ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Comparison of Floating Ladder Track and RHEDA2000 Ballast-less Track for Dynamic responses

---

A Thesis in Civil Engineering Railway Stream

By Aklilu Bekele

November, 2016

Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**Comparison of Floating Ladder Track and RHEDA2000Ballast-less Track for Dynamic Responses**' presented by **Aklilu Bekele**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

Mequannent Mulugeta		
Advisor	Signature	Date
Matias Kabtamu		
Internal Examiner	Signature	Date
Abdulsetal Siraj		
External Examiner	Signature	Date
Chair person	Signature	Date

Declaration

I certify that research work titled "**Comparison of Floating Ladder Track and RHEDA2000 Ballast-less Track for Dynamic Responses**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged / referred.

Signature of Student

Aklilu Bekele

Abstract

The purpose of this thesis is concerned with the comparison of FLT and RHEDA2000 ballast-less Track-form with respect to their dynamic performances. The comparison is done based on the analysis of the simulation results and it would be achieved via FEM software (ABAQUS). The analysis have been done in time domain at various Speed of the moving Load and the mode of vibration as well as natural frequencies of both track-forms were extracted from frequency domain analysis.

The analysis is done by varying the speed of the rotating wheel from 120 to 420 Km/hr and keeping track stiffness's constant. As the speed of the moving load increases from 120 to 420 Km/hr, the vertical displacement of the rail in FLT is increasing to nearly 8mm, in contrast the vertical displacement of Rheda2000 is slightly increasing to 3mm throughout their time domain. With similar manner, the comparisons of these Tracks' with respect to peak value of stresses variation on the Rail have been done and in FLT this value vary from 130Mpa to 250Mpa in its time domain. Then again, the maximum stresses on Rheda2000 ballast-less Track varies from 136Mpa to 160Mpa in its' time domain. Besides, it is possible to understand that the vertical acceleration level of Rail in FLT is comparatively less than the vertical acceleration of Rail in Rheda2000 ballast-less Track. The maximum acceleration level of Rail in FLT is 70m/s^2 and maximum acceleration level of Rail in Rheda2000 is about 200m/s^2.

Moreover, from the analysis, it was found that FLT has better capacity of vibration reduction than Rheda2000 ballast-less Track at higher frequency but at frequency lower than 400Hz, there is no much difference in both track forms. The other dynamic responses of both track-forms are nearly comparable and in both tracks form as the speed of the moving load increases the dynamic response increases. However, at similar speed of moving load, the dynamic performance of Rheda2000 ballast-less track is better than the dynamic performance of FLT. From the discussion, it could be deduce that FLT is good for vibration reduction and Rheda2000 have better dynamic performances.

Key words: Dynamic Responses, Natural-Frequency, Finite Element, Maximum-Acceleration level, Time domain, Frequency domain

ACKNOWLEDGMENTS

First and most of all, I would like to show my greatest gratitude to Almighty God for His help during the study of this Thesis.

I am heartily thankful to my advisor, Mr. Mequannent M. whose encouragement, guidance and support starting from the initial to the final level of this thesis enabled me to perform my study properly.

Lastly but not the list; I owe my deepest gratitude to my friends whose encouragement, support, giving comments and provide the material for achievement of this Thesis.

Acronyms

ABL	Asphalt Bearing Layer
BOEF	Beam on Elastic Foundation
CBL	Concrete Bearing Layer
CRCP	Continuously Reinforced Concrete Pavement
DAF	Dynamic Amplification Factors
EBBM	Euler-Bernoulli Beam Model
EBBT	Euler-Bernoulli Beam Theory
FE	Finite Element
FEM	Finite Element Model
FES	Finite Element Software
FLT	Floating ladder Track
FPL	Frost Protection Layer
HBL	Hydraulically Bonded Layer
RTBM	Rayleigh Timoshenko Beam Model
RTBT	Rayleigh Timoshenko Beam Theory
UCI	International Union of Railway
2D	Two Dimensions
3D	Three Dimensions

Table of Contents

List of Figures

Chapter One

1. Introduction

Ever increasing of the demand of transportation was the main cause to the development of railway technology in the world. Even though railway is the old means of transportation from the beginning, it is emerging in fast to satisfy the highest demand and safety requirement in transportation. Railway transferred to modern and sustainable transportation system in times from old nature through improvements of railway system components, like the improvement of locomotive and the track forms at which the train passes on it. With the progress of technological advancement, the varying environment and safety requirements and increasing customer demands, railways needed to upgrade its structural components and their various operational activities frequently.

Rail supporting members like sleepers and slabs play a vital role as the interface to connect the rail with the track-bed and structures as they are highly related to the issue of safety, economy, maintenance, and track-system environment. To ensuring these issues, researchers proposed new interface in their innovative like Floating Ladder track [1].

Now a day in the developed world especially in China, the development of railway track system improved fast and the demand to use high-speed train also incredibly grow fast. With related to this, the usability of ballast-less track is necessary to accommodate high design speed improvements [2]. As the speed of the moving train is increased, the dynamic effect on the structures of the track also increases even if it would vary on different track types. Therefore, it is crucial to select appropriate track system that has the capacity to reduce the dynamic effect on the track including the effect of vibration and for this purpose; the usability of ballast-less track is high. As suggested in the previous studies that the floating ladder track and Rheda2000 ballast-less track are excellent for reduction of dynamic effects specially for vibration reduction [3] [1] [4]. However, it is necessary to examine which track system is the most appropriate for high-speed condition of the moving train from different comparison parameters.

Therefor it needs to make comparison between floating ladder track and slab track (RHEDA2000) to identify which is effective for reduction of dynamic responses as compared to each other. That is the reason why this study focused on comparison of Floating Ladder Track versus Rheda2000 ballast-less Track with respect to dynamic response for different speed condition of the moving train.

1.1 Statement of the Problem

Knowing the dynamic responses of railway tracks due to railway operation become essentials to minimize the dynamic impacts on the track and to take measurements to its effect. Dynamic impact on the track is significant concern for public comfort by forming nuisance like vibration to train as well to the environment and it may cause for damage of railway track structures. The dynamic responses of the track directly related to speed condition of the moving train. As the speed of the moving load varies, the dynamic impacts in the track-forms due to the moving load will vary significantly. In the other hand, the dynamic behavior of the track depends on the supporting condition of the rail.

Now days, some high-speed track forms are emerged with good dynamic behavior such as Floating Ladder Track and Rheda2000 ballast-less Track with the nature of reducing vibration. However, the vibration reducing nature of those track forms would vary depends on the rail supporting nature, dynamic property of the track forms, the speed, the support and the track stiffness, magnitude of axel load of the moving vehicle, wheel/rail interaction and so on.

Till to date, the clear difference of those track forms regarding their dynamic performance is not yet known. Therefore, it is necessary to find out the difference and make comparison between Floating Ladder Track and RHEDA2000 ballast-less track. hence, the main intent of this study is to compare FLT and RHEDA2000 with respect to responses for dynamic and determine which track form is the most effective by their dynamic performances.

1.2 Significance of the Thesis

It can clearly see that every increasing of the demand of transportation is the main cause to the development of rail track and railway technology. The railway technology development can achieve by either increasing the capacity of track or improving the speed of the train or both. Despite of railway advancement benefits, its dynamic effect could be serious issue with related to increasing of train speed and it should be taken in to consideration.

Regarding to this, the significance of the study can be recognize through the better understanding as well as making comparison of Floating Ladder Track and Rheda2000 un-ballasted Track forms. Therefore, this study has the significance of being useful in:

- Understanding and differentiating whether Floating Ladder Track or Rheda2000 Un-Ballasted track, could have less dynamic responses' effect under high-speed moving Train condition. This enable to understand which track-form have better dynamic performance.
- Determining the which track form have better capacity for vibration reduction from low frequency to high frequency range
- Reviewed and Realize which track forms are adaptable, easiness of constructability and maintenance free or less maintenance

1.3 Objective of the research

In this study, the comparison of FLT and RHEDA2000 ballast-less tracks with respect to dynamic responses are accomplished. This enables us to answer which track-form has better dynamic performance under high-speed train. The study encompasses the following general and specific objectives.

1.3.1 General objective

The objective of this study is to thoroughly analyze the difference between and compare FLT with RHEDA2000 as well as to study the tracks dynamic performance under different speed condition of the moving Train.

1.3.2 Specific objective

This thesis would proceed through the following specific objective:

- ✓ Modeling of FLT and RHEDA2000 to make a comparison with and investigate tracks' dynamic responses of high-speed condition of the moving train.
- ✓ Frequency analysis of the vertical vibration level of the rail for FLT and RHEDA2000 will carried out with FEM in order to see what the resonance in the track and receptance of the tracks
- ✓ Analyze the vertical displacement and deflection of the rail
- ✓ Analyze stress condition of both track forms due to the moving load on the rail in order to analyze the stresses of both track-forms under varying speed of train

1.4 Scope and Limitation of the Thesis

The scope and limitations of the study presented in this thesis includes:

i. Review and Examining the behaviors of Floating ladder track and Rheda2000 ballast less track

ii. Development of dynamic modeling of both track-forms by using FEM technique and the dynamic analysis is done by 2D model. The thesis would not develop a model to study the lateral and longitudinal dynamic effect

iii. Determining the dynamic nature of these track form's for varying moving speed of the train on each individual track-forms, but varying track's mechanical and geometrical properties as well as track irregularity not considered in this study

1.5 Structure of the Thesis

The study described in this thesis categorized in to the following four main parts:

- Understanding different nature of FLT and RHEDA2000 blast-less track i.e. dealt with Section 2.1 ,2.2 and 2.3
- Identification of dynamic nature of tracks and the variables which can have effects on the track i.e. Section 2.4
- Developing dynamic model for time domain and frequency domain of FLT, Rheda2000 track forms, the discussion of the results and making comparisons of Those track-forms based on the analysis is dealt in chapter 3 and 4 i.e. all Section 3 and Section 4
- Conclusion and Recommendations are included in the Section 5 (5.1 and 5.2)

Generally, this Thesis has five different main chapters i.e. Chapter 1 Introduction, Chapter 2 Background and Literature review, Chapter 3 Methods and Methodology, Chapter 4 Analysis and Discussion of the modeling result, Comparison of FLT and Rheda2000 track forms based on the modeling results, and finally Chapter 5 Conclusion & Recommendation. All main chapters consist of their detail in the Sections and sub-sections under each chapter.

Chapter Two

2. Background and literature review

Both Floating ladder track and Rheda2000 un-ballasted track forms are at present widely applicable for high-speed train in railway technology in developed countries like China and Japan.

2.1 Background of floating ladder track

The traditional crosstie rail track has transverse sleepers at intervals along its length, in a familiar system usually supported by substantial gravel ballast and extensive earthwork in route. However, there are now quite different rail track systems in place or under development. Many modern rail systems use longitudinal sleeper rather than transverse sleepers. Longitudinal sleepers are constructed from reinforced steel or pre-stressed concrete beams, and provide superior rail support. Engineers at the *RTRI of Japan Railways* appreciated that a rail track with two parallel longitudinal sleepers that should maintain the transverse distance between longitudinal sleepers and compare with rail tracks using traditional crosstie sleepers in weight per unit track length. This led them to construct and extensively test "ladder tracks" [4] [5].

As discussed in the above, the Ladder track was developed by the Railway Technical Research I institute of Japan and consists of Ladder type sleepers fastened to two longitudinal pre-stressed concrete supports. In between longitudinal sleepers, there are tabular steel joints with constant interval to maintain track gauges. Ladder track can be either Ballasted Ladder Track or Floating Ladder Track according to the material under the longitudinal sleeper.

Slab track can also be significantly causes more vibration than traditional ballasted track. While this is in some part attributable to slab track's decreased sound absorption qualities, a more significant factor is that slab track typically uses softer rail fasteners to provide vertical compliance similar to ballasted track; these can lead to more noise, as they permit the rail to vibrate over a greater length [6] [7].

Where it is critical to reduce vibration, the concrete slab can supported upon soft resilient bearings. This configuration, called "floating slab track", is expensive and requires more depth or height as compared to ballasted tracks, [6] but can reduce vibration by around 80% [8]. Alternatively, the rail can supported along its length by an elastic material; when combined with a smaller rail section, this can provide a significant noise and vibration reduction over traditional ballasted track [7].

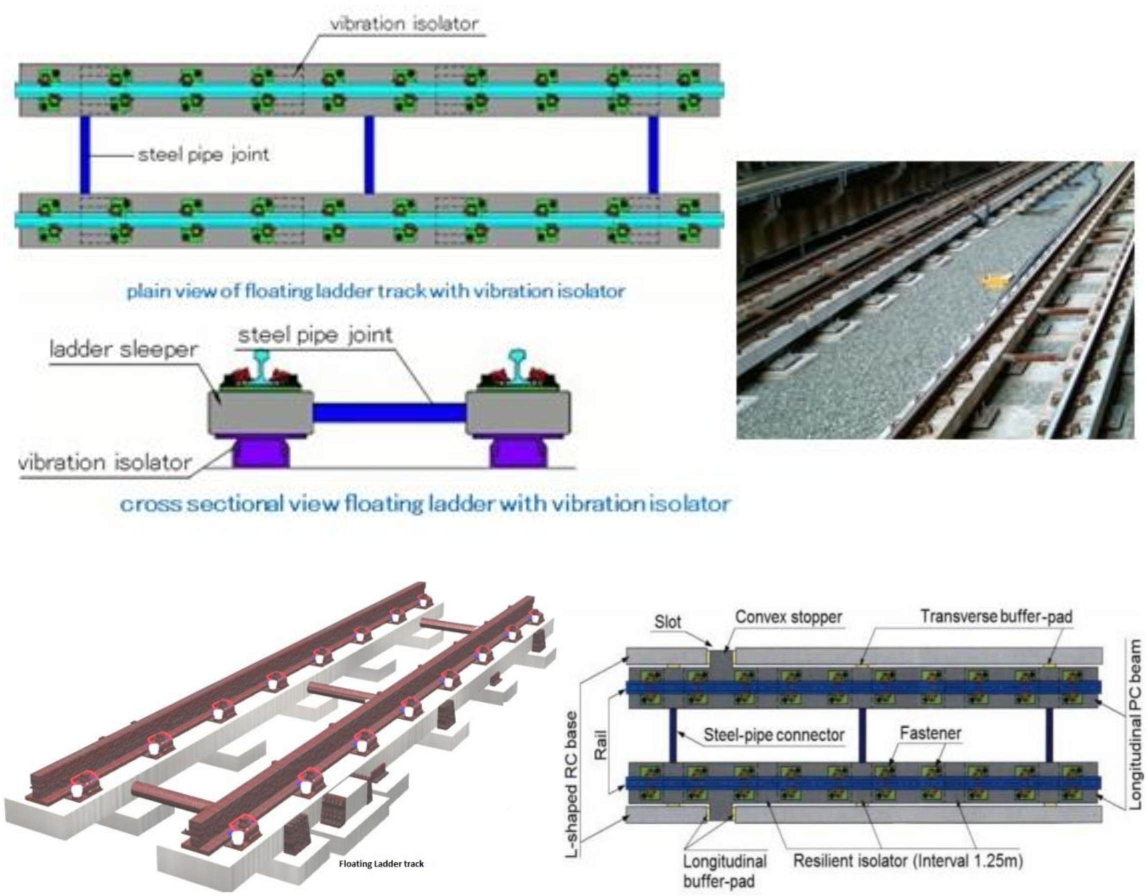

Figure 1: Plain and Cross-sectional view of FLT with Resilient Pad

Floating Ladder Track has the following parts that are an essential Feature of the FLT design:

- ✓ High speed Rail
- ✓ Discretely Support/Rail Pads
- ✓ Longitudinal concrete Sleeper with transversely connectors Steel Bar
- ✓ Discretely Flexible support/ Resilient Pads- for vibration isolation
- ✓ Solid Concrete Bed / Supporting Platform

2.2 Background of Rheda2000 un-ballasted track

Slab track is designed with no underlying ballast is required. Rheda2000 is types of slab track that have been most used in Europe. The first tracks were mountain railways (like pilatus railway, built in 1889) with rails attached directly to the mountain rocked. From the late 1960’s onwards, German, British, Swiss and Japanese Railways experimented with alternatives to the traditional railway sleeper in search of solution with higher accuracy, longevity, and lowered maintenance costs. The ballast-less track has been improved since it first introduction in 1972 on the line from Bielefield to Hamm, Germany, at the Rheda station. Based on the first test sections to investigate the construction and behavior of ballast-less tracks in Germany (Rheda1972) numerous systems had been designed and optimized based on the technical and economical aspect. Rheda system is one of the most commonly and widely used slab track system in the world due to its adequate performance, long experience and very flexibility allowing to design change as compared to other slab track forms. Starting to its birth, different development and modification of the system has been carried out. The RHEDA (CLASSICAL), RHEDA(SENGEBERG), RHEDA-BERLIN HGV(V1, V2, V3) and RHEDA2000 are the most significant design version of Rheda system [9] [10].

The latest modifications of Rheda2000 include the employment of specially integrated of bi-block lattice-truss sleeper and combines in situ concrete and reinforced concrete trough slabs that produced in one working step presents a cross section of slab track system [11] [10]. The first installation of Rheda2000 track system was in July 2000 as part of German high-speed section between Leipzig and Halle [12]. In addition, the actual design of Rhedaa2000 by company rail-one integrating the lattice girder sleepers directly within the continuously reinforced concrete pavement (CRCP). Cracks are controlled by the prefabricated concrete element for the rail seats which are integrated in the CRCP. With respect to ballast-less track system the crack width shall be limited to max 0.5mm. This requires respective amount of longitudinal reinforcement, which is typically 0.8% to 0.9% of concrete cross section [13].

The slab track systems of Rheda-family are applied for almost three decades, so they belongs to the most proven and successfully ballast-less types of supper structure. In the meantime of many significant modifications had been develop which helped to improve the durability and reliability of monolithically slab track system as well as the efficiency of their installation methods [14] and as stated in this literature the ongoing development of the classic Rheda-system via Rheda-Berlin into the RHEDA2000 construction was undertake with the main goals bear in mind:

- Simplification of the system construction
- Reduction of the construction height and width
- Improving the combined interaction between the sleeper and the concrete cast
- Simplification and rationalization of the installation techniques
- High load bearing capacity of the track

These systems offer the advantage of superior stability and almost complete absence of deformation. Ballast-less track systems incur significantly lower maintenance costs compared to ballasted track. Due to the absence of any ballast, damage by flying ballast is eliminated, something that occurs at speeds in excess of 250 km/h [6]. In addition, the RHEDA2000 track system because of its structural properties insensitive to water and erosion it well suited in application both on open track section as well as in tunnels [10].

Under Rheda2000 slab track system the rails discretely supported by each sleeper from the above, and sleepers are directly imbedded in the slab, forming monolithic assembly as shown in the following figure 2.

