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Modelling of Balfour Beatty Embedded Rail System (BBES) for Dynamic Analysis

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A Thesis in RAILWAY ENGINEERING STREAM

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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 '**Modelling of Balfour Beatty Embedded Rail System (BBES) for Dynamic Analysis'** presented by **Mesfin Hailu Nigussie**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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ABSTRACT

The main purpose of design of track structure is to have cost effective good riding quality with optimum speed. Recently, several findings are giving attention for a track of high speed with maximum comfort to have ideal track. However, most tracks of these types are prone to huge initial investment, so that still on the ground, the old traditional ballasted track system is dominantly under construction with its several problems. The Balfour Beatty Embedded Rail Track System (BBES) is invented to offer economical as well as safety and comfort advantages.

In this thesis, dynamic response of BBES studied. Track dynamic analysis has been done by modeling the prototype track using finite elements and analyzing the spatial responses of the track. The first step was developing a finite element model of the track using known modeling software- ABAQUS. The modelling algorithm was made in 3D to analyze the system responses. The dynamic responses of the track evaluated and some responses are compared to that of traditional ballasted track from literatures of previous studies. The natural frequency, modal dynamics and response spectra of the track analyzed using ABAQUS steady state dynamic solver. Effect of rail pad stiffness on the on the rail has been investigated under single harmonic load. The finite element solutions obtained from the solver software are based on frequency domain.

The results of the track dynamic responses are encouraging that it could be the best fit of requirements of track structures of the era. The vertical displacement of the BBES rail is lower than that of the conventional ballasted track system. Dynamic spectrum shows that most BBES dynamic responses are maximum at lower frequencies so that the period of vibrations are longer at these maxima. Higher displacement is shown in lower stiffness rail pad so that dynamic aggressiveness decreases in decreasing the pad stiffness.

The thesis discussion also includes the potential of manufacturing the components of BBES in Ethiopia. The presence of companies in Ethiopia potentially capable to manufacture different components of the track and the small number of components needed for the track make it's life cycle cost less than that of conventional ballasted track.

The thesis finally indicates further research directions and recommendations.

Keywords: Dynamic Modeling, BBES, Balastless Track, Dynamic Responses, Steady State Dynamic Analysis, Harmonic Load

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ACRONYMS

BBES	Balfour Beatty Embedded Rail System
ERS	Embedded Rail Structure
CBL	Concrete Bearing Layer
HBL	Hydraulically bonded Layer
ABL	Asphalt Bearing Layer
FPL	Frost Protection Layer
EN	European Norm
LCC	Life Cycle Cost
INNOTRACK	Innovation Track System
v	Poisson ration
E	Elastic Modulus
K p	Stiffness of Rail Pad
C p	Damping of Rail Pad
M	Mass
m	meter
Hz	Hertz
ω	Vibration angular frequency
A	Amplitude

1 INTRODUCTION

1.1 Background

The current fast advancement of technology is in need of modernized transportation system to minimize travel time (increase speed) and maximize comfort and axle load to increase productivity. Even though it has passed long history, railway transportation is becoming rationalized and best land transportation system starting from 1970s and 1980s. The advancement of the system is mainly due to the advancement of the track system. The headaches of rail way transportation is its dynamic effect and life time cost.

Different literatures on track structures show that in history of railway infrastructure, the track structure component has undergo several modifications to suit specific applications as technology advances. This is to satisfy the demands of heavy axle loads and fast running speed with minimum life time cost. This improvement however has problem of high initial investment so that it needs further innovation to minimize initial as well as life time cost securing its heavy axle load and high speed capacity. The advancement shown to date is from ballasted track to ballastless track even though the reality is still dominated by ballasted track due to the above mentioned reasons. Ballasted tracks have inherited shortcomings from lateral instability, the tendency to float in lateral and longitudinal directions, excessive settlement, and deterioration of ballast under axles and high destruction by vibration loads.

It has been argued that slab track (ballasteless track) systems require less maintenance than ballasted track forms, however this benefit is often outweighed by the perceived high first installation cost. This statement suggests that for slab track to be broadly adopted the high installation cost has to be closer to that of ballasted track. From different types of slab track systems Balfour Beatty Embedded Rail track System (BBES) is innovated to solve the aforementioned problems and to push the technology further ahead one step.

This research is to conduct dynamic modeling of Balfour Beatty Embedded Rail Track System to study the dynamic performance of the track system using ABAQUS software.

1.2 Aim of the study

This thesis mainly focuses on studying of dynamic response of Balfour Beatty Embedded Rail Track System (BBERS) using Finite element analysis and modelling software (ABAQUS). The main dynamic effect responses such as track vibration modes, response functions, deflection and performance of the systems will be analyzed. In addition, the thesis made comparison between conventional ballasted track from literatures and Balfour Beatty Embedded Rail Track System (BBERS) based on responses and discuss on potentials in Ethiopia to adapt this system.

1.3 Scope of the thesis

The scope of the study presented in this thesis includes:

1. Analyzing dynamic response of BBERS which is limited to analyzing the dynamic behavior and response of the track, identifying the response frequencies and global deflection of the track.
2. Assessing performances & life cycle cost comparison with ballasted track and potentials to manufacture components of BBES.

The non-availability of different data, capable processing computer, laboratory experiments and study time have their unfortunate effect on the study so that continuous further study on the area is needed.

1.4 Application of the study

The results obtained from this research can be applied for further research and optimization of BBERS for evaluation of performance of BBERS in the dynamic loadings etc. BBERS is not a familiar type like that of ballasted track; therefore, the research output will indicate the applicability of the track form for different railway lines. Adapting and optimizing using laboratory experiment of the technology for the Ethiopian situation will be the next step of this study. BBERS can be feasible and cost effective option to replace existing old ballasted tracks in many parts of the world.

1.5 Structure of the Thesis

The study described in this thesis is separated into five main parts:

Chapter 1 introduces study and discusses what the current situation needs in track technology advancement. It presents the project aim and then defines a specific scope for the study presented in this thesis. The application of the study is mentioned and the structure of the thesis document is discussed.

Chapter 2 discusses development of railway track systems: the ballasted track type, different ballastless track, T- track and Balfour Beatty Embedded Rail Track System. Track dynamics and dynamic analysis in Abacus are also discussed.

Chapter 3 details Balfour Beatty embedded rail track system modeling: simplification, assumption and modeling and analysis of different components.

Chapter 4 describes Balfour Beatty embedded rail track system modeling and analysis results: different dynamic results of the track and comparison of ballasted track and BBERS.

Chapter 5 provides the main conclusion and recommendations presented through this thesis. The future direction of the BBERS project is discussed.

2 LITERATURE REVIEW

2.1 Railway Track System

To guide the train in safe manner and to resist the vertical, longitudinal and lateral forces are primary purposes of railway track system. In the development of technology, different expertise results of track types are being applied starting from the first era of the system. These track systems are chronologically updated type of the previous one in which some problems of the previous are solved even if each type has its own demerits. Some of these systems are to be mentioned in this paper.

2.1.1 Ballasted Track System

Starting from the wagon track version of rail way transport system to the present sophisticated magnetic levitation (MAGLEV) form of rail way system it has gone through several stages of development.

The conventional ballasted track system serves longer time in the railway system due to the following merits:

- Low class of expertise needed in construction
- Relatively low initial cost of construction (Initial economic benefit)
- Easily removal of rail in maintenance purpose
- Easily removal of water from the ballast for drainage purpose
- Availability of ballast material locally
- Relatively not sophisticated technology needed in construction
- Sound absorbing capacity of ballast and sub ballast
- Resilient properties of the ballast and sub ballast to reduce dynamic effect of the train (low excessive deflection and vibration)
- Simple empirical design solution

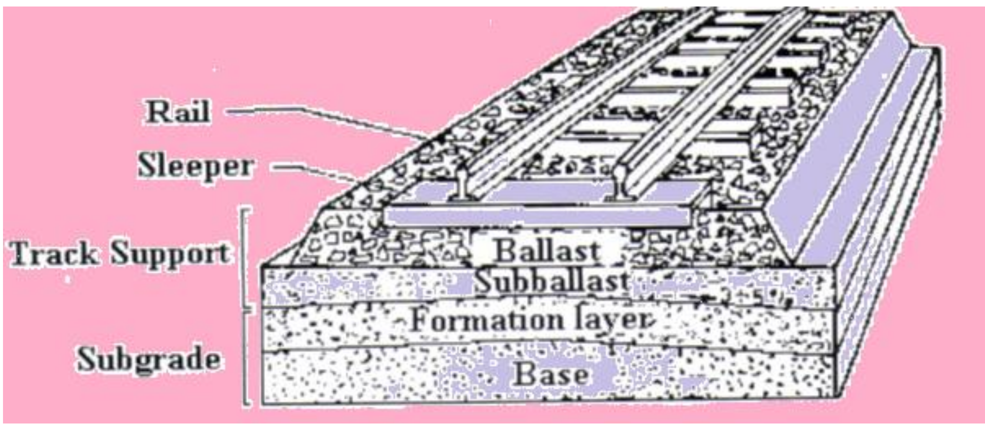


Figure 2-1: A typical Ballasted Track structure [6]

However, there are other parameters to evaluate that make this system in need of different improvements of which few are described below.

- High speed train demand
- Large track load demand
- Technologically advancement of construction equipment in need of reduction construction time and labor
- Reduction of maintenance time to reduce large obstacles in this mode transportation
- Reduction of cost in the life of the system
- Lateral stability for better comfort

Regarding these parameters, the conventional ballasted track system has the following short comings:

- Ballast bowling in high speed train
- Relatively Low static load capacity
- Distractive advanced construction equipment (e.g. tamper)
- Large number of components in which construction and maintenance are tedious
- Routine maintenance in its life time
- Settlement problem in loose soil subgrade area
- geometrical imperfections due to non-uniform support conditions;
- tendency to float in both directions
- crushing and contamination of ballast grains
- differential movement between rail and sleepers
- rail corrugation due to waving
- rail buckling

To mitigate these demerits different scholars have studied the system if other options are to use.

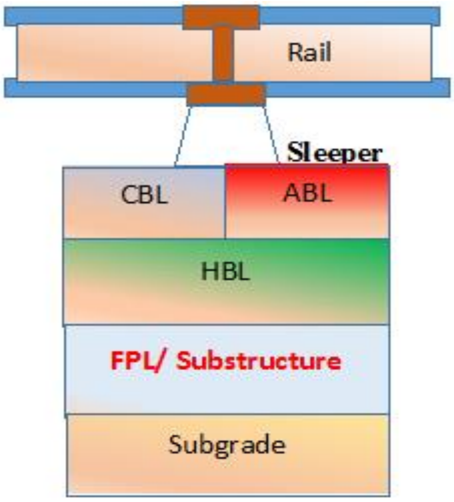
2.1.2 Ballastless Track System

Balastless track systems are all track systems that don't have ballast components designed structurally. These are developed to mitigate disadvantages of ballast. Hereunder are some of them classified according to their similar characteristics.

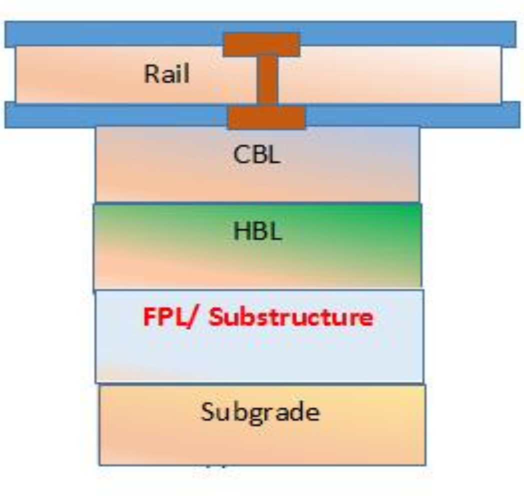
2.1.2.1 Slab Track System

Slab track is a concrete or asphalt surface that is replacing the standard ballasted track due to its merits against the drawback of ballasted track. This structure is made of stiff and brittle materials, hence the required elasticity can be obtained by inserting elastic components below the rail or/and the sleeper. [15]

Modulus of elasticity decreases down to depth and it is called substructure from the bottom of hydraulic bearing layer down ward.



a)



b)

Figure 2-2: Usual construction profiles for slab tracks: a) Design with Sleepers, b) Design without Sleepers

Slab track system by itself has been studied several times by different scholars to make it adaptable for different conditions. This resulted to fabrications of several slab track types adaptable for different conditions or one is the advanced of the other. In this paper, slab track types are mentioned in categories as follows: [8]

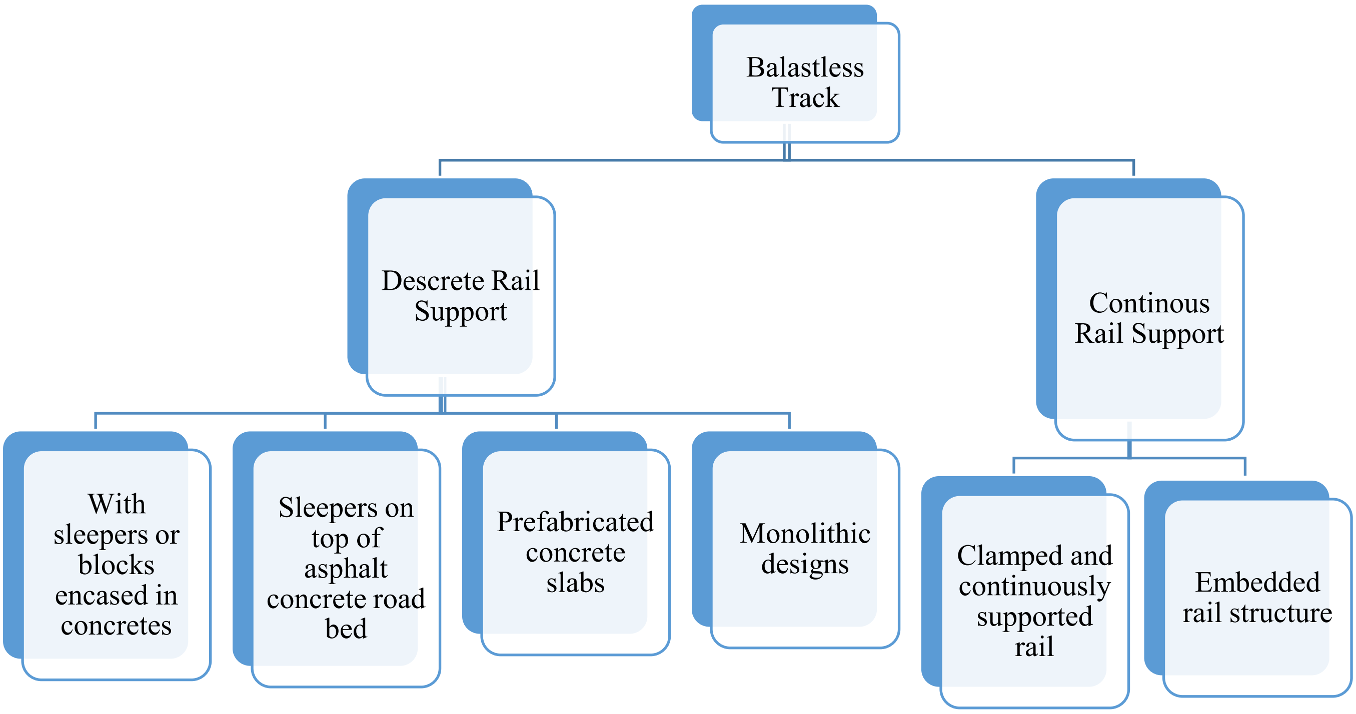


Figure 2-3: Ballastless track classification

A. Discrete Rail Supports

In discrete rail support categories of slab track system, rail is attached on supporting points usually being fastened on sleepers. This category is further divided to the following types.

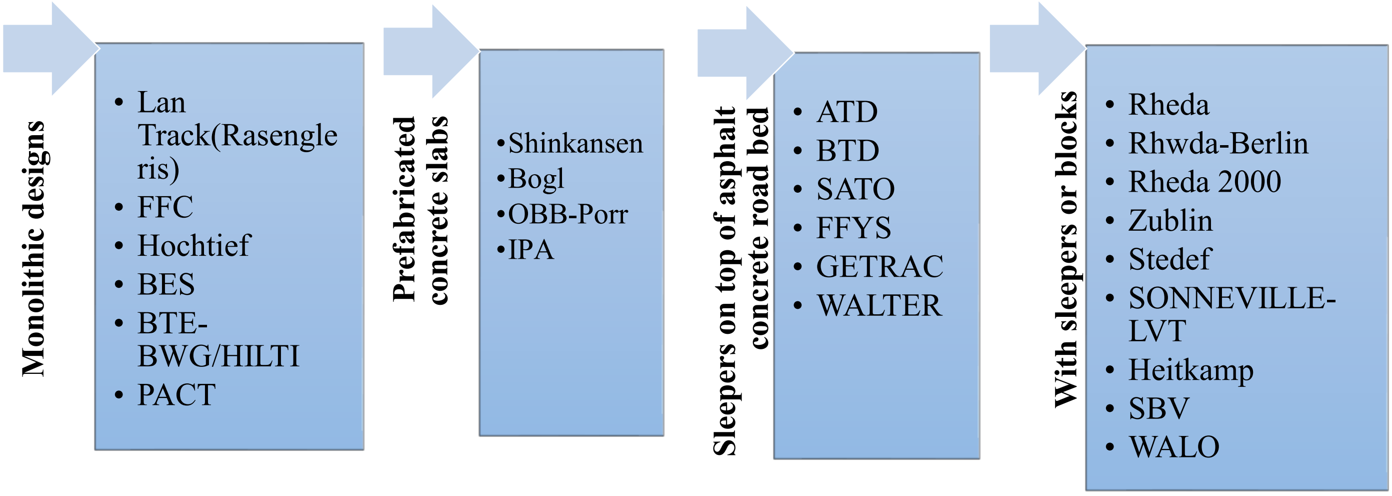


Figure 2-4: Classification of Discrete Rail Supports in Ballastless Track

These are different discrete rail support balastless tracks developed in different countries at different times. [8], [2]

B. Continuous Rail Support

The rigidity, the discrete support system, the sound pollution are the next problems to be solved from discrete rail support system. Continuous rail support systems are to be expected to solve this problems.

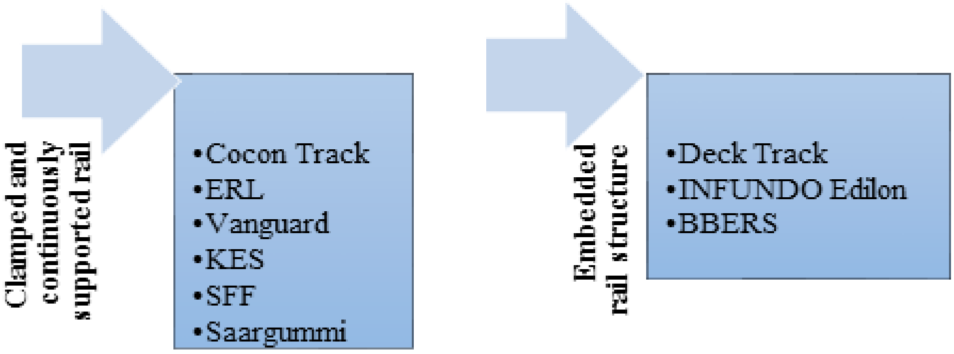


Figure 2-5: Classification of Continuous rail supports in ballastless track

These continuous rail support balastless tracks are developed in different countries at different times in searching of ideal track fitting for different conditions. [2], [8]

i. Clamped and Continuously Supported Rail

These systems provide continuous support of the rail by clamping the web of the rail.

ii. Embedded Rail Structure

Embedded rail structure (ERS) is a continuous elastically supported rail by means of a compound such as cork and polyurethane. The rail fixation is established by an elastic compound surrounding the whole rail profile except the rail head. This system includes the full range from high-speed tracks to light rail. What characterizes this concept is the absence of additional components to secure track gauge. [8]

The characteristic principles of the rail fixation in this concept are the following [5]:

- An elastic strip provides continuous support under the rail.
- The rail is guided in a groove by elastic fixation.
- Top-down alignment of the rail.
- The rail profile is fixed by an elastic compound.
- Optimization of the elastic compounds, the groove dimensions and strips for specific elasticity.

This System is even advantageous than that of Clamped and continuously supported rail system in reduction of noise, height for road crossing, maintenance due to rail web support, and better elasticity for reduction in dynamic effect and longer life.

From the embedded rail support types of tracks Balfour Beatty Embedded track system is the latest one in which different improvements in different parameters are undertaken.

2.1.2.2 T-Track

T-Track is a type of ballastless track in which it avoids using of ballast and sleepers from conventional ballasted track and attain its lateral support by gage bars while that of vertical support by reinforced concrete beams (latter in tubular modular track resilient pad in between the beam and the rail). This system of track has better economic advantages and better application in desert and drainage problematic area in addition to reducing dynamic effect by its continuous resilient pad support. However, track floating, derailment and rail shear capacity needs further study. [7]

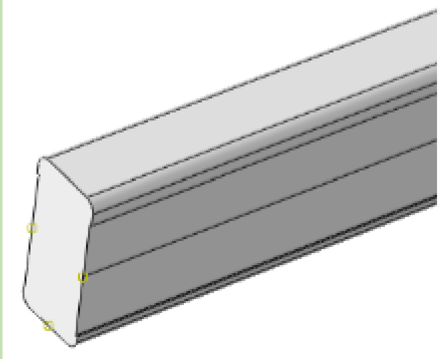
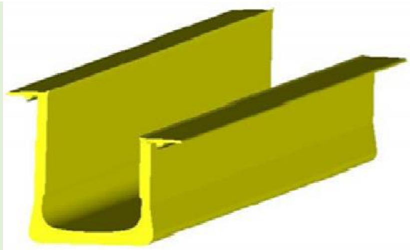
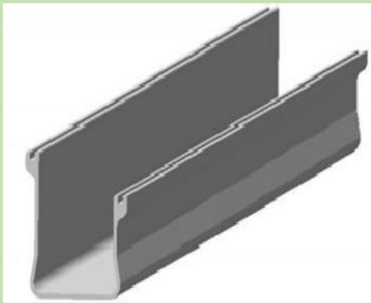
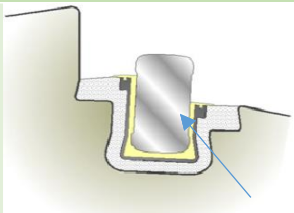
2.2 Balfour Beatty Embedded Rail (BBES) Track System

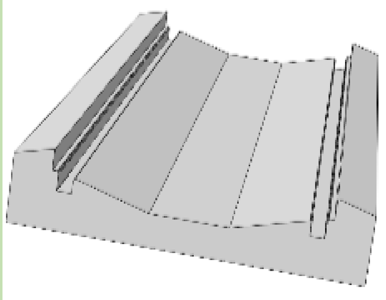
The system was first successfully installed at Medina Del Campo in Spain in 2002 followed by Crewe, UK in 2003. The system received Network Rail Acceptance in February 2006. [1]

2.2.1 BBES Track Components

The BBERS is a system of which the rail is incased by resilient pad except at its head and the pad in polyethylene shell which in turn is in a grout in concrete slab.

