply supported beam, so if one or more of the supports are hanging the rail will have the large deflection at that point. This show the reason why when the rail which is unsupported will affect the performance of a railway system. The researcher in this paper quantified the effect of the unsupported sleeper and track irregularities in form of variation of contact forces between wheel and rail.

The design and analysis of rail track systems requires a knowledge of stress and displacements due to the combined action of the applied loads and environmental factors. A new low profile rail system lightweight low profile rail steel track system (LR55) was found to be very capable of withstanding loading up to main line railway standard. No structural deterioration was noticed during testing in both dry and wet conditions [24].

Xu et al [25] modeled the wheel-rail contact as a simply supported beam with a normal distributed load. This load is due to the rolling motion of the wheel from one point to another. For a simply supported beam there is two supports one from the left and the other to the right side. In railway the support of the rail are the sleepers, and for any irregularity there will be vibration at the contact point between wheel and rail.

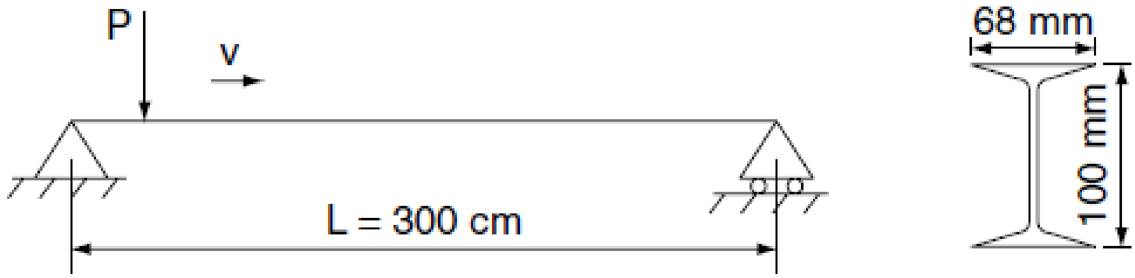

Figure 8: The simply supported beam under the moving load [26]

For a tilting train on a curved rail it is highly affected by track irregularities and earthquake as it was proved by Yung-Chang Cheng and Chin-Te Hsu [27] that a derailment quotient and an offload factor evaluated with an earthquake taken into consideration are larger than those obtained without consideration of the earthquake. And for the safety of passenger when the effects of irregularities is combined with the earthquake. Also the earthquake will amplify the track irregularities. Even if the earthquake is rare to happen but when it happens it leave some deformation on the ground and those deformation will intervene in the track irregularities amplification.

At low frequencies waves propagate in a rail as bending, extensional or torsional waves. At higher frequencies, above about 1.5 kHz, the rail cross-section deforms and many higher order wave types exist. This cross-section deformation has to be taken into account for an accurate evaluation of the dispersion properties at high frequencies [28]. The dynamic behavior of railway track in the frequency region 100-5000 Hz is of great importance in relation to the generation of noise by moving trains [29]. As it is shown in the figure below as the frequency is increasing the rail becomes unstable.

In order to study a railway vehicle/track interaction, it is essential that the track should be quantitatively described in a manner useful to the vehicle designers. The track can be described as a smooth one or it can be described as the one having irregularities, the track irregularities are described in terms of the x, y, and z coordinate system [30].

It is well known that profile irregularity of the railway line is one of the essential vibration sources to vehicle and track. It is a dominating source for rolling noise too. This results in fatigue and damage of components of the track structure will emerge, and settlement of the rail will occur under repeated action of dynamic loads. The deterioration of the railway conversely intensifies the vibration of locomotives and rolling stocks [31].

Different parts of the rail network are subjected to different types of stress conditions, where rail wheel contact induces very high contact stresses due to rolling and sliding [32]. This is due to that when the wheel is rolling there are forces that are being applied at the contact point between wheel and rail. When the forces are higher they can cause the permanent deformation on the rail and these deformations imply the irregularities of the track.

As it is seen in this part, there are a lot of research works that have revised the track irregularities and their effects on the performance of the railway wheel rail contact.

Irregularities of the track can be classified in two types: long wave track irregularities and short wave track irregularities. The long wave track irregularities are due to errors in manufacturing and errors in finishing at the top of the rail, but short wave track irregularities are due to loads that are fluctuating and those forces are impact at the top of the rail [33]. For this shorts wave track irregularities it can be seen that due the forces that are being applied at the top of the rail these forces are causing plastic deformations and these deformations are the one considered as the sources of short wave track irregularities. For long wave track irregularities as the manufacturing of the track is having some issues with finishing this results in non-smooth top area and also some of the edges are sharp. All these are the main sources of long wave track irregularities.

2.3 Wheel-rail interaction

Due to the fact that the working of a railway system is based on the wheel-rail contact, the multibody simulation of railway vehicle dynamics needs a reliable and efficient method to evaluate the contact points between wheel and rail, because their positions have a considerable influence on the direction and intensity of the contact forces. For the simulation of the railway vehicle and rail interaction firstly it is better to know the contact point [34].

Due to the complication in modelling the wheel rail contact, the researchers have modelled numerically the contact in different ways; in those modeling there are three types of contact which are: point contact, line contact, and surface contact. For each contact type there are equations corresponding to it.

Figure 9 shows a simplified schematic drawing of wheel/rail contact on straight track, where d is the distance between the center lines of the left and right rail cross-sections, T is the distance between the backs of the two wheel flanges and W is the axle load. The relative position between wheel/rail contacts is not fixed and this implies that the contact stress changes as the position changes.

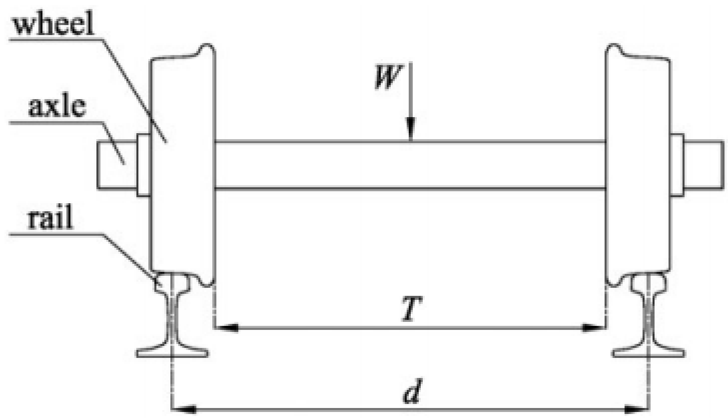

Figure 9: Schematic drawing of wheel rail contact [35]

A railway wheel, together with an axle, is one of the crucial parts that support the safe operation of railway vehicles. Wheels support the entire weight of cars; however, they cannot be designed as a failsafe structure where a backup system by other parts can be applied in case of a serious problem[36]. Railways still play a key role as a public transport facility, as well as a mean for transport of goods. The need for faster relocation and capacity of trains, Rolling Contact between the wheel and the rail becomes a big concern, in which a lot of research are being carried out [37].

As it is visible in Figure 10, the wheel is in direct contact with the rail that is the reason which always when they say wheel they add the rail. For the railway operation any problem on the track it is the source of vibrations and those vibration are causing discomfort in the whole system.

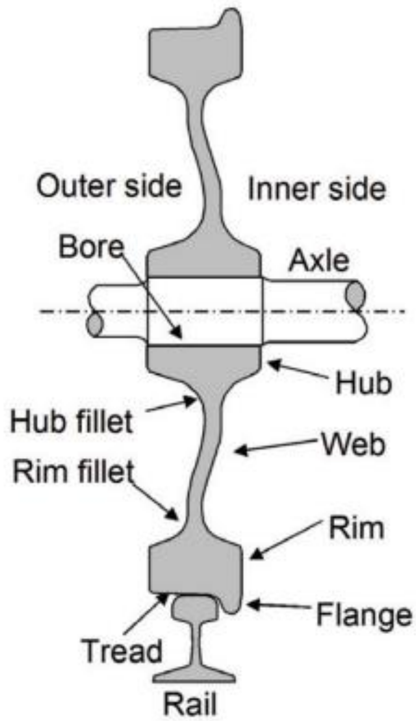

Figure 10: section view of wheel/rail interaction [36]

The wheel-rail contact is designed so that the wheel and the rail are always in contact and when it comes to miss this contact it is a serious issue that may lead to derailment. Newly machined wheel and rail surfaces are rough. As wear takes place the surfaces become much smoother. However, the position of the contact patch varies with respect to both the wheel and the rail. This means that a long wavelength surface form is also created on both the wheel and rail surfaces. Both the short wavelength surface smoothing and the long wavelength surface roughening will change the size and shape of the area of contact [38].

The contact between the wheel of a train and the rail is a rolling contact between two bodies, the wheel and the rail, which are stiff, meaning that the deformation of the bodies is small compared to the size of the bodies. Because of the small deformation in the contact bodies, the contacting area is also small compared to the size of those bodies.

As it is seen in [39], the contact between wheel and rail is of a great importance and need to be inspected to make sure there are no problem because any problem at this contact will lead to the failure of the system. And any problem at the wheel rail contact is influencing the variation of profile geometry [40]. And this change in profile geometry is contributing in fatigue issues.

For simulation in many research document in order to get fine results it is advisable to make some assumptions that cannot change the main idea of the real life. Among those assumptions in railway design they include wheel as a body of revolution with constant radius R, the rolling surface of the rail is cylindrical and for calculation of deflections real shapes of bodies are neglected and replaced locally with elastic half-spaces [41]. These assumptions are acceptable as the results that are obtained are close to real experiments.

The formulation of the problem of contact between the wheel and rail is a complex task and has been the major point of several researches and shown different solutions [42].

Background of contact pressures in the wheel/rail interface is major information needed in both fatigue and wear calculations for wheels and rails. In turn this information is needed when determining design life, re-grinding, and maintenance schedules [38].

The adhesion characteristics were investigated by theoretical analysis with a numerical model adopting the Elasto-Hydrodynamic Lubrication (EHL) theory and the Greenwood-Williamson's (G-W) stochastic model in which the surface asperity heights of contact surfaces vary according to the Gaussian distribution [43], as well as laboratory experiments by means of a twin-disc rolling contact test machine which simulates the contact situation of wheel and rail [44]. The numerical calculation and experimental results indicate that the relationship between the adhesion coefficient and the axle load (contact pressure) is affected by the running speed of a vehicle and the surface roughness of wheel/rail.

For many previous work on the wheel rail interaction, the modelling was done considering other components forming the track system and they included suspension as the components are not in direct contact between each other. In real situation the sleepers cannot be in direct contact with the rail and the sleepers cannot connect to earth directly. In this work the sleeper was considered to replace all other components under the rail and is fixed on the ground.

In previous works the researchers tried to investigate the problems and deterioration of the track [45]. In many of them they have shown that the main source of irregularities is the deterioration of the rail surface, problems of supports on the rail where some of the sleeper are not supported, and the interaction between wheel and rail [31].