Figure 2: Rheda2000 Track system before and after monolithic in-situ cast

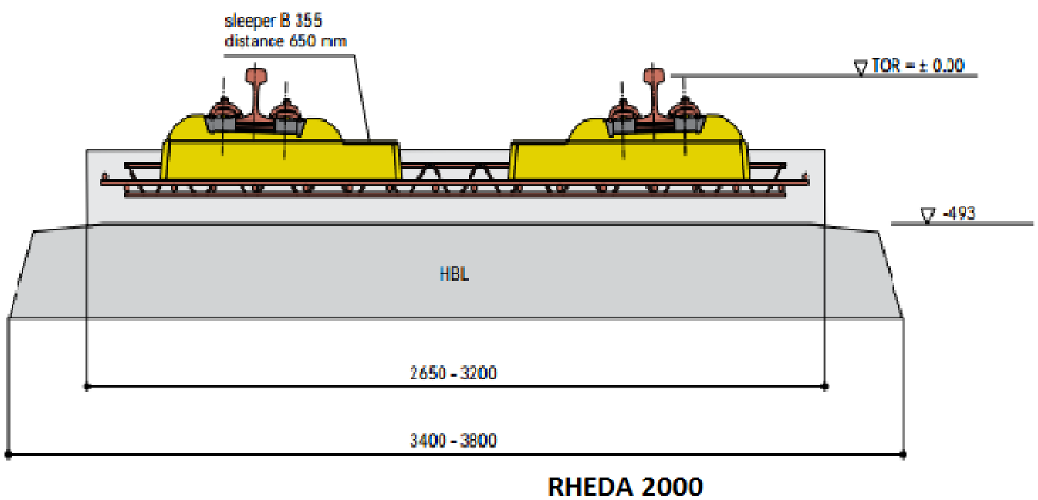

Figure 3: Section View of Rheda2000 Ballast-less track system

In most slab track-forms (that means in traditional Rheda), applied reinforcement is in the neutral axis just for crack control purposes. However based on newly designed Rheda2000 un-ballasted track system design, applied reinforcement is at the top and at the bottom of slab track to create both bending resistance and crack control. As Coenraad Esveld and etal's description the bending stiffness of such slab is considerably higher as compared to the one in traditional Rheda2000 design. Due to the significance bending stiffness of the slab, less supporting stiffness of the foundation (soil) is then required and so substantially less soil improvement would be necessary [15] [16]. This can be shown in the following figure:

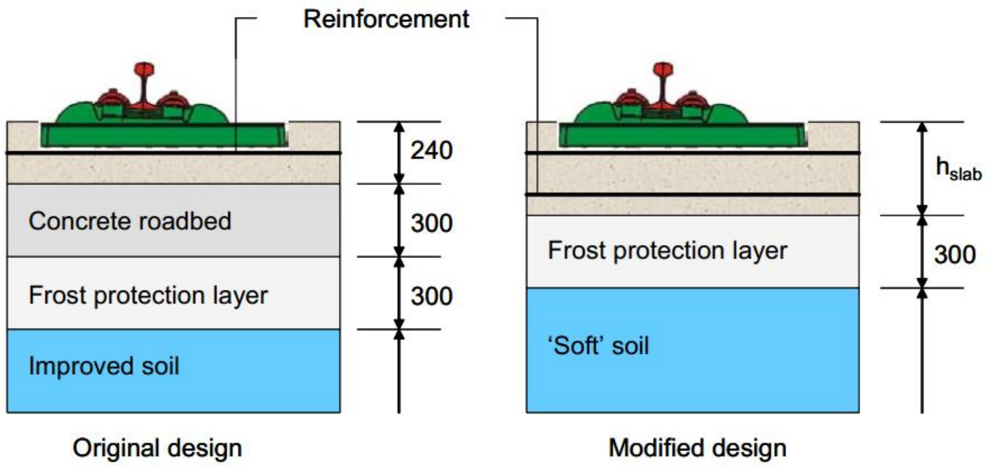

Figure 4 Original Rheda Vs modified Rheda i.e. Rheda2000 design

Name	CBL	ABL	HBL	h	H
Rheda 2000	240	-	300	61-81	773-793

Various layer height of Rheda2000 unballasted track

Figure 5 Height of Rheda2000 subsequent layers [9]

In Rheda2000 slab track system, most of the vertical flexibility and damping of the track is provided in the rail fastening system, which comprises two elastic levels: the rail pad, located between the rail and the base plate, and the other by the base plate pad located between the base plate and the sleeper, gives one.

2.3 Rheda2000 and Floating Ladder Tracks' structure Components

Railway track is a fundamental part of infrastructure and its component divided in to superstructure and substructure. The observable parts such as rail, rail pads, concrete sleepers and fastening systems referred to as superstructure, while the substructure is associated with geotechnical system under superstructure and the construction principle behind slab track is a layered structure with stiffness level that decreases from top to bottom [14] [9]. The layered structure of slab track can be shown as follow:

- Rail with rail fastening with supportive layer
- Concrete bearing layer (CBL) or asphalt bearing layer (ABL)

- Hydraulically bonded layer (HBL), it is a mix of aggregates with a bonding agent placed under the CBL or ABL
- Forest protection layer (FPL), subgrade foundation and the delineation between substructure and superstructure is between the bonded HBL and the non-bonded FPL layer. It is an important element of Rheda2000 track system is a thin intermediate layer (plastic foil, Geotextile etc.) which is placed between sup- and substructure. The purpose of this layer is to compensate the differences in stiffness of the various layers towards the subsoil and leads the surface water away rapidly.

Either Floating Ladder Track-form or Rheda2000 Ballast-less track have commonly named structure's component with different nature of arrangement and behavior. These components are so called rail, rail-pad, fastening and supports like concrete sleepers. The following table 1 that adopted from [14] shows the sub- and superstructure of slab track components:

Table 1 Structure of Railway Track

Track Type	**Super-structure**	**Sub-structure**
Slab tracks	♦ Rail ♦ Rail Fastening ♦ Rail Support ✓ Discreet with sleepers or support points ✓ Continuous support with embedded or clamped rail ♦ CSL or ASL ♦ HBL	♦ Upper non-bonded supported layer: forest protection layer (FPL) ♦ Lower non bonded supportive layer: Earthwork with compressed or improved embankment or cut formation ♦ Formation possibly compressed

2.3.1 The Rail

The rails are the first elements of the railway track-forms; these are the longitudinal steel member positioned at the top of the track that directly in contact with the vehicle wheels with the function of guiding the train wheel evenly and continuously. The vertical and the horizontal forces of the wheel transmitted and distributed by the rail in to the sleepers. It must be sufficiently stiff that capably transfer loads from wheel to the sleeper support without excessive deflection [17] [18]. The primary function of rail is to accommodate and transfer wheel/axel loads on to the supporting sleepers. As Esveld [12] reported a modern rail track also conveyed signals and act as a conductor on an electric traction railway line.

Under normal design consideration of slab track, railway construction uses rail section UCI 60. As J. M. Proença *et al* description, the choice of the UIC60 rail is justified in high-speed lines by technical and economic reasons. Other rail profiles such as S54 are used whenever lower speed or lower axel loads are present or if lower track construction height is required [14] [19].

2.3.1.1 Beam Theory

The first important beam model was the one based on the Euler-Bernoulli beam theory or classical beam theory as the result of the works of the Bernoulli's (Jacob and Daniel) and Euler. This beam model, established in 1744, includes the strain energy due to the bending and the kinetic energy due to the lateral displacement of the beam. However, in 1877, Lord Rayleigh improved this by including the effect of rotary inertia in the equations describing the flexural and longitudinal vibrations of beams by showing the importance of this correction especially at high frequencies. In 1921 and 1922, Timoshenko proposed another improvement by adding the effect of shear deformation.

To obtain the differential question of Euler-Bernoulli Beam model considering two-dimensional beam element which the beam is subjected to an external force and has distributed mass $\boldsymbol{m=\rho A}$ and flexural rigidity $\boldsymbol{EI}$ which can vary with position and time as shown below in the figure 6.

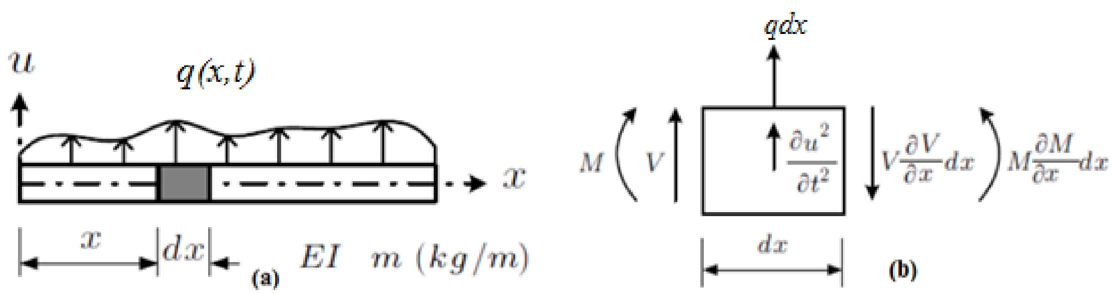

Figure 6 Figure 6: (a) Beam and applied force, (b) force acting on an element

In the Euler-Bernoulli beam model the deferential question describing the beam deflection ***w(x, t)*** is:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} = q(x,\ t) \quad \text{- - - - - - - - - - - - - - - (1)}$$

Where EI = the bending stiffness of the beam

ρ = density of the beam

A = cross-sectional area of the beam

$q\ (x,t)$ = load on the beam

t = time

In the case of Rayleigh Timoshenko beam model (RTBM), rotator inertia and shear deformation of the beam are included and two differential questions are needed to describe the vibrations. In this beam model the deflection ***w(x,t)*** and the shear deformation ***ψ(x,t)*** are unknown function. The differential question for the deflection *w(x,t)* becomes

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} - \boxed{\rho I(1+\frac{E}{kG})\frac{\partial^4 w(x,t)}{\partial x^2 \partial t^2} + \frac{\rho^2 I}{kG}\frac{\partial^4 w(x,t)}{\partial x^4}} = q(x,\ t) \quad \text{- - - - (2)}$$

Where EI = the bending stiffness of the beam

G = shear modulus

k = shear factor

ρ = density of the beam

A = cross-sectional area of the beam

$q\ (x,t)$ = load on the beam

t = time

The continuous rail can be modeled as either following the condition of Euler-Bernoulli (E-B) in which the bending of the rail taken in to account or Rayleigh Timoshenko (R-T) engineering beam theory at which both bending and shear deformation taken in to consideration. However, the first beam theory most likely adequate for to analyze the response of low frequency. It tends slightly to overestimate the natural frequencies of the higher modes [22] [23].

Due considering high-speed moving load on the track, the frequency is high. Therefore, the second beam theory that includes the rotator inertia and shear deformation of the beam is preferable to analyze the response of high frequency. Moreover, it partially corrects the overestimation of natural frequencies in the Euler-Bernoulli beam model. As related to this issue several studies commented that when the frequency of vertical excitation forces on the rail is less than 500Hz, the Euler-Bernoulli beam model leads to satisfactory results. However, in the case of high frequencies, the shear deformation effect becomes increasingly important and Timoshenko beam model leads to accurate results [24] [25] [22] [23].

2.3.2 The Rail pad and Fastening

Fastening system is required to retain the rail against the sleeper and to resist the rail from vertical, lateral, longitudinal and overturning moments of the track and keeping the rail in place. The primary components of fastening system are fastening and rail pads. A fastening includes every component that connects the rail to the sleeper. It clamps the rail gauge within acceptable tolerances and absorbs forces from the rails and transfer to the sleeper. Vibration and impacts from various sources also damped and decelerated by fastenings. [18]

The choice of the type of fastening system depends essentially on the railway, sleeper type used and on the stiffness of the tracklayers that support the sleepers. These elements should guarantee a good connection between the rail and the sleeper. The rail pads may also use to limit the stiffness of the railway track in order to reduce the dynamic effects resulted by the circulation of the trains [19]. Moreover, the rail-pads are required to provide the resiliency for the rail-sleeper system, damping of wheel-induced vibration with the rail, prevent or reduce rail-sleeper contact attraction and provide electrical insulation for the track signal circuits [17]. Rail pads are usually install on rail seats with the purpose of reducing the stress from the axel loads, to protect the sleeper from wear, to protect the abrasion of the rail and sleeper, resist lateral movement of rail and to reduce the impact of dynamic load by absorbing shocks and vibrations.

Rheda2000 track system use highly elastic rail fastening system (VOSSLOH 300) to ensure the required vertical deflection for load distribution and for smooth train travel. It’s rail fastening system use with soft elastic pad 10 ~12mm thick with elastic capacity Cs = 22.5 ± 2.5 kN/mm results in deflection of about 1.5mm under static load 22.5t axel load [9].

2.3.2.1 Properties of the rail fastening and rail pads

Rail pads are the important component of railway tracks, which installed on rail seats to plays a crucial role on the dynamic behavior of the railway track by; attenuate the excessive dynamic stress from wheel/rail impact forces. Mostly it made from polymeric compound, rubber or composite materials. The dynamic behavior of rail pads can generally represent by key parameters like dynamic stiffness, resonance frequency and damping coefficient values.

From track dynamic perspective, Rail pads influences the overall track stiffness. A number of publications have recently addressed the dynamic characteristics of resilient pad and these literature shows that a soft rail pad permits a larger deflection of the rails when the train loads the track. Hence, the axle load from the train distributed over sleepers. Besides, since soft rail pads can suppress the transmission of high-frequency vibrations down to the sleepers and further down into the next layer of the track, they also contribute to isolate high-frequency vibration [12] [26]. The physical model of the rail pad is the spring-damper system and the spring assumed linear as well as the damping assumed proportional to the deformation rate of the rail-pad.

2.3.3 Sleeper

In most rail track-forms, the existences of sleepers are highly valuable and can provide functions like: spreading wheel loads to respective track-layer, hold rails to gauge and inclination, transmit lateral and longitudinal forces, insulate rails electricity, provide base or support for rail seats and fastenings and furthermore reducing vibration for the case of ballast-less track forms [20] [18]. Until the middle of twentieth century, traditional wood sleeper was accepted as standard where the advantage of good resistance, ease of handling, adaptability with non-standard situation or electrical insulation is very important. After the Second World War, pre-stressed concrete was developed and used extensively on new structures with its great advantages of concrete was compressed enough and not exposed to tension crack during load [20] [21]. Sleeper types are many from different perspective but for the sake of this study Longitudinal and twin block sleeper types are useful and described as follow.

2.3.3.1 Longitudinal sleeper

Longitudinal sleeper is a sleeper mostly used in ballasted ladder track, floating ladder track and floating slab track system that are pre-stressed concrete element with transvers steel pipe connectors. Steel pipe connectors, which made from thick-walled pipe that rigidly jointed to the longitudinal beam by inserting it between indented pre-stressing strand, which are arranged close to the top and bottom surface of the longitudinal beam. Sufficient reinforcement is provided around the steel pipe and then high strength concrete is cast to be monolithic [1].

2.3.3.2 Twin-block sleeper

It is a sleeper, which consists of two concrete blocks joined together with a steel tie bar cast in to the concrete blocks, which used extensively in Europe, particularly in France. In the Rheda2000 track system, Modified twin-block sleepers (B 355 W60M SBS) with intentioned braced girder reinforcement are mostly used and the sleepers are securely and reliably embedded in a monolithic concrete slab [9].

The sleeper transfer wheel load from the rails and fastening system to the next layer of the track and control the movement of the rail. These sleeper types are shown in the pictures i.e. figure 7 below.

b) Twin-Block Sleeper in Rheda2000 Track System

c) longitudinal concrete sleeper

Figure 7: Types of Concrete Sleepers

2.4 Dynamic property of the Tracks

Esveld [12] defines Dynamics as the interaction between the wheel load which varies in time and track structure that are characterized by Frequency response function which is governed by mass and elastic property. These parameters determine the natural frequencies of the structure or those frequencies at which the structure is likely to vibrate. If the loads contain frequency components corresponding to natural frequencies of the structure, large amplification (Resonances) may occur.

When a railway track is excited to generalize dynamic loading, the railway track deforms and then vibrate for certain duration. Dynamic loading depends upon the situation of the track and the speed of the moving load on the railway track. Dynamic responses of the railway and its components are the key to evaluate the structural capacity of railway track and its component. If a dynamic loading resonates the railway track's dynamic responses like vibration, its components tend to have significance damage from excessive dynamic stresses. The rail vibration could cause of defects in rail or wheel and the track vibration can cause the crack damage in railway sleepers or fasteners system. Hence, the identification of railway track and its component dynamic properties is vital to avoid or reduce such damages on the track.

The interaction between vehicle and track dynamic plays crucial role in modern railway track. The dynamic interactive forces behaviors are directly related the stiffness of the track structure and its component. Since dynamic interaction is frequency dependent, it also related with mass and damping nature of tracks component. Coenraad Esveld [27] [12] states that lowering of track structures stiffness has a positive effect on the dynamic forces.

2.4.1 Dynamic Load

Dynamic load is an imposed force that is one may vary with time, sense, direction and the structural response of it such as stress and deflection vary with time function. The dynamic forces can also be defines as the load due to high frequency effect of the wheel/rail load interaction and track component response.

The dynamic response is frequently presented in *Dynamic Amplification Factors* (DAF) and it is to states how many times the static response, of a railway structure due to moving traffic. The purpose of introducing these factors are making the dynamic results easily understood as compared to the static ones and also the *Dynamic Amplification Factor* is defined as a dimensionless ratio of the absolute dynamic response to the absolute maximum static response.

The dynamic loads results in increasing of the structure's response when compared to static loads. For the sake of this study, static analysis does not taken in to consideration and amplification factor not calculated. However, usually it is crucial to analyzed for design of high-speed railway by using commercial software program taken in to account resonance effect and other vibration effects. According to Coenraad ESVELD and Valéri MARKINE statement by referring the Euro-code (ENV 1991-3:1995 6.4.3.2) the dynamic amplification due to running trains is limited to DAF_{95} = 1.67 i.e. 95% its probability. DAF_{95} limits, which are equal to 1.67 for a 'carefully maintained track' and the limit 2.00 for a 'track with standard maintenance' [28].

2.4.2 Theory of Wheel/Rail contact

Railway track dynamic behavior would demonstrate by wheel/rail contact that can induce vibration with wide band of frequency in the system. The vibration condition of the track and force transition at different label of frequency would depend on the physical Wheel/Rail contact interaction. This Wheel/Rail contact can be model by using the Hertzian Contact Theory of these two elastic bodies and Railway track dynamics use this Theory to represent the wheel/rail contact as linear or nonlinear contact stiffness. In the Herzian contact Theory, the relation between force and indentation $\boldsymbol{y}$ of the contact surface can be written as:

$$\boldsymbol{F = C_H\ y^{3/2}} \text{-- } \textbf{(3)}$$

in which $\mathbf{C_H}$ **($\mathbf{Nm^{-3/2}}$)** is a constant depending on the radius of contact surface and the material properties.

The Wheel/Rail contact can be considered as a point in two-dimensional model because of the real shape of contact area not accounted for. The real contact area assumed to be elliptical. As long as no irregularities of wheel or rail with wavelengths shorter than the contact dimensions are considered, the Hertzian Theory yields good results and no filters need to be applied [23] [22].

2.4.3 Track Stiffness

Track stiffness *k (N/m)* is generally defined as the ratio of force exerted on the top of the rail and the vertical track displacement, see in the equation 4 below. However, the track stiffness is not linear in that the track usually gets stiffer with increased loading.

$$k = \frac{Q}{y} \ldots\ldots\ldots\ldots\ldots \text{ (4)}$$

Railway track stiffness (vertical track load divided by track deflection) is a basic parameter of track design, which influences the bearing capacity, the dynamic behavior of passing vehicles and, in particular, tracks geometry quality and the life of track components. Relatively high track stiffness is desired to provide adequate track resistance to the applied loads and to limit the track deflection. This will in turn, reduce the track deterioration. Too high track stiffness and especially variations in stiffness on a stiff track can cause increased dynamic forces on sleepers, sub-layers and in the wheel-rail interface. This can lead to wear and fatigue damage on track components. Low track stiffness leads to large rail displacements and high bending moments in the rails. On the other hand, low track stiffness leads to better load distribution between sleepers and lowers train/track interaction forces [28].

For the track, which have different layer with different stiffness's, the track stiffness is a crude average or composite value of the individual stiffness values of the track's components [29].

2.4.4 Receptance

The dynamic property of the railway track can be investigated by loading the track with sinusoidal force and then analyze the receptance. The receptance can defined as the ratio of the track deflection, and the force put on the track, thus giving the deflection in meter per Newton of the load and it is the inverse of the stiffness. Receptance functions show the vibration amplitudes of track structures as a function of vibration frequencies, in particular the deflection of a track structure under a unit load.

2.4.5 Resonance

System resonance is that the response of the rail becomes most pronounced at which the speed of the moving load becomes a critical speed and it depends on the support stiffness, the mass and viscous damping of the periodic support (rail pad) of the rail.

Combined rail consisting of the rail and longitudinal sleeper mounted on periodically flexible support which representing the rail pads. Rail pads (discretely flexible support) are assumed to be elastic introducing the mass and viscous damping of the periodic support which capable of reducing the magnitude of the resonate responses.

2.4.6 Vibration

2.4.6.1 Mechanism of vibration generation

The mechanisms of railway vibration generating are quasi-static excitation and dynamic excitation. Quasi-static excitation caused by static trainload and typically dominant at low frequency (0 – 20Hz). Dynamic excitation is generated primary due to wheel/rail contact and propagates at higher frequencies as comparison to quasi-static excitation. This occurred due to unevenness of wheel/rail and this unevenness of wheel/rail excitation arises from roughness or irregularities on either the wheel or rail [22].

Railway vibrations are induced by wheel – rail surface contact and its effect is highly sensible in highest frequencies that having high wheel resonance frequencies in the range 1000 – 3000Hz.

2.4.6.2 Mode of vibration Propagation

When a railway track is designed, Eigen-frequency of the tracks component should be taken in to account. If the Eigen-frequency of one of the track component altered, the track may exposed to vibration at the altered Eigen-frequency and this may leads to the deterioration the track at that component.