Table 2-1: BBES components [1]

Component	Description	Shape
Rail(BB14072)	• Similar profile with UIC 60/CEN60 • Symmetrical in both vertical and horizontal direction • Designed according to European and British Standard (BS/EN) • Deliverable in any length in weight of 74 Kg/m • Safer than any other section in buckling	
Pad	• U-shaped resilient elastomeric • Supports the side and base of the rail • Provide vertical elasticity to distribute the wheel point load evenly along the supporting slab with reduced resultant peak stress concentrations • microcellular polyurethane cast in 2 meter lengths • Stiffness range from 10KN/mm/650mm upwards.	
Shell	• Fiber Reinforced Plastic (FRP) composite • Used to perform dimensionally accurate slot, to insure the concrete action of the elastomeric rail supports • Provides secure support to the elastomeric pads and transmits the live loads, vertical, longitudinal and transvers, from the train trough to the surrounding concrete • Responsible for electrical insulation afforded by the system and in conjunction with the elastomeric pad provides efficient insulation and effective mitigation of stray current leakage.	
Grout	• Non-shrink cementitious hold the shell in its final position • Have a 28 day strength that is approximately 30% higher than the surrounding concrete	 Grout

Concrete Slab	• Either pre cast or cast in situ designed for specific condition mostly above 50MPa concrete strength • Uses steel bar or fibers as reinforcement • Has low profile so that used in tunnels and bridges.	

2.2.2 BBES Track Modeling

Dynamic modeling of BBES is required to analyze its behavior that cannot be analyzed by static or quasi-static models. Rolling nose, corrugation growth and track damage and performance are some of the behaviors that are predicted by dynamic modeling.

Because BBES like any track structure is a dynamic system, realistic models that comprise inertia and mass has to be considered to fully understand the system performance and response.

2.2.3 BBES Track Properties

BBES track has continuous pad around the rail except at the rail head which is expected to reduce dynamic effect significantly. The spring and damping properties of the track are shown on the figure below.

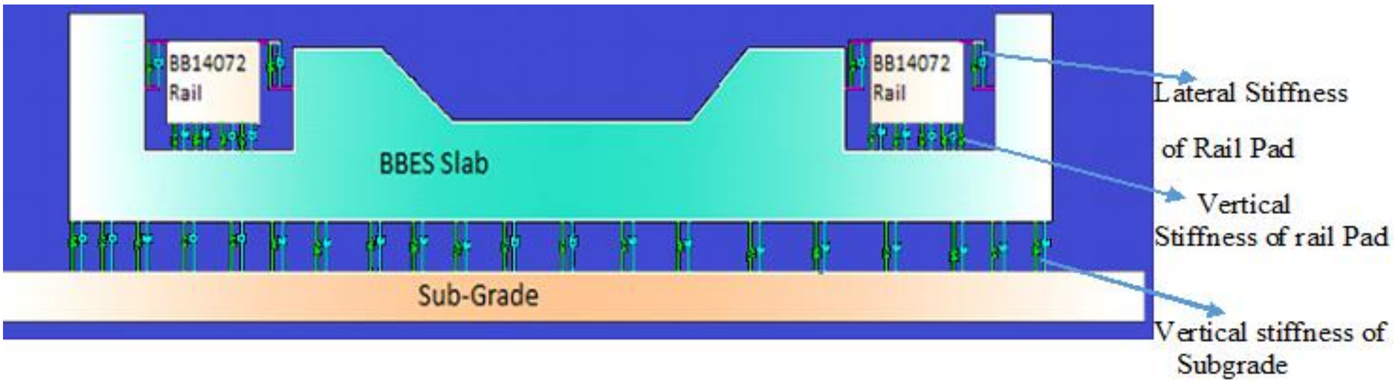


Figure 2-6: Elastic Support model of BBES (Cross Sectional View)

2.2.3.1 Stiffness Properties

The interaction between vehicle and track dynamics plays an essential role. The dynamic behavior and, more specifically the interactive forces, are directly related to the stiffness of the structure and its components.

From a simple dynamic analysis, the relationship between the dynamic pad force F and the pad stiffness k can be derived as:

$$F = Constant * \sqrt{K} \tag{2.1}$$

This means that if the pad stiffness is lowered by a factor of two, the dynamic force is reduced by 30%.[5]

In Embedded Rail Track System the continous rail support by the rail pad plays a good stiffness reduction and then reduction in dynamic force role as the model shown in figure 2.6 &2.7. Specially in Balfour Beatty Embedded Rail Track System the continous pad suppport in vertical and lateral direction has great advantage in reduction of dynamic force the model shown in Figure 2.6. The concentrated wheel load will be distributed on the slab under the whole length of the rail in which stress will be reduced significantly.

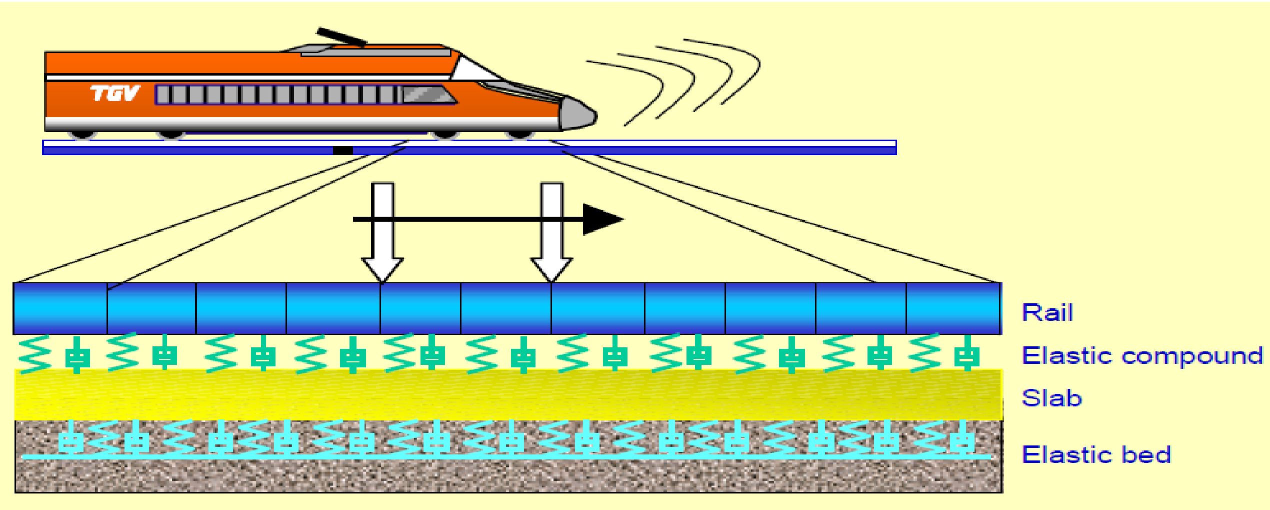


Figure 2-7: Rail model of Embedded Rail System (moving train loading case) (Side View) [22]

2.2.3.2 Resilient Properties

The reciprocal value of stiffness is flexibility or resilience. In general, one could state that enhancing the resilience, i.e. lowering the stiffness, has a positive effect on the dynamic forces. Of course one should be careful with that statement, as dynamic interaction is frequency dependent, in which not only stiffness, but also mass and damping play a role.

In this track the vertical and lateral continuous pad has great effect in increasing the resilient property.

2.3 Track Dynamics

Static or dynamic terminologies comes from the load characteristics applied. Static load are those which are not time dependent whereas dynamic load are time dependent. All loads are dynamic except dead loads in reality as they have to be applied to the structure in some way, and this would impose a time variation to these loads. However, if the applied load value varies slowly the dynamic effect will be insignificant so that considered as static. [20]

Static loads on track rail includes vertical forces; loads transmitted through the wheel, longitudinal forces; change of rail length due to temperature, longitudinal forces caused by breaking and accelerating, longitudinal forces due to internal stresses in the rail after welding, longitudinal forces due to rail creep and lateral forces; forces applied at angle at the rail head. [15]

Dynamic loads on track rail includes wheel load transfers; develop in area of inadequate super elevation which results from unbalanced centrifugal acceleration and eccentric position of the centre of gravity of vehicles, vibration excitations; due to rail surface defect, natural vehicles and track oscillations; elastic-damping systems of vehicles and track structure.[15]

Since static phenomenon are not concern of this research the focuses is on dynamic phenomenon. Dynamic analysis is necessary to know the railway systems behaviour. The nature of the track structure is complex dynamic system due to:

- random and repetitive nature of the applied load,
- composite and looseness nature of the track structure,
- complicated manner of train-track interaction
- also vehicle moment on the track,
- non-linear stress distribution over track component,
- non-uniform and variable mechanical properties and response of the track components. [7]

In track structures mass, damping and stiffness parameters determine frequencies in which the structure likes to vibrate. The largest dynamic amplification frequency of structures (resonance) comes from loads containing frequency components that corresponds natural frequencies. [7]

"The natural frequency, response spectrum and random response of the track are the primary dynamic response indicators to applied dynamic loads. These responses are depending on the load application situation, harmonic, impact or other types." [7]

2.3.1 Track Dynamic Analysis

Structures shows resistance to dynamic loads in the form of internal forces some of which are related proportionally to the displacement (spring forces) and some to the velocities (damping forces) which are time dependent that should be analysed dynamically. [20]

Track dynamic analysis is important to get reliable response data for the critical stresses and strains, understand effects of higher train speed, understand effects of track irregularities, understand effects of track misalignment, track curving, wheel irregularities, coupled with track, understand effects of frequent loading & unloading and understand effects of geometrical stiffness properties of the track. Dynamic analysis approach can be either deterministic or non-deterministic. [7]

2.3.2 Dynamic Properties of Track

Dynamic properties of track can be described as receptance and resonance in which they are obtained experimentally by loading the track with sinusoidal forces or by exciting using hydraulic cylinders/ or by an impact load depending on the frequency range the properties are needed to be investigated. [7], [18]

Receptance

Receptance is inverse of stiffness (m/N) i.e. the ratio of deflection and force which shows vibration amplitudes of track structures as a function of vibration frequencies (deflection of a track structure under a unit load). It can be described as the following function: [18]

$$H^2_{\omega F} = S_{\omega\omega}(f)/S_{FF}(f) \tag{2.2}$$

Where,

$H_{\omega F}(f)$: complex transfer function from force to displacement[m/N]

$S_{\omega\omega}(f)$: auto spectrum of displacement [m^2S]

$S_{FF}(f)$: auto spectrum of the force [N^2S]

f: vibration frequency [Hz]

Resonance

"If the mass is moved and then released, it will oscillate at natural frequency. If the force is applied at this frequency, the amplitude of the displacement will increase dramatically a phenomenon known as resonance."[19] Resonance is a very general phenomenon that happens so often and in so many systems that we sometimes ignore its existence. In the most general sense, resonance represents that the energy in a system exchanges from one form into another at a particular rate whereas resonance frequencies indicate the maxima of track receptance versus loading frequency. In a track structure several well damped resonances can be found. When the resonance is highly damped narrow resonance peak will happen. [18], [19] Rail pads and fastening are heart of ballastless track system to dissipate or damp resonance frequencies.

2.3.3 Dynamic Analysis in ABAQUS

"ABAQUS is capable of offering dynamic analysis of Linear and nonlinear problems. For purely linear systems, Eigen modes based methods are preferable because they are cost effective and can provide understanding in to the structure's behaviour which are not available in other methods whereas for nonlinear problems direct integration methods are preferable." [19] Dynamic analysis in ABAQUS therefore can be either of linear eigenvalue analysis, steady state dynamic analysis, Wilson-θ, Newmark-β, implicit dynamic analysis or explicit dynamic analysis. [19], [21] Implicit and explicit techniques are the two common dynamic integration operators. The relative economy of the these techniques of integration depends on the stability limit of the explicit scheme, the ease with which the nonlinear equations can be solved for implicit operator, the relative size of time increments that can provide acceptable accuracy with the implicit scheme compared to the explicit scheme, and the size of the model. [19], [21]

2.3.3.1 Linear Eigenvalue Analysis

Using ABAQUS in many areas of structural analysis, eigenvalues of the system are extracted to obtain its natural frequencies of vibration or to investigate possible bifurcations that may be associated with kinematic instabilities. To analyse eigenvalues ABAQUS uses two different Eigen solver algorithms, Lancozos or subspace depending on the size of the system being analysed. Lanczos Eigen solver is faster for systems with large number of Eigen modes requirement while subspace Eigen solver is faster for systems with small number of Eigen modes requirement. [7], [18], [19]

2.3.3.2 Steady-State Dynamic Analysis

ABAQUS is capable to get steady – state amplitude and phase of the response of a system due to harmonic excitations at a given frequency by steady – state dynamic analysis. This analysis is done by applying the loading at series of different frequencies and recording the responses. In a direct-solution steady-state analysis the steady-state harmonic response is calculated directly in terms of the physical degrees of freedom of the model using the mass, damping, and stiffness matrices of the system. [7], [18], [19]

2.3.3.3 Dynamic Implicit Analysis

Dynamic implicit analysis method is a direct integration method which is usually used for severely nonlinear problems to calculate transient dynamic response of a structure. Implicit dynamic analysis stability is not upper bounded due to its capacity to solve dynamic quantities at time $t + \Delta t$ based not only on values at t, but also on these same quantities at time $t + \Delta t$ though nonlinear equations need to be solved . [7], [18], [19]

“ In structural problems implicit integration scheme usually give acceptable solutions with time step typically one or two orders of magnitude larger than the stability limit of simple explicit schemes, but the response prediction will deteriorate at the time step size, Δt, increases relative to the period, T, of typical mode of response.” [19]

The extension of trapezoidal rule, Hilber-Hughes-Taylor operator, is provided in Abaqus/Standard for general direct integration methods. In implicit dynamic analysis for severely nonlinear case the dynamic response is obtained by direct time integration of all of the degrees of freedom of the finite element model. [7], [18], [19] The velocity and acceleration vectors in this method of numerical analysis are given by the following equations: [21]

$$(\frac{d^2w(t)}{dt^2})_{1+i} = \frac{4}{\Delta t^2}(\{w(t)_{1+i} - \{w(t)_i\}) - \frac{4}{\Delta t}\{(\frac{dw(t)}{dt})_i\} - \{\frac{d^2w(t)}{dt^2}{}_i\} \quad (2.3)$$

and

$$(\frac{dw(t)}{dt})_{1+i} = \frac{2}{\Delta t}(\{w(t)_{1+i}\} - \{w(t)_i\}) - \{(\frac{dw(t)}{dt})_i\} \quad (2.4)$$

Where,

w(t) = is displacement

$\frac{d^2w(t)}{dt^2}$ = acceleration

$\frac{dw(t)}{dt}$ = velocity

This method of analysis is numerically stable regardless of the length of time step duration Δt. Therefore, no restriction is necessary for time increment other than for accuracy. It is expensive computationally since it considers the structure as a whole during analysis. [21]

2.3.3.4 Dynamic Explicit Analysis

Dynamic explicit analysis method is a direct integration method which is usually used for mildly nonlinear problems to calculate transient dynamic response of a structure. It obtain values for dynamic quantities at t+Δt based entirely on available values at time t. Central difference operator is the most commonly used explicit operator for stress analysis applications and the only conditionally stable with stability upper bound limit approximately equal to the time for an elastic wave to cross the smallest element dimension in the model. [7], [18], [19]

The velocity and acceleration vectors in this method of numerical analysis are given by the following equations: [21]

$$(\frac{d^2w(t)}{dt^2})_i = \frac{1}{\Delta t^2}(\{w(t)_{i+1}\} - 2\{w(t)_i\} + \{w(t)_{i-1}\}) \quad (2.5)$$

and

$$(\frac{dw(t)}{dt})_i = \frac{1}{2\Delta t}(\{(w(t)_{i+1}\} - \{w(t)_{i-1}\}) \quad (2.6)$$

Where,

w(t) = is displacement

$\frac{d^2w(t)}{dt^2}$ = acceleration

$\frac{dw(t)}{dt}$ = velocity

Δt = time step

Unlike implicit method analysis this method analyses the structures element by element so that it is computationally cheap. It is suitable for use in wave propagation analysis and for solution of short duration dynamic problems. The time step chosen for the analysis determines numerical stability in the explicit method and it is given by the following inequality. [21]

$$\Delta t = \leq \frac{2}{\omega_{max}} \tag{2.7}$$

Where,

ω_{max} = highest natural frequency of the model

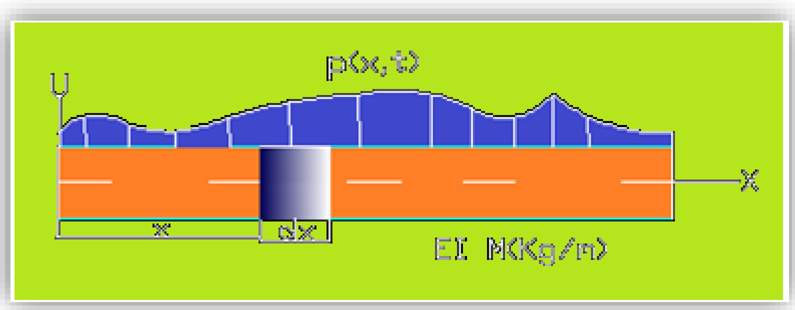
2.4 Track Modelling Using ABAQUS

ABAQUS CAE is commercial modeling software capable of analyzing and displaying of complicated problems. Hereunder are some of the analysis types mostly applied in railway track structures which can be computed by this software.

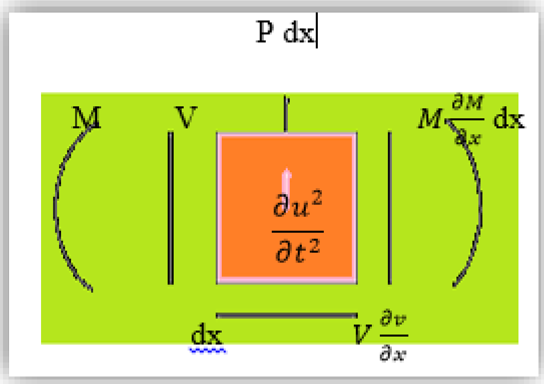
2.4.1 Beam Theories in Track Modelling Analysis

a. Euler-Bernoulli Beam (E-B beam)

The classical assumptions of Euler-Bernoulli beam theory are cross-sectional plane remains normal to the beam axis, cross-section does not deform in its plane or warp out of its plane, and internal virtual work rate is associated with axial strain and torsional shear only. It is only bending of the beam that is considered in Euler Beam theory and only mass inertia in translation of the beam is included in case of vibration. The figures below show the beam with a distributed mass $m = \rho A$ and flexural rigidity of EI subjected to an external force which can vary with position and time. [18], [7], [20]



a)



b)

Figure 2-8: (a) Beam and Applied Force (b) Force Acting on an Element

The differential equation describing the beam deflection w(x, t) in Euler beam theory excluding damping is as follows:

$$EI\,\partial^4 \frac{w(x,t)}{\partial x^4}dx + \rho\, A\, \partial^2 \frac{w(x,t)}{\partial x^{42}}dx = q(x,t) \qquad (2.8)$$

Where,

EI= the bending stiffness of the beam

P = the density of the beam

A = cross-sectional area of the beam

q(X, t) = load on the beam

t = time

Homogeneous solution of undammed stationary beam from the above equation is can be written as: [18], [7]

$$w_{hom}(X,t) = X(x).\ T(t) = X(x)\sin\omega t \qquad (2.9)$$

Where,

X(x) = beam vibration mode

ω = vibration angular frequency

b. Rayleigh-Timoshenko Beam (R-T beam)

Rayleigh-Timoshenko Beam (R-T beam) is identical to Euler Beam theory except it includes rotary inertia and shear deformation of the beam. Therefore differential equation for the deflection w(x, t) becomes [7], [18], [20]

$$EI\, \partial^4 \frac{w(x,t)}{\partial x^4} dx + \rho\, A\, \partial^2 \frac{w(x,t)}{\partial x^{42}} dx + \rho\, I\, (I + \frac{E}{KG})\, \partial^4 \frac{w(x,t)}{\partial x^2\, \partial x^2} + \rho 2 \frac{I \partial^4 w(x,t)}{KG\, \partial x^4} = q(x, t) \qquad (2.10)$$

Where,

EI= the bending stiffness of the beam

G = shear modulus

K = shear factor

P = the density of the beam

A = cross-sectional area of the beam

q(X, t) = load on the beam

t = time

Here unknowns are the deflections w(x, t) and the shear deformation. If the shear factor K of the beam is very large, the two last terms on the left hand side tend to zero and when the mass inertia in rotation of the beam cross section is eliminated i.e. $\rho I = \rho r2A = mr2$, and let r tends to zero, the third term tends to zero which finally gives E-B equation. Shear deformation of rail with frequency above 500Hz can't be neglected so that Rayleigh-Timoshenko Beam (R-T beam) theory is to be used. [7], [18]

Mass and inertia properties for Timoshenko beams (including PIPE elements) in ABAQUS may come from beam's own density and the cross-section geometry and from any additional mass and inertia properties per element length that may be applied at specified locations on the beam cross-section. [19]

2.4.2 Winkler Foundation Beam (Rail) on Continuous Elastic Foundation (BOEF)

This mathematical formulation assumes the rail modelled as an infinite Euler – Bernoulli Beam with continuous longitudinal support from a Winkler foundation which is equivalent to an infinite longitudinal line of vertical, uncoupled and elastic springs. The beam deflection and stresses are proportional to the distributed force supporting the beam. The beam bending stiffness EI (Nm^2) and the foundation stiffness (the bed modulus K= N/m2 = N/m per meter of rail) are the parameters needed. Differential equation is used to find the rail deflection. [7], [18], [19]

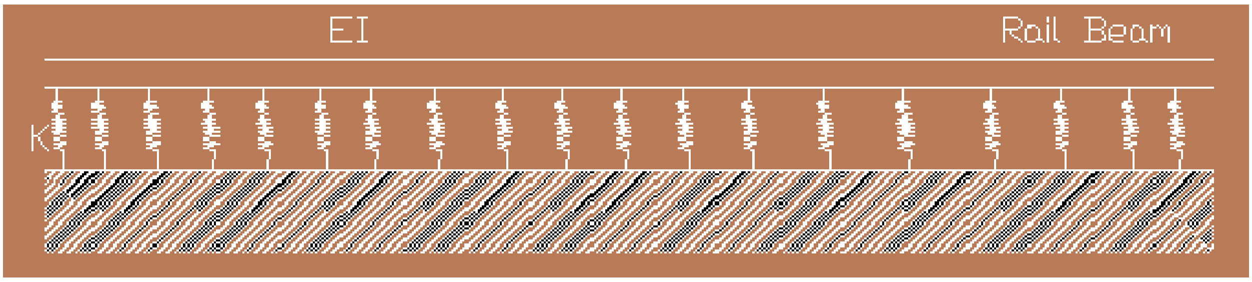


Figure 2-9: Beam (bending stiffness EI) on elastic foundation (bed modulus K)

$$EI\, d^4 \frac{w(x)}{dx^4} + k\, w(x) = q(x) \qquad (2.11)$$

Where,

EI = beam (rail) bending stiffness

W(x) = rail deflection

K = bed modulus

q (x) = distributed load on the rail

Dynamic effect cannot be analyzed using this model as it contains no mass or inertia so that it is always used for static loading of a track on a soft support. However, as shown below on the figure, uplift in front and behind the wheel can be shown in this model due to discrete support in discrete rail support track whereas it negligible in continuous rail support track.