Usually the concrete sleeper modulus is around 3000 MPa and this is used when all the component of the track are available[46]. In this project the sleeper alone was used and the modulus is adjusted to mean value of 400 MPa so that the effect of the wheel interaction is the same as when all component the tack were used. This have simplified the modeling and also the computational time is reduced as the number of components is few.

In previous works it is shown that mostly the problem of the track comes when the speed is increased [16] and others tried to model the track irregularities including longitudinal stiffness variation but when the static load is applied at the top of the rail[47][48]. In this project the track irregularities were analyzed when the dynamic wheel is rolling at the top of the rail.

3 Methodology

3.1 Material and material properties

In this project the interaction of wheel rail is evaluated and as it costs to conduct experments about the wheel rail interaction. There was the use of software.

Table 1: physical properties of a train in AALRT

Gauge	1435mm
Method of power supply/voltage	OCS/DC1500V
Dead weight	43t
Axle weight	≤11t
Main size of rolling stock	Length: 28400mm Width: 2650mm Height （roof to rail top）: 3700m Height from floor to rail top: low floor area: 365 mm； high floor area: 865 mm；

	Rate of low floor: 70% Rated axle base: 2200～2300mm Diameter of wheel: Power wheel: 660mm（half wearing 640mm Driven wheel: 600mm（half wearing 580mm
Doors on each side of single coach	4

As it is mensioned in Table 1, the train at AALRT has many physical properties but in this project we use a simplified geometry of the wheel and thererore we only need the real wheel diameter, and axle load. We chose the motor driven wheel, and it has a diameter of 600mm.The axle load at AALRT is less than 11ton.

In this project the axle load that was used is expressed in term of force and is 98 kN [49]. This axle load is being applied in the center of the wheel.

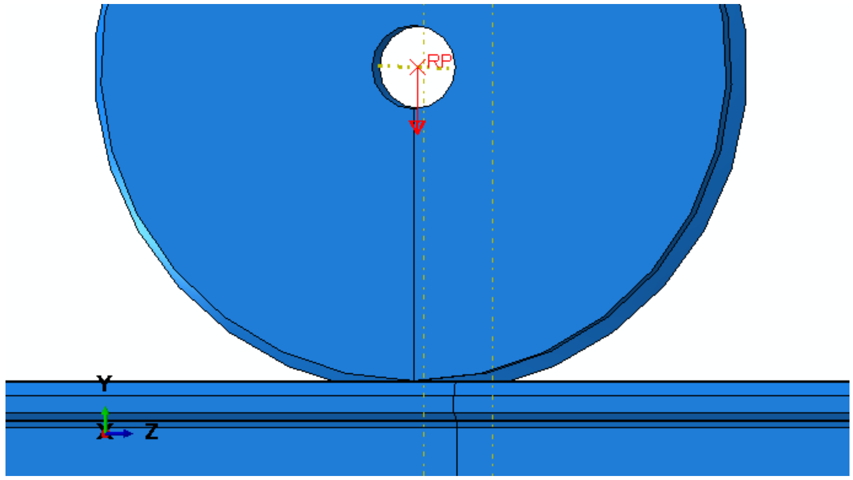

Figure 11: axle load applied in the center of wheel

The software were used to analyse the data collected at AALRT; those software are: Abaqus,python, Matlab, and solidworks.

For simulation the model was composed by 12 sleepers, a rail, wheel and the primary suspension as it is shown in Figure 11.

3.1.1 Properties of the wheel and rail at AALRT

The rail at AALRT is modelled as UIC60.as it is seen on the rail profile shown in Figure 16 The model has some of the features eliminated to simplify the modelling complexities. Due to those features some of the results are different from the one in standard system but the difference is negligible.

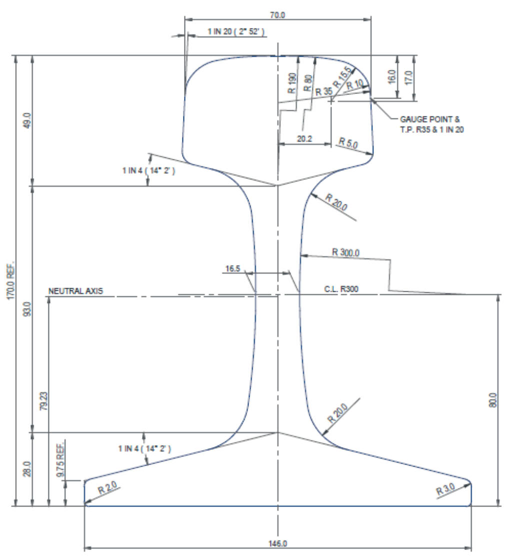

Figure 12: UIC60 rail profile [50]

Table 2: Mechanical properties of the whole model

Part	Properties
Rail	Modeled as isotropic elastic material

	UIC 60 I-profile Elastic modulus=210GPa Yield stress= 475MPa Density=7.8e-09 Poisson ratio=0.3 Friction coefficient=0.3 Length=11m
Wheel	Modeled as isotropic elastic material UIC 60 Elastic modulus=210GPa Yield stress= 650MPa Density=7.8e-09 Poisson ratio=0.3 Radius=300mm Friction coefficient=0.3
Sleeper	Concrete sleeper Cubic profile Elastic modulus=400MPa

	Density=2.4e-09 Poisson ratio=0.2 Height=210mm Length=500mm Width=300mm Spacing=600mm Friction coefficient=0.3

The rail and wheel are all made of Manganese steel which has the properties shown in the table below.

Table 3: Chemical composition of the Rail at AALRT

C	Mn	Si	Cr	P	S	Fe
1.14	12.81	0.26	0.12	0.05	0.05	Balance

3.1.2 Track stiffness modelling parameters

To estimate the variation of track modulus in FEM without introducing all track elements, which would require large computer memory, the rail is tied on sleepers which are fixed on their base. Then the mean value of sleeper Young's modulus is reduced to a value that yields same deflections and stresses in rail as in real situation (see section). From the literature this sleeper modulus parameter is estimated to be around 400 MPa [2]. The sleeper moduli, with this mean, are then chosen randomly and repeatedly for standard deviations of 20 MPa, 40 MPa, and 60 MPa. For finite element it is better to take a small region to be analyzed and make some conclusion. In this project a track rail with twelve (12) sleepers are used and their random modulii are shown in *Table 4*, as function of their standard deviations (SD).

Table 4: Random values of the sleeper modulus.

	Random variables	Standard deviations
1	[401.1422, 375.0966, 373.9058, 396.4552, 385.1468, 416.6338, 428.0068, 381.926, 413.663, 433.9454, 380.9117, 413.1667]	20 MPa
2	[387.53, 348.7278, 359.6358, 382.2814, 418.3309, 420.2309, 427.0376, 378.137, 468.1535, 428.7988, 331.9767, 449.1596]	40 MPa
3	[495.259, 347.6881, 426.7946, 456.263, 306.5955, 362.0002, 386.794, 443.6789, 341.1255, 324.3427, 448.6352, 460.8232]	60 MPa

As for simulation it is time consuming and requires a higher computer storage when the wheel is to run on the whole rail. The best way was to analyze the system according to the path, where the wheel have passed through. By this it is better to get the sample standard deviation which is obtained from the sleepers where the wheel is acting.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \qquad \text{Equation 1}$$

Where, μ is the sample mean value (elastic modulus), σ is the sample standard deviation, n is the number of items, x_i is the elastic modulus of the sleeper i,

For this model the wheel is rolling between sleeper no11 and sleeper no8. This means that there are 4 sleepers that are mostly affected and the standard deviation becomes sample standard deviation and for every case there is the standard deviation which is different from the one when there are 12 sleepers. By using *equation 4,* the standard deviations are: 25.83746, 59.34911, and 65.8733 MPa. As it is seen from sample standard deviation after taking a small sample as the wheel is rolling between four sleepers the values are different from the standard deviation when there are 12 sleepers. Also for this idea of sleeper modulus variation it can be bigger or smaller compared to the average sleeper modulus and due to that in this scenario there is where sample mean value is greater to population mean value. This affect in the values of stresses and deflection of the rail and in the result values of the output will on the value of the sleeper modulus of elasticity.

3.2 Finite element modeling of the rolling loaded train wheel on a rail track of longitudinally varying track stiffness

3.2.1 Basics of finite element modelling

The finite element method is a common tool within various fields of engineering. It is used for advanced numerical calculations and is developed from the theories of continuum mechanics, which studies equilibrium, motion and deformation of physical solids. FEM prerequisites that the mathematical models which describe the motions of the media has to be based on continuous functions.

In FEM the continuous functions are approximated by a discrete model where the body to be studied is divided into several smaller parts, so-called elements. The discretized model is composed by a number of element functions that are continuous over each separate element. These elements are connected through nodes, which is primarily where the calculations are made. Numerical values for the nodes are compiled to make the element functions an accurate approximation of the global function. Accuracy improves when the number of nodes increases or when the mesh size is small. In particular, our simulation is done using ABAQUS UNIFIED FEA, and as it is done in many other modelling software, it involves three major procedures which are: preprocessing, processing, and post processing.

In railway, at this time the researchers are trying to develop the system by which the travel time is reduced and the time reduction is achieved when the speed is increased. Basically increasing the speed results in vibration and sometimes deterioration of railway system. For a light rail system especially AALRTs the maximum speed is 70km/h and it is assumed that the higher the speed the more the vibration. In this project the speeds are 30km/h (10m/s), 54km/h (15m/s), and 70km/h

(20m/s). Apart from speed the rolling motion of the wheel is affected by the amount of torque applied on the wheel axle in the center of rotation. The torque points from the axis of rotation toward the point where the force is applied. When the wheel starts a rolling motion the interaction between wheel and rail results in some deformations of the track, and this deformation is related to track stiffness. As the railway system is in operation the track stiffness changes because of climatic conditions, the track arrangement, missing supports, loose supports, and bad material.

To create an ABAQUS/CAE model first of all the set must be well installed and make sure that the computer has enough space for saving the model, and then choose the directory where the files for the model can be saved. Abaqus can be used for modelling and simulation or it can be used for simulation only when the models are imported from other software as a geometric representation like Solidworks, Ansys, CATIA, etc. For this model all the parts are modeled in Abaqus and then the simulation also was in Abaqus. In Abaqus the model can be standard/explicit or electromagnetic. For this model as there is no electric properties which are used electromagnetic model can't be used. In this project standard/Explicit was used. Also the model can be in 2D or 3D. The first step is to define the geometry. Thus, a three-dimensional, deformable body with a solid, extruded base feature is created. After defining the geometry the first model to be modeled was the rail and is shown in figure 13.