Railway Track may have different mode of vibration in every component of the track. Translation, rotation bending mode, the first bending mode, the second bending mode, etc. are the example of mode of vibration of the track components.

Pin-pin frequency is one of the most preferred vibration modes of the rail, which support at equal distances. Pin-pin resonance is a vibration that appears in one basic (first) mode and several higher modes; however, the basic mode will have the highest amplitude. In operational conditions of the railway, pin-pin resonance only partly influences wheel-rail contact of the train while the speed dependent sleeper-passing frequency is more important. Among other track resonance, pin-pin resonance plays an important role in noise and vibration radiation of the rails and can be used as a meaningful instrument in track system dynamics recognition and optimization [31].

Forces generated due to the quasi-static and dynamic excitation mechanisms are propagating through the track and ground as seismic wave i.e. ground-born vibration. These waves can categorized as either body wave or surface wave. Surface waves travel along a structures (i.e. soil) surface and decay exponentially with depth. Body wave propagate primarily beneath the soil surface [30] [22]. A variety of modes of vibration is possible with in the ground and the principal types are:

i. **Compression wave or longitudinal waves (P-wave) –** with particle motion being an oscillation in the direction of propagation; P-wave propagate in the longitudinal direction and travel faster than other mode of vibration wave.
ii. **Shear wave (S-wave) –** with particle motion being an oscillation in a plane normal to the direction of propagation; S-wave propagate in a transverse direction and although they travel faster than Rayleigh wave, they always travel slower than P-waves.
iii. **Rayleigh wave** – which are surface wave, with a particle motion generally elliptical in a vertical plane through the direction of propagation and this types of mode of vibration waves are the slowest types of vibration wave.

As stated in [22] although other types of mode of vibration wave theoretically possible, Compressional, shear and Rayleigh are the most common. Rayleigh wave transmit approximately two-third of the total excitation energy (Rayleigh waves ≈ 67%, S-waves ≈ 26%, P-waves ≈ 7%).

Literatures [31] discuss the generation, propagation and reception of vibration due to the moving train on track. With respect to generation of the vibration, they recognized both quasi-static and dynamic vibration, and according to them, the vibration energy not shared equally among the modes and most of the energy is carried by Rayleigh wave at a significance distances from the train. Under here it's also mentioned, the effect of shocked wave formed in the ground to the surrounding is highly dependent on the moving speed of the train and if it moves faster than the propagation velocity of the ground the effect is serious to the surroundings.

Therefore based on these literature discussions, Rayleigh waves, S-waves and P-waves are most likely mode of vibration have capacity to cause negative effects in both railway track and nearby structure [22] [31].

2.4.7 Damping

The material Damping can be defined as the function of the mass and stiffness matrix and damping ratio can be expressed in terms of Rayleigh damping using α and β and can be expressed as:

$$\boldsymbol{C} = \boldsymbol{\alpha M} + \boldsymbol{\beta K} \text{- - - - - - - - - - - - - - - - - -} \mathbf{5}$$

Where α the mass Proportional damping coefficient and β is stiffness proportional damping coefficient. α and β are often determined from experiment using:

$$\alpha = \frac{2D\omega_1\omega_n}{\omega_1 + \omega_n} \qquad \text{-----------------} \; 6$$
$$\beta = \frac{2D}{\omega_1 + \omega_n}$$

Where ω_1 is the first natural frequency of the system and ω_n is the highest natural frequency. D is the damping ratio, which is expressed as the fraction of critical damping.

Damping is introduced into the model via Rayleigh damping material model essential to ABAQUS in order to obtain a realistic transient response of the track. The Rayleigh damping model assumes that the damping ration depend upon the frequency through only two constants that are usually chosen based upon matching the system damping to the experimental values at two of the system's natural frequencies. The relation between the damping ratio and the structural frequency is as follow:

$$\zeta_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \qquad \text{-------------------} \; 7$$

where ζ_i and ω_i are the damping ratio and frequency of the i^{th} mode respectively, α is the mass proportional damping constant and β is the stiffness proportional damping constant.

The relationship between Mass damping(α), Stiffness damping(β) and Rayleigh damping can be illustrated by the following graph [22]. From this graph, it can be realized that the mass proportional damping attenuates low frequency responses whereas Stiffness Damping attenuates the higher frequency response.

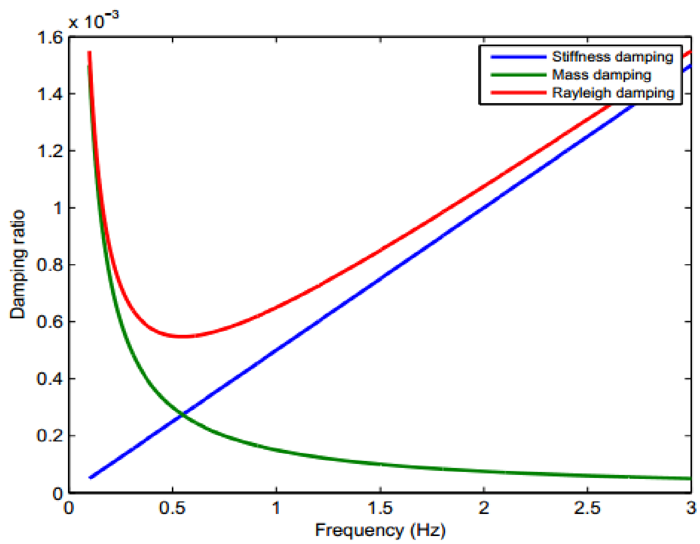

Figure 8: The relationship of Mass damping, Stiffness Damping and Rayleigh Damping

2.4.8 Actual condition of FLT and Rheda2000 track forms for vibration

In the history of railway track development, FLT and Rheda2000 ballast-less Tracks take the prior share to play vital role of mitigation of dynamic effect (particularly vibration) of high-speed train. Track component's structure such as rail, rail-pad, fastening and supports are significantly influence the vibration behavior of superstructure. These components behavior have a significance impact on the interaction of wheel and rail caused vibration.

Dynamic loading gives vibrations of the interacting system of the moving train and the track. The vibration behavior of the railway track structure in the mid and high frequency range (40 – 1500Hz) can act as indicator for the performance of track structure with respect to vibration sensitivity and wheel-rail interaction forces [32]. As indicated in this literature, the vibration behavior of track structures pay attention to performance based issue of contact stiffness. The issue is relating with this vibration behavior of the track to the vertical force of wheels loading on the track.

2.4.8.1 Condition of Floating Ladder track for vibration

Floating ladder track is a type of blast-less railway track in which the rail is laid on the longitudinal support (longitudinal pre-stressed concrete sleeper) with transverse connector holding the two rails at the correct gauge distance. The basic structural concept of Floating ladder track is a combined rail composed of the steel rail and pre-stressed concrete longitudinal sleeper with its feature of high rigidity and remarkably stable against track buckling. It is lightweight and vibration-proof track system, which floated from the concrete track-bed by supporting ladder sleepers with low-stiffness springs at constant intervals [1].

Z.Q. Yan and et al description the structure of FLT as a mixed ladder shaped structure composed of twin longitudinal pre-stressed concrete beams and transverse steel pipe connectors. The transverse steel pipe connector, which made from thick walled pipe, is rigidly joined to the longitudinal beam by inserting it between indented pre-stressing strands, which are arranged close to the top and bottom surface of the longitudinal beam. According to the study, the influence on the vibration of the most significant ladder track parameters have been analyzed and the simulation result have been compared with the measured data obtained from the instrumentation of the rail top. After the parametric study of this track, that optimal solution of ladder track parameters are found that minimize the vibration [3].

As stated in the literature, the ladder track is designed to be isolated from the concrete track-bed using soft elastomeric bearings or resilient placed at a constant interval. The longitudinal pre-stressed concrete beams can regarded as a secondary longitudinal beam except for the rail, the rail and the sleeper bear the trainload together. From the structure of FLT, the resilient pad (small-mass sprung system) placed with the objective of providing maintenance free and less vibration track system [3].

Longitudinal pre-stressed concrete sleeper provide continuous support to the rails by lay on a resilient pad on the concrete track-bed or they can install as a floating track insulated from the concrete track-bed by discrete resilient mountings (Resilient Pads). The Ladder Tracks result in ensuring train safety, assuring maintenance reduction as well as mitigating for ground-borne vibration [33]. As stated by Tsutomu Watanabe which is newly adopted FLT offer excellent performance in terms of reducing vibration. Floating ladder Track has the load distribution effect due to the high bending rigidity of the ladder sleeper in the longitudinal direction and a load transfer reduction effect due to low supporting coefficient of the track [34]. Researchers perform frequency analysis of FLT to evaluate the effectiveness of the track for reduction of vibration and they found that floating ladder track can reduce the vibration level of velocity by approximately 13.4dB over non-ballasted crosstie track as shown in figure below [1]. According to Roger J. Hosking's study [4], the acceleration level difference of FLT over non-ballasted crosstie track is about 21.1dB as shown in the figure 9 shown below.

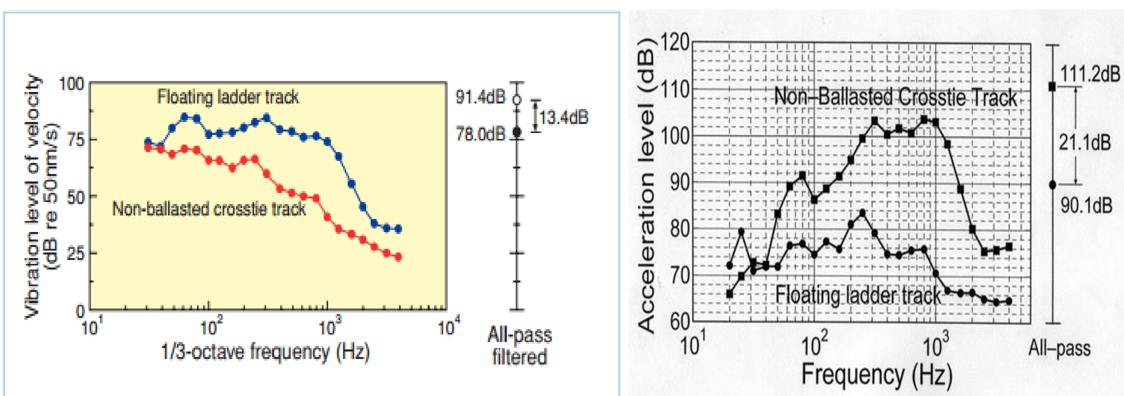

Figure 9 Comparison of vibration level of velocity and level of acceleration

Additionally, acceleration versus time graph of Floating Ladder Track corresponding to Non-Ballasted crosstie Track while the moving train runs on the Tracks also showed in the figure10 below. As shown in this figure, Comparatively FLT accelerates less and vertical acceleration of Non-Ballasted track is higher than FLT.

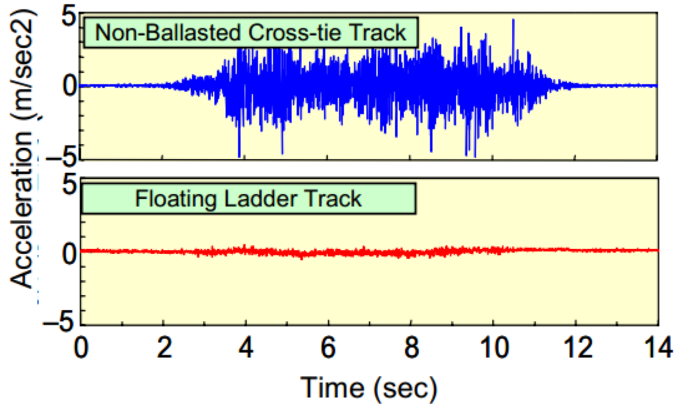

Figure 10: Acceleration level of FLT and Non-Ballasted Crosstie Track

As Kiyoshi ASANUMA [1] stated that due to the effect of low-stiffness springs, the floating ladder track can significantly reduce the vibration on the rail. According to the Roger J. Hosking [4] as well, FLT which consists of a ladder track mounted upon discrete flexible supports (Resilient pads) laid on a solid concrete track-bed and the rail pad's resilient nature insist the Floating Ladder Tracks structure to reduce traffic vibration significantly. Based on this interesting nature of the track, the Floating ladder track has been installed in urban rail system of Tokyo region and Chinas have considerable interest in potential vibration mitigation measures of Floating ladder track. Floating ladder track is an appropriate measure to mitigating vibration for high-speed train. In addition to this all, Hao Jin et *al* state that FLT is an effective method for reducing vibration for underground railway system and it has better vibration mitigation properties above 35Hz, compared with ballast track form [35].

2.4.8.2 Condition of Rheda2000 un-ballasted track for vibration

Rheda200 ballast-less track system is monolithic bi-block sleeper with lettuce trusses has reinforcement partially cast in to the sleeper and this is the most advanced development from the Rheda ballast-less track families. This types of ballast-less track systems is practically maintenance free, long life cycles, top speed, ride comfort and great load-carrying capability that ensure more cost-effective solution over the long run.

Increasing of speed of the train is the critical issue in the advancement of railway transportation technology. The increases in train speed, axle load, and traffic volumes on current train line have also led to increases in the vibration to which the surrounding area subjected. When irregularities between wheels and rail as well as the dynamic deformation of the tracks when the rolling stock passes, introduced vibration in to the subgrade and the surroundings and this is the critical issue to be solved. As stated in [10], one of the most effective measures against the development of the structural vibration is mass-spring system used in the Rheda2000 track system to attenuate the transmission of vibration in to the surroundings. This track system is advisable especially in densely populated areas sensitive to vibration.

In addition, here also stated that the deeper the frequency of the vibration to be reduced, the higher the required the mass track concrete layer and here the structure of Rheda2000 ballast-less track system offers benefits to the entire system. The appreciable mass of the track concrete layer with its bi-block sleepers embedded in concrete, contributes significantly to attenuation of vibration [10].

Chapter Three

3. Methods and the methodology of this Thesis

This section deal with how the study would conduct to attain results for the objectives of this study. It dealt specifically on the method of data collection, model development, how the result are extracted out of the models' simulation and how the analysis are done to make comparisons of FLT and RHEDA2000 for dynamic responses.

3.1 Methods of data collections and its Description

Different data types would collect for the purpose of this thesis, to achieve the objectives of the study. These collected data's to be used in FE modeling process are secondary data, the sources of these data's were secondary data Source, and secondary data used for model which are collected from manuals and literatures. These data includes:

- Geometrical characteristics of the track-forms like track components dimensions, and relevant values
- Mechanical Properties such as Elastic modules, poison's ratio, damping properties and other relevant properties of track-forms component

3.1.1 Methodology

The methodology would be followed through this thesis to come up with the required result is by developing 2D dynamic model for FLT and Rheda2000 Track-forms via FE software (ABAQUS). In order to reduce the computational time, the model is two-dimensional (longitudinal and vertical direction) and considered material behavior is Elastic.

A track-forms structure is represented by a serious of alternative hard and soft layers. The hard layers represented by Timoshenko beam elements can be used for modeling track structural components such as rail, sleepers, concrete slabs etc. Distributed spring and dashpot combinations represent the elastic interfaces between layers, which can be used to model the rail pads and resilient pads.

The study would establish with FEM by considering different combination of track parameters. Models would develop for each track-forms and run the models simulation by considering different speed condition of the moving wheel. From 2D models and its simulation, the dynamic response of both FLT and RHEDA2000 un-ballasted track would make known.

The steps that followed throughout this study are listed below:

Step -1 Collect the literatures that are relevant for the study

Step -2 Identify dominant parameters of the study

Step -3 Develop models of the tracks with FEM/ABAQUS

Step - 4 Revise and Run the models

Step - 5 Extract the output from FE model which relevant to the study

Step - 6 Interpret and describe results from output of the model

Step - 7 Compare the results for both track-forms

Step - 8 Draw conclusions standing from the modeling results

Step - 9 Report Writing and make necessary revisions

3.2 Parametric condition of the track-forms model

The main parameters that are considered in this study are the vertical rail displacement, stresses, and vertical rail acceleration due to the moving wheel load on the track at varying speed, vibration generation by wheel-rail contact force at frequencies from 0Hz to 2000Hz, track resonance and receptance at a certain frequency.

3.2.1 Assumptions and Simplifications

The following assumptions made to develop a model for analysis of this Thesis:

- The model is Simplified to 2D model to save the running time of the analysis
- Constant and Elastic parameters of the track are assumed in both the geometry and behavior of the track components' properties
- The wheel and Rail contacted are represented by Hertzian contact stiffness theory

- The loading condition is assumed a single wheel to analyze the effects
- Horizontal and Lateral responses are not taken in to account in the analysis

3.2.2 Material properties used

The material properties used in the Models are tabulated in the following table 2 and as described in the method of data collection, material properties are collected from different literatures and manuals [19] [35] [36] [37] and some variable values are assumed by considering the appropriateness of the assumed values. Since those tracks are standard track, the data used in the model are organized as follow based on the tracks standards.

Table 2 Materials properties used in the Modeling with ABAQUS FE Software

1. Element of Rheda2000 track	Parameters of the railway track	Symbol	Values
			FLT and Rheda200
UIC60	Cross section	S_r [cm_2]	76.86
	Mass	m_r [kg/m]	60.34
	Elasticity modulus	E_r [GPa]	210.00
	Poisson's ratio	ν_r [-]	0.30
	Vertical bending inertia	I_{xx} [cm_4]	3050 / 6.11x10^-5m4
	Lateral bending inertia	I_{yy} [cm_4]	515.60 / 7.925x10^-3m4
	Specific weight	γr [KN/m3]	76.93 = 7841.998Kg/m3
Rail Pad	Dynamic stiffness	K_p (MN/m)	Variable
	Damping	C_p (kNs/m)	Variable
Pre-stressed Sleeper of Rheda	Mass	M_s [kg]	-
	Spacing	l_s [m]	0.65
Rheda2000 slab . *Grade of concrete 35/45*	Specific weight	ρL [kN/m_3]	26.37 = 2688.03Kg/m3=2700
	Length x Height	Lxh [mxm]	0.24
	Elasticity modulus	E_L [GPa]	34.00
	Poisson's ratio	ν_L [-]	0.20
CBL	Elasticity modulus	E_{CBL}[GPa]	35
	Poisson's ratio	ν_{CBL}[-]	0.2
	Density	σ_{ls} (Kg/m^3)	2400
Geo-textile	Vertical stiffness	K_{Gt} [GN/m/m]	20E03
	Damping	C_{Gt}[GNs/m/m]	20
Sub Structures	Elasticity modulus	E_{Sb} [GPa]	2400
	Poisson's ratio	ν_{sb} [-]	0.2
2. Elements of Floating Ladder Track			

Rail UIC 60	Similar properties with Rheda2000 track type		
Rail Pad	Dynamic stiffness	K_p (MN/m)	Variable{60MN/m}
	Damping	C_p (kNs/m)	Variable
	Spacing	Ls(m)	0.6
Longitudinal sleeper	Elasticity modulus	E_{ls}[GPa]	50
	Poisson's ratio	ν_{ls} [-]	0.167
	Density	σ_{ls} (Kg/m^3)	2000
	Dimension	M	6.15 x 0.46
Supporting Platforms	Elasticity modulus	E_{sp}[GPa]	36
	Poisson's ratio	ν_{sp} [-]	0.167
	Density	σ_{sp}	2600
	Dimension	M	0.86 x 0.4
Resilient Pad	Dynamic stiffness	Kr_p (MN/m)	Variable{25MN/m}
	Damping	Cr_p (kNs/m)	Variable

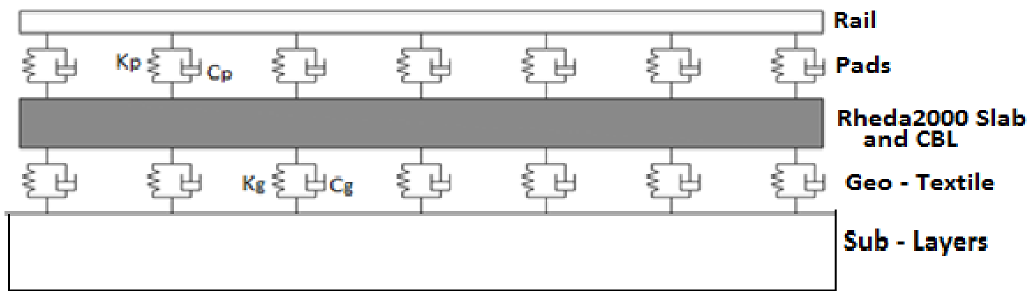

Figure 11 Schematic representation of the Rheda2000 model.