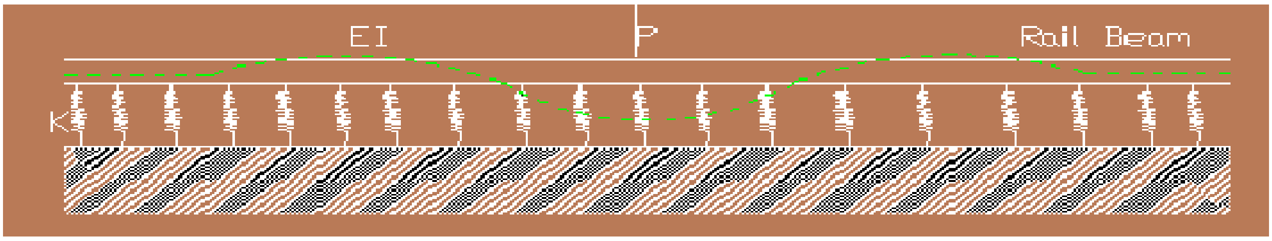


Figure 2-10: Deflection of Point force (p) of wheel loaded Beam (bending stiffness EI) on elastic foundation (bed modulus K).

2.4.3 Pasternak Foundation Model

The assumption in Pasternak foundation model is the shear interaction between the Winkler springs. The shear interaction between the Winkler springs is achieved by connecting the ends of springs to the beam consisting of incompressible vertical elements, which only deforms by transverse shear. The interaction between the springs represents shear element and it is connected to the rail element. Therefore the rail is supported discretely whereas distributed load on the rail is assumed to be zero. This gives better approximation than the Winkler's continuous support for ballasted track model and make the application of standard discrete and finite element method programs easier which give great flexibility as regards load forms and support conditions. [7], [18]

2.4.4 Beam on Continuous Support Model

The Beam on continuous support model can be created by placing the rail on the pad with properties of a spring and damper in ABAQUS as shown in figure 2.6. This spring-damper system models the rail pad. Below this, another beam element models the longitudinal reinforced concrete beams with shell and grout assuming act monolithically, is placed. The RC-beam rests on an elastic foundation which is another spring-damper system. Figure 1.14 show how in BBES the rail is supported by the pad continuously. [1]

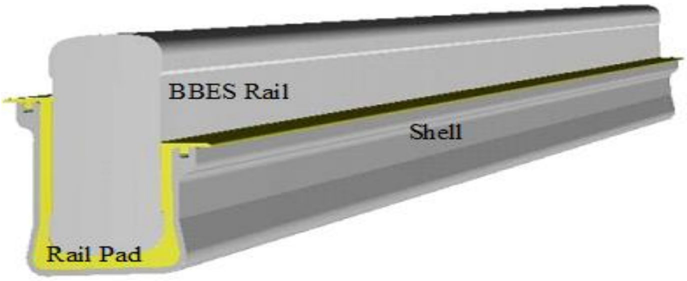


Figure 2-11: Continuous support model of BBES on rail pad

3 BALFOUR BEATTY EMBEDDED RAIL TRACK SYSTEM MODELING

3.1 General Considerations

Different finite element computer packages can perform a very detailed analysis of displacements, stress and strains of track components. The accuracy of these analysis results depend on the dimension of the track used in modelling. The more dimension used in modelling the more complex and costly it is and the more accurate analysis results expected since it represents the more actual case. In this thesis three dimensional model have been developed for different analysis cases to study Balfour Beatty Embedded Rail Track system using ABAQUS software.

Beam (rail) on continuous support embedded in RC slab model was created in ABAQUS as shown in figure 3.1. The rail was placed in a spring and damper both in vertical and lateral in parallel. This spring-damper system models the rail pad and the shell. At the side and below the rail, solid element of RC slab is placed. The RC-slab element is assumed to be placed on firm ground.

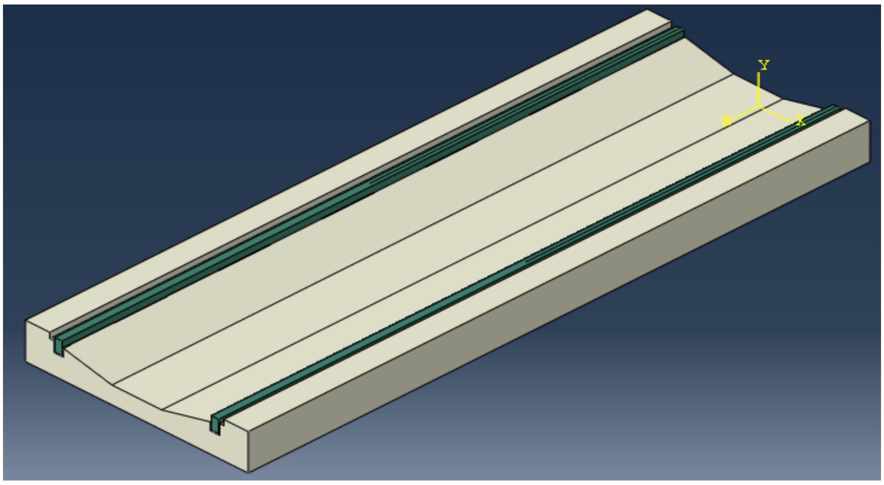


Figure 3-1: Three dimensional modeling of BBES.

3.2 Simplifications and Assumptions

The full response of the track can be better examined by developing the complete interaction model of the track-train systems. In this thesis, the model assumes a simplified system, which models the vehicle system's influence as a mass applied on the track system. However, the dynamic force also existed in the vehicle body i.e. the primary and secondary suspensions, and the track components vibration under applied loads are considered in the simulation and modelling. The following assumptions made to develop the required models of the track system for analysis.

3.2.1 Geometric Assumptions

- Rectangular shape rail profile is used due to the small deviation with the actual rail profile in cross section
- All components are assumed as 3D deformable elements
- Idealized infinitely continuous system but 650mm long segment is commonly used in in different laboratory tests whereas 6m length of the system is used in this modelling
- The model is solid model
- Depth of slab from top of rail is 370mm
- Standard gage 1435mm

3.2.2 Material Assumptions

- Parameters of the track system are constant and linear in geometry
- Damping and stiffness reduction is provided by the Rail Pad and the shell
- The shell and grout are used as for geometric perfection
- The shell in addition to Geometric perfection used to provide damping and stiffness

3.2.3 Loading Assumptions

- The harmonic loadings are transmitted/distributed on the two rails symmetrically
- Dynamic movement is studied in three dimension
- 25tone axle load is applied harmonically which is design axle load in Ethiopia applied A=sin (ω)

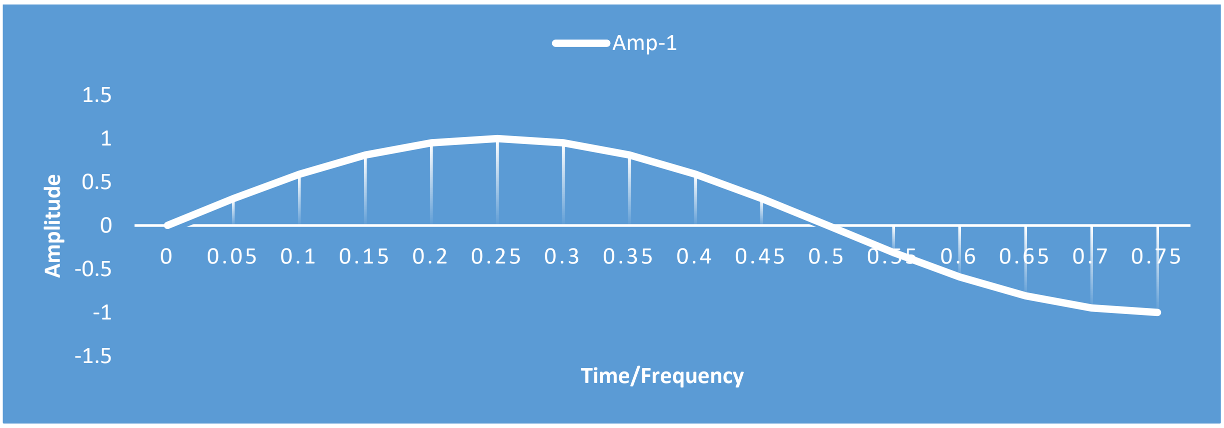


Figure 3-2: Harmonic property of the applied load at the middle of the rail

3.2.4 Finite Element Analysis (ABAQUS) Assumptions

For the finite element modelling and analysis in this research, the ABAQUS suite of computer programmes was employed. In particular, three are used;

- ABAQUS CAE for modelling

- ABAQUS Standard for the finite element analysis using the Steady State dynamics method
- ABAQUS Viewer to display the results.

3.2.4.1 Boundary Conditions

As the track assumed as beam, its boundary conditions and dynamic load are symmetric transversally which is modelled in full width with two rails (both subjected equal loads) transversally and 6000mm longitudinally. Hence, the boundary conditions are modelled as pin supports at the ends of the beam (track) longitudinally, free from support both sides of the beam (track) transversally and vertically the whole section is supported.

3.2.4.2 The Numerical Integration Scheme Used in the Analysis

According to Version 6.13-1 ABAQUS/Steady-State solver operates to calculate the effects of the harmonic load applied on the track. Effects of this load are displacement, velocity, acceleration and stresses in frequency domain.

3.2.4.3 The Time Step Chosen for the Analysis

According to version 6.13-1 user's manual ABAQUS software is capable to estimate automatically efficient size for the time increment immediately during analysis and continuously adjust for minimum cost.

3.2.4.4 Type of Finite Elements and Meshing Techniques

Since the track is assumed as beam problem, the model for this research was built using Euler-Bernoulli beam elements of tetrahedral geometric order chosen from the ABAQUS extensive library of Steady state elements. Because it needs very fine mesh to model the real shape of the rail and the very fine mesh in turn needs high processing capacity machine, approximate Tetrahedral-shape rail profile has been used.

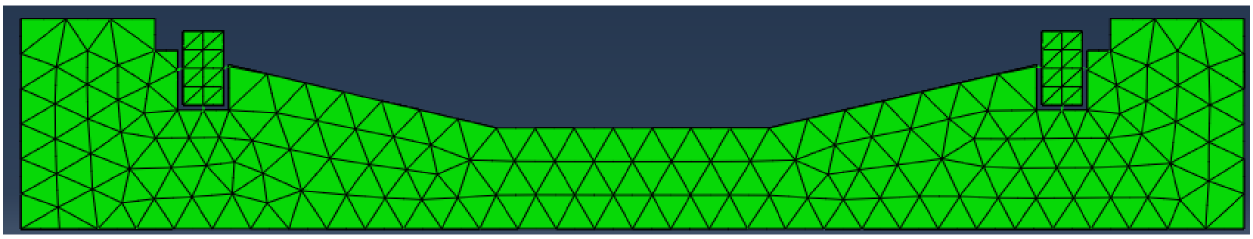


Figure 3-3: Cross-sectional view of meshed continuous support BBES model

The utilization of these beam elements allows for wave propagation in the analysis. For meshing the full width in the model, 115,009 elements were used. As found from the convergence studies carried out for the meshing, using this number of elements gave accurate results and was not very expensive computationally.

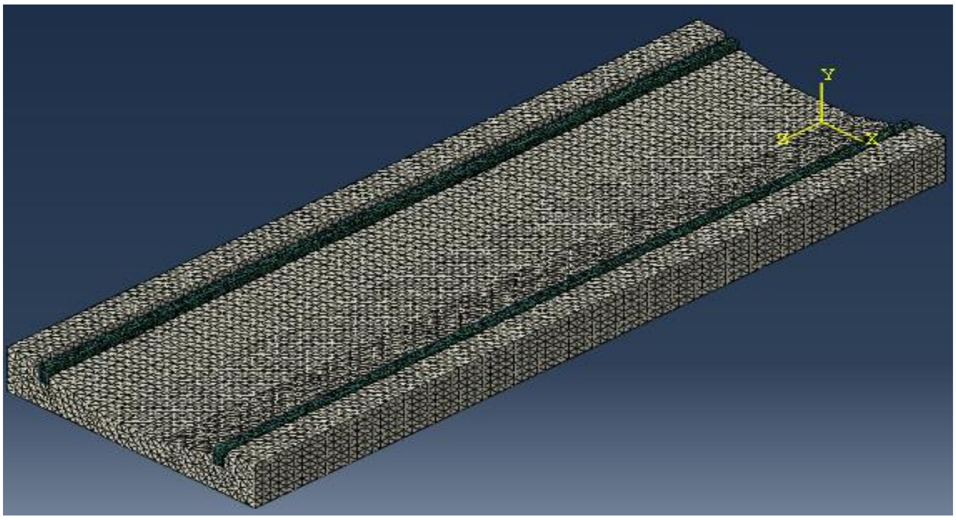


Figure 3-4: Meshed three dimensional model of BBES track

3.3 Modelling Parameters

BBES has different components with different material properties. Hereunder are the parameters applied in this thesis.

3.3.1 BBES Components Parameters

The concrete slab has 50MPa compressive strength and the rail (rail type BB14072) has 74Kg/m weight whereas the rail pad used in BBES can have stiffness 100MN/m upwards and half of this lateral. The parameters in Table 3.1 are used as input in this modelling.

Table 3-1: Material parameter for track components modelling and Rail pads and shell vertical stiffness and damping values.

Materials	Density, ρ (Kg/m^{3})	Elasticity (GN/m^2) E	Poisson ration, *ν*	Length, m
RC-Slab	2400	39.1***	0.22****	6
Rail	7850	210	0.33	Variable
Dynamic Stiffness			**Damper**	
Rail pad	K_p	50-100MN/m*	C_p	10-80 KN.s/m**

*Combined stiffness of rail pad and shell in series

**For both the rail pad and the shell

***Combined Elasticity of RC slab and Grout

****Combined Poisson ration, *v* for RC slab and Grout

3.4 Modelling BBES Track Structure Components

The model of BBES Track is described as a resilient pad surrounding the rail sides and base and is continually embedded in a shell grouted into a concrete trough. This model is relatively resembles to the actual cross section and conditions of track structure parts.

3.4.1 Beam Elements (rail)

Various types of static and dynamic analysis can be accomplished using beam element of finite element modelling. "For example, first-order, shear-deformable beam elements (B21, B31) should be used in any simulation that includes contact whereas if the transverse shear deformation is important, use Timoshenko (quadratic) beam elements (B22, B32)." [7], [19]. The rail is modelled as 3D deformable.

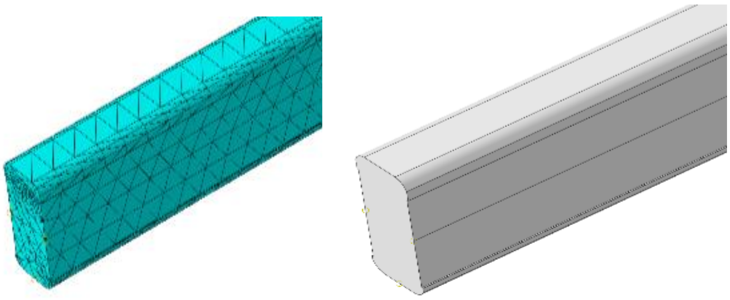


Figure 3-5: Three dimensional model of BBES rail

3.4.2 Springs and Dashpot (Pad & Shell)

Actual physical springs and idealization of axial or torsional components are modelled using spring elements. To form the imaginary part of the spring stiffness spring elements are also used to represent structural dampers by specifying structural damping factor. Relative velocity dependent force or torsional resistance and energy dissipation mechanisms are modelled using dashpot. The rail pad and the shell are modelled as spring and dashpot in this modelling. As shown in the figure 3.4 below the spring and dashpot interaction is continuously applied both vertically and laterally.

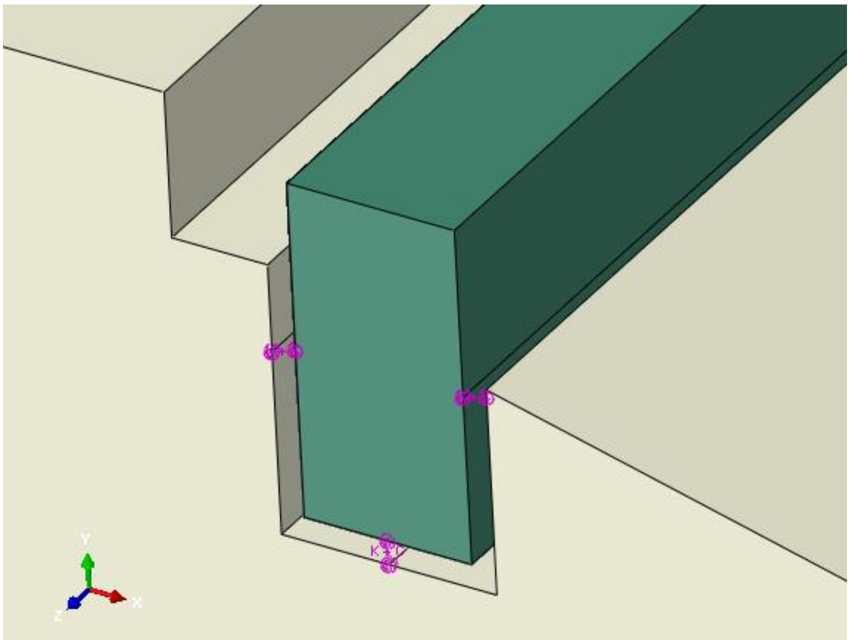


Figure 3-6: Vertical and Lateral spring &dashpot model between RC Slab and Rail

3.4.3 RC Slab & Grout

In modelling the slab component we should consider shear deformations (if applicable). It can be modelled as an infinite Timoshenko beam with constant cross-section. “A two-parameter foundation model represents the soil. Both beam and foundation assumed as homogeneous and isotropic.”[7] But in this model, the concrete slab with the grout is modelled as 3D deformable in this modelling.

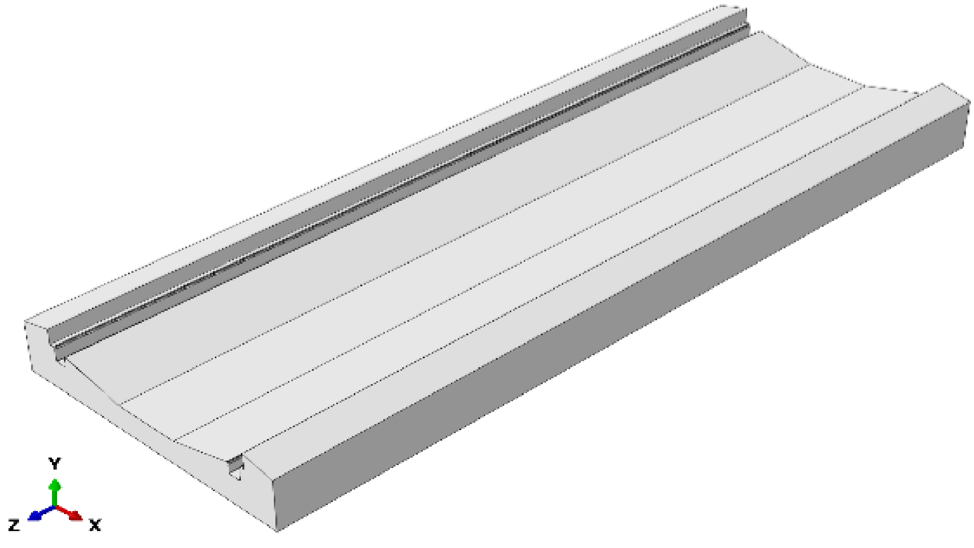


Figure 3-7: Three dimensional model of BBES slab

4 BALFOUR BEATTY EMBEDDED RAIL TRACK SYSTEM ANALYSIS RESULTS AND DISCUSSIONS.

4.1 Modeling Results

The results from the finite element modeling and analysis in ABAQUS are presented. The dynamic analyses including natural frequency extraction & modal dynamic analysis utilized to examine BBES response. In addition, resonance frequencies and response spectrum analyses have been studied. The lateral and vertical vibration modes have been extracted using LANCZOS method. The steady-state dynamic response have been analyzed by applying a harmonic load at the middle of the rail, which has been used to study dynamic effect of different track component dynamic effect.