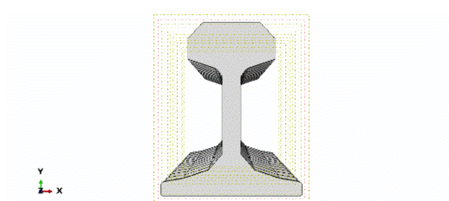

Figure 13: Rail

The rail which was used has the features of UIC60 rail. For simulation in order to make the modeling easier some of the features are ignored and others are modified. The number of sleepers is 12 and are the same geometric shape. In modelling the top of the rail was considered to be straight.

After all the parts are modelled, they are assembled in one model which is known as wheel-rail interaction. In assembling the rail is coupled with the wheel at the contact point, and then the sleeper are added below the rail. As in the model 12 sleepers are required after putting one sleeper the linear pattern software feature is used to multiply the sleepers. Then, the sleepers are tied with the rail. And the assembled model is shown in Figure 18.

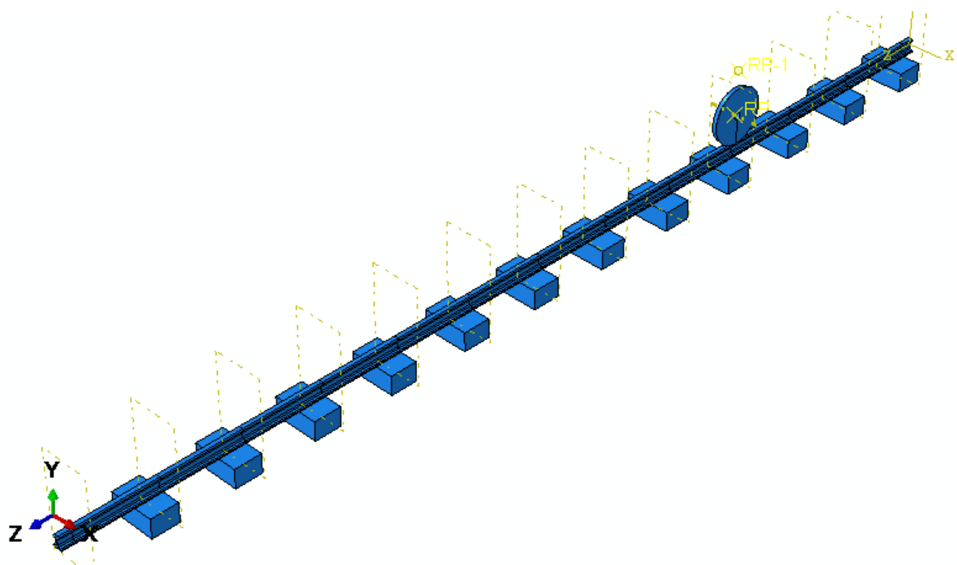

Figure 14: wheel rail model from abaqus

In order to reduce the computational time the wheel is set to roll for a small distance on the rail.

After getting the assembled model the interaction is set; the interaction between the wheel and the rail is set to be penalty contact method which means that the penetration between the two parts is negligible. The sleepers are connected to rail by a tie constraint. Which means that the whole mass of the rail is supported at the sleepers.

In every engineering problem there is the boundary conditions because in software it is not possible to put everything as it is. So the features that are not present can be replaced by the boundary conditions. These boundary conditions are as follow:

- The end of the rail is fixed so that it can't move in any direction and this is due to the fact that the rail is having the infinite length but the small part was used for simulation.

- The wheel moves forward a certain distance which is proportional to the wheel radius and the angle of rotation.
- The bottom of the sleeper is fixed with the encastred boundary condition which is implying that the sleepers are connected with the soil.
- The wheel rotates through the center and a coupling constraint is applied to the wheel center which helps the wheel to rotate.
- The wheel is only moving longitudinally and is not moving laterally, this reduce the computational time. The figure is the one showing the boundary condition.
- Also in the boundary conditions module the loads are applied and these forces are the forces applied in the center of the wheel which are known as the axle load. Also the torque is applied in the center of the wheel.
- The wheel is rolling on the rail and the interaction is affected by the amount of axle load also affected by the torque.

For every modeling software before running a model it must be meshed. The smaller the mesh size the more the results are accurate and take too much time to compute. Every instance is meshed independently and assembled to the model in Figure 15.

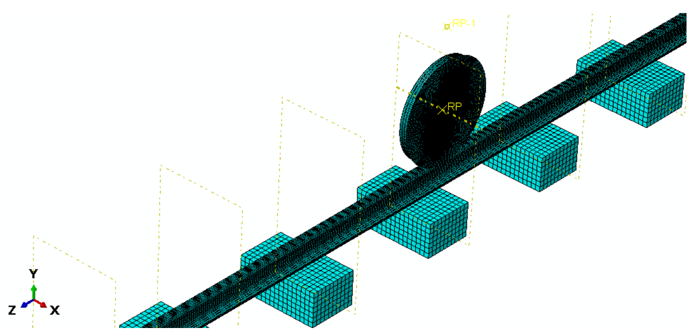

Figure 15: meshed model

After meshing the model, the model is ready to be run. And before running a model the job must be created and do a data check to see if there is no error. If there is error the cross check of the model must be done. If there is no error the input file must be written which can be used to run the model. Or submit module can be used.

This model has 3 steps which are:

- Initial step
- Step one which is for applying loads in the system
- And step two which is the rolling of the wheel.

3.2.2 Longitudinal variation of track stiffness

The properties of the track is mainly due to drainage, the drainage is affected by the level of contamination. During the rain time there will be the clay which will be stuck on the sleeper surface and this will affect the drainage system of the track. For the track there is a certain critical drainage capacity at which when it is less the drainage condition is not acceptable. It has been seen that moisture, density, and stress level of the sleeper are affected by the level of contamination, mainly it is clear that the increase of degree of contamination implies the decrease of hydraulic conductivity of the ballast. All this contamination are implying the variation of resilient modulus which is the measure of track stiffness, and is to provide a way to analyze stiffness of materials under different conditions.

The resilient stress is related to the modulus of elasticity, and as the level of contamination is changing the resilient modulus is changing as well. And this implies the change of rail support stiffness.

In this model it is assumed that the sleeper is supported by the soil and they are in a direct contact which is the one explaining the contamination of the sleeper surface by the clay, mad, and other material from the underground. Logically when the properties of two successive sleepers, ballasts, substructure, etc., are different, the rail is subjected to varying support stiffness. Also, if there is a transition from the slab track to ballasted track the support stiffness suddenly changes. Furthermore, the rail support stiffness varies along the track when the track structural elements such as fastenings, sleepers do not mate with neighboring elements uniformly along the track. For example, loose sleepers and loose fasters at certain section of the rail. As a result, rail has different values of vertical displacements for a same applied load. As the way to estimate the variation of the track modulus the experiments to measure the track modulus is very complicated and require a lot of equipment.

For modelling purpose, Nkundineza and Turner [2], developed a method of using equivalent sleeper modulus to solve the inherent computational complexity. This equivalent sleeper modulus is used in finite element models to provide same rail stress and deflections as those obtained by field measurements. In their findings, a sleeper modulus of 500 MPa corresponded to a measured rail deflection of 2 mm for the main line railway. In this thesis a wheel is rotated on the rail across fixed sleepers such that their average Young's modulus represent equivalent track stiffness. A Young' Modulus of 400 MPa is chosen. The Young's moduli of the sleepers is generated randomly for various standard deviations as are represented in Table 4.

3.2.3 Processing

After defining the whole parameters the model started running and the running time depends on different things. But mainly as the number of increment increases the computational time increases and the storage required increases.

In the processing step there are two ways it can be done, first is when the model is run using ABAQUS interface module called "job", or the model can be run in the background using a bash script.(See in Appendix job submit file.)

When running using the module job running two jobs at the same time will affect the performance of the computer and it will take more time to run all the models. But when a bash script file is used it is possible to take more than one input file and put them in one folder and run the bash script to run them. In this method one model will be running at a time till is completed and when one is finished running another will start, and the process will keep repeating following an alphabetic order.

3.2.4 Post processing

The visualization module shows the results in form of color codes and according to the color on the model and the same color on color code tree the output can be known. All the information that are obtained in the visualization module are controlled in the step module, and the number of output data requested must be in line with the input database. Also the more the output data are requested the model take a lot of time to finish running.