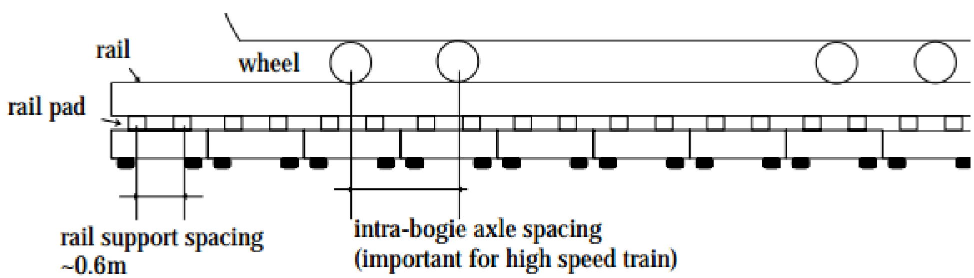

Figure 12 Schematic representation of FLT model

3.3 FEM section and its Processing

ABAQUS is a general-purpose FE software suite developed by Dassault systems, which has high application in both academic and industrial application and widely acceptable with its large material and element libraries.

This section deals with FEM software i.e ABAQUS and the followed modeling techniques of FLT and Rheda2000 railway track by using this software. Under here the modeling process by ABAQUS/CAE and followed logical Procedure in the modeling modules like defining the tracks geometry, defining material properties for each part of the track, generating mesh, creating jobs and so on would be presented.

Models created by ABAQUS/CAE start with creating different parts separately in the part modules and defining the material properties in the property module. Different part may need different material property accordingly. Material properties parameters used are available in ABAQUS such like density, elastic and plastic behavior. Then model assembled in the assembly module, by combing the different instances originates from different parts. In the step module, the analysis is divided in to different sequences of analysis procedures as required. The created interaction between different parts, the boundary condition and applying load also performed under respective modules. After the load and the boundary condition established in the whole mode is meshed in the mesh module but the meshing techniques vary with the element types and geometry of the model [38]. Under mesh module, the recommended mesh techniques are followed to come up with the best result.

In this study, the model is graphically created using FE software ABAQUS/CAE, that provides a simple, consistent interface for creating, submitting, monitoring, and evaluating form ABAQUS/Standard and ABAQUS/Explicit modeling process. Defining the geometry and material properties, as well as generating a mesh has done by moving from module to module.

3.3.1 ABAQUS's Elements used in the Modeling

ABAQUS has a wide-ranging element library to provide a powerful set of tools for solving many different problems. All elements used in ABAQUS are divided into different categories, depending on the modeling space. The element shapes available are beam elements, shell elements, solid elements and the modeling space is divided into 3D space, 2D planar space and axisymmetric space.

Beam Element-Beam elements have been used for the rails and sleepers modeling. A beam element is an element in which assumption are made so that the problems reduced to one dimension mathematically. The primary solution variable is then functions of the length direction of the beam. There are two main types of beam elements formulations, the Euler-Bernoulli theory and the Timoshenko theory, which are discussed under section 2.3.1.1 of this study.

Rigid Element- A rigid part represents a part that is so much stiffer than the rest of the model that its deformation can considered negligible.

There are two kinds of rigid parts: discrete rigid part and analytical rigid part. When describing a rigid part an analytical rigid part will have the priority because it is computationally less expensive than a discrete rigid part [39] and used to represent simple rigid bodies. In other side, discrete rigid elements are used to model rigid bodies that have complex geometries and require FE mesh.

In this study, rigid elements are used to create the wheel in both Floating Ladder Track and Rheda2000 track-forms as well as to create the Pre-stressed part of the Rheda2000 slab.

3.4 Modeling of the Tracks

Track modeling can be either continuously supported rail beam or discretely supported rail beam. The first cases is based on beam on elastic foundation (BOEF) theory and with this theory BOEF model ignore the discrete support of the rail and discrete mass of the sleeper and elastic foundation represents all track components and it is modeled by evenly distributed linear spring system. The second one is similar to continuously supported models and often has different layers representing rail, sleeper, rail pad and substructures. Discretely supported model can be solved in both frequency and time domain analysis, but frequency domain techniques rich their limits if non-linearity inside the track structure are taken into account [23].

3.4.1 Modeling of the rail

In the modeling with ABAQUS, the rail is modeled as beam element with its bending stiffness (EI) and mechanical properties as discretely supported underneath by parallel spring and dashpot elements.

3.4.2 Modeling of the sleeper

In both FLT and Rheda2000 track-form modeling of sleepers are modeled as suspended mass connected with the rail beam in the top through the parallel systems of spring dampers which representing the rail pad properties. In FLT model, the bottom part of the sleeper connected through parallel spring damper system that represents the resilient pad properties. From the top of the sleeper the distance of parallel systems of spring dampers are defined by the space of the fastening system and from the bottom of the sleeper elements space is defined by the space of the resilient pad. In the case of Rheda2000 track; pre-stressed sleepers are directly embedded within the continuously reinforced concrete pavement (CRCP) for the purpose of Crack control by the prefabricated concrete element for the rail seats as described in section 2.2 of this study. Therefore, the pre-Stressed parts of Rheda2000 track are modeled by discrete rigid elements, which are embedded with Rheda2000 Slab. The Rheda2000 slabs are modeled as deformable solid element with Solid homogeneous section, which have direct contact from the bottom with CBL. The simplified models of the track-forms are shown schematically as follow:

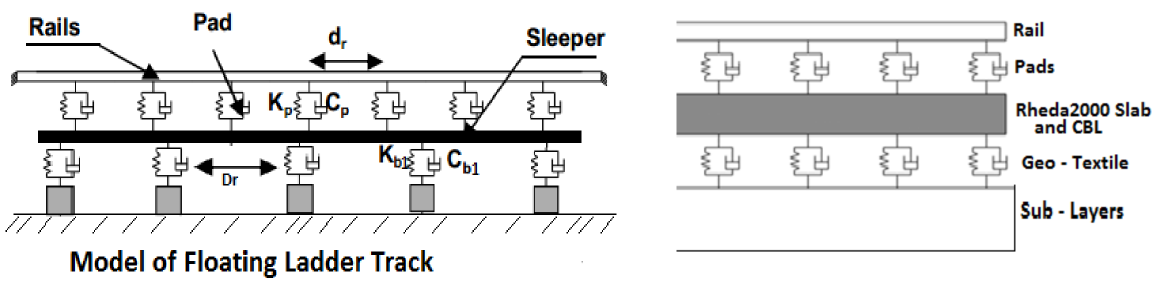

Figure 13: Figurative sketch of FLT and Rheda2000 Track Model

3.4.3 Modeling of track layers under the sleeper

In this study, modeling of tracklayers under sleeper would vary depending on the track type and its property. In the model of FLT, the model consists with parallel spring damper system under sleeper that represents the resilient pad properties, which are placed at constant distance D_r as shown in the above figure 13. The resilient pads are supported underneath by supporting platforms and these platforms are modeled with solid homogenous element.

In the case of Rheda2000 track model, CBL is represented by deformable homogeneous element with its mechanical and elastic property. The layers under CBL (i.e. HBL and FPL) are modeled by parallel spring damper system that are connected with CBL form the top and substructure from the bottom. The substructure is also considered as solid homogeneous element with its mechanical properties.

The following figure 14 and figure 15 the 2D model by using ABAQUS of Rheda2000 ballast-less Track and Floating Ladder Track respectively.

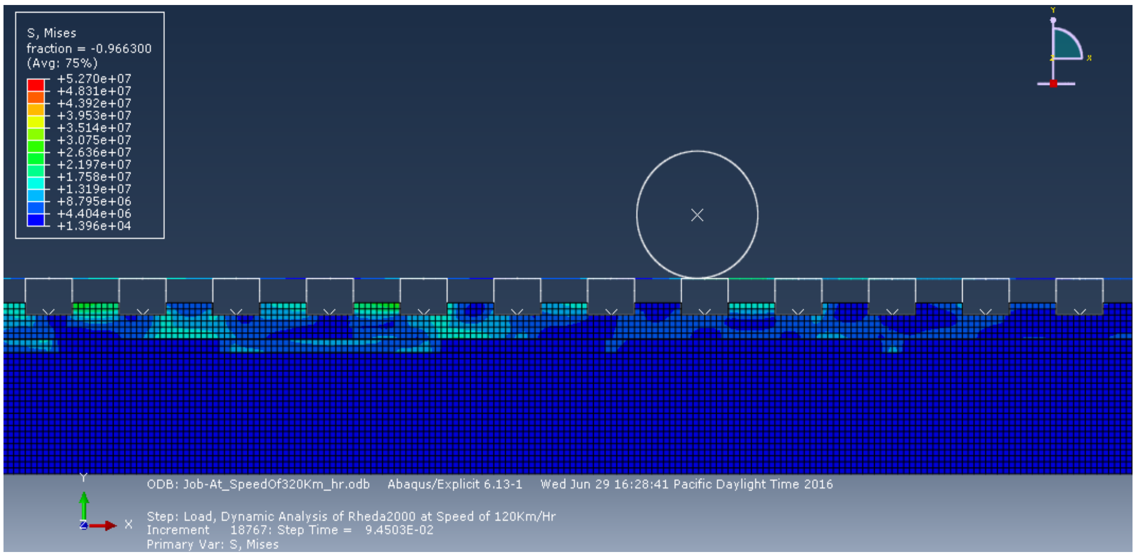

Figure 14: ABAQUS 2D Model of Rheda2000 Track by using Software

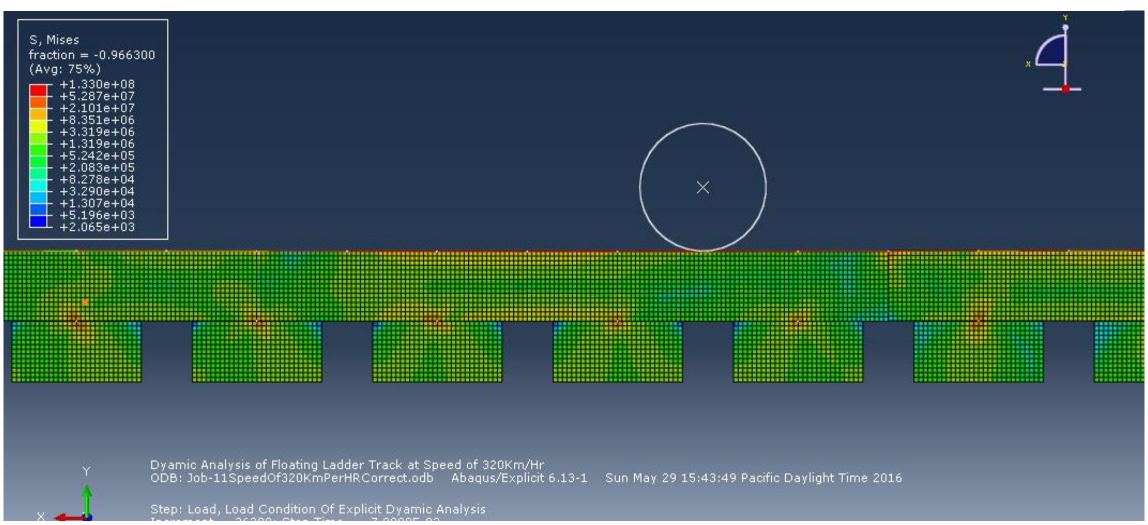

Figure 15: 2D Model of FLT by using ABAQUS Software

Chapter Four

4. Analysis and Discussion of the modeling Results

4.1 Analysis

The response of the dynamic system of the moving load and rail track structure can be found in either the Time Domain or the Frequency Domain Analysis. Wheel-rail interaction models have generally been classified in to two categories: models based on frequency dependent or time dependent solution techniques.

4.1.1 Frequency Domain Analysis

The frequency domain techniques are analytical tools that establish the relationship between the receptance of the track according to a unit force displacement of varying frequency. In this form of analysis, the responses of dynamic system calculate by applying varying frequencies to the track at the fixed position. The calculations undertaken in the frequency domain always assume that the model is linear. However, in reality there are several Non-linearity in the system. For example, Components like rail pad shows the non-linearity of the system.

The Advantages of this analysis technique are fast to run (mainly used for higher frequencies study vibration and noise related issues) and its disadvantages are that the properties must be linearized (unsuitable for discrete events - rail joints, hanging sleepers, varying ballast stiffness, etc.).

4.1.1.1 Frequency Eigenvalue Analysis

Eigenvalue analysis is useful to analyze the mode of vibration of rail track structures. An Eigenvalue analysis is performed after both static and steady state steps using Lancoz analysis for Eigenvalue solver to compute the natural frequency and mode of vibration in both FLT and Rheda2000 Track form's model.

Frequency response analysis is used to compute the structural response to a steady state oscillatory excitation, which is sinusoidal in nature. This load is defined as having

Amplitude at specific frequency and the tracks responses are obtained in steady state dynamic analysis by applying a harmonic load at the middle of the rail.

4.1.1.2 Steady state Dynamics

After Eigenvalue analysis and frequency extraction, steady state Dynamics is the next procedure used to compute the frequency responses of the rail tracks to an applied load excitation. Steady state dynamics direct methods uses the Eigen modes extracted in the frequency step. In the steady-state dynamic procedure, ABAQUS/Standard calculates the steady-state harmonic response directly in terms of the physical degrees of freedom of the model, using the mass, damping, and stiffness matrices of the system.

In this study, important results obtained from a frequency analysis are the modes of vibration at frequencies and acceleration level of the rail.

4.1.2 Time Domain Analysis

The time domain techniques make full use of available FEM software or can be coded into scientific tools they use time integration techniques. This can use modal superposition method to increase the speed of the model without significant loss of accuracy. Time domain analyses calculate dynamic solutions by applying dynamic loads on the center of rotating wheel that move along the rail over a specified period. The Advantages of this technique is non-linear properties or discrete events can be included but taking the longer time to run is it’s disadvantage.

4.2 Discussions Of the Result

In this section, the modeling results of FE Analysis of FLT and a Rheda2000 un-ballasted track-form is presented. The model is carried out based on time domain analysis and frequency analysis by using ABAQUS software. The purpose of this analysis is to study the dynamic properties under different speed of the moving load and vibration responses of those track-forms.

In the time domain, analysis of both track form models the stress, displacement, velocity and acceleration versus time function at varying speed of the moving load have been analyzed. The analyses are carried out at speed of 120 Km/Hr., 220Km/Hr., 320Km/Hr. and 420Km/Hr. In the same manner, the frequency analysis also carried out for both track forms at frequencies ranges from 0Hz to 2000Hz and the acceleration level of the rail as well as different mode of vibration are the extracted output of the numerical simulation of the model. The outputs of the modeling result and the analysis have been demonstrated in the following sub-sections.

4.3 Results of Floating Ladder Track

4.3.1 Time Domain Analysis

Under this sub-section, numerical simulation analysis of FLT is carried out in time domain and the result is presented as follow. The following figure 16 illustrates the stress responses versus time functions with constant material properties of FLT to consider the effect of speeds on the tracks dynamic responses. From this graph, it can be clearly observed that the stresses on the rail are increases from130Mpa to 250Mpa as the speed of the moving wheel increases from 120km/hr. to 420Km/hr. As the time domain increases from 0.1sec to 0.4sec, the stresses increases in a significant manner as the speed of the rotating wheel increases. Nevertheless, from 0.4-0.7sec the stresses variation due to the speed of the wheel increases with less variation.

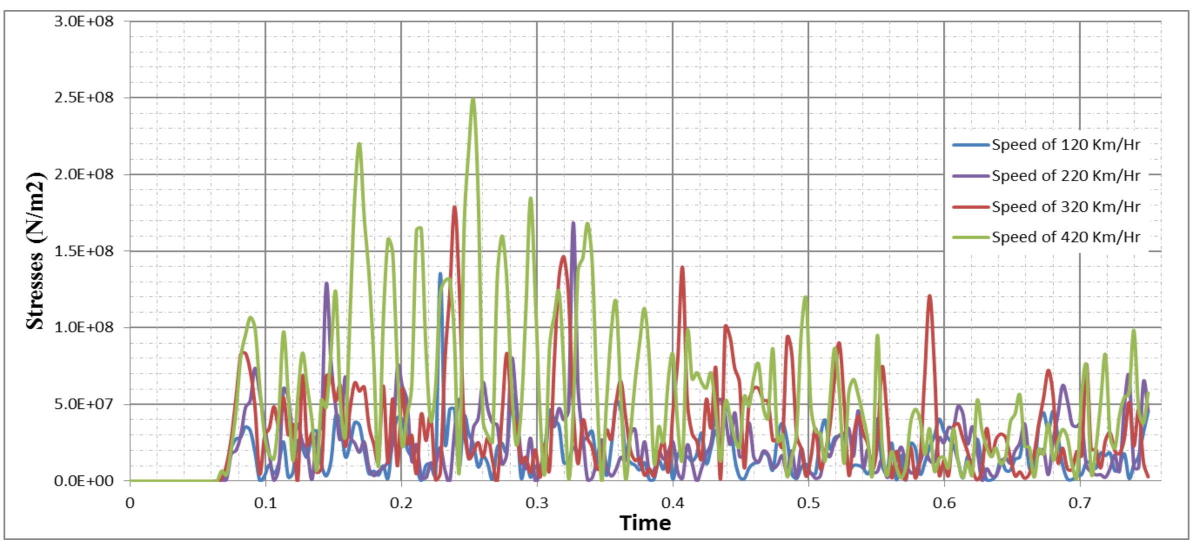

Figure 16: Stress of FLT at mid of Rail varying Speed of the Moving Load

The time history of rail Displacement at the mid of the span of the Floating Ladder Track is shown in the following Figure 17. This is to consider the effect of speeds on this tracks dynamic responses with keeping material properties constant. As stated above the speed varies from 120Km/Hr. to 420Km/Hr. and this shows that the vertical displacement of the rail increases as the speed of the moving load on the FLT track. As the speed of the rotating wheel varies from 120 to 420Km/hr, the maximum vertical displacement observed on the rail is 8mm at speed 420Km/hr of the moving Wheel. The displacement response pattern shown from the following graph varies with all range of the domain. In the range of 0.1 – 0.5sec of the time domain, the displacement is high at speed of 320Km/hr. But above 0.5sec of the time function, the highest displacement is at speed of 420Km/hr and within this time domain the displacement increases as the moving wheel speed increases.

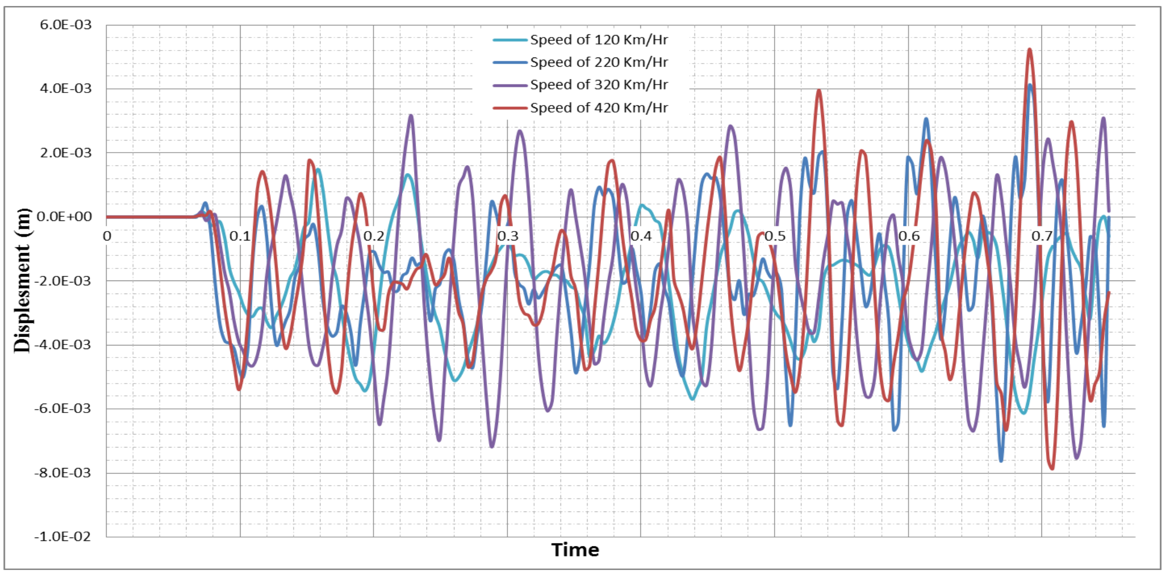

Figure 17 Displacement of FLT with varying Speed of the Moving load at mid of the Rail

In the following graphs, vertical Acceleration of rail with time functions is discussed by considerations of constant material properties of Floating Ladder Track. This has been done to consider the effect of speeds on the tracks dynamic responses of vertical acceleration at speed vary form 120Km/hr. to 420Km/hr. This fig.18 shows that as the speed of the moving Train increases the vertical acceleration level of rail also increases.