4.2 General Dynamic Response of Balfour Beatty Embedded Rail Track System

Dynamic responses of BBES under this modeling are described hereunder.

4.2.1 Steady State Dynamic Analysis

The track responses such as deflection, acceleration, velocity, reaction forces and stresses in three dimension for selected nodes have been generated by steady state dynamic analysis in ABAQUS. This results have been found by applying series loading at different frequencies at the middle of the rail which represent series wheel load of a train at a node.

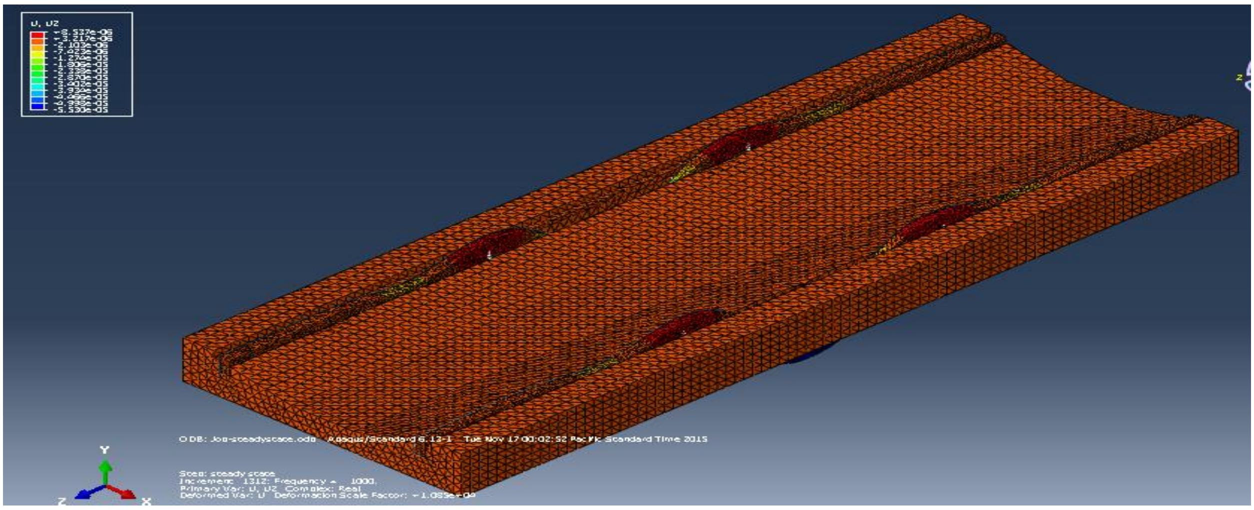


Figure 4-1: Vertical downward deflection of the rail

4.2.2 Natural Frequency Analysis

Lower modes are more responsible in response structural dynamics analysis. [7], [19], [24] Nevertheless, enough modes should be extracted to provide a good representation of the dynamic response of the track structure. To checking that, a sufficient number of eigenvalues being extracted is to compare the total effective mass participation in each degree of freedom, which indicates how much of the mass is active in each direction of the extracted modes. Ideally, the sum of the modal effective masses for each mode in each direction should be at least 90% of the total mass. [7], [19] In addition to mass participation, energy distribution in the model is also important focus. Kinetic energy exists in the model because of the motion of the mass and strain energy is present as a result of the displacement of the structure.

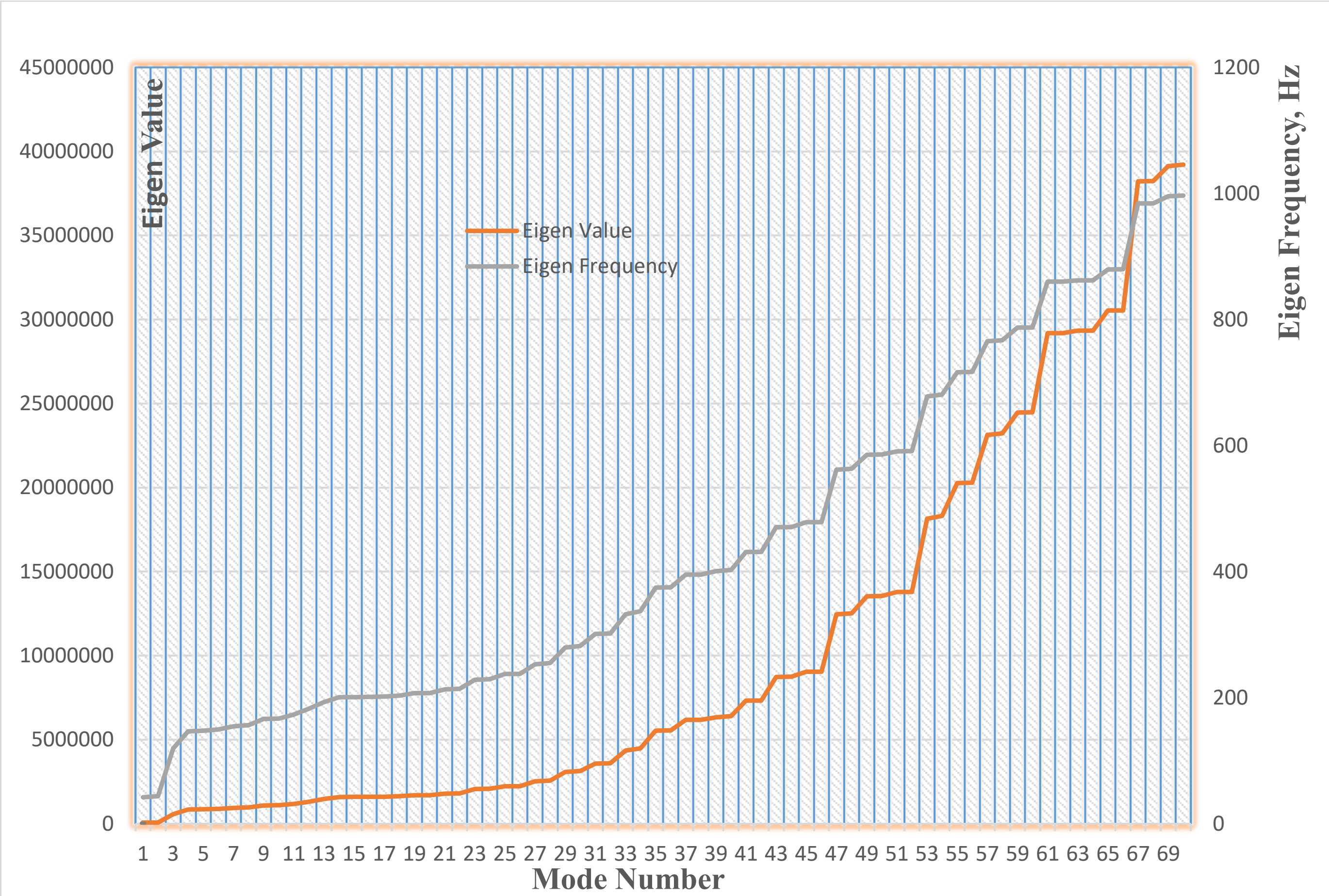


Figure 4-2: Eigen value and Eigen frequency extracted for the whole model

As shown in the Fig.4.3 and Fig.4.4 below it seems that for the lower modes (up to mode number 30) enough mass participated in vertical as well as lateral direction.

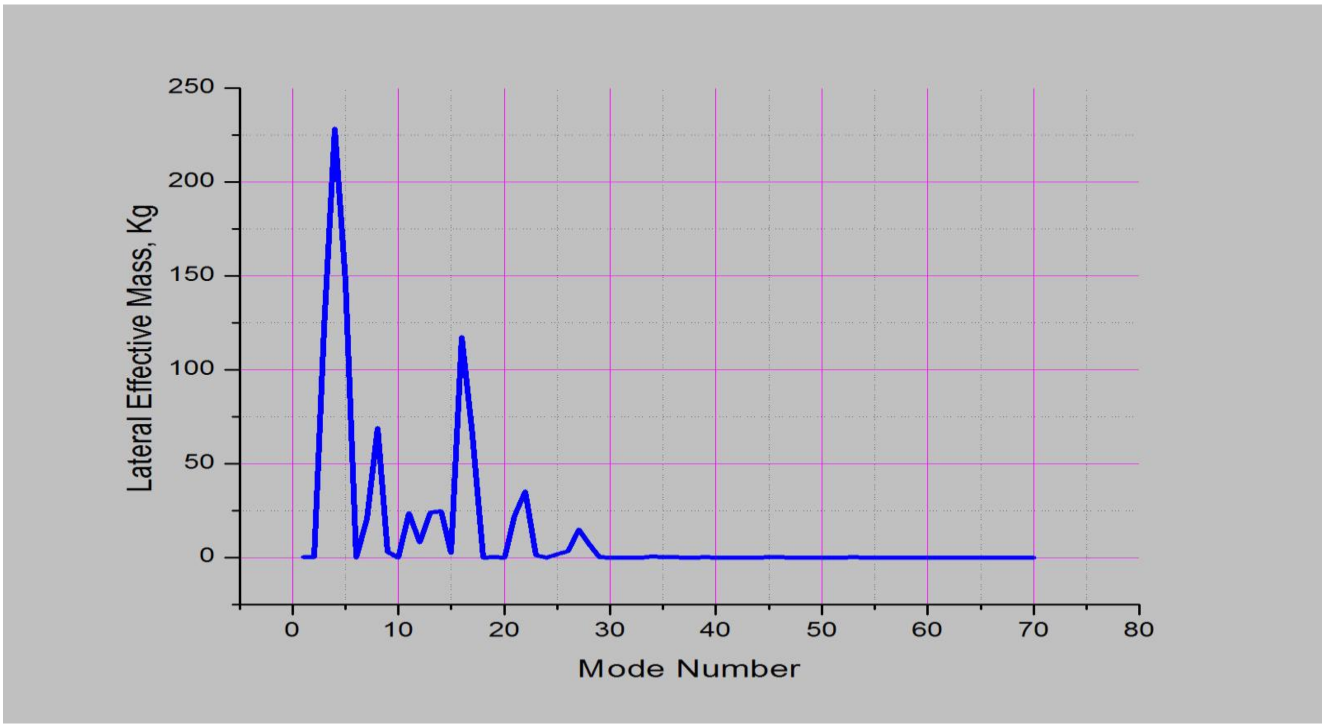


Figure 4-3: Effective mass participated in lateral direction

Maximum mass is participated at mode number five in lateral direction whereas at sixteen for vertical direction. These corresponds to the rail modal vibrations maxima.

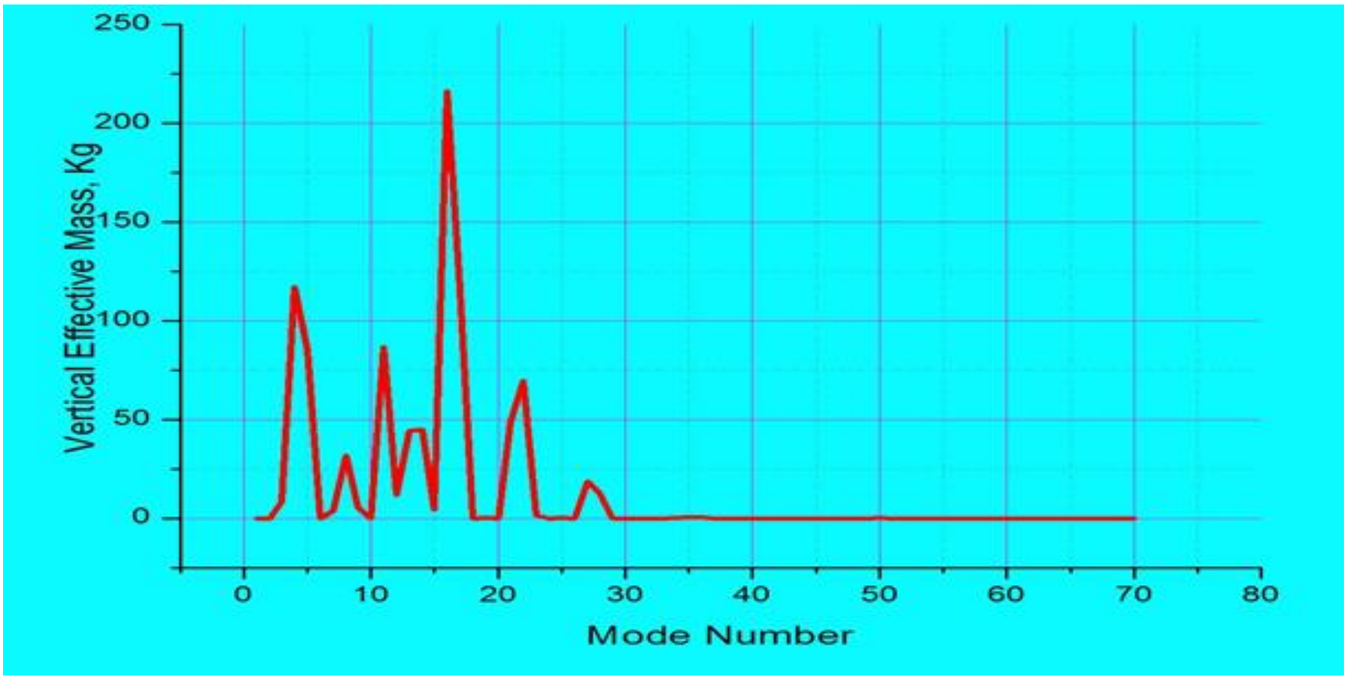


Figure 4-4: Effective mass participated in vertical direction

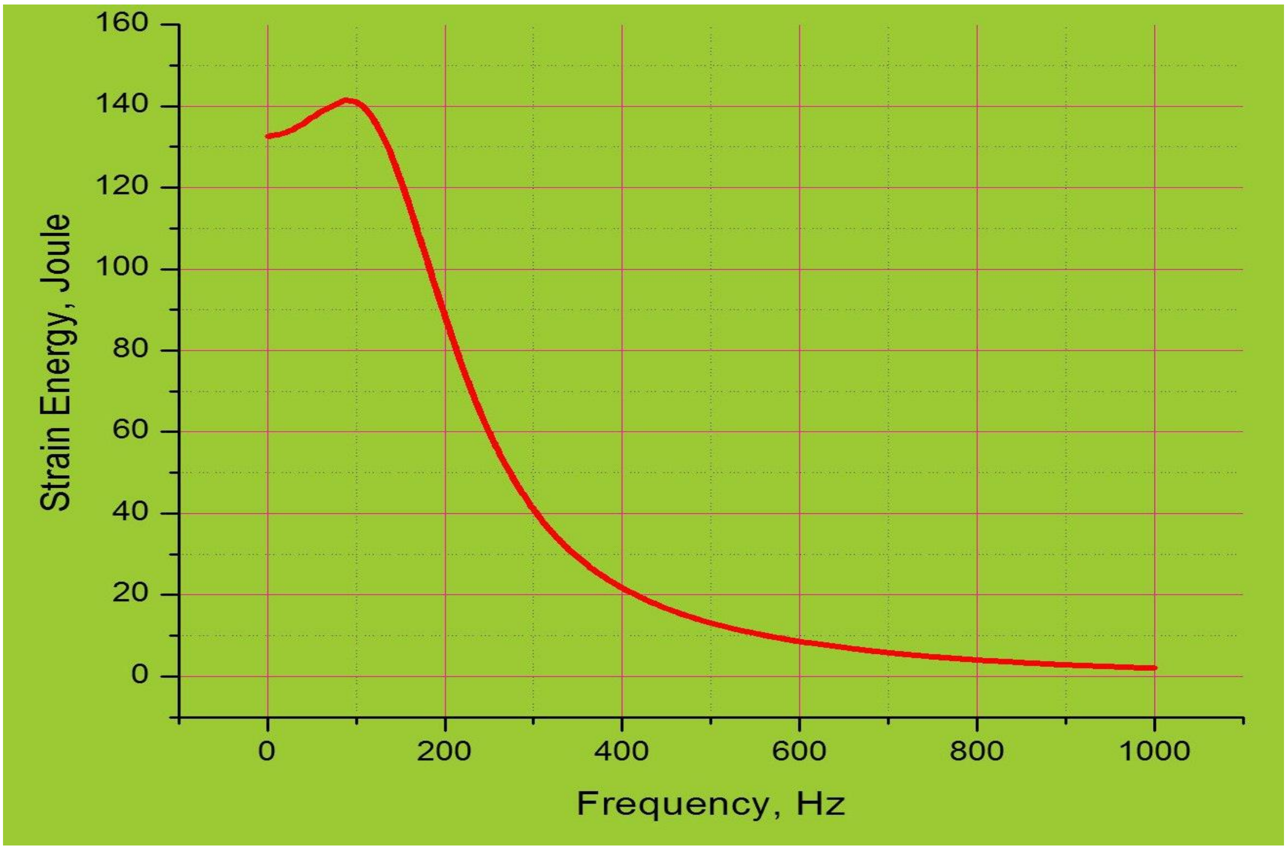


Figure 4-5: Strain energy for the whole model

The strain energy graph in figure 4.5 corresponds the displacement graphs of figures 4.15 and 4.19 that shows for frequency of large displacement large strain energy transfer is expected.

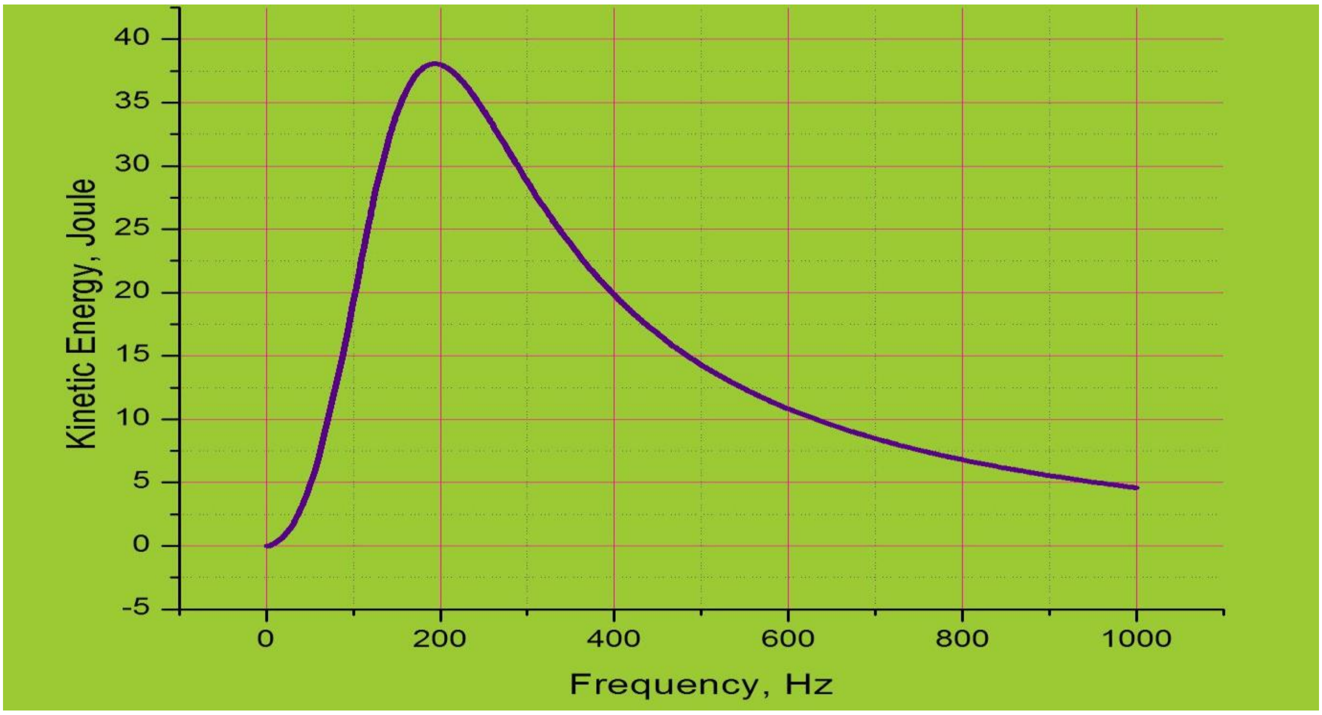


Figure 4-6: Kinetic energy for the whole model

The kinetic energy graph of figure 4.6 corresponds to velocity graphs of figure 4.17 and 4.21 that for large change in velocities large kinetic energy transfer is expected (at 200Hz).