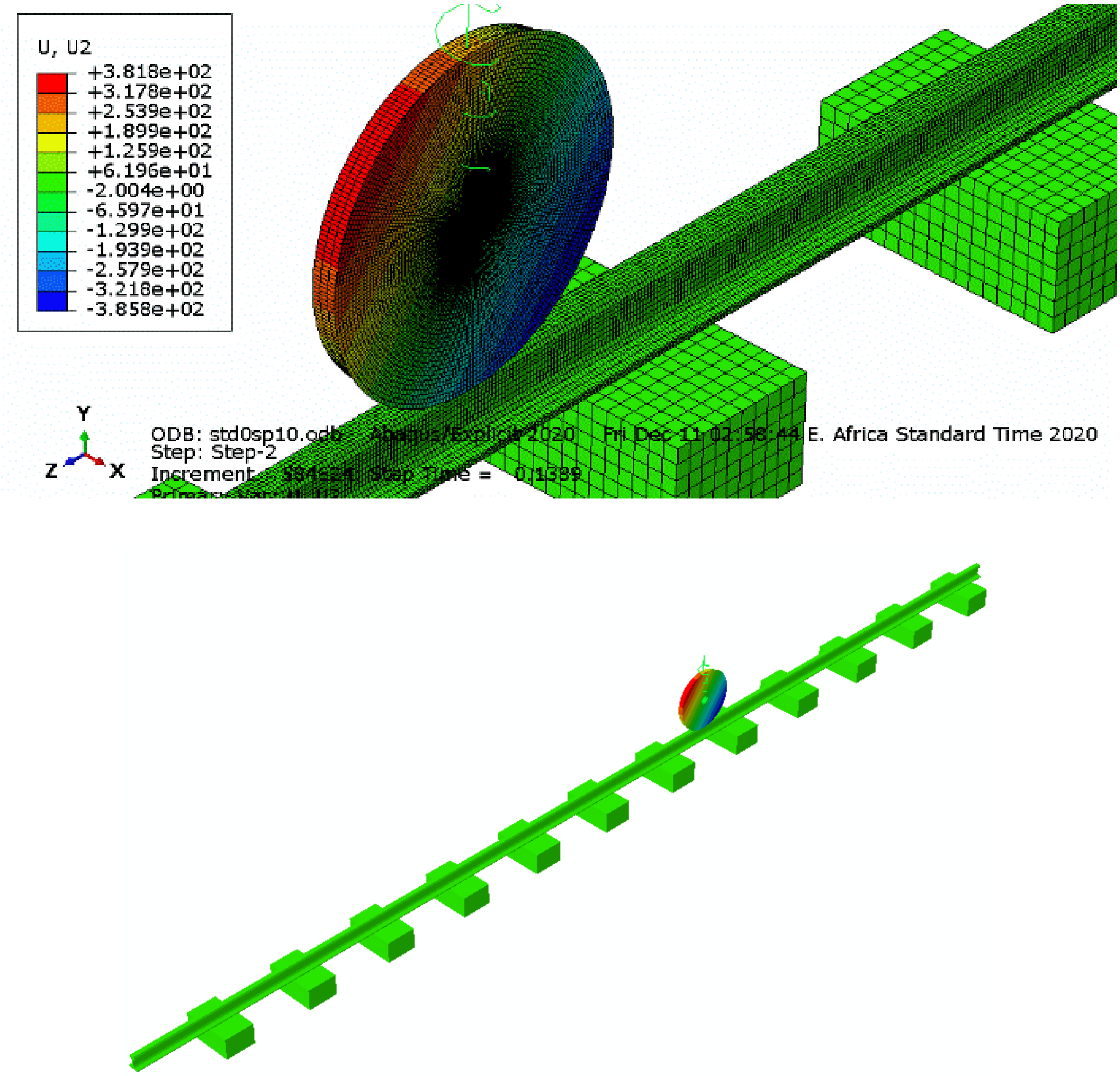

Figure 16: wheel-rail interaction displacement

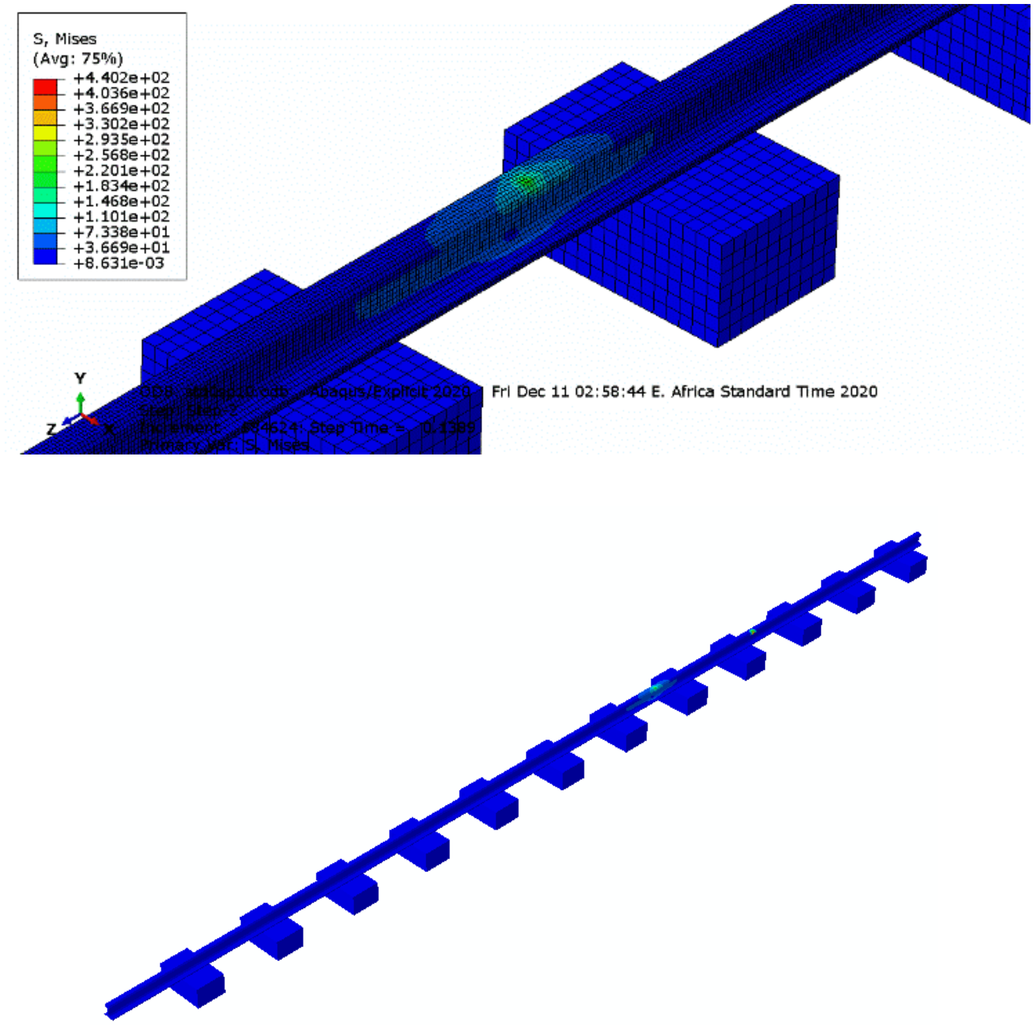

Figure 17: rail stress

As it is seen in the Figure 16, according to the color of the rail and using the color code the results can be extracted. From this the rail as it is constrained its deflection is -2.004mm as it is indicated by the green color in the color code. And as the wheel is rotating and moving there are points on the wheel which are having large displacement because the point can move up down for a displacement equal to the diameter of the wheel. Where it is red the displacement is 3.818e2mm meaning that the points are moving upwards and where it is blue the displacement is -3.858e+2mm meaning the points are moving downwards.

In FEM software there is a link with other programing and graphing software like python and Matlab. After a model processing is completed, there is an output database (odb) file and from the odb file, there are all the results but they are not easy plot and explain. And the data that are found after processing are not all needed in the analysis. That is the reason why programing is required to choose what to extract from the odb file. In this project the results that are needed the most are rail vertical deflection and von mises stresses. In this project there are twelve odb files. Also python programming is linked with command prompt which is another programming way made in every computer. After the data are extracted they are just saved in an excel sheet file. In any field of this life the best way to analyze data is first of all make graphs and from graphs it is easier to interpret.

In Matlab there is a way to import data from other working software and plot the results. After the results are obtained in excel they are exported in Matlab and then plotted in graphs. In Matlab from excel sheet there is also the way to plot different data in one figure and from that it is easier to interpret and explain. As in this project there is variation of speed and variation in elastic modulus. As for simulation it is not easy to get the results when two or more variables are changing at the same time. So for this at every standard deviation there are results when the speed is 10m/s, 15m/s, and 20m/s and for each speed the standard deviation is varied.

4 Result analysis and validation

4.1 Wheel center deflection at a regular track

For a rolling object when the speed is increasing, the chance of vibration to increase is also big. As it is seen in Figure 18, when the wheel is rolling the regular track the main concern is the speed and as the speed is changing the remarkable change of the wheel center deflection.

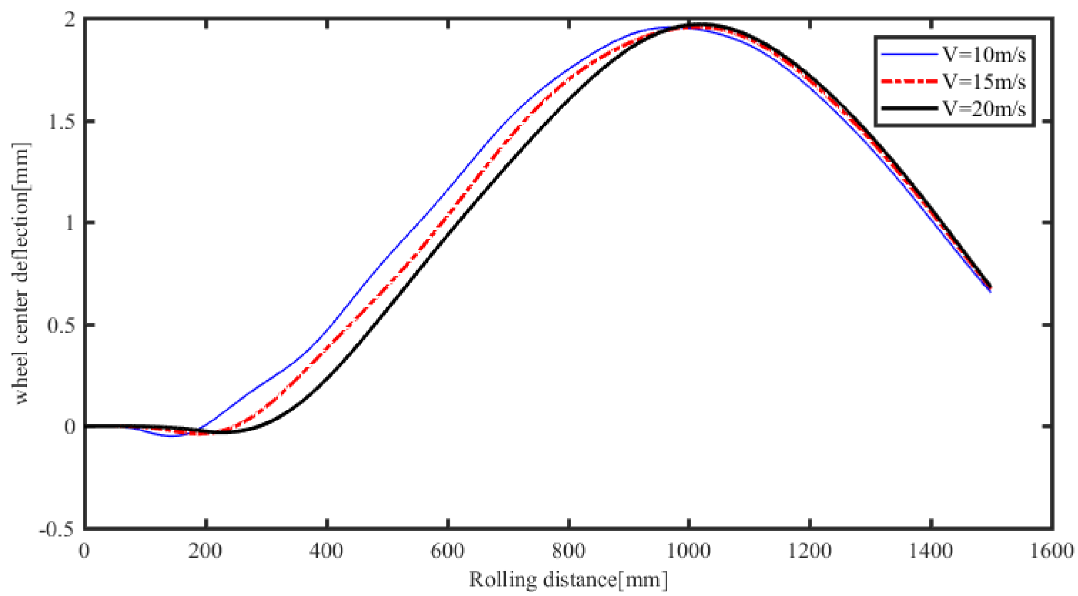

Figure 18: wheel center deflection on regular track

As it is shown in the Figure 18, when the wheel is rolling, the center is deflecting and the deflection is proportional to the speed. When the speed is small at the starting the center of the wheel is experiencing higher deflection compared to when the speed is higher. This is because the same force is applied at the center of the wheel and this force has the more impact when the wheel is like static, after a time when the wheel is rolling at higher speed this results in increased wheel center deflection magnitude. Mostly it is seen that the increasing of speed implies the increase in wheel center deflection. The maximum deflection is seen when the wheel is at a distance of 1000m this due to that the wheel is in the location where there is no sleeper which results in higher deformation of the rail and it results in higher deformation of the wheel as well.

4.2 Effect of speed variation on rail deflection at for a given standard deviation of track stiffness

In this project there is a model which has one rail, one wheel, one suspension, and twelve sleepers. The running time depends on many factors which can be the capacity of the computer, the size of the model, number of components, the mesh size, the steps, and the step size (period). For this model because the computating time is too large even if there are 12 sleepers the wheel is rolled through 4 sleepers and the distance is 1.35m.

The wheel has a radius of 300 mm. The rolling distance is proportional to the rolling angle and the wheel radius. The rolling distance is obtained from the formula when the object is moving on a circular path.

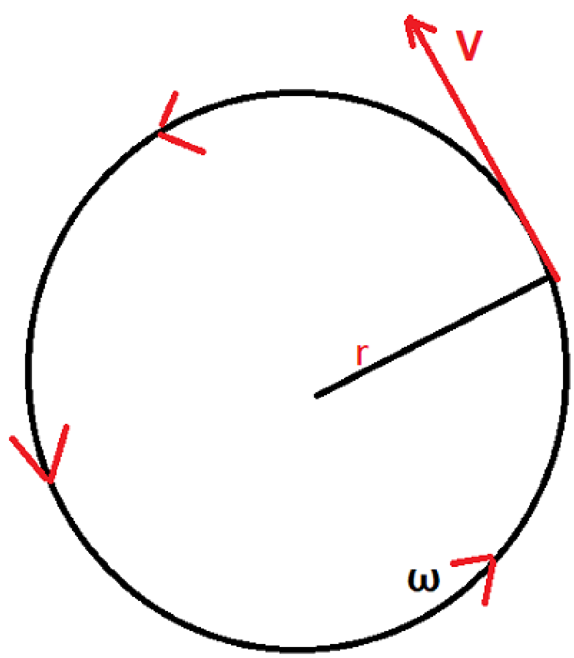

Figure 19: a point moving on circular path

As it is shown in the *Figure 19*, the linear velocity is proportional to the angular speed and the radius of the path. From the linear velocity the travelling time is calculated as the running distance is known.