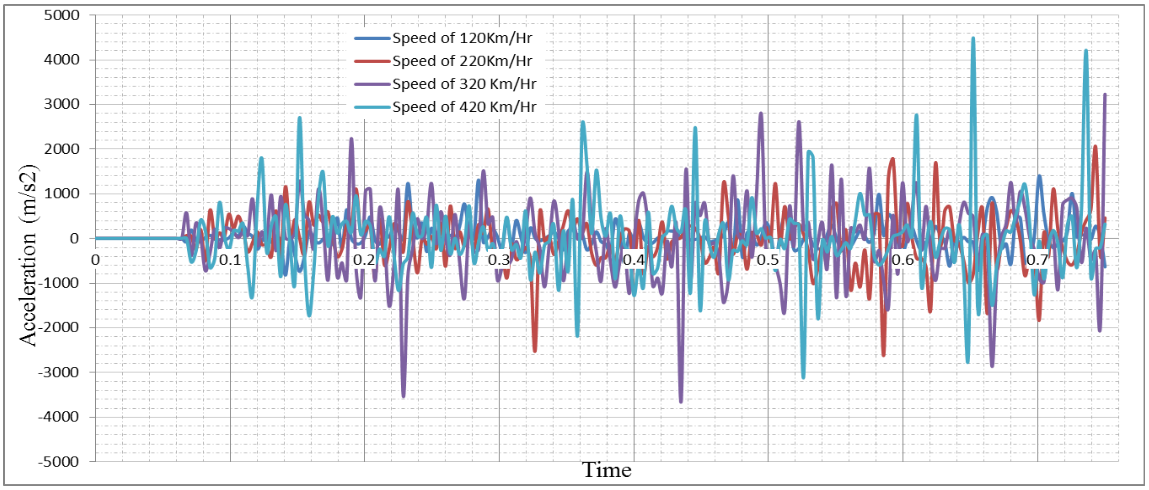

Figure 18: Acceleration of Rail in FLT with d/t Speed of Moving load at mid of the Rail

The following graphs are Vertical Velocity versus time functions graph of FLT with constant material properties and by consider the effect of speeds on the tracks dynamic responses. As shown in the following fig.19 the speed varies from 120Km/Hr. to 420Km/Hr.

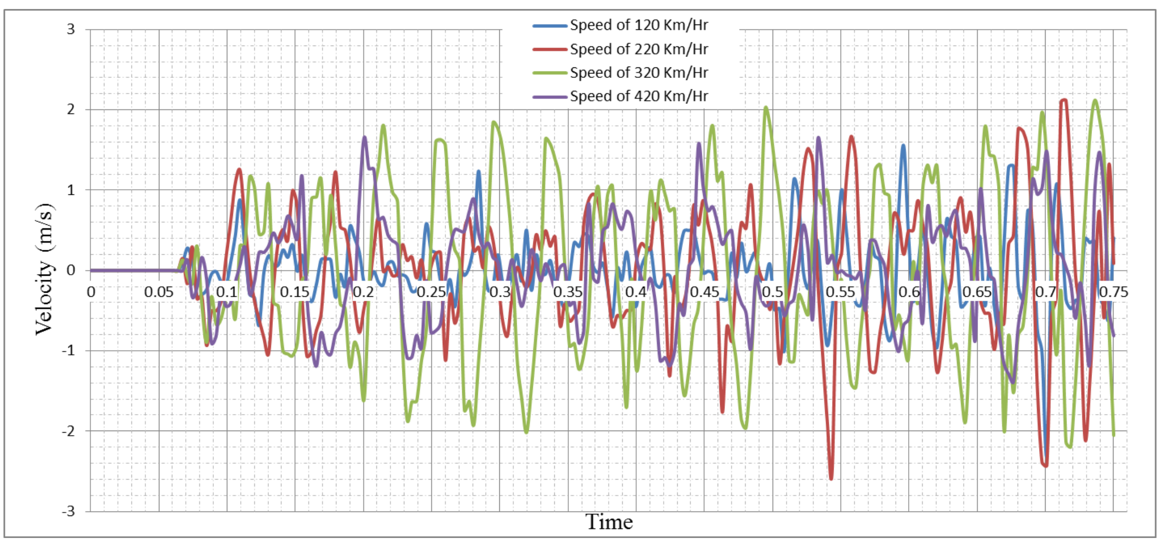

Figure 19: Vertical Velocity of Rail in FLT with Different Speed of the Moving load

4.3.2 Frequency Analysis

Based on the discussion of the section 4.1.1.1 in this study, an Eigenvalue analysis is performed in the frequency and steady state dynamic steps using Lancoz Eigenvalue solver to compute the natural frequency and mode shape of vibration at varies frequencies of FLT form's model. For this type of track, the lowest natural frequency start from 310.29Hz and the analysis is done for frequency domain range from 0Hz to 2000Hz.

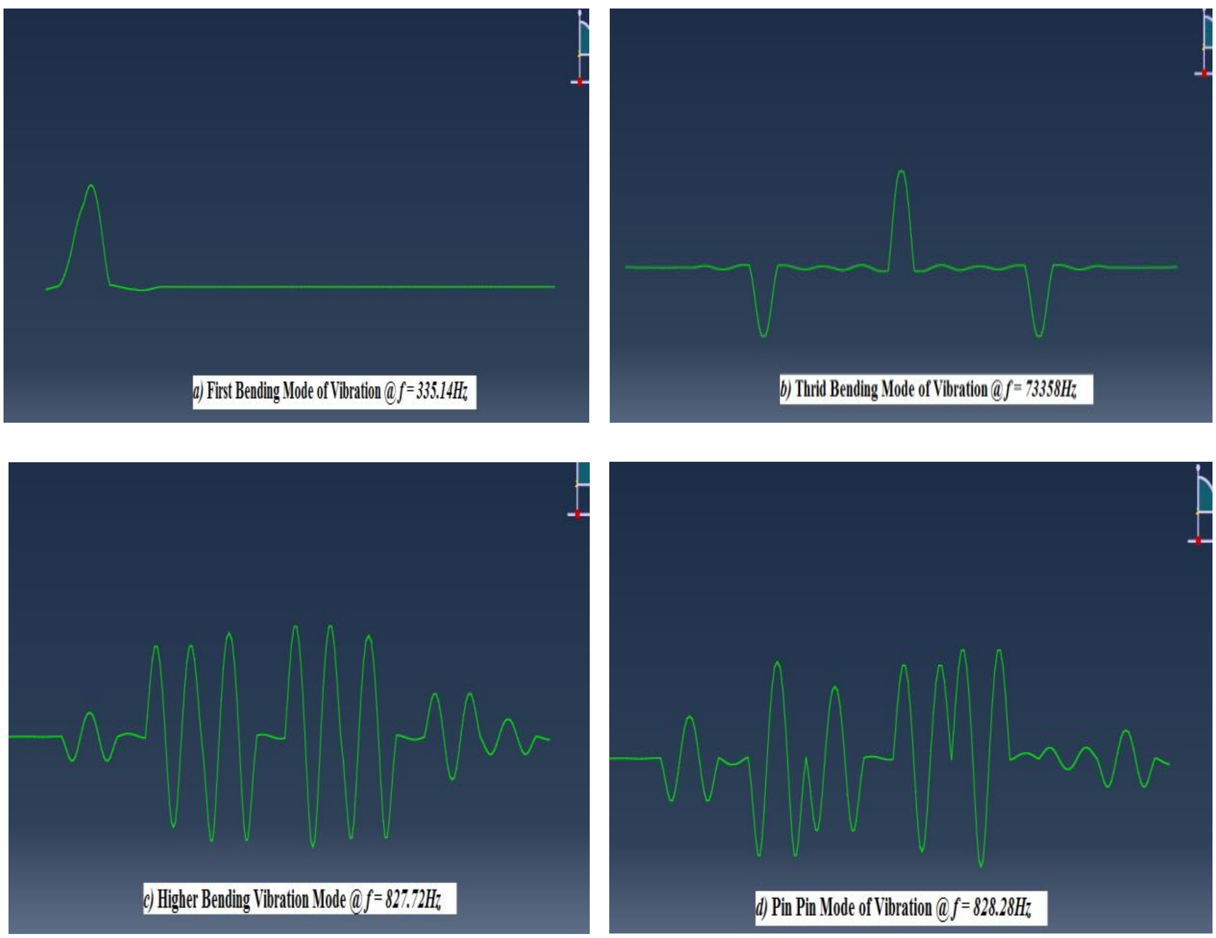

Figure 20: Different Mode of Vibration of Rail on Floating Ladder Track

From frequency extraction step of FLT model, about 162 different mode of vibration of rail are obtained. As shown in the above fig. 20 from fig *a* to fig *d* first bending mode, third bending mode, higher bending mode and nearly pin-pin mode of vibrations are types of vibration mode observed in this type of track and higher mode of vibration is most observable mode of vibration.

In the following figure 21 shows, the acceleration level of the rail in FLT at different frequencies that are obtained from steady state dynamic analysis. As presented in the following graph, for frequency nearly less than 400Hz the acceleration level of the rail is very trivial and above the this frequency, the acceleration level of the rail is significant at some frequency interval.

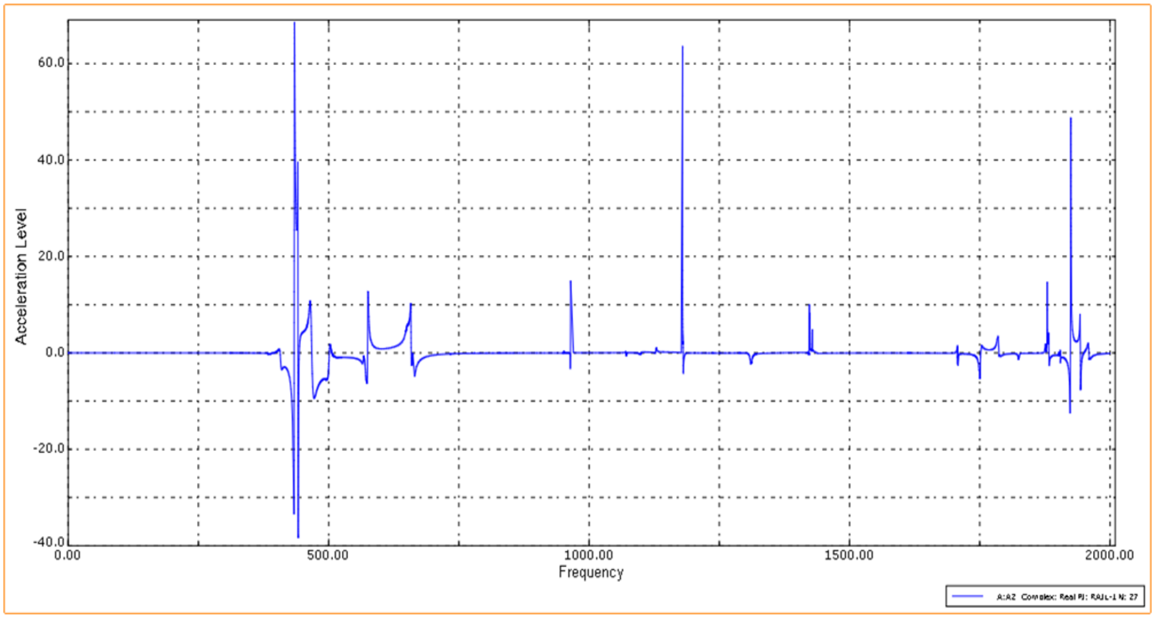

Figure 21: Acceleration Level vs. Frequency of Floating Ladder Track

The maximum acceleration level 68.5m/s2 is observed at Frequency of 450Hz, and others peak values of acceleration level of rail at frequency of 980Hz, 1170Hz, 1450 and 1800Hz are observed. If the loads contain frequency component corresponding to these peak natural frequencies, the structure of this rail track faced large amplification or resonance may occur at these frequency intervals.

4.4 Results of Rheda2000 un ballasted Track

4.4.1 Time Domain Analysis

The numerical simulation of Rheda2000 ballast-less Track is carried out in time domain analysis and the result is presented as follow. The following figure 22 illustrate the stress responses versus time functions with constant rail-pad and tracks stiffness of Rheda2000 ballast-less Track to consider the effect of speeds on the tracks dynamic responses. The stress responses increases from approximately 100Mpa to 160Mpa as the speed of the moving wheel varies from 120Km/hr to 420Km/hr. In its entire domain the response of stresses increases and at the 0.4 – 0.5 sec some sort of decreasing observed for the speed varies from 120 to 320km/hr but at speed of 420 Km/hr, the maximum stress observed with this domain as shown in the following graph 22.

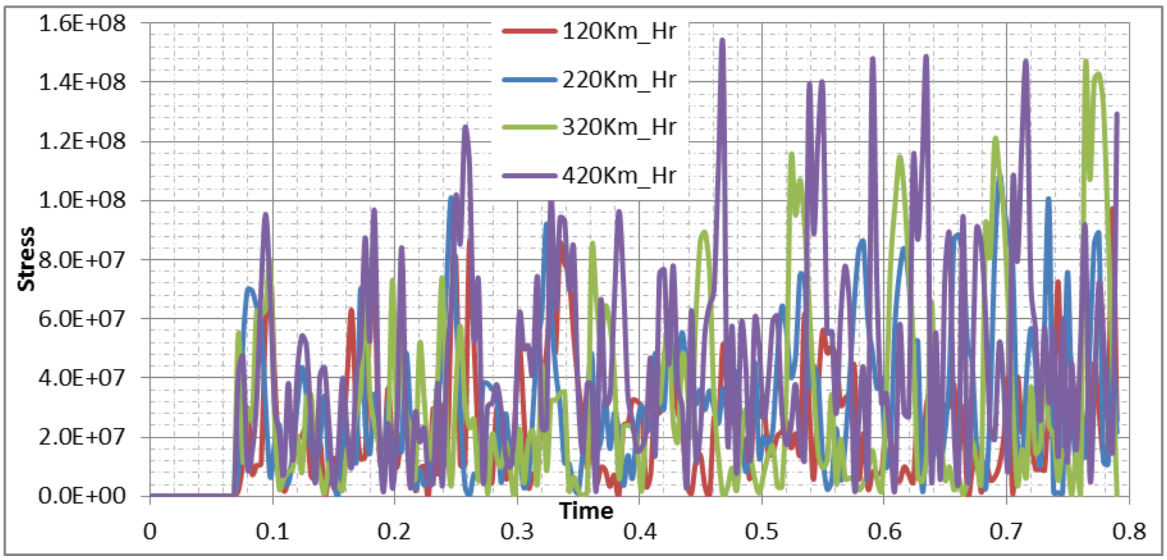

Figure 22: Stress of Rheda2000 ballast-less Track's mid of Rail at d/t Speed of the Load

The time history of rail Displacement at the mid of the span of the Rheda2000 Ballast-less Track is shown in the following Figure 23. This is to consider the effect of speeds on this tracks dynamic responses with keeping stiffness and material properties constant. The speed of the moving load varies from 120Km/Hr. to 420Km/hr and the graph below shows that the vertical displacement of the rail increases as the speed of the moving load on the Rheda2000 ballast-less track-form. As the speed of the rotating wheel varies from 120 to 420 km/hr, the maximum vertical displacement observed on the rail is 3.4mm at speed increases to 420Km/hr. As shown below, vertical deflection of the rail varies with its time domain and from the domain 0.1sec to 0.2sec, the deflection increases as the speed increases. Within the domain range of 0.2 sec to 0.5sec, it can be shown the deflection responses are uniform. Moreover, after time domains range of 0.5sec the responses are increases as the speed increases.

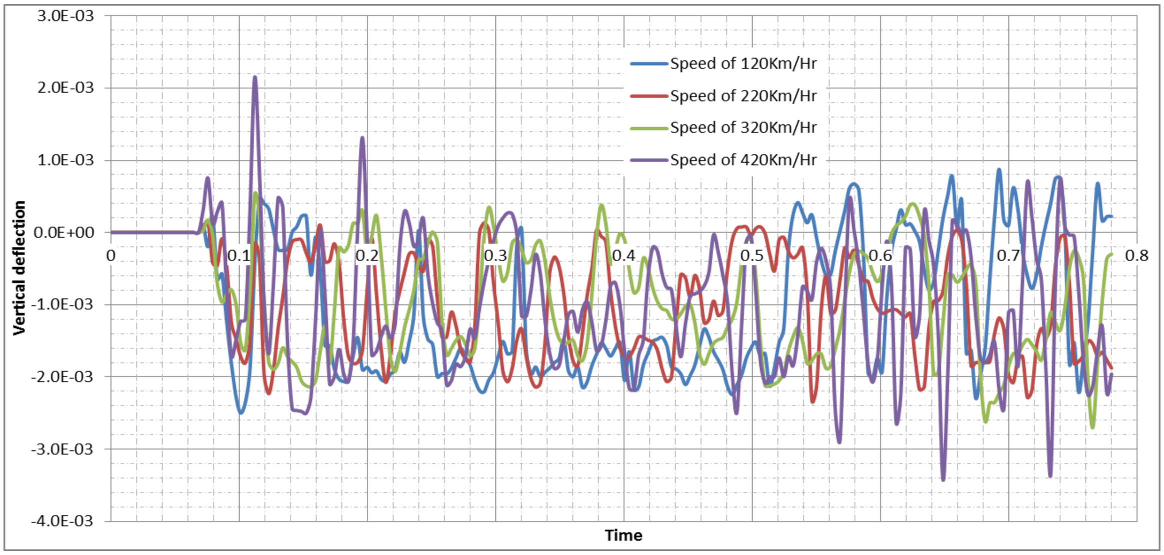

Figure 23: Displacement of Rheda2000 track at Speed of the load at the mid of the Rail

The following fig.24 are Vertical Velocity of the rail versus time functions graph of Rheda2000 ballast-less Track with constant stiffness and material properties by consider the effect of speeds on the tracks dynamic responses. As shown in the following graph the speed varies from 120Km/Hr. to 420Km/Hr.

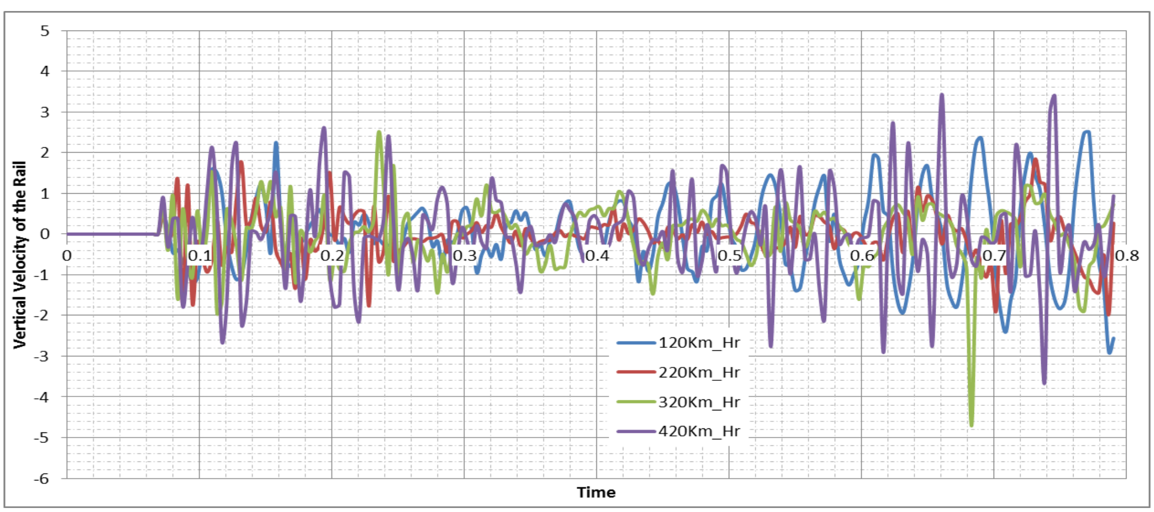

Figure 24: Velocity of Rail in Rheda2000 Track with Different Speed of the Moving load

From graph 24 above, it can simply observed that the velocity responses are uniformly decreases within the domain of 0.1 sec to 0.3 sec and starting from 0.4 sec the responses are increases as each speed of the rotating wheel but at 0.7 Sec of the domain the highest value is observed at speed of 320Km.hr. Throughout its domain the velocity responses increases as the speed varies from 120 to 420Km/hr except 0.7 sec of the domain.