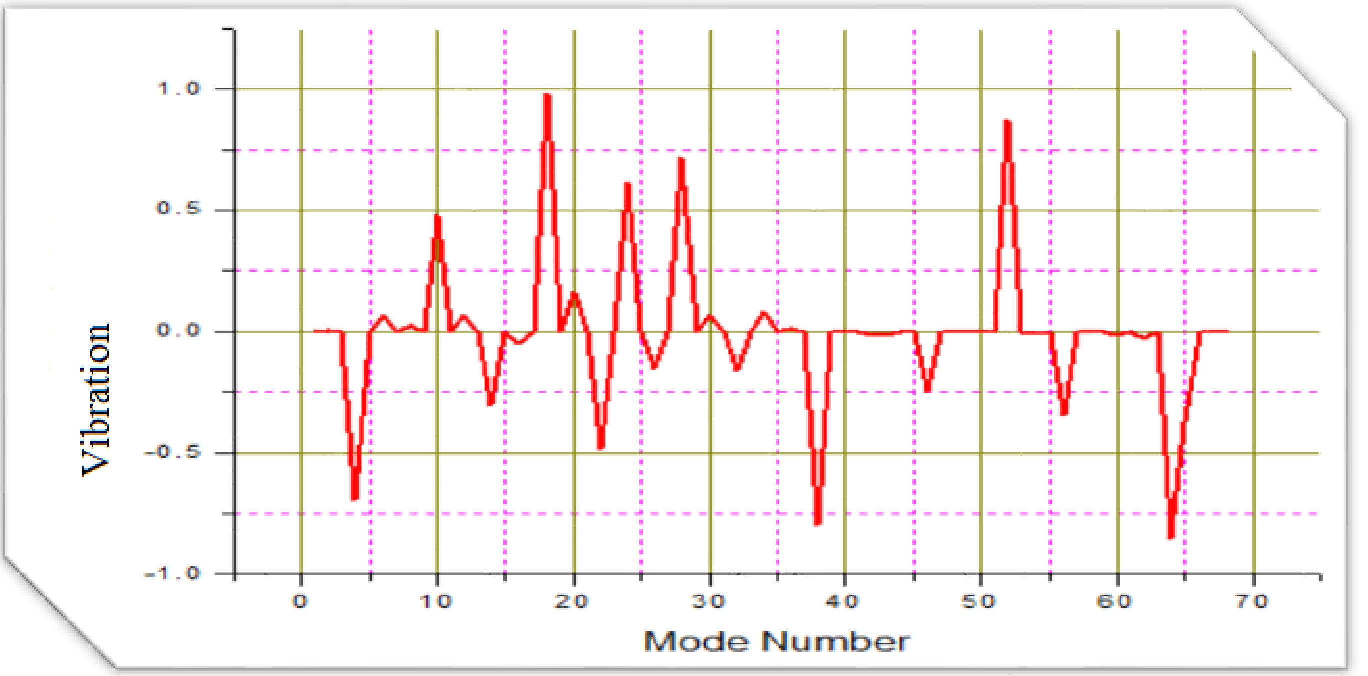


Figure 4-7: A single rail node vertical deflection with in all modes of vibration

As we can see from the Fig.4.7 above, the rail start vibrating and dominates in the vertical downward direction from 3 to 5 modes of vibration. However, from 8 to 13 modes of vibration it starts vibrating in the upward direction and from 16 to 30modes vertical vibration dominates whereas from 30 to 70 modes seems to vibrate equivalently. Nevertheless, the pattern and shape as well as the vibration amplitude looks quite similar for the vibration modes. All these indicate that lower modes of vibration can represent and explain the dynamic response of the structure.

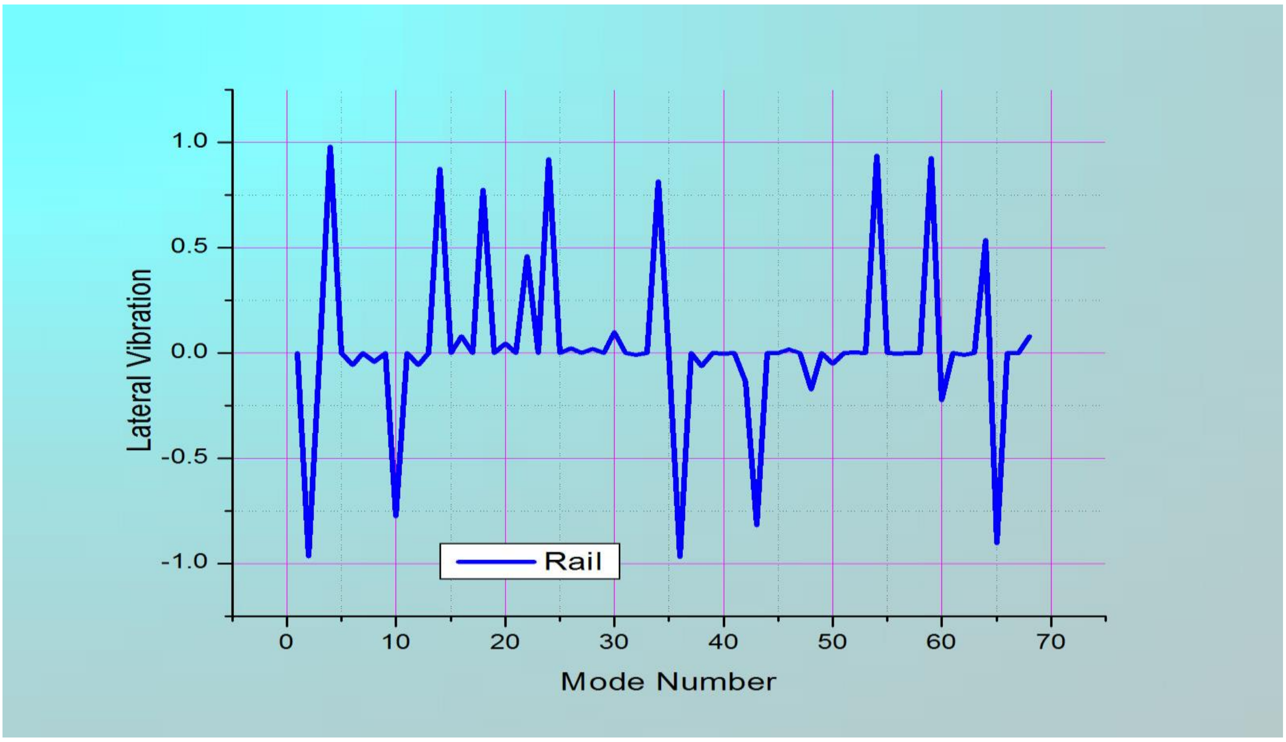


Figure 4-8: A single rail Node lateral deflection with in all modes of vibration

Lateral deflection of the rail, Fig.4.8 shows experience of vibration in both directions throughout the modes. It seems that similar patters repeat themselves at regular interval so that lower modes of vibration can represent and explain the dynamic response of the structure.

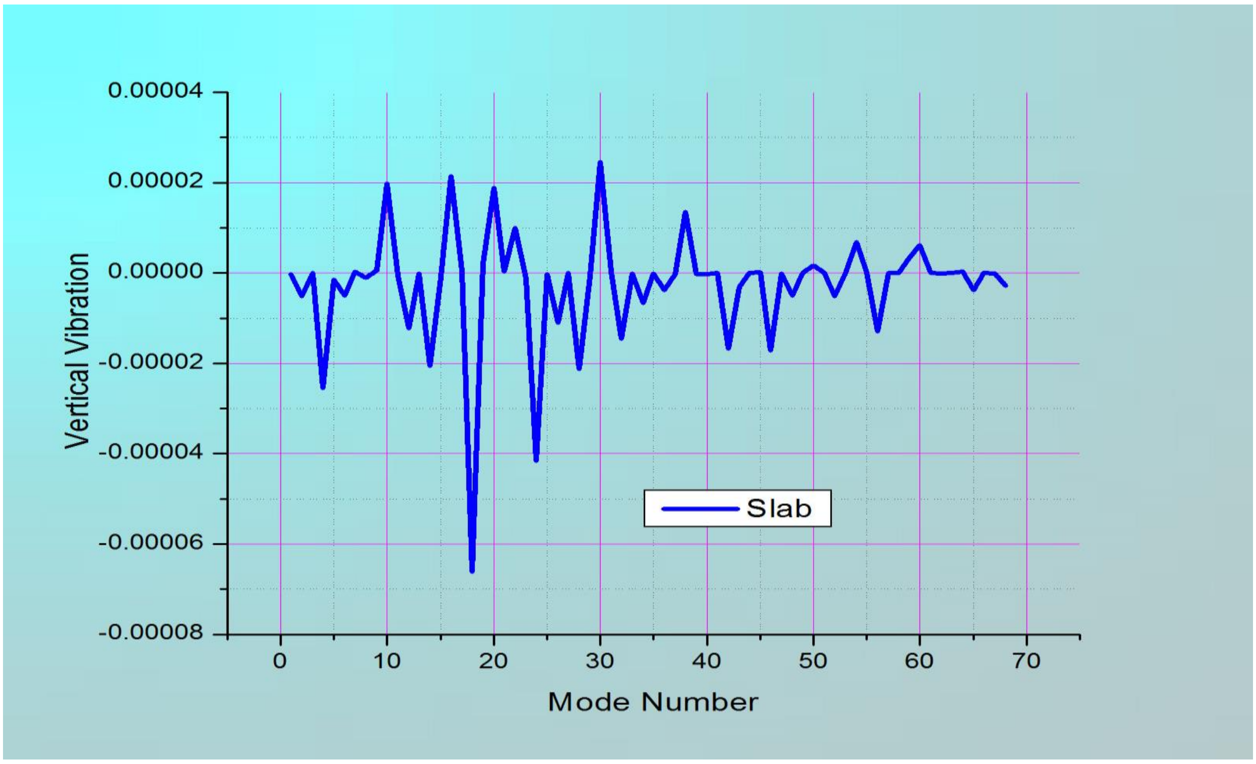


Figure 4-9: A single slab Node vertical deflection with in all modes of vibration

As we can see on the Fig.4.7 and Fig.4.9 after mode number 30 the rail deflection dominates that of the slab which have to be compensated by rail pad.

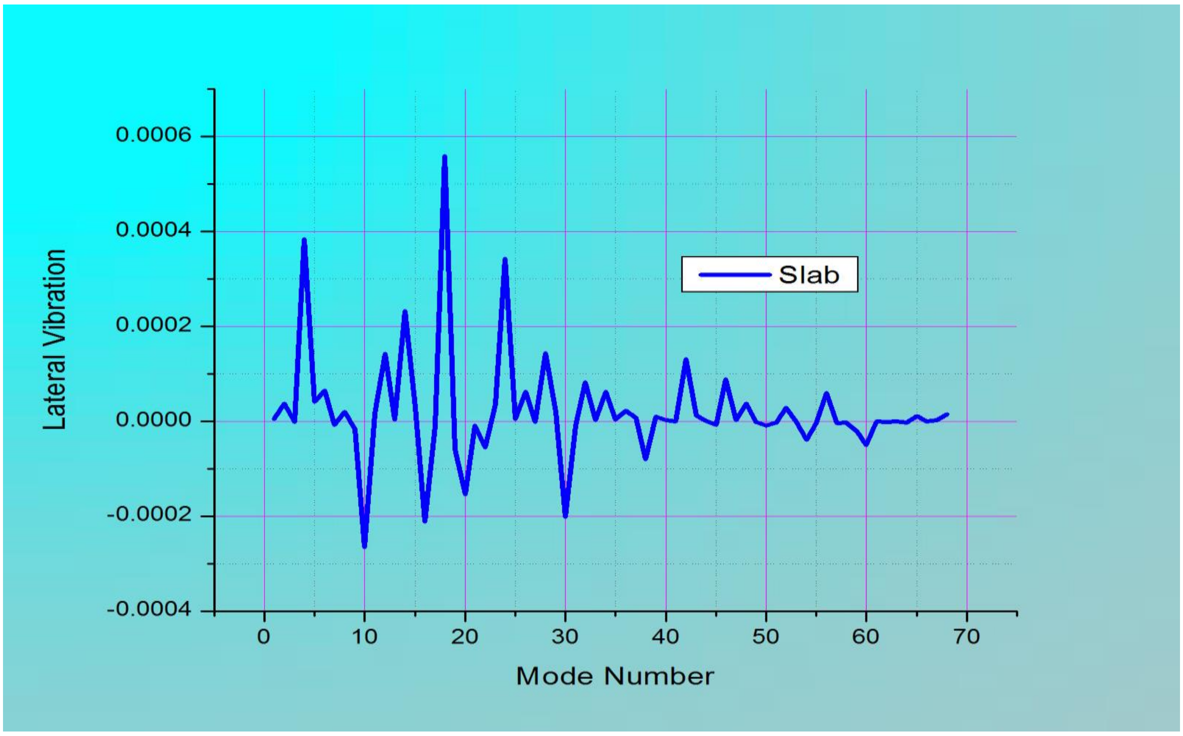
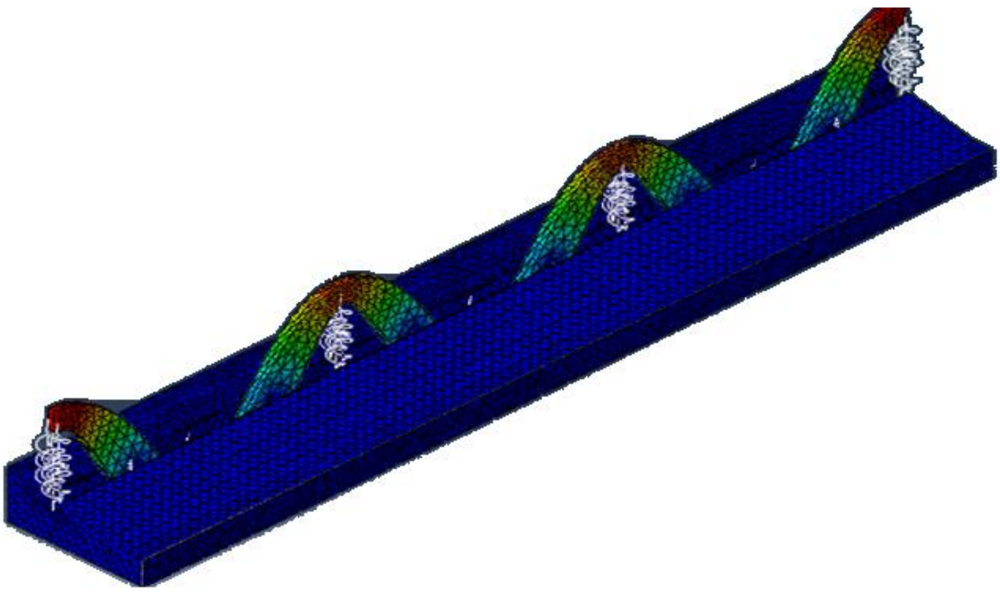


Figure 4-10: A single slab Node lateral deflection with in all modes of vibration

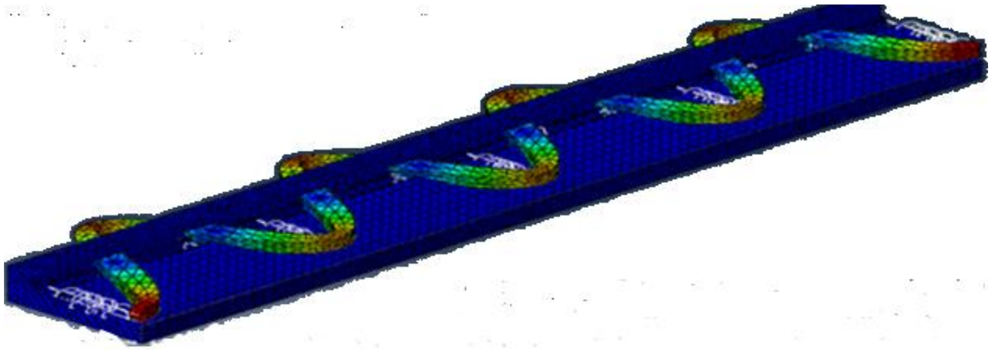
We can see that the vertical and lateral vibration of the slab decreases after mode number 30 whereas the rail don't so that the rail pad shall play a role in compensating this vibration difference.

4.2.3 Vibration Modes and Eigen Analysis

Eigen value analysis for BBES in ABAQUS enable us to analyze the whole structure and to observe global modes such us rail vibration. It can be simulated clearly that which component of the track has higher amplitude.



a)



b)

Figure 4-11: 3D BBES Rail vibration modes in ABAQUS Simulation (a) Vertical vibration mode at frequency 383.32 Hz and (b) Lateral vibration mode at frequency 358.27Hz

The rail vibrates in vertical and lateral directions in different modes. As the frequency increases the mode number also increases. The severity also increases with frequency.

Figure 4-12: 3D BBES Slab vibration modes in ABAQUS Simulation at frequency 1660Hz

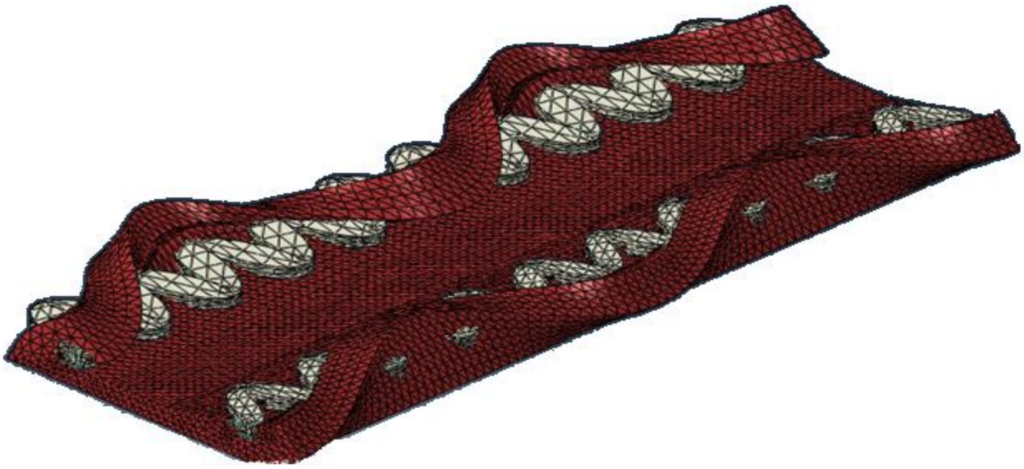


Figure 4-13: 3D BBES Slab and Rail vibration modes in ABAQUS Simulation at frequency 1697Hz

The modes of vibration of the slab are not sinusoidal as that of the rail due to the boundary condition and interactions properties.

It is observed that the vibration starts in lateral direction at lower frequency and then vertical vibration starts. Additional observation is that the rail starts vibrating at lower frequencies whereas the slab vibrates at higher frequencies. For extremely higher frequencies both the rail and the slab starts to vibrate.

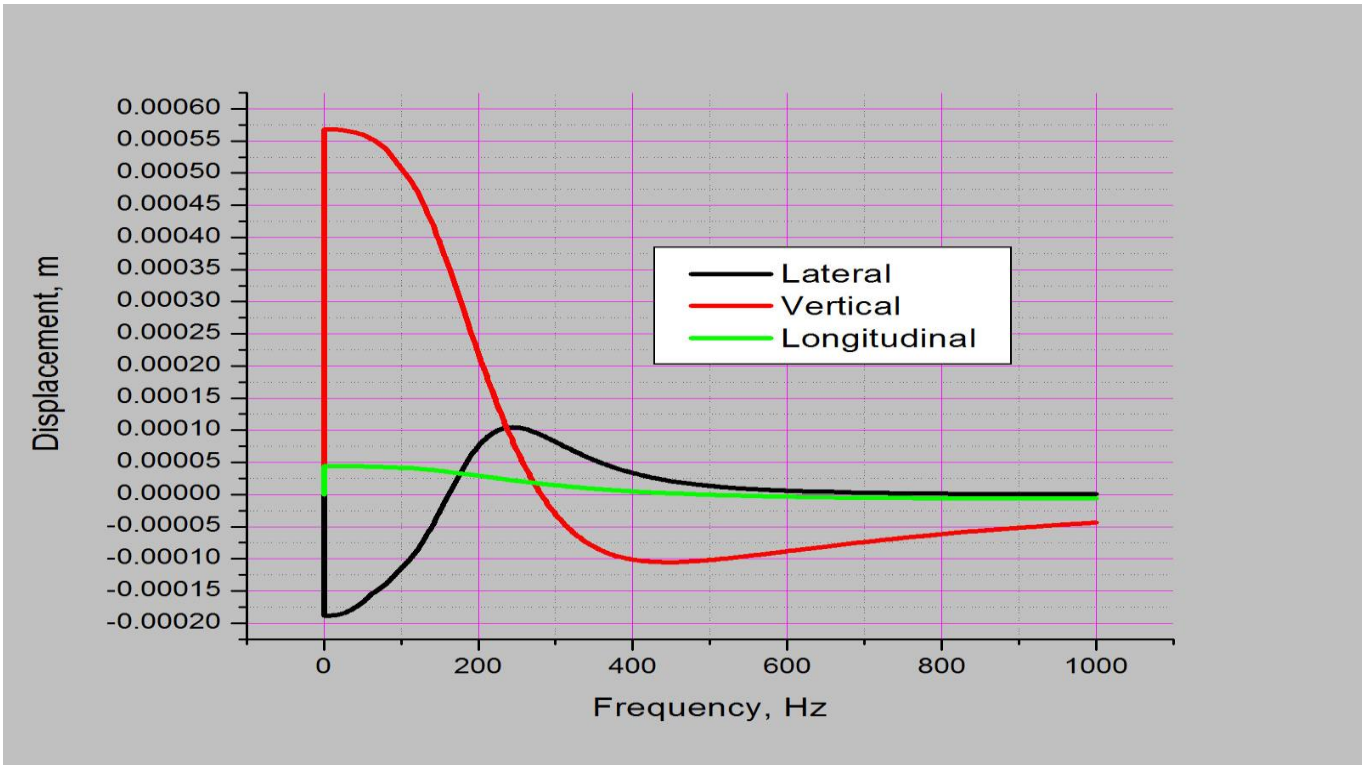


Figure 4-14: Three dimensional displacement at the node of middle of rail

As shown in the Fig.4.14 above the rail starts vibrating highly in both vertical and lateral direction when the frequency starts to increase from zero and immediately the vibration decrease up to the frequency 160 Hz. From 160 Hz to 300 Hz the vertical vibration continue decreasing while that of the lateral increases and the starts to drop. From 500Hz to higher frequencies both the vertical and lateral vibrations tends decrease. Except from 250Hz to 330Hz the vertical vibration dominates most excitation.