As the wheel is rolling on the top of the rail, the rail is having deformations and is having stresses caused by the loading and rolling of the wheel on the rail. The rail is supported like a simply supported beam. Here, the sleepers are supporting the rail. Between two sleepers there is a space which is known as sleeper spacing, this space is helping the track system not to be too stiff. And as it is seen in the Figure 20, the rail deflection is changing from one point of the rail to another. This is due to the fact that as the rail is considered as a beam that is supported between two sleepers the largest deflection will be seen in the middle point of the two consecutive sleepers and when the wheel is at the top of the rail where there is a sleeper the deflection value is smaller as compared to the point where there is no sleeper. Because of that effect the rail deflections fluctuate.

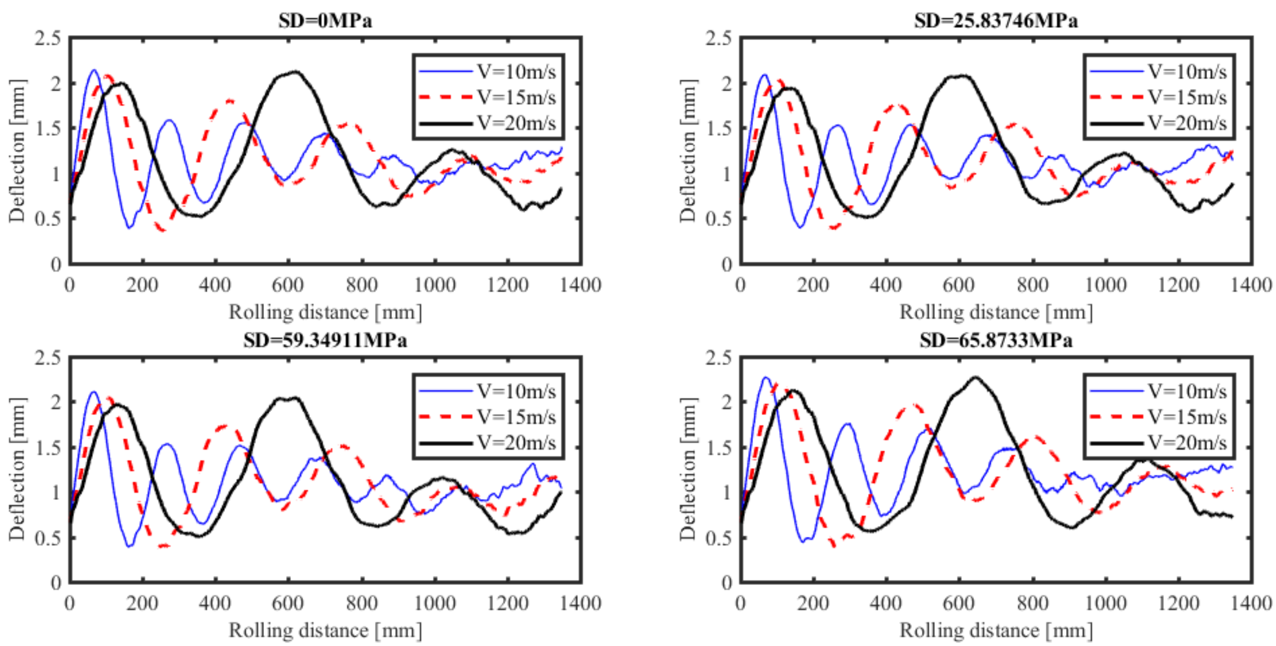

Figure 20: Absolute maximum rail deflections for a given standard deviation for various speeds

From Figure 20, we can see the effect of speed on the deflections of the rail for a given standard deviation. These results demonstrate that the deflection values are different when the speed is changed. For sinusoidal functions when there is no intervention of an external force the function will not be damped and the system will tend to be unstable.

When the speed increases the amplitude of deflection increases and will not be damped easily compared to a lower speed. As the wheel is moving between two points the time it takes is responsible for the vibration of the wheel. When the wheel take a small time means there is too much vibration and this will cause the rail to have greater deformation at higher speeds. From all the sleeper modulii, it is seen that the rail has greater deflections at the speed of 20m/s. at every point, it is seen that when the speed increases also the deflection increases as well.

For a regular track that is having the sleeper modulus that is the same there is no big change in the deflection of the rail. Logically when the beam is supported by two supports and their reaction forces are different this can be responsible to the vibration.

4.3 Effect of speed variation on rail stresses for a given standard deviation of track stiffness

For a simply supported beam when the moving load is applied it is deformed according to the magnitude of the force and the material property of the beam. As it is commonly accepted that the history of elasticity theory began with the studies of Robert Hooke in the 17th century who explored the fundamental concepts of deformation of spring and the displacement of a beam. When a body, in an initial state of equilibrium or undeformed state, is subjected to a body force or a surface force, the body deforms correspondingly until it reaches a new state of mechanical equilibrium or deformed state.

The inner body forces are the result of a force field such as gravity, while the surface forces are forces applied on the body through contact with other bodies. The von Mises stress is a criterion for yielding, widely used for metals and other ductile materials. It states that yielding will occur in a body if the components of stress acting on it are greater than the criterion.

The maximum stress in the rail as it is shown in Figure 21 is changing from one point to another, and is related the material properties of the wheel, rail, and sleepers.

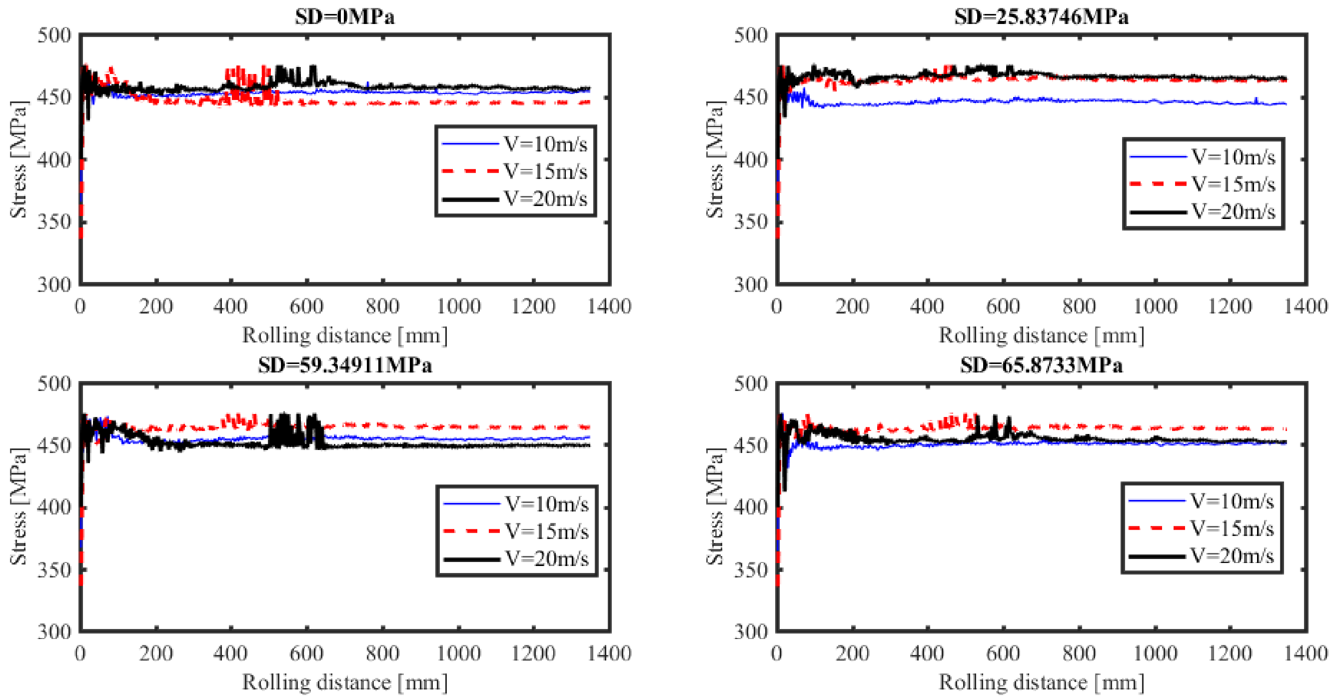

Figure 21: Maximum von Mises in the rail for a given standard deviation for various speeds

In Figure 21, it is shown that for the speed that is small, the maximum stresses have small amplitudes and are constants over the rolling time. As the speed increases the amplitude is increasing. When looking in stress curves, it is seen that when the wheel is rolling at the speed of 10m/s the curve becomes straight after short time compared to when the speed is 15m/s and 20m/s.

Briefly, it can be concluded that when the rolling speed is increased the stress increases.

4.4 Wheel center deflection at irregular track and comparison with regular track

The wheel center deflection is mainly due to the weight and the magnitude of the force applied in the center of the wheel. And the behavior of the track doesn't influence the displacement of the wheel center as the wheel center is connected to suspension.

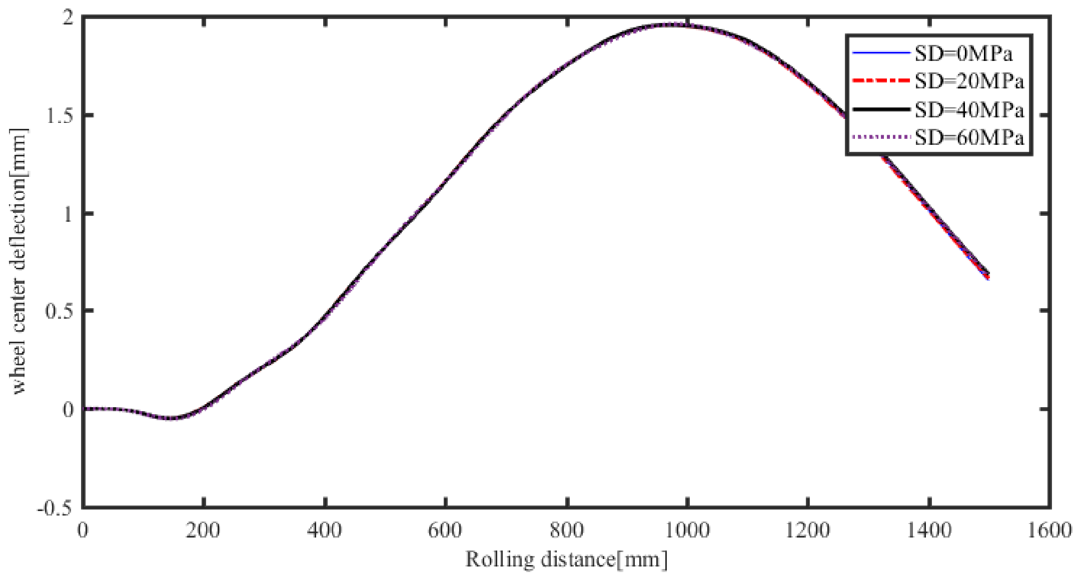

Figure 22: wheel center deflection at speed of 10m/s

Figure *22* is showing that as the track becomes irregular there is no remarkable change in the wheel center deflection. And this is due to that the wheel center is not having the interaction with the rail.