In the following figure 25, vertical Acceleration of rail with time functions is presented form simulation result of the model. The analysis is done by considering the constant material properties of Rheda2000 Ballast-less Track. This has been done to consider the effect of speeds on the tracks dynamic responses at varies of speeds. Based on the graph shown below, the responses of the vertical acceleration increase as the speed increases. Within the domain ranges from 0.1 to 0.3 sec and 0.6 to 0.75 sec the tracks are highly accelerate while the speed increases and some peak values are observed in all domain.

Figure 25: Acceleration of Rail in Rheda2000 Track @ Speed of the wheel at mid of Rail

4.4.2 Frequency Analysis

As discussed in the section 4.1.1.1 of this study, An Eigenvalue analysis is performed in the frequency and steady state dynamic steps using Lancoz analysis for Eigenvalue solver to compute the natural frequency and mode of vibration the model at varies frequencies of Rheda2000 Track-form. For this type of track the lowest natural frequency start from 104Hz and the analysis is done for 2000Hz.

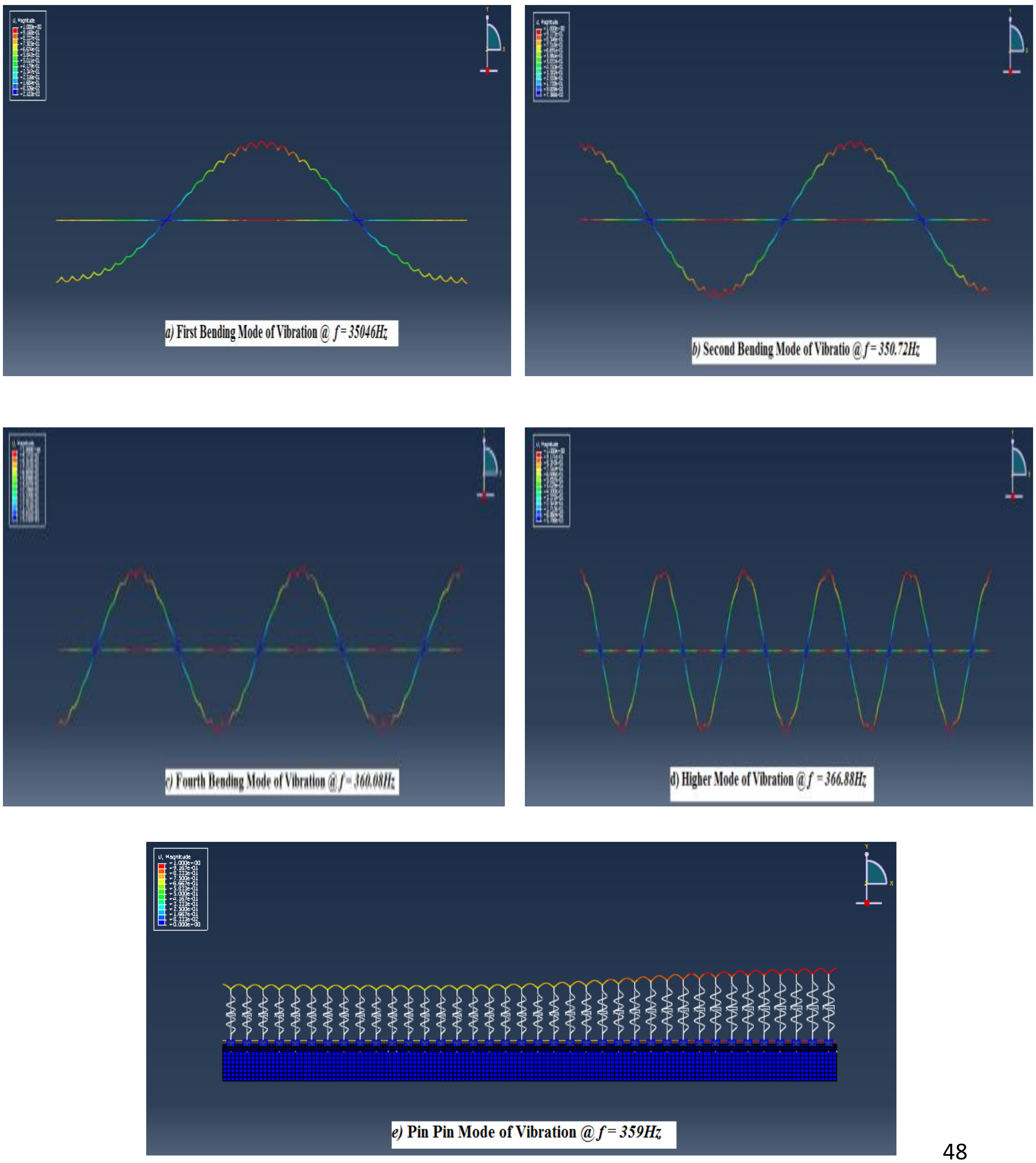

Figure 26: Different Mode of Vibration of Rail on Rheda2000 ballast-less Track

From frequency extraction step of Rheda2000 track model, about 331 different mode of vibration are obtained as the samples are shown in the above fig. 26 from fig *a* to fig *e* and in this type of track higher mode of vibration is most observable mode of vibration.

The following graph 27 illustrates that the acceleration level of the rail in Rheda2000 ballast-less track at different frequencies that are obtained from steady state dynamic analysis. As shown from the graph, for frequency nearly less than 450Hz the acceleration level of the rail is slight and above the specified frequency, the acceleration level of the rail is high. At frequency of 500Hz, 1250Hz and above 1500Hz are the peak acceleration level of rail is observed as presented in the following graph 27.

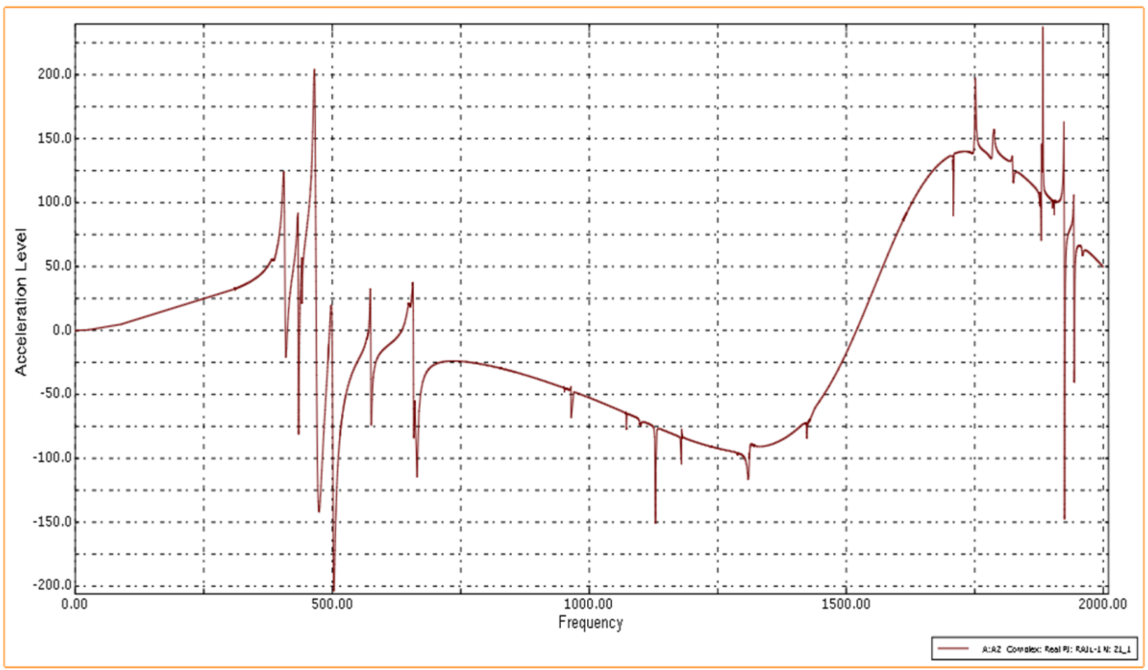

Figure 27: Acceleration Level vs. Frequency of Rheda2000 ballast-less Track

4.5 Comparison of Rheda2000 and Floating Ladder Track

4.5.1 With respect to Dynamic responses

Under this sub-section of this study, the comparisons of FLT and Rheda2000 Ballast-less Track based on the simulation result of their Dynamic model have been done. The effects of the speed on the dynamic responses of the Tracks are studied by varying the speed of the moving wheel on these tracks and by keeping the stiffness and mechanical properties of both tracks constant.

As described in the section 3.2.1, the models of the tracks are two-dimensional (longitudinal and vertical direction) and the vertical response of the tracks are taken under consideration for the comparison of dynamic performance of the tracks based on the results. Therefore, Vertical Displacement, Vertical Velocity, Vertical Acceleration of the rail and stresses on the rail are the dynamic responses selected for comparisons of the tracks and the results are presented as follow.

The time function of rail Displacement of FLT and Rheda2000 ballast-less Tracks at 120Km/hr speed the moving load which are taken form the mid span of the tracks are shown in the following graph 28. As shown in this graph, at speed of 120Km/hr the maximum displacement of FLT is 6.2mm and the maximum displacement of Rheda2000 2.5mm.

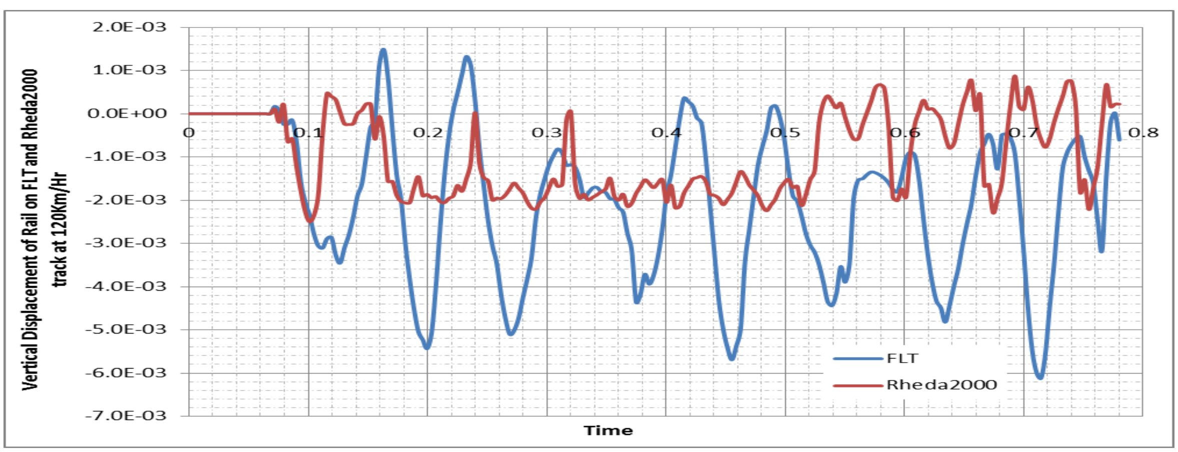

Figure 28: Displacement of Rail on FLT and Rheda2000 at speed of 120Km/Hr.

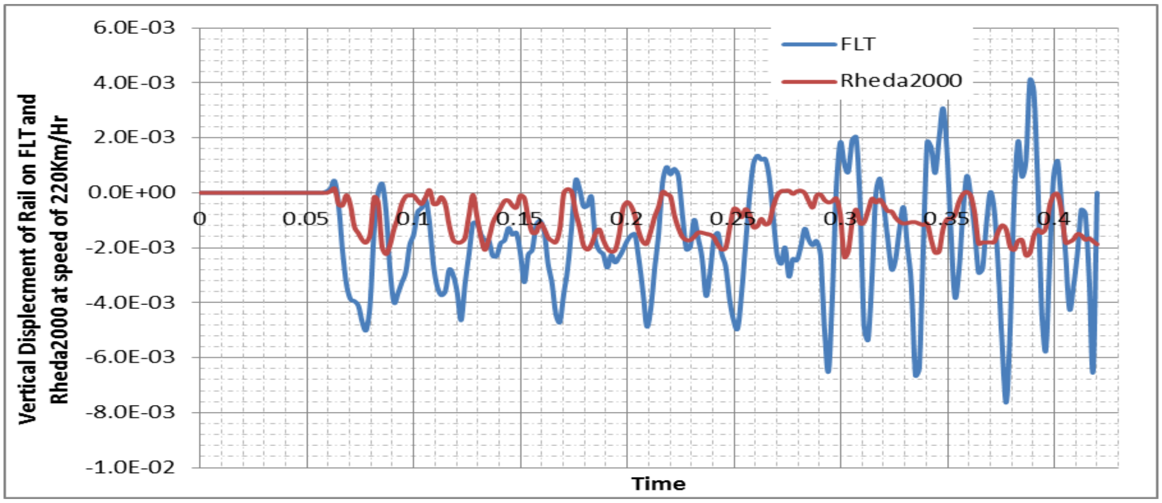

Figure 29: Displacement of Rail on FLT and Rheda2000 at speed of 220Km/Hr.

In similar manner as the speed of the wheel increases to 220 Km/hr, the maximum vertical displacement observed in Floating ladder Track is about 7.5mm but the maximum displacement of Rheda2000 approximately keeping similar with speed of 120Km/hr as the results are shown in the above fig. 28 and 29.

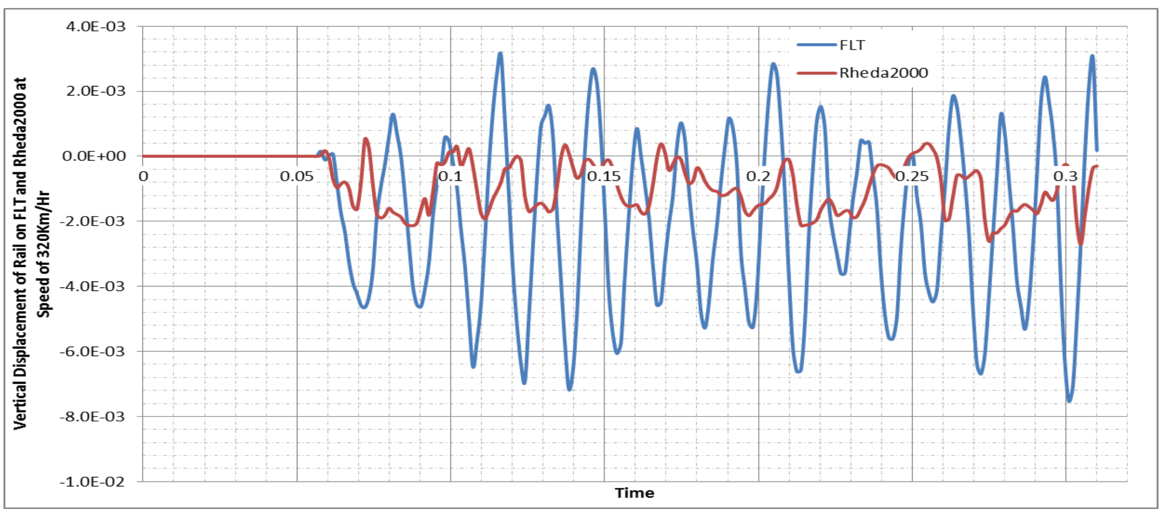

Figure 30: Vertical Displacement of Rail on FLT & Rheda2000 at speed of 320Km/Hr.

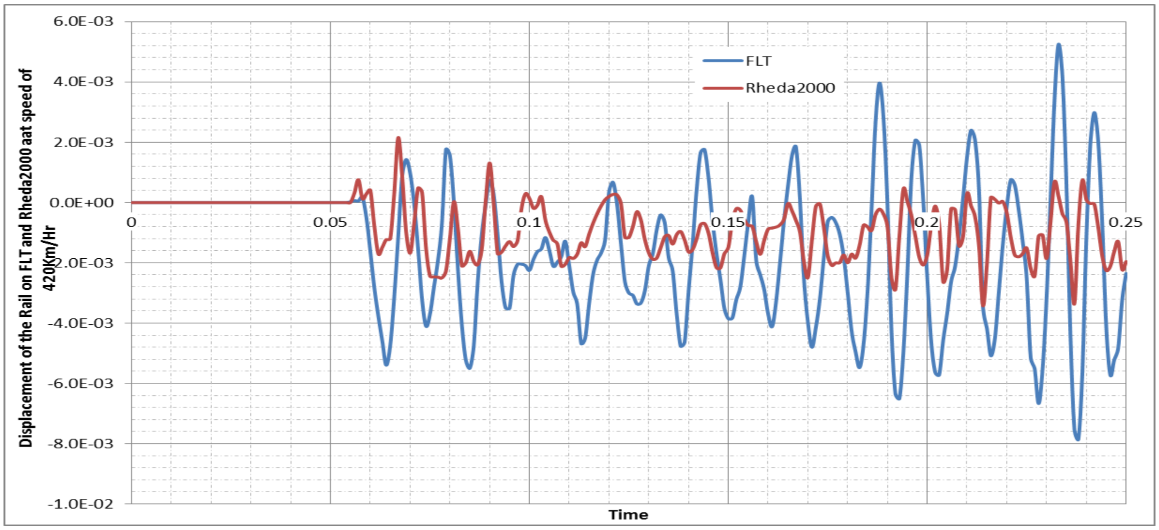

Figure 31: Displacement of Rail on FLT and Rheda2000 at speed of 420Km/Hr.

Form fig. 28, 29, 30 and 31, it is possible to observe that the vertical displacement on the rail of Floating ladder track is greater than vertical displacement in the Rheda2000 Track. As the speed of the moving load increases from 120 to 420 Km/hr, the vertical displacement of the rail in Floating Ladder Track is increasing to nearly 8mm but vertical displacement of Rheda2000 is slightly increasing to 3mm.

As shown in the above graphs, the displacement responses of FLT increases throughout its domain as the speed vary from 120 to 420Km/hr. However, in case of Rheda2000 there is increasing in responses from 0.1sec to 0.2 sec of the domain, uniform displacement responses from 0.2 to 0.5 sec and with the rest domain the sort of increments in response observed as the speed varies.

Similarly, the comparison of Floating Ladder Track and Rheda2000 ballast-less track with respect to Stress-time function with varying Speed of the moving load are presented with the following respective figures.