Natural frequency is a resonance frequency in which the structure tends to vibrate in all unrestrained degree of freedom. Logically, it is the largest resonance frequency of the structure.

4.2.4 Response Spectra Analysis

The peaks values of the track kinematic response such us displacement, velocity, acceleration and stress thresholds can be analysed for the track or track components. From these peaks responses the behaviour and performance of the track can be evaluated. This analysis is helpful for the preliminary design of the track components. The peak spatial responses can be correlated with the resonance frequency of the track.

Displacement, velocity and acceleration and stress vectors are the main components of the frequency response curve. By using ABAQUS standard the response spectrum peaks values can be obtained in frequency domains.

4.2.4.1 Response Spectra Analysis for BBES Rail

We can observe from the Fig. 4.15 - 4.18 that the frequency range that is responsible for high value of dynamic responses is from zero to 500Hz frequency except vertical acceleration. Stresses and displacements are pick immediately after zero frequency whereas vertical and lateral velocities are at 270 Hz and 170 Hz frequencies respectively. The vertical acceleration specially has pick value about frequency of 1000 Hz as the vertical velocity change trend seems to indicate.

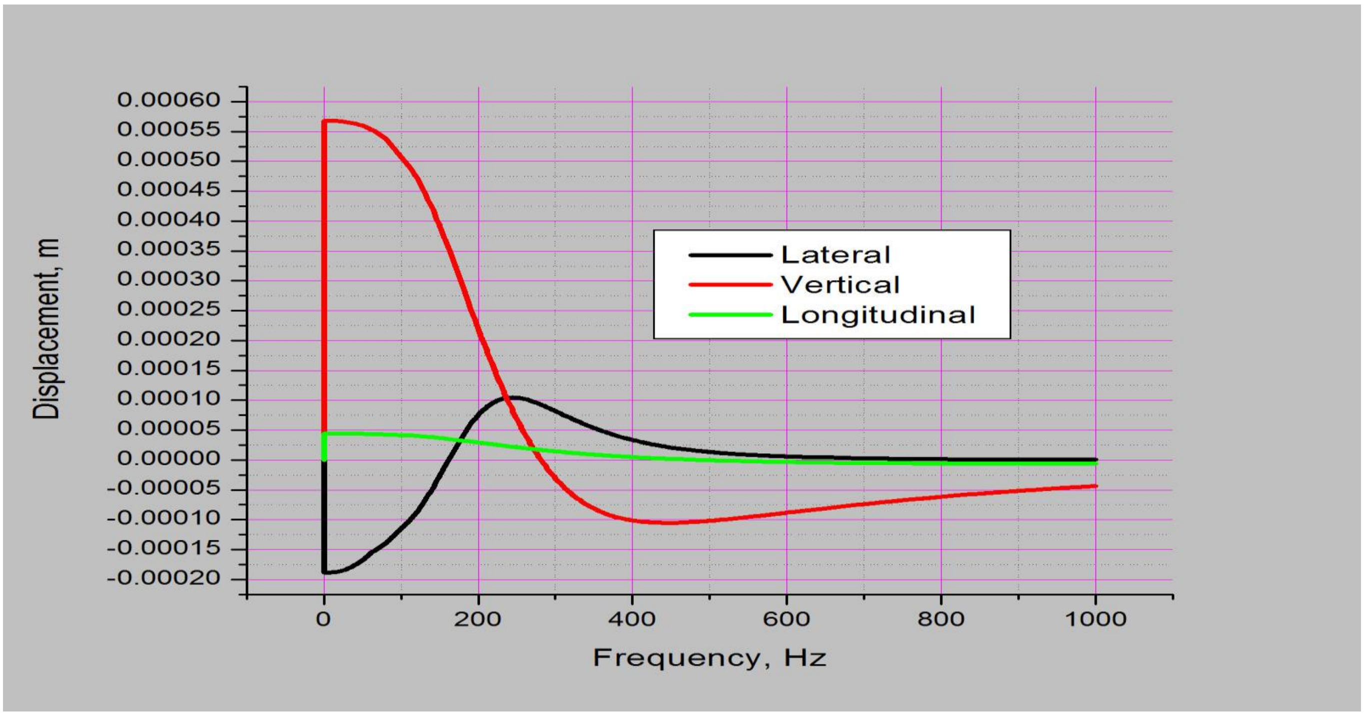


Figure 4-15: Longitudinal, vertical and lateral deflections at the node of middle of rail

Vertical displacement dominates in almost all ranges of frequencies as will be expected from the loading direction and boundary conditions. Lateral displacement takes the second dominancy since the component of the load in this direction is lower than that of vertical. The longitudinal one due to the presence of boundary condition and absence of rail pad as well as lower load component, it has lower displacement than the other direction.

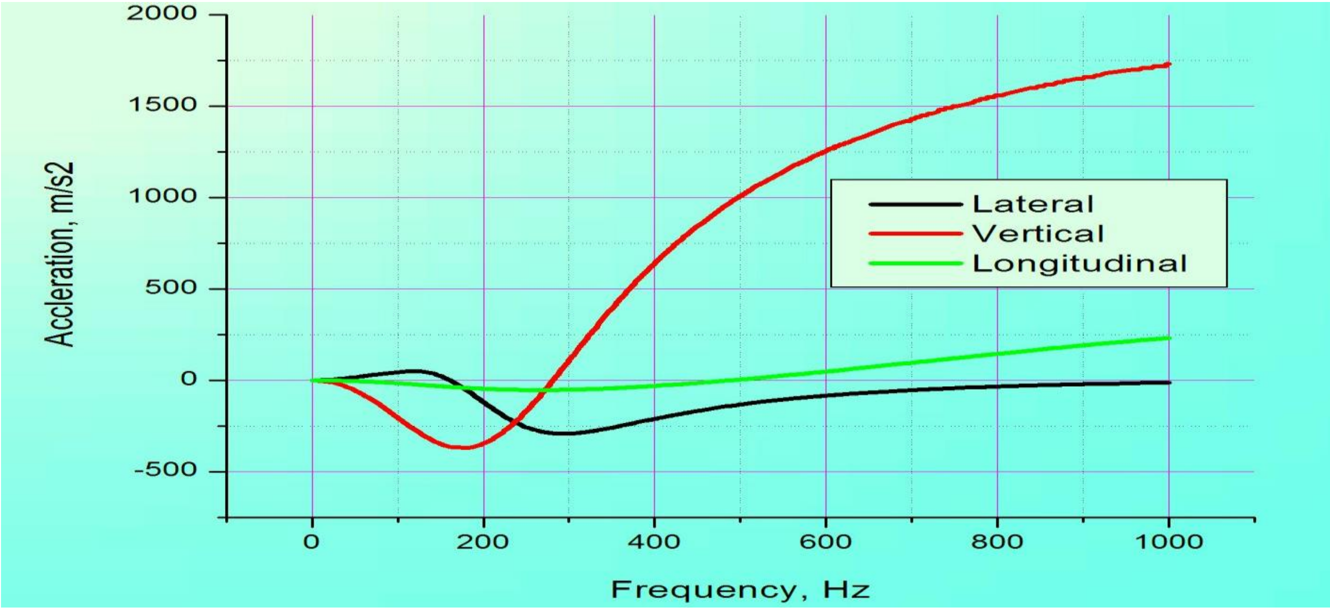


Figure 4-16: Longitudinal, vertical and lateral accelerations at the node of middle of rail

Vertical acceleration of the rail dominates in almost all ranges of frequencies. Figure 4.16 shows frequency ranges where lateral acceleration dominates and where longitudinal dominates comparing lateral and longitudinal directions. From 250 – 350 Hz the lateral displacement dominates. Dominancy comparison is made in scalar.

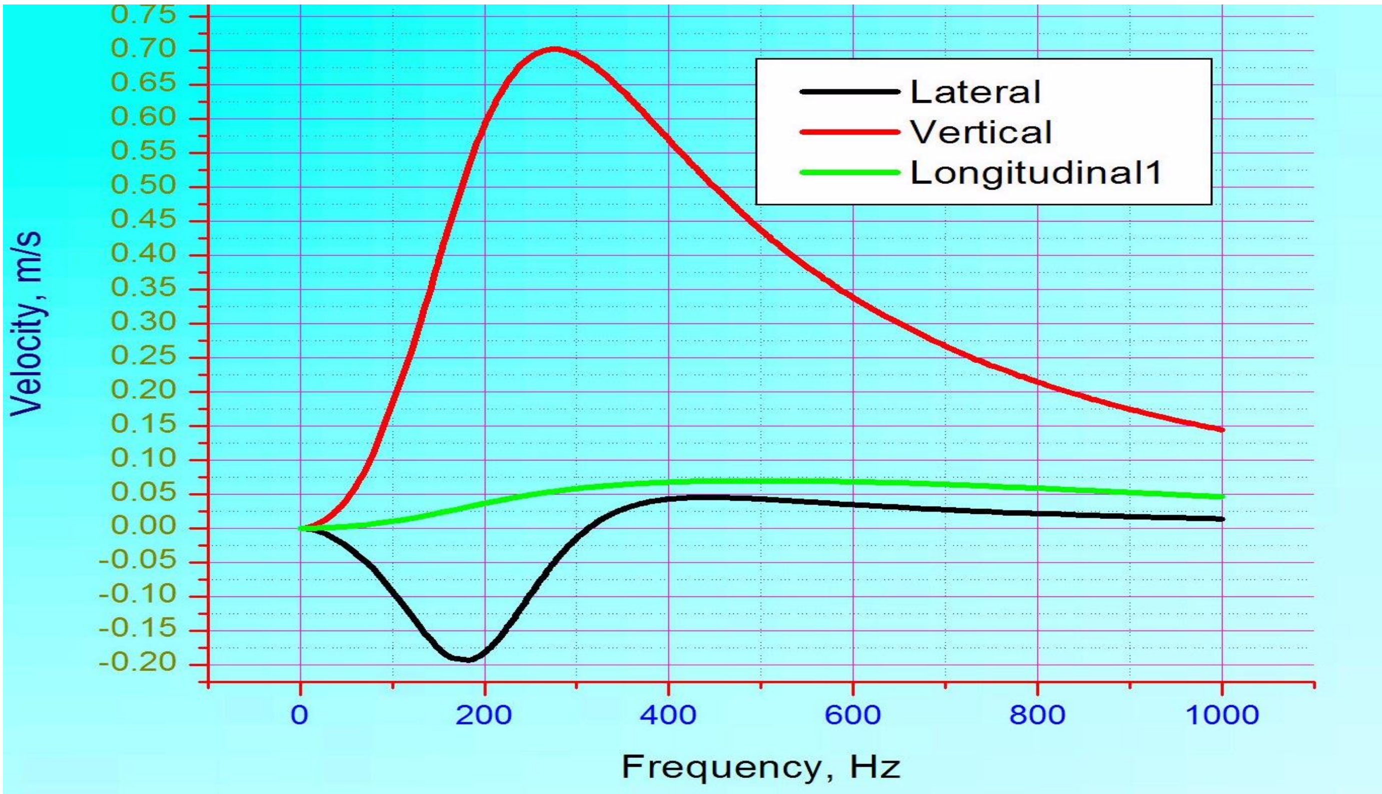


Figure 4-17: Longitudinal, vertical and lateral velocities at the node of middle of rail

In all dimensions the velocities approach to zero at higher frequencies and changes decreases indicating the accelerations to be zero at this frequencies.

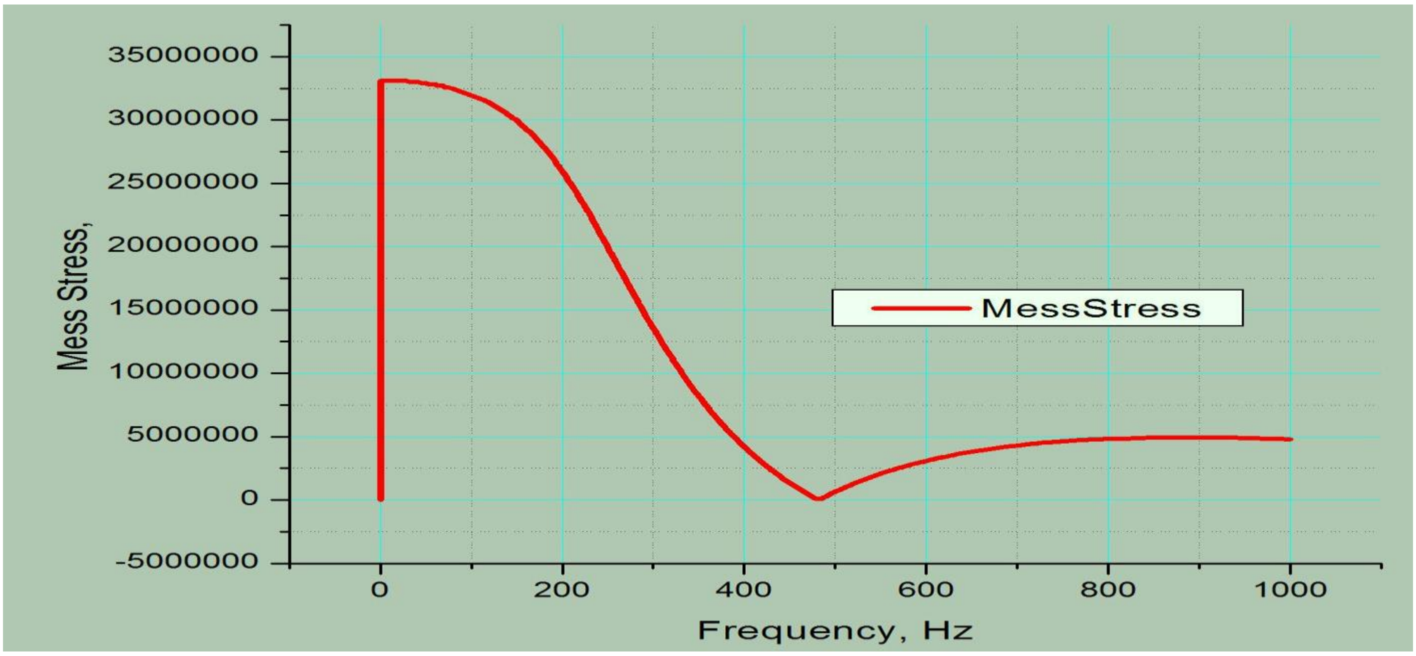


Figure 4-18: Misses Stress at the node of middle of rail (N/m2)

Average stress is lowest at frequency 480 Hz and highest at frequency immediately after zero. Adversely decreasing after the peak point to 0 N/m2 and starts to increase afterwards slowly finally seems to become constant.

4.2.4.2 Response Spectra analysis for BBES Slab

We can observe from the Fig. 4.19 - 4.22 that the frequency range that is responsible for high value of dynamic responses is from 100Hz to 500Hz frequency except vertical and longitudinal acceleration. Stresses and displacements are pick at frequency of 200Hz whereas vertical, lateral and longitudinal velocities are at 300 Hz, 330Hz and 400Hz frequencies respectively. The vertical acceleration specially has pick value at frequency of 1000 Hz as the vertical velocity change trend seems to indicate.

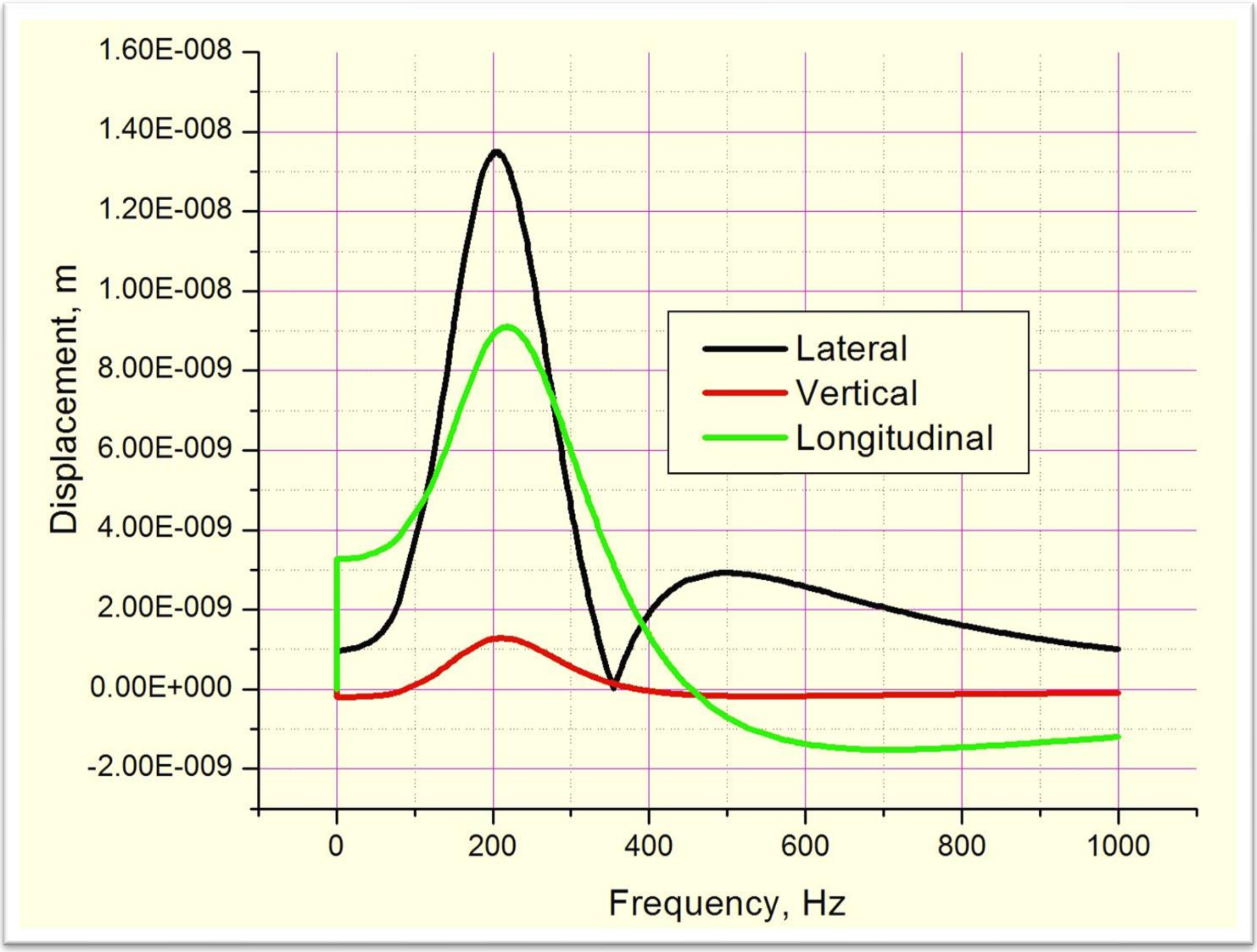


Figure 4-19: Longitudinal, vertical and lateral displacements at the node of middle of Slab

The slab displacement in lateral and longitudinal directions are higher than that of vertical direction which seems to come from the boundary condition. The no boundary condition lateral direction exceed from the pin support longitudinal direction and fixed support vertical direction.

Longitudinal displacement is higher than lateral and vertical displacements in frequency ranges from 0 -100Hz and 300 – 400Hz.

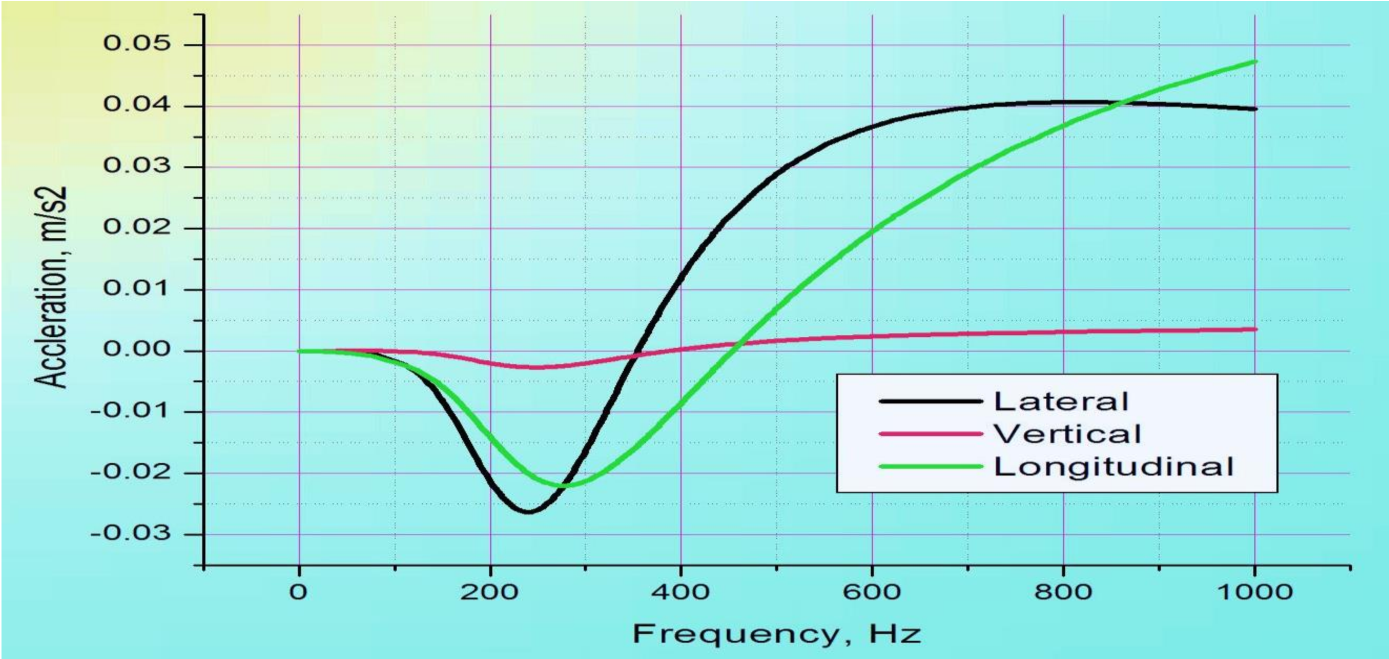


Figure 4-20: Longitudinal, vertical and lateral accelerations at the node of middle of Slab

Except from 0 – 100 Hz, 280 – 400 Hz and above 870 Hz where the longitudinal acceleration exceeds, the lateral acceleration dominates. Due to the fixed vertical boundary condition the vertical acceleration is minimum in all frequency ranges.