4.5 Track deflection at a given point at unit of time

In the interaction of wheel and rail at every point of contact the whole track is having deformations and these deformation differ from one point to another. In this work one point is chosen after the wheel has rolled 0.00429 seconds. When the wheel is rolling the maximum values of stress and deflections are found at the point of contact.

As the wheel has rolled for a small distance, the deflection and stresses are plotted with the influence of mean sleeper modulus and as the mean sleeper modulus is small the deflections are bigger as it is indicated in Figure 23.

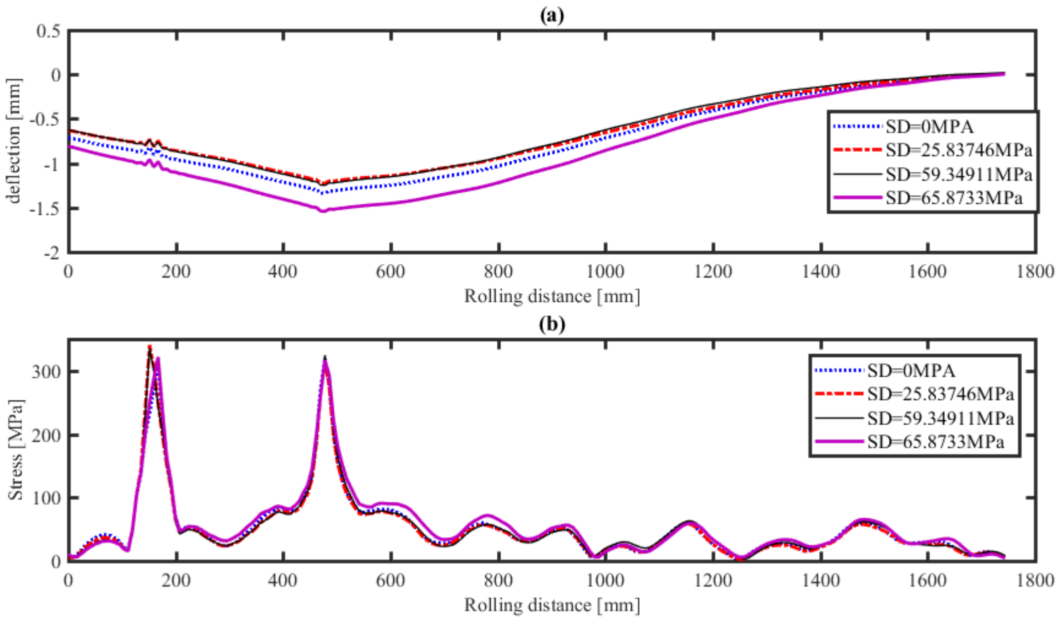

Figure 23: rail deflection (a) and stress (b) after 0.00429 seconds

As it is shown in Figure 23, after some time when the wheel is rolling, the deformations that occur at one point are different from another point at the same time, considering the location of the contact point. And at the point that is far from the contact region its deformation is almost zero. As the point of study in this work includes the effect of track irregularities on wheel rail contact performance, the speed is kept constant and the results are obtained according to the variation of standard deviation. It is seen that as the standard deviation is increasing the rail is having higher deflection which are responsible for the vibration. And the more the stresses on the rail, fatigue is likely to happen. As this project is analyzing the effects of track irregularities the speed was kept constant and the standard deviation is varying. In figure 22 (a) it is seen that maximum deflection at higher value of mean sleeper modulus is smaller compared to one of smaller value of mean sleeper modulus. In figure 22 (b) the stress at 175mm length from the start is higher and it due to the static step and the high stress level is due to the time the wheel was static. At 500m the stress level is higher and it is relative to the position of the wheel at the rail. For an object in motion and the one which is static when all the object have the same properties; the one that is static is causing higher stress at the contact region.

4.6 Effect of track stiffness variation on rail deflection for a given train speed

In this case the analysis is done when at every speed the standard deviation is varied. In this case the main concern is to see the effect of changing the sleeper modulus parameter known as equivalent Young's modulus. And it has been seen that when it is taken into consideration the sample averages of sleeper modulii for standard deviations of 20, 40, and 60 MPa are 402.6115, 401.7665, 389.4456 MPa respectively. And as the values for sample average modulii indicate, as the average sleeper modulus increases the rail deflection decreases. Also it is seen that the change is remarkable for the standard deviation of 60 MPa, and for the deflection the real change at every speed is seen at standard deviation of 60 MPa.

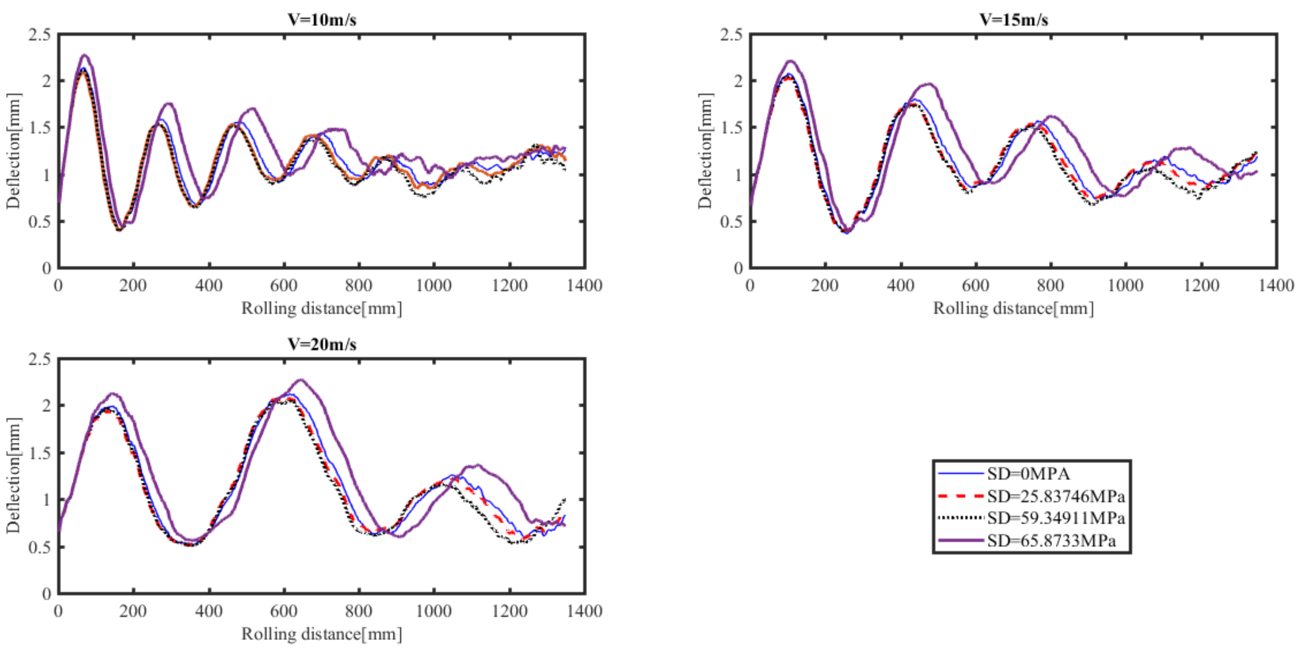

Figure 24: Absolute maximum rail deflections for a given speed for various standard deviations

In Figure 24, the highest maximum deflection is found at the standard deviation of 60 MPa. Accordingly the sample average sleeper modulii for SD= 0, 20, and 40 MPa are almost the same and their deflections are almost the same as well.

4.7 Effect of track stiffness variation on rail stresses for a given train speed

The stresses in an object depend mainly on the material, and the amount of forces applied. In this model the material property taken into consideration is the modulus of elasticity of the sleepers, and when it is fluctuating it will affect the working of wheel rail contact mechanics. At low speed the system is stable and the effects of modulus variation is not that remarkable. As it is seen in the graphs showing the variation of stress along the track, the stresses are fluctuating mostly between 400 and 500 MPa. This is due to that the rail was set to be modelled as a perfect plastic meaning that after yielding there will be no more stress increase. And also in modelling it was set to show the maximum stress at every increment.

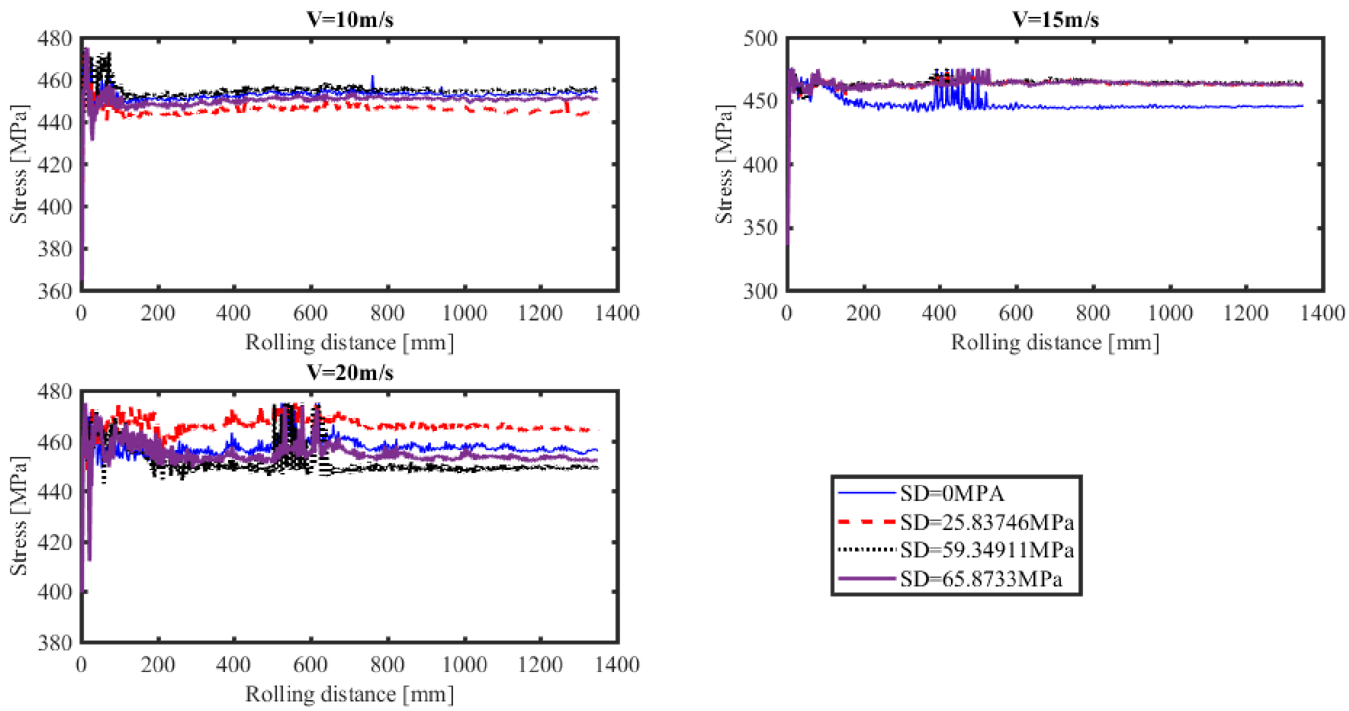

Figure 25: Maximum von Mises stresses at for given speeds for various standard deviations

As it is remarkable in Figure 25, at speed of 20 m/s there are a lot of stress fluctuation and this implies that the speed is the one that is affecting the most in the railway system. For the system that is stable the stresses curve was supposed to be a straight and from that it is concluded that higher speed modulus variation will have great impact on the wheel rail contact induced stresses.