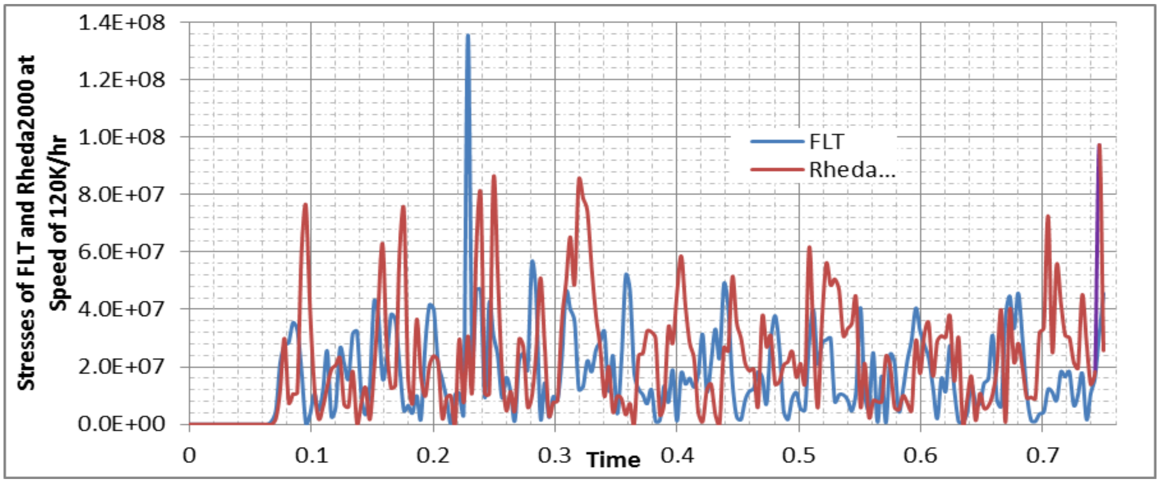

Figure 32: Stress of FLT & Rheda2000 Track at Speed of 120Km/hr. of the Moving load

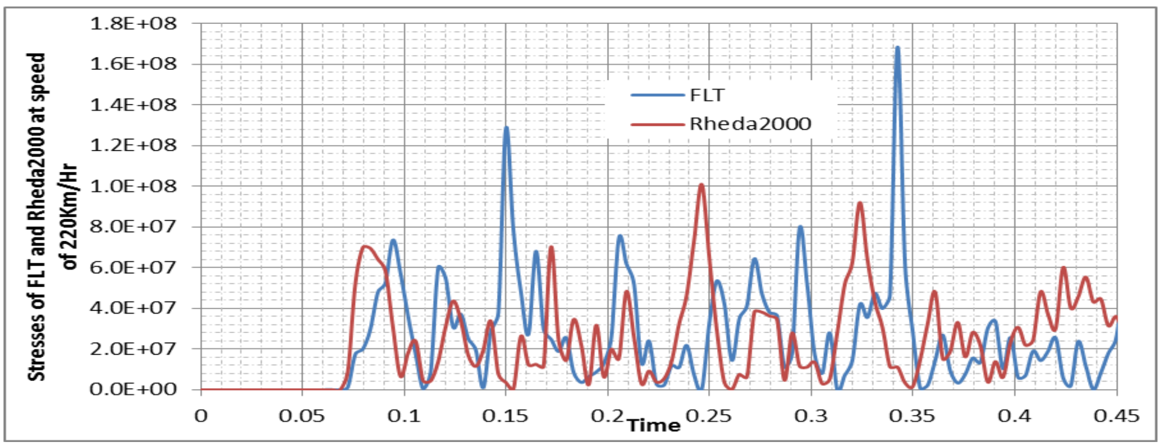

Figure 33: Stress of FLT and Rheda2000 Track at Speed of 220Km/hr. of Moving load

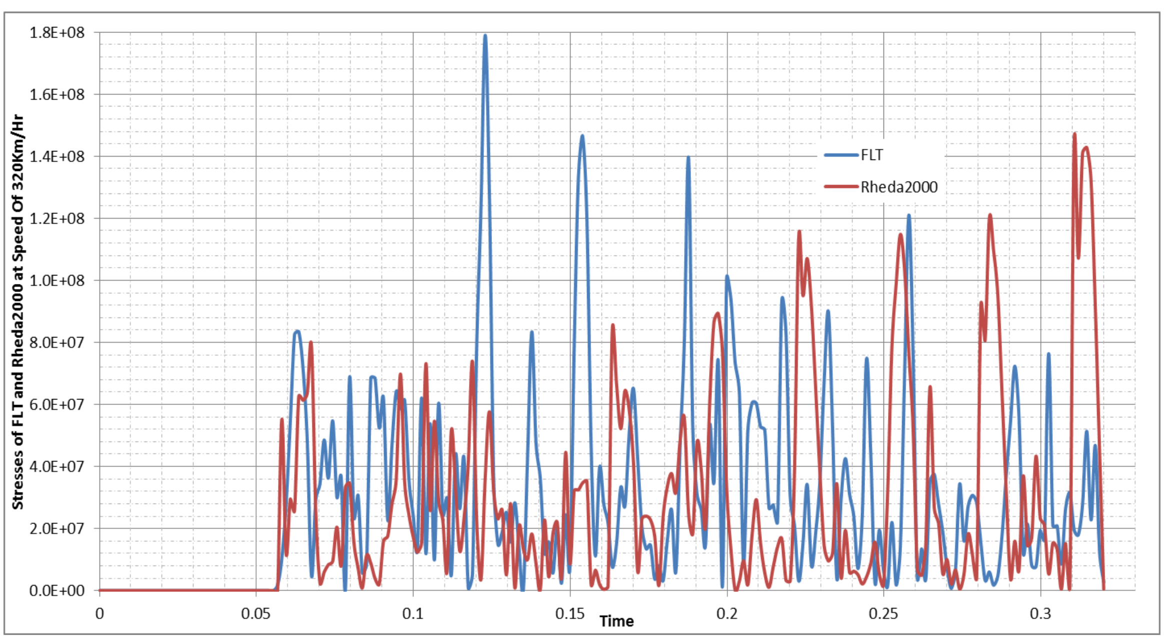

Figure 34: Stress of FLT & Rheda2000 Track at Speed of 320Km/hr. of the Moving load

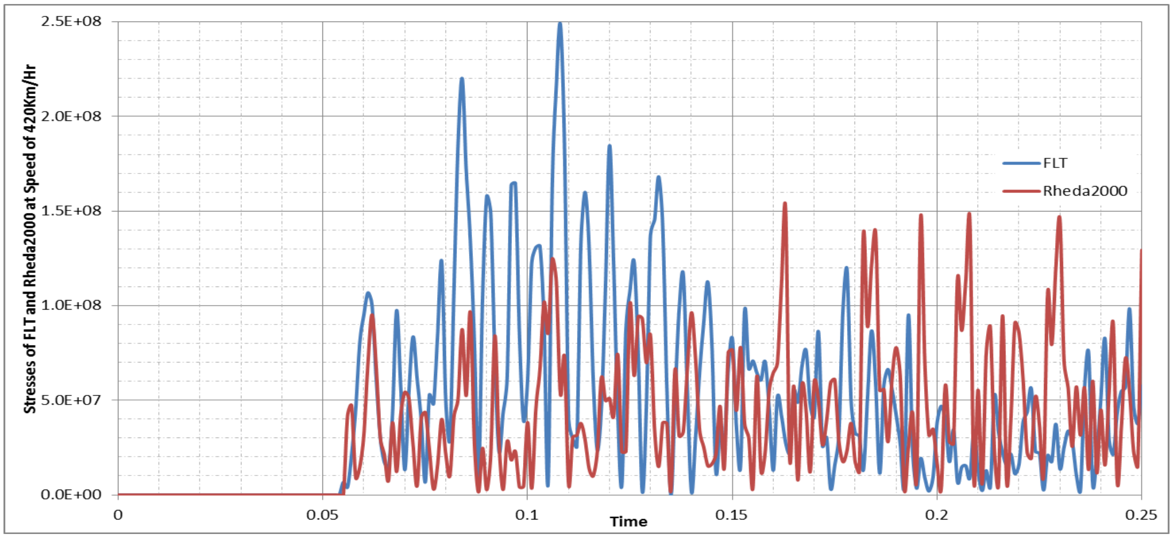

Figure 35: Stress of FLT & Rheda2000 Track at Speed of 420Km/hr. of the Moving load

As shown in fig.32 – 35 shows the comparisons between Floating Ladder Track and Rheda2000 ballast-less Tracks' stress variation on the Rail when the speed of the moving load varies from 120Km/hr. to 420Km/hr. The maximum stresses in Floating Ladder Track vary from 130Mpa shown in fig. 32 to 250Mpa shown in fig.35. On the other hand, the maximum stresses on Rheda2000 ballast-less Track varies from 136Mpa to 160Mpa shown in similar figures in the above.

The comparison of Floating Ladder Track and Rheda2000 ballast-less track with respect to Vertical Acceleration with time function while the speed of the moving load varying is presented by figures shown below.

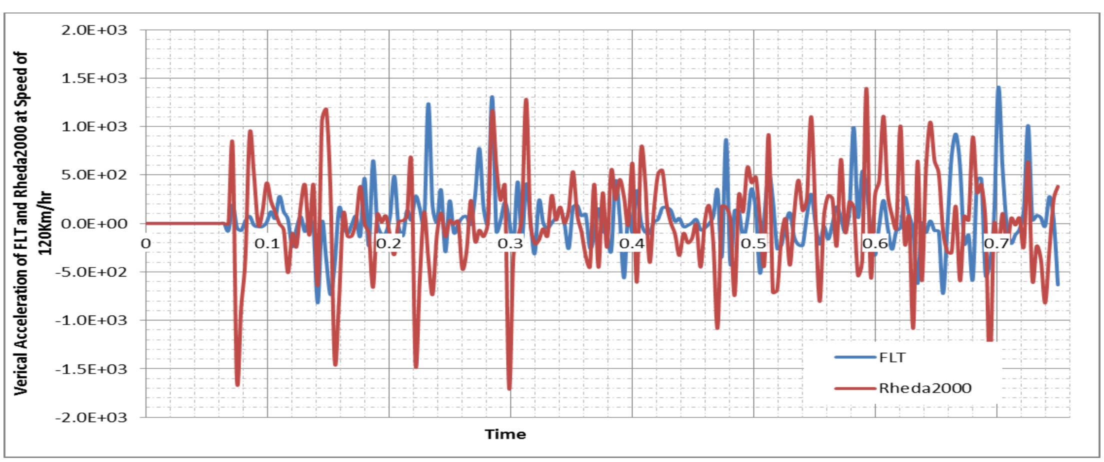

Figure 36: Vertical Rail Acceleration of FLT and Rheda2000 at Speed of 120Km/hr

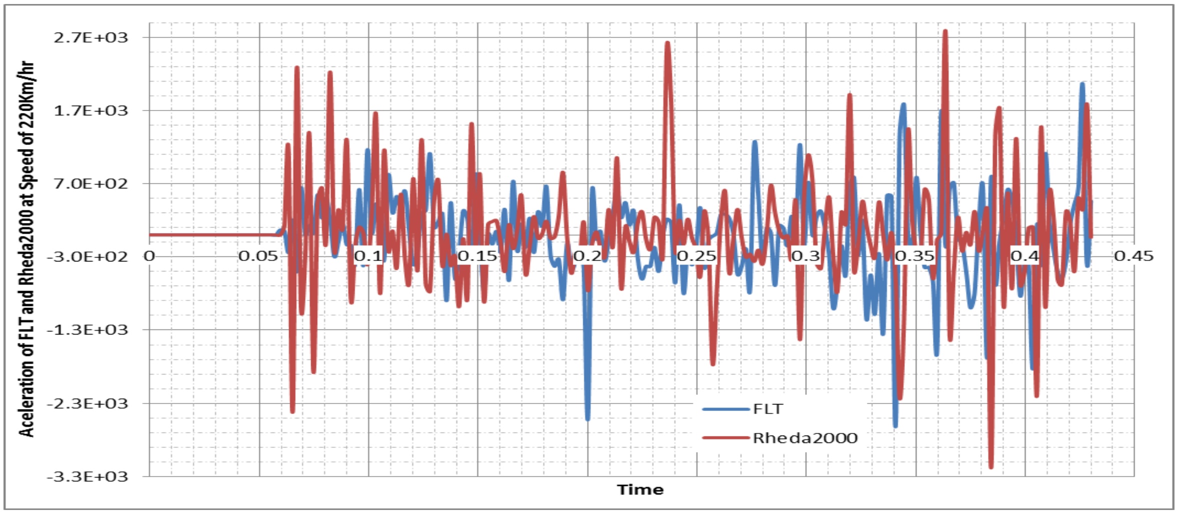

Figure 37: Vertical Rail Acceleration of FLT and Rheda2000 at Speed of 220Km/hr

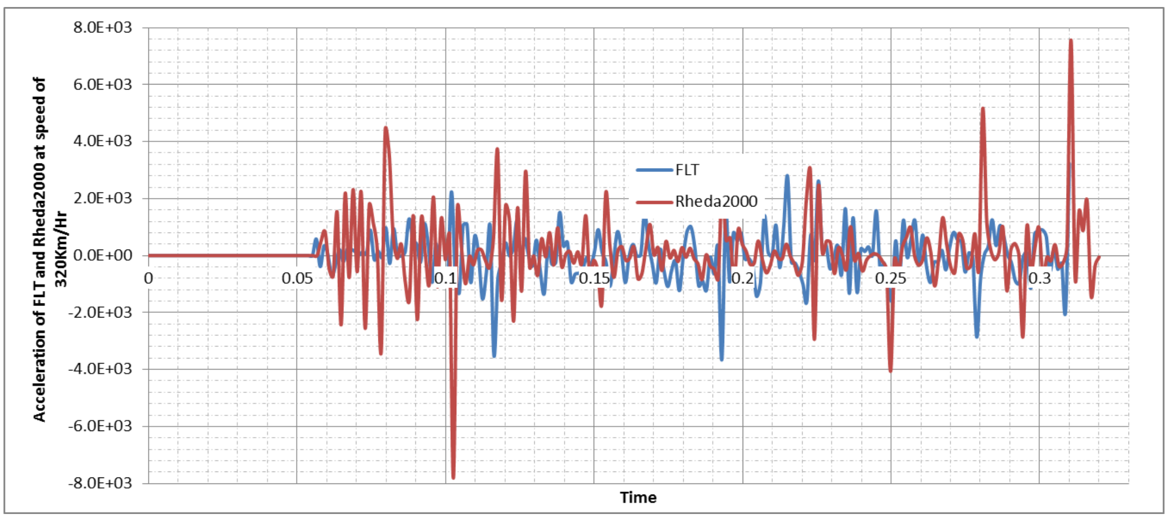

Figure 38: Vertical Rail Acceleration of FLT & Rheda2000 at Speed of 320Km/hr

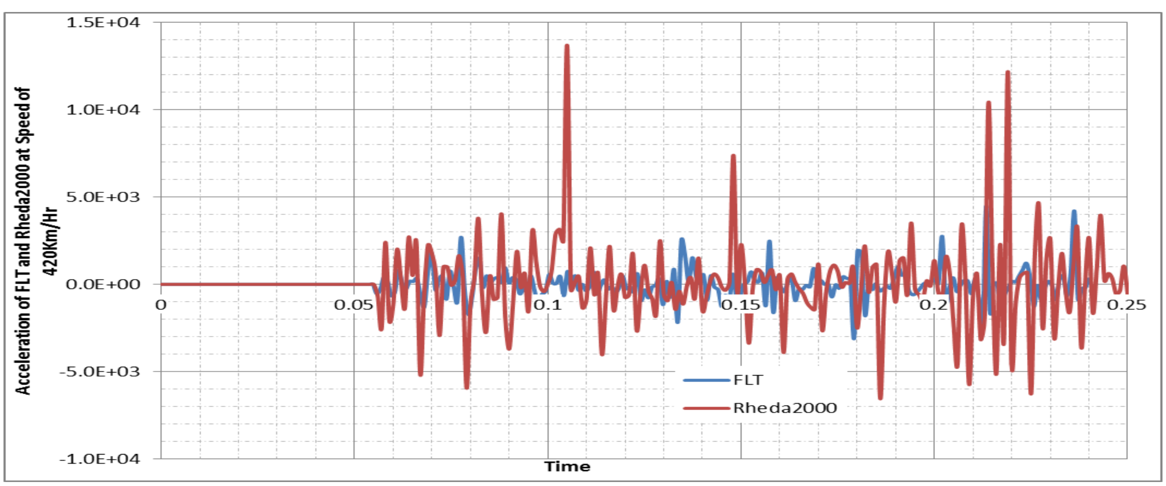

Figure 39: Vertical Rail Acceleration of FLT and Rheda2000 at Speed of 420Km/hr

The figures 36 to figure 39 shown above shows that the comparison of vertical acceleration of Rail on both Floating Ladder Track and Rheda2000 while the speed of the moving load varies from 120Km/hr to 420Km/hr. From this simulation result graph, it is possible to understand the vertical Acceleration of Rail in Rheda2000 ballast-less track is higher than Vertical Acceleration of Rail in Floating Ladder Track.

Based on the simulation result of the model, FLT and Rheda2000 can be compared with respect to Rail vertical velocity and in the following figures; the comparisons of both track-forms are described.