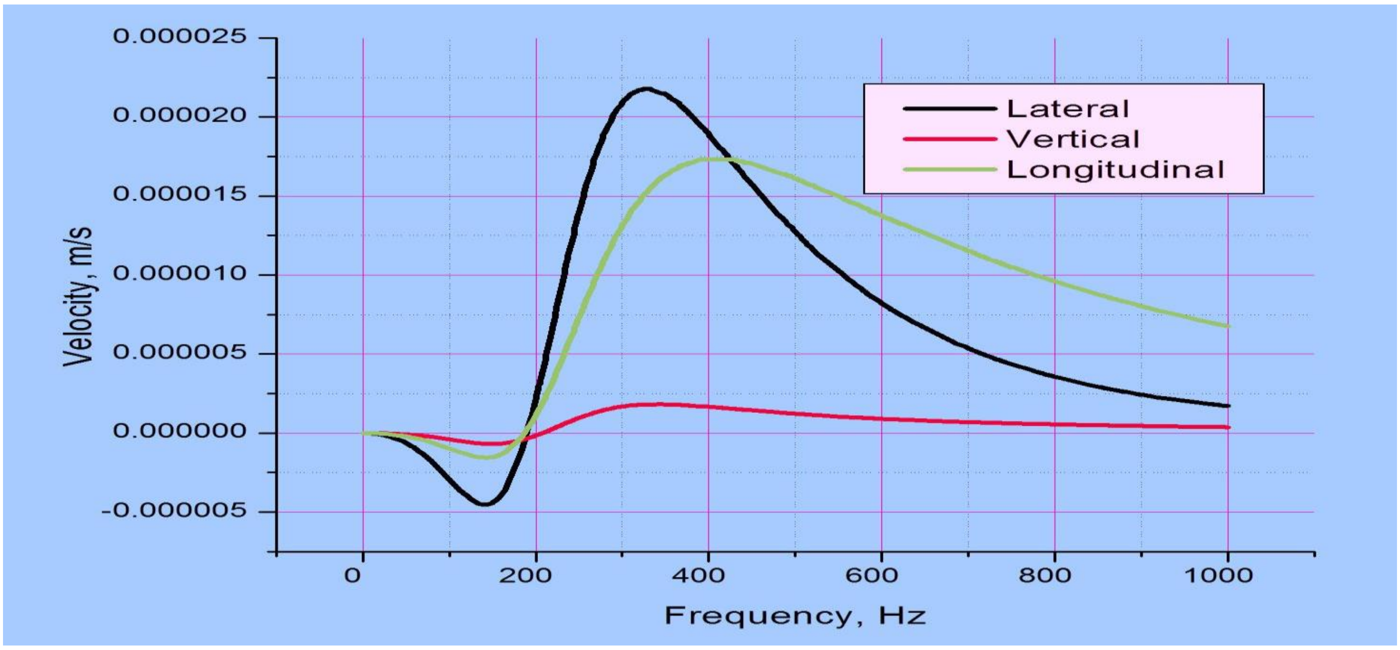
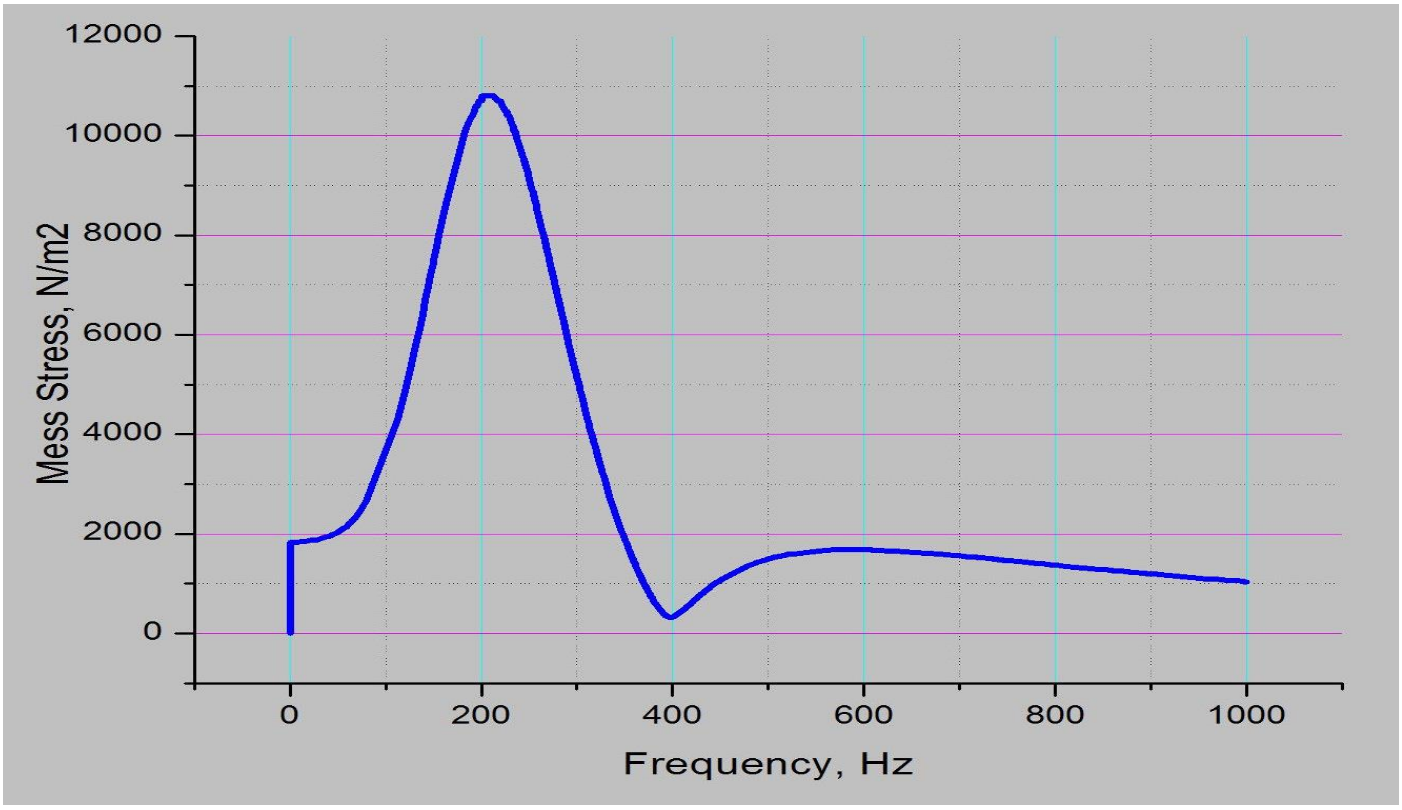


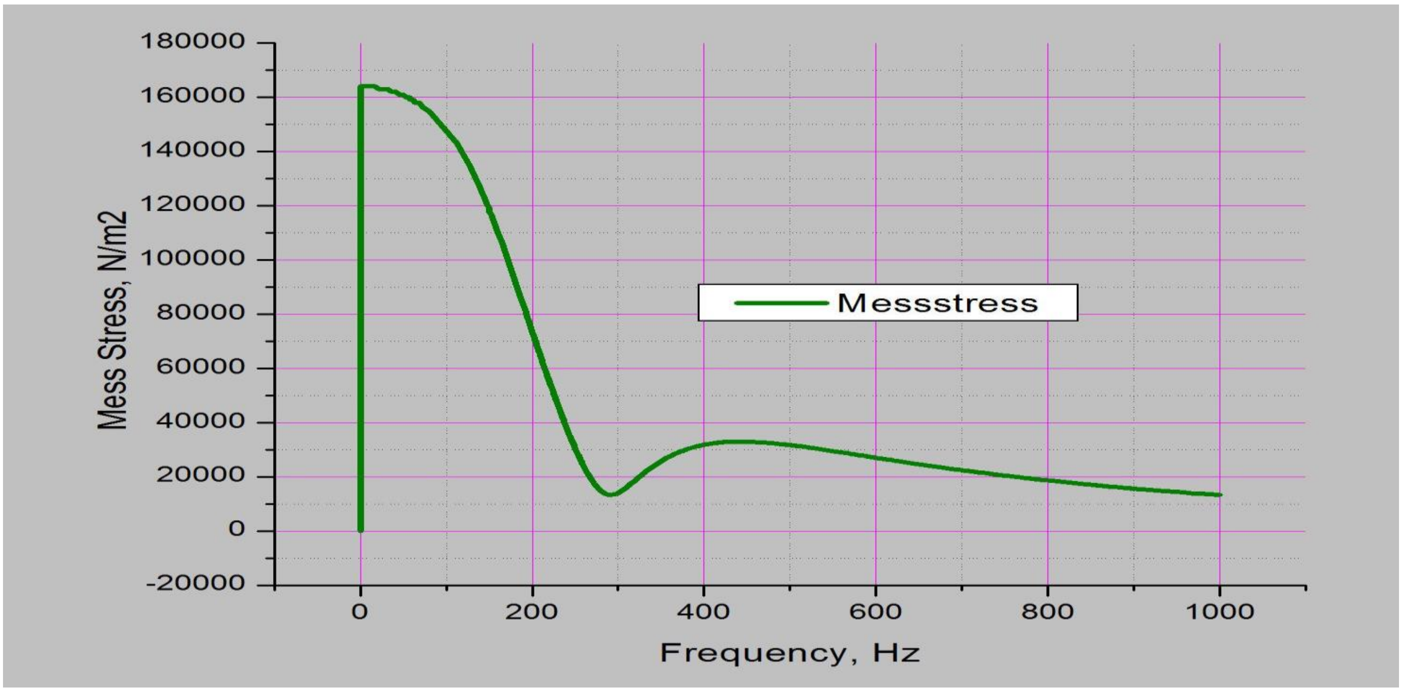
Figure 4-21: Longitudinal, vertical and lateral velocities at the node of middle of Slab

Here the lateral velocity dominates from frequency 0 – 190Hz and from 190 – 415 Hz whereas the longitudinal one dominate after frequency 415Hz. The three velocities will be equal at frequency 190Hz and all velocities approach to zero at higher frequencies.

We can observe from figure 4.19 - 4.21 that in average in almost all frequency ranges the lateral dynamic responses has higher value than the longitudinal and vertical values whereas the vertical value has lower values which comes from the boundary conditions applied.



a)



b)

Figure 4-22: Mess stress at the node of a) middle of slab b) slab near to the middle of rail

We can observe from Figure 4.22 that the stress on the slab decreases away from the rail and the frequency of minimum stresses also decreases. However the trend of stresses are the same.

4.2.4.3 Relative Spectra of BBES Rail and RC Slab

From figure 4.23 we can observe that vertical displacement of the rail is much higher than the slab in lower frequency (up to 200Hz) in upward direction, equal at 300Hz and at higher frequencies the displacements become equal and approaches to zero. This dynamic responses has positive implications on the track that the maximum displacement is at lower frequency at which the dynamic effect is minimum.

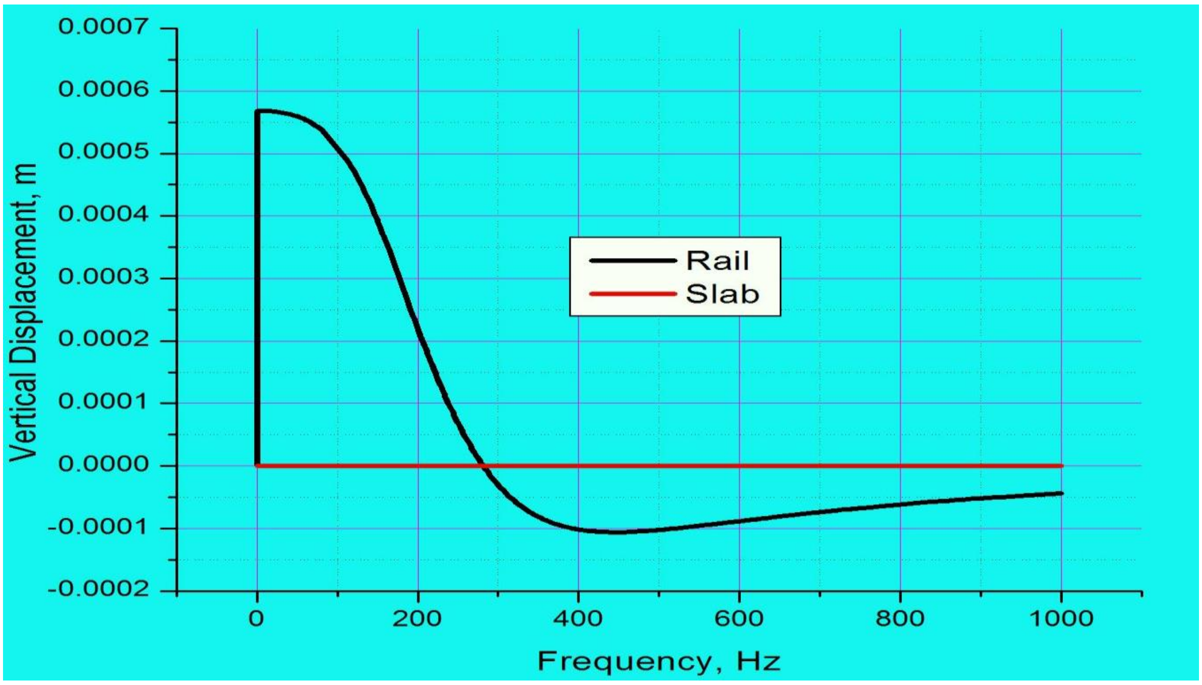


Figure 4-23: Vertical displacements of BBES rail and slab

The vertical velocity of the rail is maximum immediately after zero frequency whereas that of slab is at 200 Hz even though the magnitude of the rail displacement is much higher than the slab displacement. The rail displaces upward first and the slab down ward showing opposite displacements at the immediately after zero frequency. At higher frequencies both the rail and the slab displacements approach to zero. These can be seen clearly on figure 4.15 and 4.19.

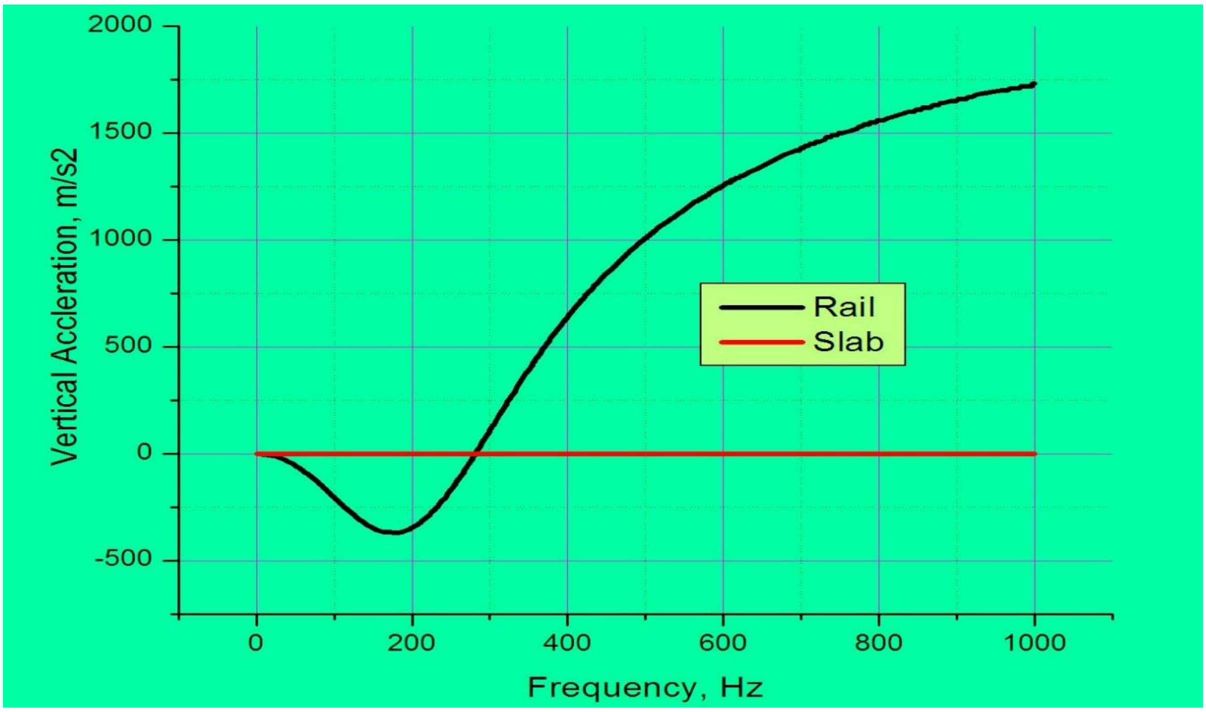


Figure 4-24: Vertical accelerations of BBES rail and slab

The trend of vertical acceleration is the same for both the rail and the slab negative in lower ranges of frequency and positive in higher frequencies. However the negative maxima are at frequencies of 180Hz and 250Hz for rail and slab respectively. These can be seen clearly from figures 4.16 and 4.20.

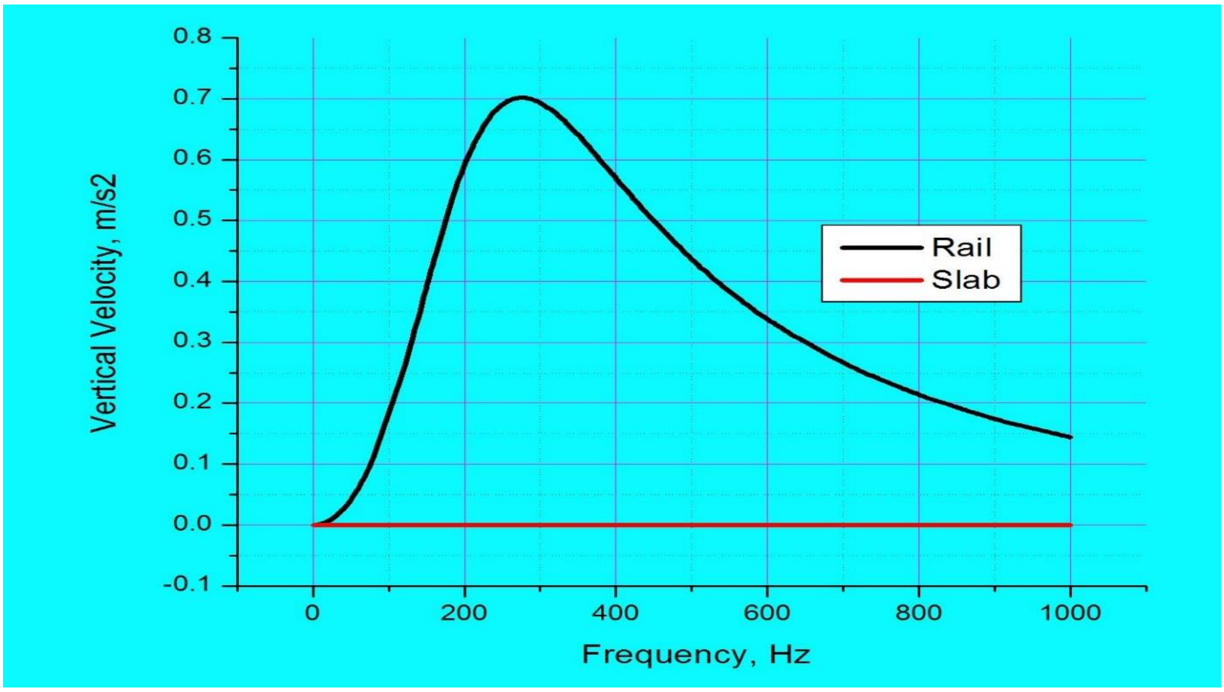


Figure 4-25: Vertical Velocities of BBES Rail and Slab

The vertical velocities of both the rail and the slab decreases to zero for higher frequencies. However the slab velocity is negative in lower frequencies whereas that of the rail is positive in all frequency ranges. These can be shown clearly from figures 4.17 and 4.21.