4.8 Long track model

When modelling the accuracy depends on the size, and the components of the model. As the wheel is rolling at a small distance it is not easier to obtain the general conclusion. As it is shown in Figure 26, the graphs for stresses and deflection have changed and it is due to that mainly when the body starts moving it is not stable at the starting but after time the general trend can be seen. This shows that the deflection of the rail when the wheel rolled a longer is small compared to when the wheel rolled a short distance. This is due to that as the number of supports are increasing the deflection decreases.

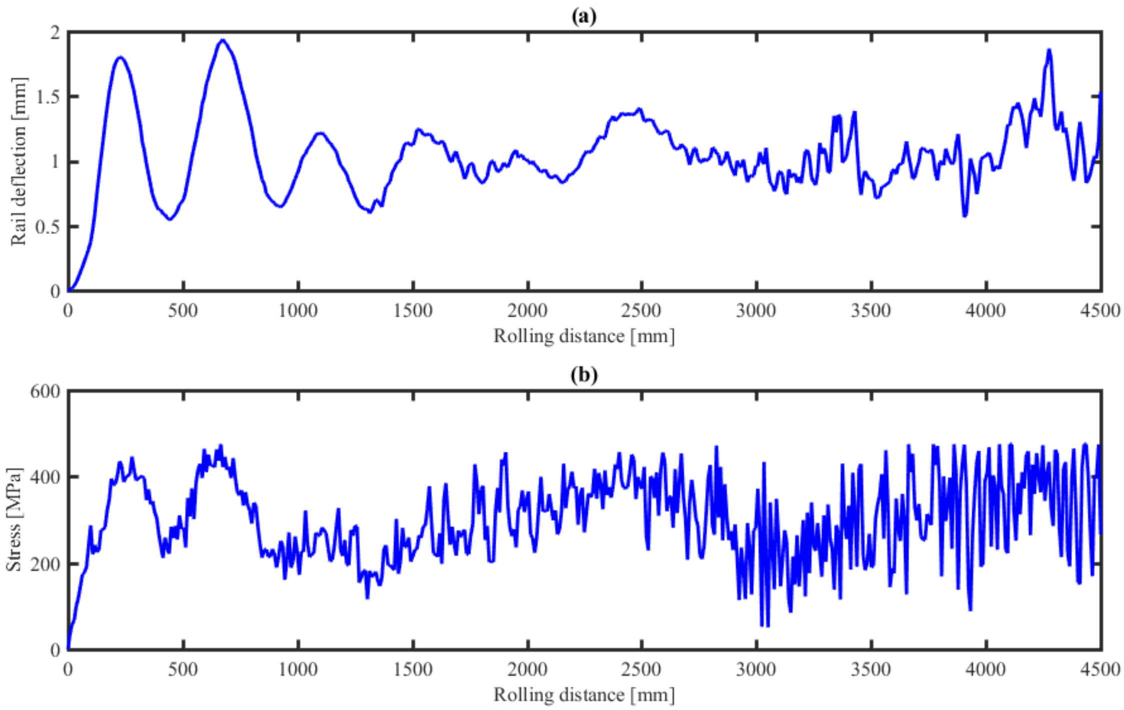

Figure 26: long track model (a) rail deflection, (b) stresses

For modeling when the size of the model is big it needs more computational time and large storage capacity in the computer. Also as it is seen in the shape of the graph in Figure 26, at the starting the behavior is the same but the magnitude are different, this shows that when the number of sleepers where the wheel has to run through is increased the deflection decreases. And it shows that the maximum deflection is 1.90mm in figure 26 (a) for longer track model and it is 2.3 mm for shorter track model as it is shown in figure 27.

4.9 Validation of the work

- Winkler model

From the Winkler model, the vertical deflection profile of a rail is only dependent on the track modulus value when the rail size and vertical loads are known. In the Winkler model it was assumed that the track modulus is constant and this is compared to the results in this project when the wheel is rolling on the track uniform sleeper modulus of 400 MPa.

"The dynamic effects of track–train interactions are not considered during the simulations due to the software's limitation. This is acceptable within the scope of this study which mostly focuses on the Canadian freight lines where speeds are most likely lower than 65 km/h"[51].This project is focusing on AALRT for which the speed is varying up to 70km/h, which means that the Winkler model results from simulation for AALRT case are acceptable.

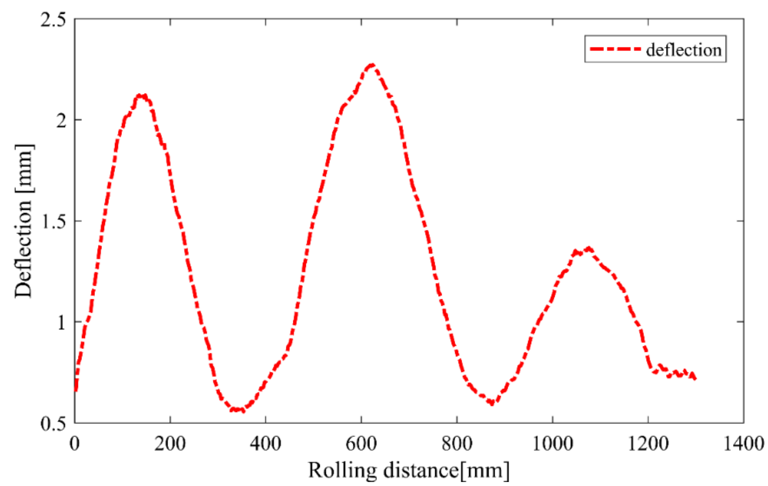

Figure 27: FEM maximum rail deflection

From Figure 27, the wheel run at a distance of 1.4m at a speed of 54 km/h which 15 m/s and the maximum deflection was fund to be 2.3 mm.

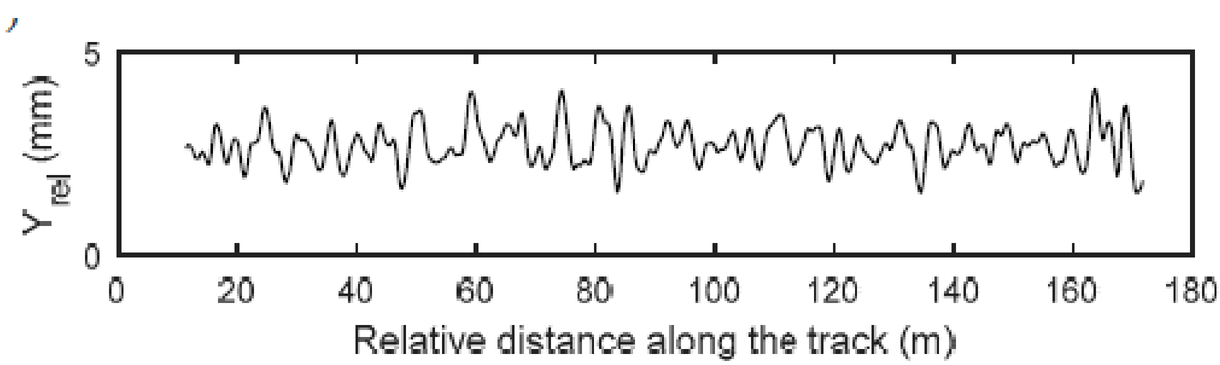

Figure 28: Rail deflection with Winkler model [3], [4]

As it can be seen from Winkler results in Figure 28, the speed is up to 65 km/h and in the model it can be seen that the wheel was running at a distance of 180m. The deflection of the rail was found to be fluctuating between 0 and 5 mm.

Experimental results have shown the Winkler Model is a good representation of track deflection. The Winkler Model describes the deflection of an infinitely long beam resting on an infinite continuous, uniform, elastic foundation in response to a single point load. In this model the deflection of the beam under an applied load is linearly proportional to the pressure between the base of the rail and the foundation. The vertical deflection of the rail, y, as a function of longitudinal distance along the rail x is given by:

$$y(x) = -\frac{P\beta}{2u} e^{-\beta x}[cos(\beta x) + sin(\beta x)] \qquad \text{Equation 2}$$

Where,

$$\beta = (\frac{u}{4EI_z})^{\frac{1}{4}}$$

Where

P is the load on the track.

u is the track modulus.

E is the modulus of elasticity of the rail.

I_z is the moment of inertia of the rail.

X is the longitudinal distance along the rail.

- Static load (BOEF model)

When the wheel is rolling on the rail, practically its effects are difficult to be measured if the wheel is in motion. For a static and a semi-static load it is shown that the rail deflection increases due to the increase in axle load. Skoglund,2005 [47] have used a static load of 100 KN, and has compared the results with the BOEF model and it was seen that the maximum deflection of the rail at the point where the load is applied is 2mm. At the end of his project he concluded that when the railway sleepers are set to be vertically constrained, the deflection of the rail is the same as the one in BOEF model.

As the wheel is moving, at a given point it is causing the deformations on the rail and by considering the results obtained in this work, this work is validated by BOEF model as well. This project can be validated by BOEF model as well.

- Effect of axle load on rail deflection (Experiment)

In this project it is seen that the only one axle load was used which is 98 kN and it is seen that from simulation the maximum deflection is 2.3mm.

As in Arthur et.al [52] through the experiment, when the train is moving with a speed of 64 km/h it was identified that the rail deflection of the rail that is supported by concrete sleepers changes as the axle load is changing. And for their experiment the axle load was varying from 0 to 180 KN and the rail deflection is varying from 0 to 3 mm. and according to the results in their experiment; this project can be validated by this experiment. In this this project it is concluded that the results of simulation are validated by the experimental results in the literature.