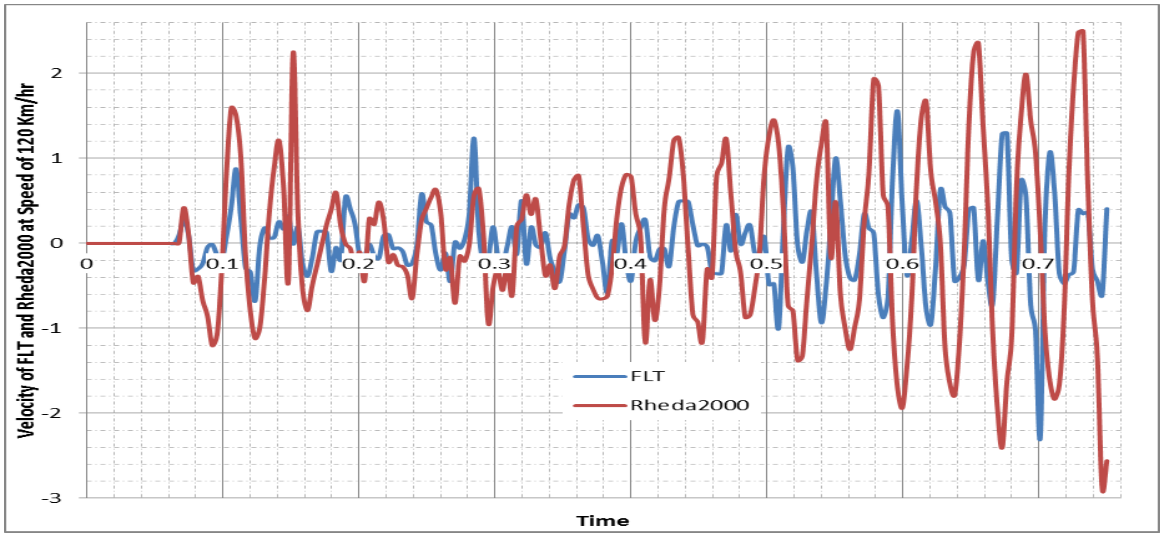

Figure 40: Rail Vertical Velocity of FLT & Rheda2000 Track at Speed of 120Km/hr

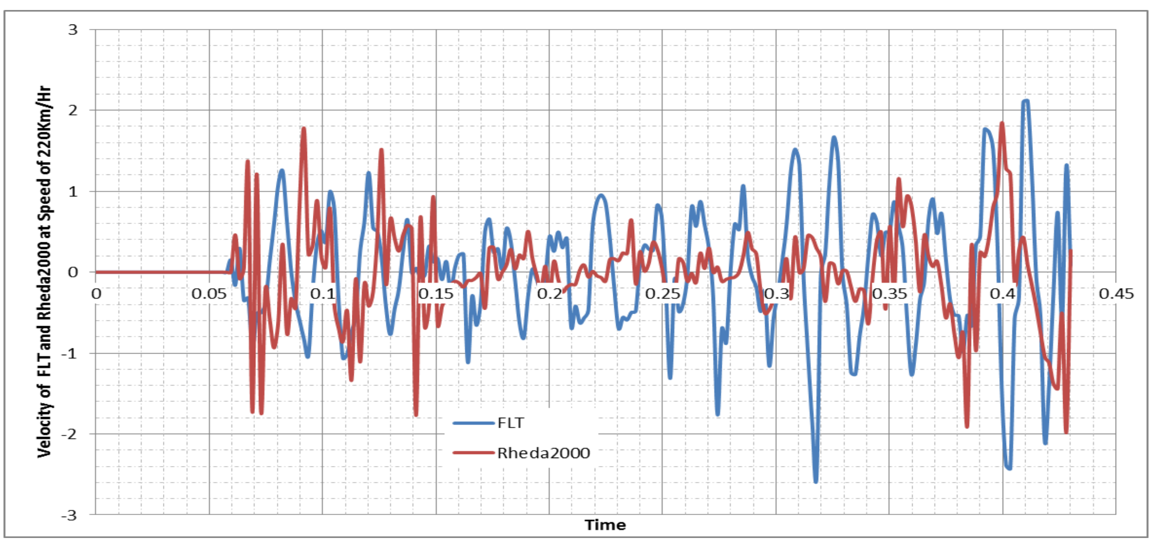

Figure 41: Rail Vertical Velocity of FLT & Rheda2000 Track at Speed of 220Km/hr

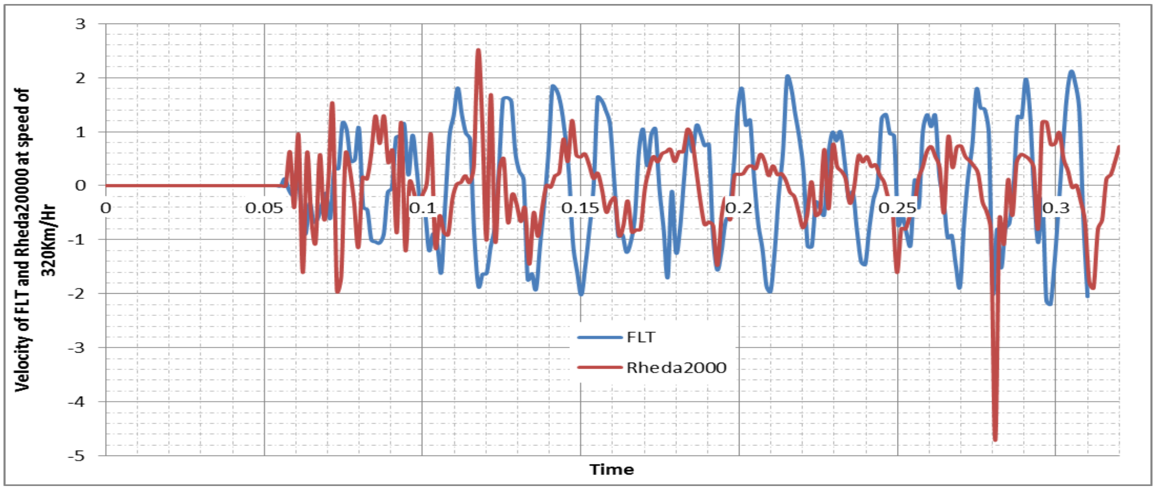

Figure 42: Rail Vertical Velocity of FLT & Rheda2000 Track at Speed of 320Km/hr

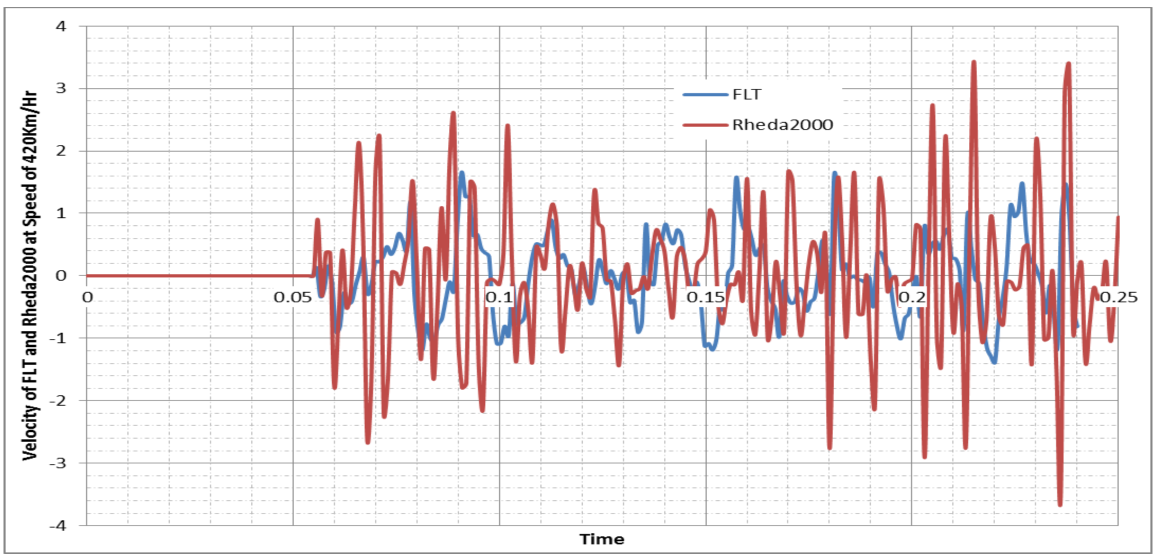

Figure 43: Rail Vertical Velocity of FLT & Rheda2000 Track at Speed of 420Km/hr

The figure 40-43 shows that the comparisons of Floating Ladder Track and Rheda2000 with respect to Rail vertical velocity by varying the speed of the moving load. From this simulation result of the model, it is possible to see that rail's vertical velocity of Rheda2000 ballast-less track is much higher than Floating Ladder track.

4.5.2 With Respect to Vibration Responses and Reduction

The simulation result of frequency domain analysis in ABAQUS presented in the following graph 44 shows that the vertical acceleration level of rail in Floating Ladder Track and Rheda2000 ballast-less Tracks for frequencies ranges from 0 Hz to 2000Hz.

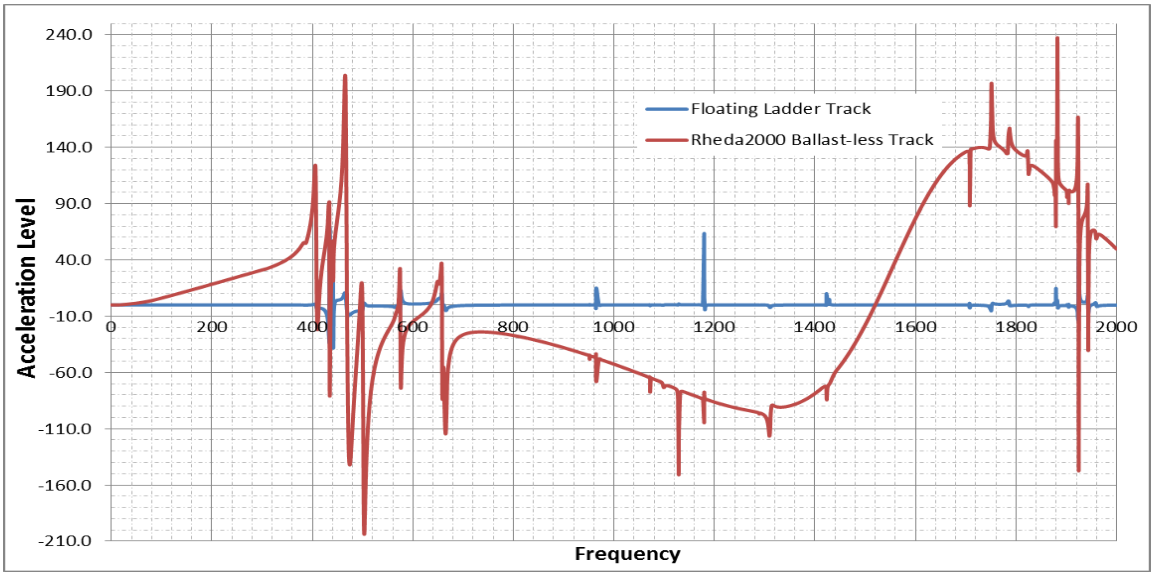

Figure 44: Comparison of FLT vs. Rheda2000 with Acceleration Level

From this graph, it is possible to understand that the vertical acceleration level of Rail in Floating Ladder Track is comparatively less than the vertical acceleration of Rail in Rheda2000 ballast-less Track. The maximum acceleration level of Rail in FLT is 70 and maximum acceleration level of Rail in Rheda2000 is about 200. This can clearly shows that vertical acceleration level of FLT is less than vertical acceleration level of Rheda2000 Ballast-less Track and FLT have high vibration reduction capacity than Rheda2000 ballast-less Track.

Chapter Five

5. Conclusions and Recommendations

The tenacity of this Thesis was to compare Floating Ladder Track and Rheda2000 ballast-less track by their dynamic properties for high speed of the moving wheel Load as well as vibration reduction capacity of both track-forms based on 2D model analysis using Finite Element Software named ABAQUS. By considering selected parameters for comparison, based on the analysis results, the conclusions are drawn, and based on the drawn conclusions recommendations are suggested in the following sub-sections:

5.1 Conclusions

This study make efforts to compare Floating Ladder Track and Rheda2000 ballast-less track by their dynamic responses and vibration reduction capacity by modeling the Tracks with FE software. The 2D model have been develop for both track-forms and in the modeling the Rail is modeled as beam element with its bending stiffness (EI) and mechanical properties as discretely supported underneath by Rail pad, which is modeled as parallel spring and dashpot elements. The pre-Stressed part of sleeper in Rheda2000 ballast-less track is modeled as discrete rigid elements. The dynamic analysis of both track have been done in time domain at various Speed of the moving Load and frequency domain analysis in ABAQUS, then after the comparison is done based on the outputs of the simulation results of the models.

From the analysis, it would be reached at the conclusions that the time domain analysis results shows that the dynamic responses like vertical deflection of the rail, velocity and acceleration of both floating ladder track and Rheda2000 are increases as the speed of the moving load getting higher. However, comparatively the dynamic responses in Rheda2000 ballast-less track is less than dynamic responses in Floating Ladder Tracks and from this, it can understood that Rheda2000 ballast-less track have higher dynamic performance than Floating Ladder Track.

The output obtained from Frequency analysis indicates that the vertical Acceleration Level of Rail in Floating Ladder Track is much less than Vertical Acceleration Level of the Rail in Rheda2000 ballast-lees Track. This shows that Floating Ladder track have high vibration reducing capacity than Rheda2000 ballast-less Track and this is due to the Resilient Pad under longitudinal sleeper. The resilient pads in Floating Ladder Track are enabling the track to absorb the vibration effect more than Rheda2000 ballast-less Track.

5.2 Recommendations for Future Study

This study tried to addressed the comparison of Floating Ladder Track and Rheda2000 Track systems dynamic behavior and vibration reduction capacity of these tracks by 2D modeling using ABAQUS. Based on the analysis results the above conclusions are drawn. Standing form this conclusions, the following recommendations are made for further studies:

- To save the running time of the analysis the Track's models in this Thesis are 2D model, so the dynamic responses in the transverse dimension not taken in to account. Therefore, to take in to consideration the dynamic responses of the track in the transverse dimension, the model shall be 3D.
- For the sake of simplicity, the constant and linear parameters of the track are assumed in both the geometry and behavior of the track components' properties. However, the assumption of constant and linear parameters of the tracks may not be always true in reality. Hence, it is suggested to take in to account the non-linearity of the tracks' parameters for the advanced and future studies.
- ABAQUS FE Software does the model in this thesis, but for further comparison of dynamic responses of these Tracks, the model shall be done by using other FE Software in addition to ABAQUS.

References

x

[1] Kiyoshi ASANUMA, "Ladder Track Structure and Performance ," in *Railway Technology Avalanche No.6*, Colorado, U.S.A, September 1, 2004, p. 35.

[2] Weihua Zhang · Jing Zeng · Yan li, "A review of vehicle system dynamics in the development of high-speed trains in China," *Springer-Verlag Berlin Heidelberg 2013*, 13 March 2013.

[3] V.L. Markine, A.J. Gu and Q.H. Liang Z.Q. Yan, "Dynamic Optimization of Ladder Track Components to Minimize the Subway Vibration," in *Proceedings of the Eleventh International Conference on Computational Structures Technology, Civil-Comp Press, 2012*, Stirlingshire, Scotland, 2012.

[4] The way to go. RAIL.ONE. (2011, April) RHEDA 2000 BALLASTLESS TRACK SYSTEM. ebook.

[5] Roger J. Hosking1 and Fausto Milinazzo2, "Modelling the Floating Ladder Track Response to a Moving Load by an Infinite Bernoulli-Euler Beam on Periodic Flexible Supports," *East Asian Journal on Applied Mathematics* , vol. Vol. 2, No. 4, pp. pp. 285-308, November 2012.

[6] Roger J. Hosking1 and Fausto Milinazzo2, "Modelling the Floating Ladder Track Response to a Moving Load by an Infinite Bernoulli-Euler Beam on Periodic Flexible Supports," *East Asian Journal*, vol. Vol. 2, No. 4, , pp. pp. 285-308, November 2012.

[7] pp. 79–80 Bonnett 2005. (2015, November) Railroad tie explained. [Online]. http://everything.explained.today/Railroad_tie/

[8] p. 177 Krylov 2001. (2015, November) Railroad tie explained. [Online]. http://everything.explained.today/Railroad_tie

[9] p. 22 Lancaster 2001. (2015, Novmember) Railroad tie explained. [Online]. http://everything.explained.today/Railroad_tie

[10] Georgios Michas, "Slab Track Systems for High-Speed Railways," Royal Institute of Technology School of Architecture and the Built Environment Division of Highway and Railway Engineering, SE-100 44 Stockholm, Sweden, Master Degree Project TSC-MT 12-005, 2012.

[11] S.T., M.T. Dina Rubiana Widarda, "Longitudinal forces in continuously welded rails due to nonlinear track-bridge interaction for loading sequences," TECHESCHE UNIVERSITAT DRESDEN, Bandung-Indonesien, Dissertation 6 February 2009.

[12] COENRAAD ESVELD, *Modern Railway Track*, Second Edition ed., 2001.

[13] Bernhard Lechner, "GENERAL REQUIREMENTS FOR BALLASTLESS RAIL-TRACKFORMS ASPHALT AND CONCRETE PAVEMENT DESIGN," *International Journal of Pavements Conference*, vol. 1, p. 2013 IJPC Paper 108, 2013.

[14] Fraunhofer Gesellschaft, Karlsruheand Nigel Ogilvie, Prof. Dr. Franz Quante, Innovations for a cost effective RailwayTrack, November 2001.

[15] Coenraad ESVELD, DEVELOPMENTS IN HIGH-SPEED TRACK DESIGN, 2011, Delft

University of Technology Delft, Netherland.

[16] Valeri Markine and Milan Duškov, Coenraad Esveld1, FEASIBILITY OF EPS AS A LIGHTWEIGHT SUB-BASE MATERIAL IN RAILWAY TRACK STRUCTURES, The Paper presents the result of a study on feasisblty of EPS material on Railway track.

[17] Massachusetts, U.S.A and John M.Waters Railway Geotechnical Consultant Derby,England Ernest T.Selig Professor of civil Engineering University of Massachusetts Amherst, *TRACK GEOTECHNOLOGY and SUBSTRUCTURE MANAGEMENT* , 2nd ed. London, Heron Quay: Thomas Telford Publications, 1995.

[18] Alexander Remennikov, Sakdirat Kaewunruen, *Dynamic properties of railway track and its components : a state-of-the-art review*. New York, Hauppauge: Nova Science Publishers, 2008, pp. 197-220.

[19] H. Casal, and M. Neves J. M. Proença, "EFFECT OF THE TYPE OF TRACK ON THE DYNAMIC BEHAVIOUR OF HIGH SPEED RAILWAY BRIGDES," in *COMPDYN 2011 3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Lisbon, Portugal, 25–28 May 2011.

[20] David P. Connolly, "Ground borne vibrations from high speed trains," The University of Edinburgh, PhD Thesis, 2013.

[21] David Martyn Steffens, "IDENTIFICATION AND DEVELOPMENT OF AMODEL OF RAILWAY TRACK DYNAMIC BEHAVIOUR ," Queensland University of Technology, Master of Engineering Thesis May, 2005.

[22] David Thompson, *Railway Noise and Vibration: Mechanisms, Modelling and Means of Control*, First ed. Netherlands, AE Amsterdam, 2009.

[23] José Nuno Varandas da Silva Ferreira, "Long-Term Behaviour of Railway Transitions under Dynamic Loading Application to Soft Soil Sites," Funda¸ c˜ ao para a Ciˆ encia e Tecnologia, PhD Thesis, February, 2013.

[24] Sakdirat Kaewunruen and Alex M Remennikov, "RESPONSE AND PREDICTION OF DYNAMIC CHARACTERISTICS OF WORN RAIL PADS UNDER STATIC PRELOADS ," in *14th International congress on Sound & Vibration* , Cairns Australia, 9-12 July, 2007, p. 3.

[25] F.I.C.E., F.I.Struct. E. Clifford F Bonnett C.ENG., *PRACTICAL RAILWAY ENGINEERING*, 2nd ed., Tjan Kwang Wei, Ed. London WC2H 9HE, Covent Garden: Imperial College Press, 2005.

[26] Wikipedia. (2015, October) the free encyclopedia. [Online]. http://en.wikipedia.org/wiki/Ladder_track

[27] Coenraad Esveld. DIGITAL EUROPEAN RAILWAY REVIEW NEWS. [Online]. www.europeanrailwayreview.com

[28] Coenraad ESVELD and Valéri MARKINE, SLAB TRACK DESIGN FOR HIGH-SPEED.

[29] Eric Berggren, "Railway Track Stiffness Dynamic Measurements and Evaluation for Efficient Maintenance," KTH Engineering Science , PhD Thesis ISBN 978-91-7415-293-7, April 2009.

[30] David Martyn Steffens, "Identification and Development of a Model of Railway Track

Dynamic Behaviour ," Queensland University of Technology, Thesis for Degree of Master of Engineering May 2005.

[31] Huan Feng, "3D-models of Railway Track for Dynamic Analysis," Royal Institute of Technology, SE-100 44 Stockholm, Master Degree Project ISSN 1650-867X, 2011.

[32] SINAN AL SUHAIRY, "PREDICTION OF GROUND VIBRATION FROM RAILWAYS," SP Swedish National Testing and Research Institute, BORÅS, Sweden, Thesis ISBN 91-7848-823-0, ISSN 0284-5172, 2000.

[33] Mehdi Bahrekazemi, "Train-Induced Ground Vibration and Its Prediction," Division of Soil and Rock Mechanics Dept. of Civil and Architectural Engineering Royal Institute of Technology, Stockholm, PhD Thesis TRITA-JOB PHD 1005, ISSN 1650-9501, 2004.

[34] Coenraad ESVELD, and Amy DE MAN, Use of Railway Track Vibration Behaviour for Design and Maintenance, 2002.

[35] Nobuyuki Matsumoto and Hiromi Inoue Hajime Wakui, "TECHNOLOGICAL INNOVATION IN RAILWAY STRUCTURE SYSTEM WITH LADDER," Railway Technical Research Institute, Structural Engineering Group, 2-8-38 Hikari-cho, Kokubunji-shi, Tokyo 185, Japan,.

[36] Tsutomu WATANABE, "Development of Silent Steel Railway Bridge," *Railway Tchnology Avalanche No.32*, p. 6, September 22, 2010.

[37] Weining Liu, and Shunhua Zhou Hao Jin, "Optimization of Vibration Reduction Ability of Ladder Tracks by FEM Coupled with ACO," *Hindawi Publishing Corporation Shock and Vibration*, vol. 2015, no. ID 484827, p. 6, 10 June 2015.

[38] J. Santamaria, E.G. Vadillo and O. Oyarzabal J. Blanco-Lorenzo, "Dynamic comparison of different types of slab tracks and ballasted track using a flexible track model," *Journal of Rail and Rapid Transit*, vol. 225, no. 6, pp. 574-592, November 2011.

[39] S. Mohammadzadeh, E. Esmailzadeh D. Younesian, "Dynamic Performance, System Identification and Sensitivity Analysis of the Ladder Tracks," , Ontario, Canada.

[40] ANDREAS ANDERSSON AND RICHARD MALM, "Measurment evaluation and FEM simulation of bridge dynamic," Royal Institute of Technology, Sweden, 2004.

[41] (2016, January) ABAQUS Online Documentation. [Online]. http://abqdoc.byv.kth.se.20016/v6.9/

[42] (2015, August) RAIL.ONE. [Online]. http://www.railone.com/products-solutions/railways-and-commuter-traffic/ballastless-track-systems/

[43] Weihua Zhang · Jing Zeng · Yan li, "A review of vehicle system dynamics in the development of high-speed trains in China," *Springer-Verlag Berlin Heidelberg 2013*, 13 March 2013.

[44] Z.Q. Yan, V.L. Markine, A.J. Gu and Q.H. Liang, "Dynamic Optimization of Ladder Track Components to Minimize the Subway Vibration," in *Proceedings of the Eleventh International Conference on Computational Structures Technology, Civil-Comp Press 2012*, Stirlingshire, Scotland, 2012.

[45] (2015, April) Wikipedia, the free encyclopedia. [Online]. http://en.wikipedia.org/wiki/Ladder_track

[46] Tsutomu WATANABE, Development of a silent steel Railway Bridge, September 22,2010.

[47] Xiaoyan Lie Chongda Jiang, "Analysis of vibration reduction effect of steel spring floating slab track with finite elements," *(s) SAGE JOURNALS*, May 13 2014.

[48] 2, V.L. Markine2, A.J. Gu1 and Q.H. Liang1 Z.Q. Yan1, "Dynamic Optimization of Ladder Track Components to Minimize the Subway Vibration," 1School of Civil Engineering Beijing Jiaotong University, China 2Faculty of Civil Engineering and Geo-Sciences Delft University of Technology, Netherlands, 2012.

[49] Kiyoshi ASANUMA, "Ladder Track Structure and Performance," , September 1, 2004, p. Railway Technology Avalanche No. 6.

[50] "RHEDA 2000® Ballastless Track System," in *RAIL.ONE*, *The way to go*, Germany, 2011, p. 12.

[51] SingiresuS.Rao University of Miami, *Mechanical Vibrations* , Fifth Edition ed.: 2004 Pearson Education, Inc., publishing as Prentice H a l l , 2011.

x