5 Conclusions, Recommendations, and future works

5.1 Conclusions

- The main objective for this project was to use finite element analysis to investigate the effects of track irregularities on the wheel rail interaction. Basically it was found that there are many types of irregularities that have been investigated and in this project it investigated the effect of irregularities due to track stiffness variation.
- In this project the use of software is preferred and it is found that it is effective as the results obtained are equivalent to the experiment result.
- It is seen that as the equivalent sleeper modulii varies due to track stiffness variation, it affects the mechanics of wheel rail interaction. And even when the track is regular; the variation in speeds has more significant influence on increase in rail deflection and stresses than track stiffness variation.
- It is also noted that, statistically, there will be a significant increase in deflection and stresses for a high level of stiffness variation is affecting the wheel rail interaction remarkably.
- Moreover For example, it is asserted that the variation of track modulus has more effect at the standard deviation of 60 MPa. It is concluded that the wheel rail stresses and deflections are not highly affected and the interaction is not showing any problem at low speeds of 10 m/s and 15 m/s with standard deviation which is low, not beyond 40 MPa. And when the speed is increasing and the standard deviation reaches at 60MPa there are a lot of changes and it is affecting the wheel rail interaction.
- And the track irregularities are responsible for the vibration. The future upcoming work will include the results of a wheel rolling through ought the total length of the rail described in this model, as well as contact lost energy, and wheel deflections.

5.2 Recommendation and future works

- For proper performance of the rail vehicle and long lifetime of the rail, the variation in track stiffness can be eliminated by proper track design and performing consistent track maintenance in a given interval of time.
- The measurement of track modulus is not an easier task and is expensive but it is not costly as compared to what can happen if there is an accident caused by track stiffness problems.

Therefore railway companies such as ERC can be recommended to implement a method of track stiffness measurement along the railway track.

5.3 For future works

- Researchers can model this model but considering that the wheel is rolling the maximum distance as much as possible.
- In this project the simulation was performed using ABAQUS/CAE. For other researchers it can be recommended to use other software and mathematical modelling. And compare to their results with those obtained in this project.
- Compute the fatigue cycles of rail under rolling wheel and influence of track irregularities.
- Rotate two wheels simultaneously.
- Use nonlinear plasticity material model of the rail.

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Appendix

- Job run batch

```
@ECHO OFF

FOR %%f in (*.inp) DO abaqus job=%%f interactive
```

- Data extraction code for rail deflection and rail stresses

```
odbfile='C:\Users\Venuste Masabo\OneDrive\Documents\scripting\Job-1.odb'
Exstract_FromInstance={'U':'Railway track vertical displacement'}
Instance='SIMULIS-1'
Datarequest=[Exstract_FromInstance,Instance]
filename2='C:\Users\Venuste Masabo\OneDrive\Documents\scripting\max_datas.xls'
odbfile='C:\Users\Venuste Masabo\OneDrive\Documents\stress\st0sp20.odb'
Exstract_FromInstance={'U':'rail vertical displacement','S':'rail maximum principal tensile stress'}
Instance='SIMULIS-1'
Datarequest=[Exstract_FromInstance,Instance]
filename2='C:\Users\Venuste Masabo\OneDrive\Documents\stress\max_datas.xls'
extractdata(odbfile,Datarequest,filename2)
```

- extractdata.py (Dr.Celestin Nkundineza, Abaqus and python training materials, 2020)

```
def extractdata(odbfile,datarequest,filename2):

myOdb = odbAccess.openOdb(path=odbfile, readOnly=False)

#Get the  steps separately and give them variables such as step1 and step2

step1 = myOdb.steps['Step-1']

step2=myOdb.steps['Step-2']

#Instance to extract deflections and stresses

myinstance=myOdb.rootAssembly.instances[datarequest[1]]

# Also, initialize a text file name 'max_press.txt' that will store the data and let give it a
variable fmcp, and let it open to take data

fmcp2=open(filename2,'w')
```

```
#Write headings for each columns

fmcp2.write('Total Time'+'\t')

[fmcp2.write(str(datarequest[0][titledata])+'\t') for titledata in datarequest[0].keys()]

## Go to the second line for next data writing

fmcp2.write('\n')

#Let loop over each step

#initialize initial time to be zero

t0=0.0

#From initial step add the total step time of step 1 (From which step 2 time starts). Note that we are extracting data in step 2 only. If extracting data in step 1, replace step2 by step1

steptime=t0

for step in myOdb.steps.values():

    #Within each step we want to get the field output data  at each frame (or time increment) ; then, we want to acquire the maximum data at each

    #Then loop over each frame or requested time increment

    for frame in step2.frames:

        #Extract step time times

        steptime=t0+frame.frameValue



        fmcp2.write(str(steptime)+'\t')
```

```
        #Extracting data components from instances

        for datav in datarequest[0].keys():

            datatypes=frame.fieldOutputs[datav]

            datatypes_region=datatypes.getSubset(region=myinstance)

            n_data2=len(datatypes_region.values)

            all_datas=[]

            for i in range(n_data2):

                if datav=='S':

                datavalue=datatypes_region.values[i].minPrincipal

                else:

                    #extract vertical displacement (in this case y
direction: U2)

                    datavalue=datatypes_region.values[i].data[1]

                all_datas.append(datavalue)

            all_datas=[abs(all_datas[i]) for i in range(len(all_datas))]

            max_d=max(all_datas)

            fmcp2.write(str(max_d)+'\t') #the paramter '\t' allows us to write the
next value at the next column.

        fmcp2.write('\n')

    t0+=step.timePeriod
```

Matlab code for plotting stresses and deflection

```
%% Import the data

data1 = xlsread('E:\ange\Results\excels\500frames\std0sp10.xlsx','Sheet1');

data2 = xlsread('E:\ange\Results\excels\500frames\std0sp15.xlsx','Sheet1');

data3 = xlsread('E:\ange\Results\excels\500frames\std0sp20.xlsx','Sheet1');

data4 = xlsread('E:\ange\Results\excels\500frames\std20sp10.xlsx','Sheet1');

data5 =
xlsread('E:\ange\Results\excels\500frames\std20sp15.xls.xlsx','Sheet1');

data6 = xlsread('E:\ange\Results\excels\500frames\std20sp20.xlsx','Sheet1');

data7 = xlsread('E:\ange\Results\excels\500frames\std40sp10.xlsx','Sheet1');

data8 = xlsread('E:\ange\Results\excels\500frames\std40sp15.xlsx','Sheet1');

data9 = xlsread('E:\ange\Results\excels\500frames\std40sp20.xlsx','Sheet1');

data10 = xlsread('E:\ange\Results\excels\500frames\std60sp10.xlsx','Sheet1');

data11=xlsread('E:\ange\Results\excels\500frames\std60sp15.xls.xlsx','Sheet1'
);

data12 =
xlsread('E:\ange\Results\excels\500frames\std60sp20.xlsx','Sheet1','A2:C501')
;

%% Create output variable

% data = reshape([raw{:}],size(raw));

%% Create table

% std60sp20 = table;

std0sp10 = table;

%% Allocate imported array to column variable names

std0sp10.VarName1 = data1(:,1);

std0sp10.VarName2 = data1(:,2);

std0sp10.VarName3 = data1(:,3);

std0sp15.VarName1 = data2(:,1);

std0sp15.VarName2 = data2(:,2);

std0sp15.VarName3 = data2(:,3);
```

```
std0sp20.VarName1 = data3(:,1);
std0sp20.VarName2 = data3(:,2);
std0sp20.VarName3 = data3(:,3);
std20sp10.VarName1 = data4(:,1);
std20sp10.VarName2 = data4(:,2);
std20sp10.VarName3 = data4(:,3);
std20sp15.VarName1 = data5(:,1);
std20sp15.VarName2 = data5(:,2);
std20sp15.VarName3 = data5(:,3);
std20sp20.VarName1 = data6(:,1);
std20sp20.VarName2 = data6(:,2);
std20sp20.VarName3 = data6(:,3);
std40sp10.VarName1 = data7(:,1);
std40sp10.VarName2 = data7(:,2);
std40sp10.VarName3 = data7(:,3);
std40sp15.VarName1 = data8(:,1);
std40sp15.VarName2 = data8(:,2);
std40sp15.VarName3 = data8(:,3);
std40sp20.VarName1 = data9(:,1);
std40sp20.VarName2 = data9(:,2);
std40sp20.VarName3 = data9(:,3);
std60sp10.VarName1 = data10(:,1);
std60sp10.VarName2 = data10(:,2);
std60sp10.VarName3 = data10(:,3);
std60sp15.VarName1 = data11(:,1);
std60sp15.VarName2 = data11(:,2);
std60sp15.VarName3 = data11(:,3);
std60sp20.TotalTime = data12(:,1);
```

```
std60sp20.railmaximumprincipaltensilestress = data12(:,2);

std60sp20.railverticaldisplacement = data12(:,3);

subplot(2,2,1)

plot(9642.857*(std0sp10.VarName1),std0sp10.VarName2)

xlabel('Rolling distance [mm]')

ylabel('Deflection [mm]')

hold on

plot(15000*(std0sp15.VarName1),std0sp15.VarName2)

xlabel('Rolling distance [mm]')

ylabel('Deflection [mm]')

hold on

plot(20769.231*(std0sp20.VarName1),std0sp20.VarName2)

xlabel('Rolling distance [mm]')

ylabel('Stress [MPa]')

legend('V=10m/s','V=15m/s','V=20m/s')

% title('SD=0MPa')

% subplot(2,2,2)

% plot(9642.231*(std20sp10.VarName1),std20sp10.VarName3)

% xlabel('Rolling distance [mm]')

% ylabel('Deflection [mm]')

% hold on

% plot(15000*(std20sp15.VarName1),std20sp15.VarName3)

% hold on

% plot(20769.231*(std20sp20.VarName1),std20sp20.VarName3)

% legend('V=10m/s','V=15m/s','V=20m/s')

% title('SD=25.83746MPa')

% subplot(2,2,3)

% plot(9642.231*(std40sp10.VarName1),std40sp10.VarName3)
```

```
% xlabel('Rolling distance [mm]')

% ylabel('Deflection [mm]')

% hold on

% plot(15000*(std40sp15.VarName1),std40sp15.VarName3)

% hold on

% plot(20769.231*(std40sp20.VarName1),std40sp20.VarName3)

% legend('V=10m/s','V=15m/s','V=20m/s')

% title('SD=59.34911MPa')

% subplot(2,2,4)

% plot(9642.231*(std60sp10.VarName1),std60sp10.VarName3)

% xlabel('Rolling distance [mm]')

% ylabel('Deflection [mm]')

% hold on

% plot(15000*(std60sp15.VarName1),std60sp15.VarName3)

% hold on

% plot(20769.231*(std60sp20.TotalTime),std60sp20.railverticaldisplacement)

% xlabel('Rolling distance [mm]')

% ylabel('Deflection [mm]')

% legend('V=10m/s','V=15m/s','V=20m/s')

% title('SD=65.8733MPa')
```