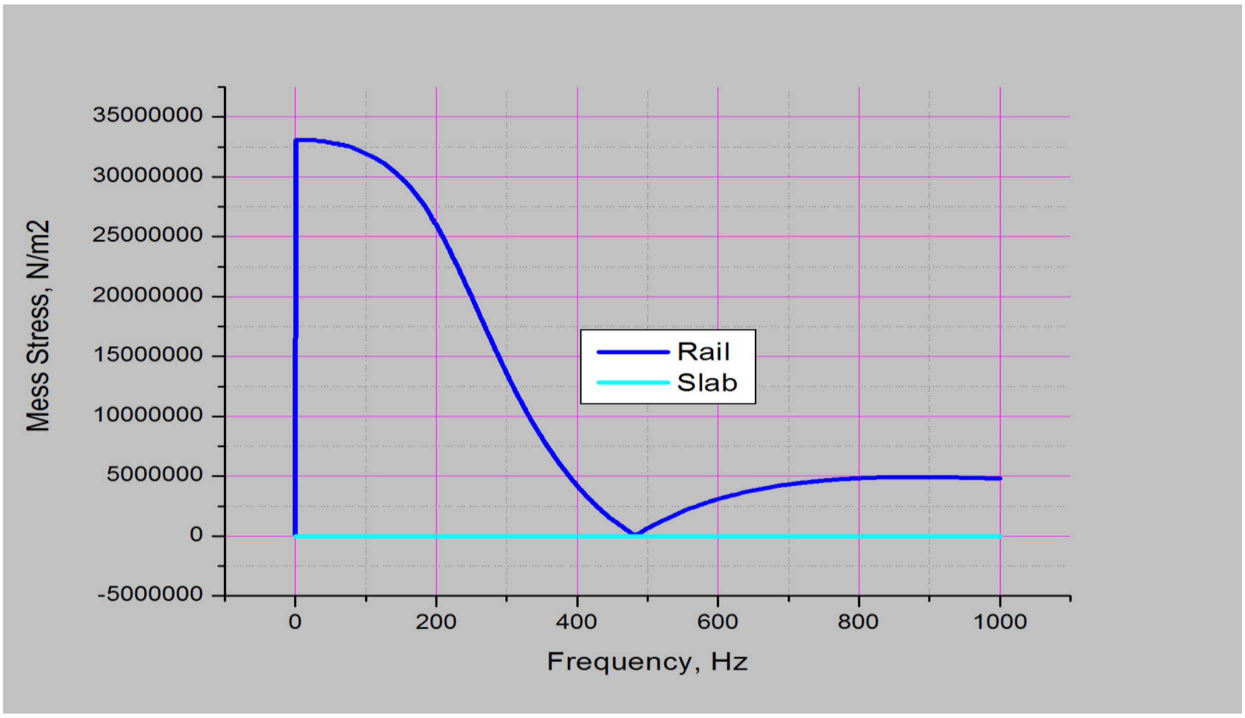


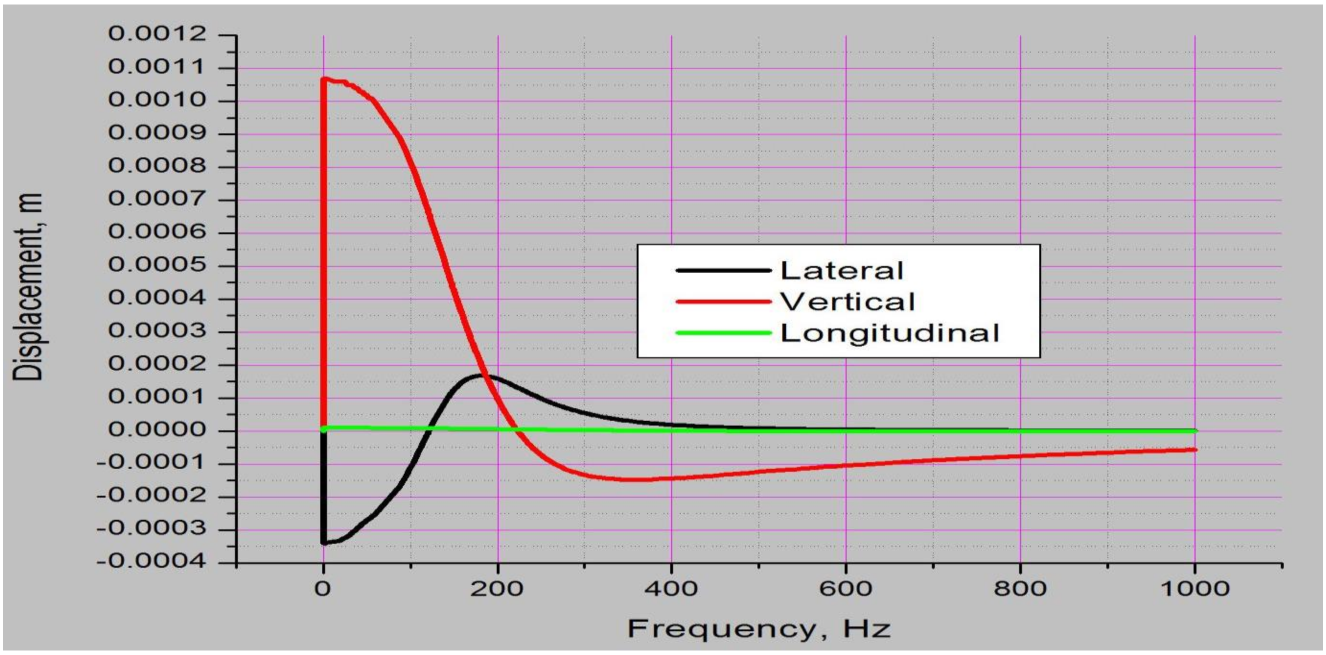
Figure 4-26: Mess stresses of BBES slab and rail

Average stresses are similar in trend for the whole frequency ranges. But the minima of the stresses are at different frequencies 480Hz for rail and 400 Hz for slab. These can be seen clearly from figures 4.18 and 4.22 a.

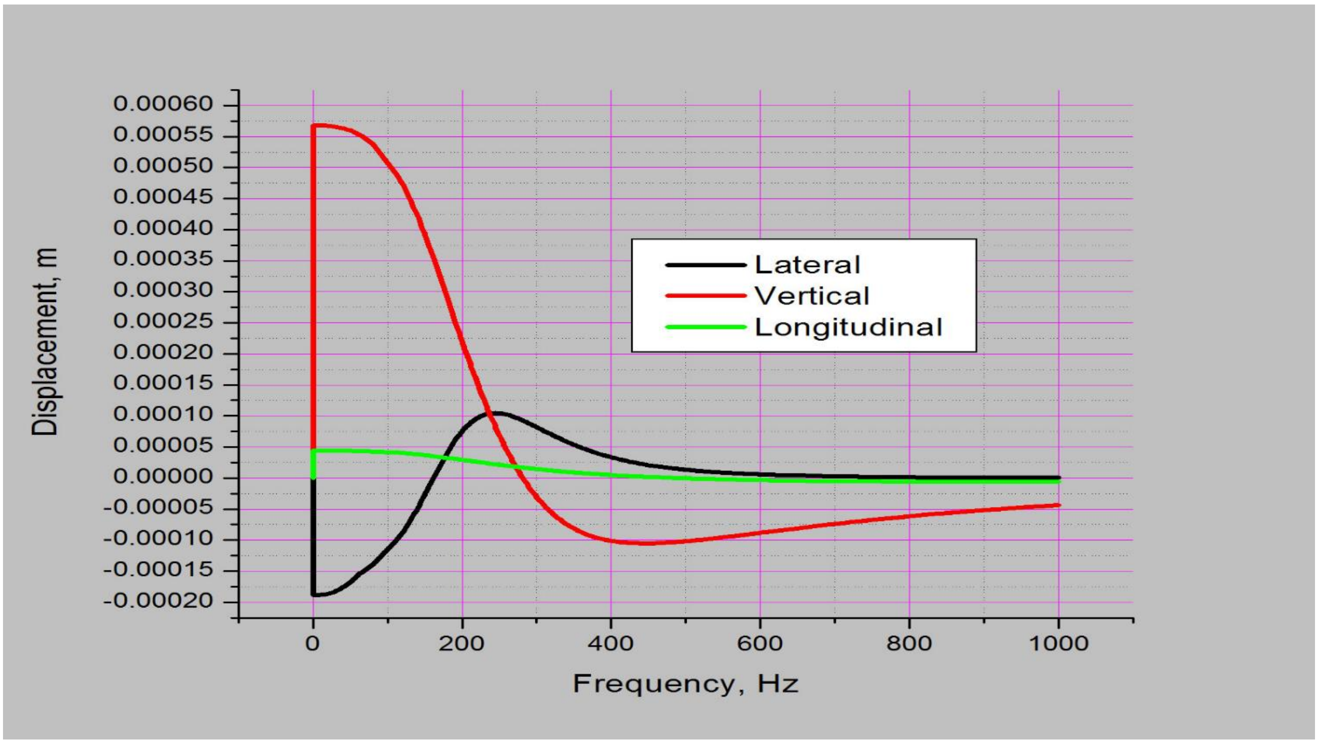
From figure 4.23 – 4.26 we can observe that the dynamic responses of RC slab is much less than that of the rail in almost all frequency ranges that theses should be compensated by the rail pad.

4.2.5 Effects of the Rail Pads

The rail pads have an important role in isolating high frequency vibrations in the track structure. The vertical rail pad stiffness studied here. It can be shown on fig.4.27 that the stiffness or softness of the pads have an important effect in isolating the vibration undulations. The stiffness or softness of the pads have an important effect in isolating the vibration undulations. However, the aggressiveness of dynamic force will increase with stiffer rail pads whereas the deflection will be the reverse.



a)



b)

Figure 4-27: Rail Middle node vertical deflection (a) 50MN/m (b) 100MN/m

4.3 Comparison of BBES and Ballasted Track

BBES and ballasted track systems are unlike in dynamic responses and performances. This comes from their components behavior and interactions between them. The dissimilarity on the other hand has economic as well as performance effects. The few number of components, the continuous support of the rail pad and the convenient geometric shape of the BBES opportune for better performance and lower life time cost compared with ballasted track system.

4.3.1 Dynamic Response Comparison

In Figure 4.29, the frequency spectra of the dynamic displacement of the rails is represented, obtained from simulations with a single vehicle wheel set. The displacements of the rail point beneath the vehicle's wheel set, and the displacements of the rail point 2.5m away would have been, are represented for the case of the ballasted track. In fig.4.28 the results for the BBES types of track are qualitatively similar to those of the ballasted track. It can be seen that the displacements of the point 2.5m away would have been, are much smaller than the displacements beneath the modelled load in the case of both the ballasted track and BBES , at all frequencies. In the case of the BBES, after frequency 290Hz the direction of the deflection changes still the magnitude being large. In all frequency ranges shown in the graph the deflection for BBES is larger than that of ballasted showing BBES is more flexible than ballasted. The dynamic effect for flexible track is lower so that BBES is good in dynamic load.

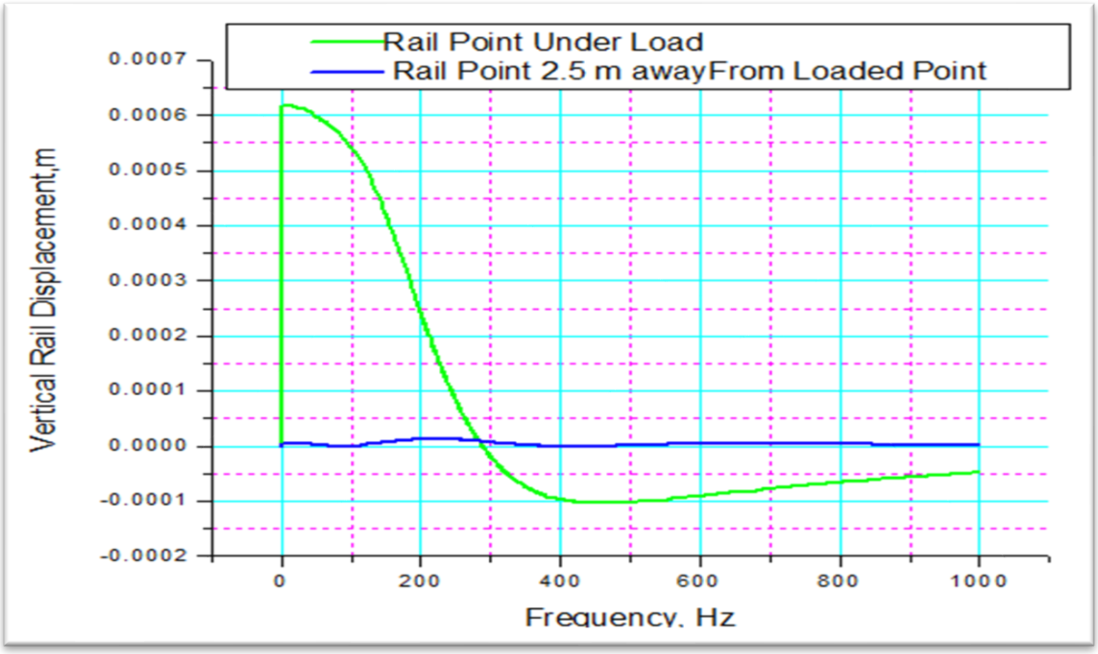


Figure 4-28: BBES frequency spectra of the dynamic rail displacements of the rail obtained from simulations with the FEM Steady State model and with a single load, at the point beneath the load (green line), and at the point 2.5m away the single load would be (blue).

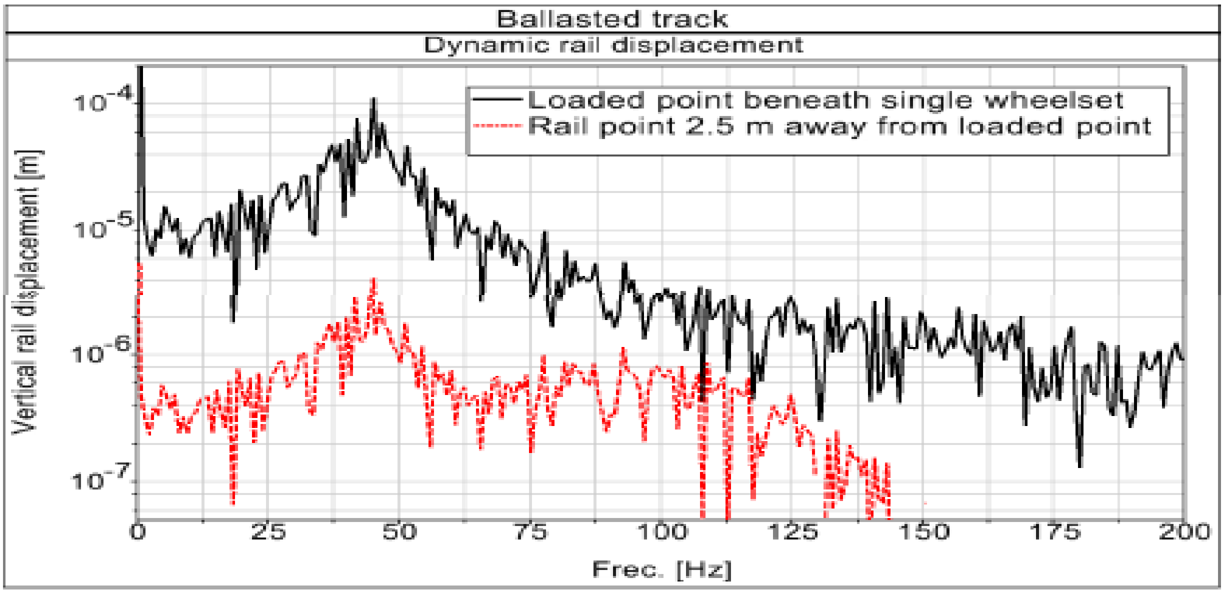


Figure 4-29: Ballasted track frequency spectra of the dynamic rail displacements of the rail obtained from simulations with the FEM vehicle-track models and with a single vehicle wheel set, at the point beneath the wheel set (solid line), and at the point 2.5m away[26]

In ballasted track the range of resonance frequency most susceptible to dynamic effect is known as pinned-pinned resonance frequency. This is the highest (850 Hz to 1200 Hz), which occurs when the wavelength of the bending waves of the rail is twice the sleeper spacing. In this case, the bending vibration of the rail has nodes at the supports, i.e. at the sleepers. The pinned-pinned frequency is so lightly damped; mainly the steel rail material itself (propagating waves along the rail) is involved in damping this vibration and very little vibration energy is transmitted to the surroundings (ballast). [7] However, in BBES the frequency range to mostly prone dynamic effect is from zero to 500Hz. This shows that ballasted track is sensitive for higher frequencies whereas BBES is for lower frequencies.

In BBES, the resonance frequencies will be dissipated or damped by the continuous elastic rail pad. The pin-pin amplitude vibration in ballasted track however limit high dynamic effect causing loads operations like for high speed trains i.e. not applicable or larger rail section has to be selected.

4.3.2 Economic Comparison in LCC (Life Cycle Cost))

Life time cost is the direct or indirect costs that are to be expend throughout the whole life of the track intended to be used as track.

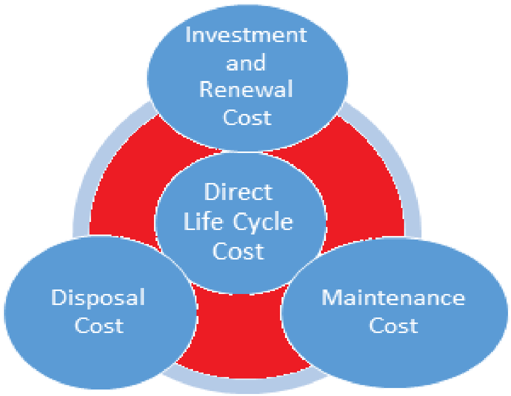


Figure 4-30: Direct Life Cycle Cost

The life cycle cost scope in addition to direct costs described on the figure above includes: semi direct cost like working possession time (operation cost and train delay), society loss like passenger loss and train operators costs, environmental impacts (accidents, pollutions, vibrations' and noise).[13] Transport time reduction (using high speed and avoiding maintenance time delay).

Table 4-1: Comparison of LCC of BBES and conventional ballasted track [1]

	Ballasted Track	BBES	Remarks
Investment			
Ballast	Required	Not required	
Sleeper including fastenings	Required	Not required	
Rail (including freight)	Required	Required 25% heavier than CEN 60	
Under sleeper pad	Required	Not required	

Subsoil measurement	Required	Required	
Installation costs			
Rail renewal	Frequent	Less frequent	• Greater mass per meter • Continuously vertically and laterally support • Greater headwear allowable • 30% longer service life
Disposal or recycling of materials costs	More components to be disposed and fewer components to be recycled	Fewer components to be disposed and more components to be recycled	• Rail can be recycled like any metal • Pad can be recycled or disposed as any inert west • Slab can be crushed and reinforcement recycled • Ballast continuous extraction and transportation needed
Residual value		Have Residual value	BBES has about 60 years design life and ballasted track much less design life in which the difference is residual life in which the cost difference is residual value.
Maintenance			
Tamping	Required	Not Required	Total tamping cost saved in BBES Ballast drop and regulation availability of track during tamping are additional expense in ballasted track
			Direct ballast cleaning saving in BBES

Ballast cleaning	Required	Not Required	Planning to train and manage the cleaners, managing the staffs and availability of the track during cleaning are additional expenses in ballasted track
Rail grinding	Frequent	Less frequent	Continuously supported, high quality rail alignment and precise tolerance rail in BBES make corrugation development less
Manual visual inspection	High inspection frequency	Reduced inspection frequency	The less components in BBES reduces inspection frequencies
Control of vegetation	Easy for vegetable to incubate	Impossible for vegetable to incubate	Vegetable incubation will decrease the ballast quality so that it needs controlling mechanism needed.
Inspection vehicle (e.g. Track recording vehicle)		Vehicular inspection is to be applied	Since degradation rate and mode of failure are low, vehicular inspection frequency is low.
Ultrasonic inspection		Less ultrasonic inspection frequency	Vertical and lateral continuous support and larger critical defect size make fracture frequency of the web low so that ultrasonic inspection frequency low.
Drainage	Problematic	Less problematic	Little or no fines interring the drainage system

			Presence of slab structure will eliminate water interring the structure Therefore maintenance burden for drainage will be reduced
Re-padding	High frequency of pad replacement	Low frequency of pad replacement	Pad in BBES has twice life span than that of ballasted track.
Day-to-day track maintenance	Many day to day maintenance activities	Less day to day maintenance activities	Replacing fastenings, discrete replacement of insulators, sleepers and ballast in ballasted track.

4.3.3 Performance Comparison

Performance of BBES can be understood from resistance to different loads perspective and from functional advantage to conventional track system point of view. Mainly Performance of the track is determined by the change in clamping force, longitudinal restraint, vertical stiffness and rail position, and visual inspection of the components during test.

Table 4-2: Average Test results of for BBES [1], [14]

Test	Initial testing result	Post-repeat loading result	% Change	EN13481-5 Specification
Clamping force	5.9KN/650MM	5.8KN/650mm	2% Decrease	change ≤ 20%
Pull-out force	15.3KN/650mm	15.7KN/650mm	3% Increase	
Longitudinal rail restraint	11.1KN/650mm	10.1KN/650mm	11% Decrease	change ≤ 20
Vertical Stiffness	25.7KN/650mm	30.8KN/mm/650mm	20% Increase	change ≤ 25%

The test results show that BBES system have met requirements specified in current European and British standards. [1], [14]

Longitudinal Restraint

Unlike the conventional ballasted track BBES do not have discrete rail support with fasteners to be retained longitudinally. Rather, the rail has a continuous resilient pad support embedded in a shell. A pad pre-compression & friction coefficient between the pad, the rail and the shell combined together to resist longitudinal movement. According to BS/European standard for railway requires longitudinal restraint greater than 9KN for UIC 60 in which BB14072 rail has 22% greater cross-sectional area so that it requires 22% greater longitudinal restraint (11KN). But the test results for BB14072 gives 16.2KN. [1], [17]

Vertical Stiffness

The elastomeric pad plays the role for vertical stiffness characteristics of Balfour Beatty Embedded Rail System. The vertical stiffness characteristics of this track system can be adjusted simply by changing the density of the elastomeric pad to suit specific track and vehicle designs and any other requirements needed on standards. Varying vertical stiffness is possible over a wide range since the action of longitudinally restraining the rail is separate from the job of rail suspension unlike traditional ballast fastening systems which use the rail pad to act both as a suspension component and as a medium which the rail is fastened against so that stiffness variation is limited to provide sufficient longitudinal rail restraint. [1], [17]

Clamping Force

The geometric interlock between the rail foot, pad and shell and the friction provided by the pre compressed pad walls against the rail web are responsible for clamping force in BBES. According to European standard for railway requires clamping force change of initial and repeat loading $\leq$ 20% in which BBES has only 2% change. [1], [17]

The other performances of the track are functional advantages like derailment protection and sound reduction when compared from other track systems.

Derailment Protection

Derailment is the most responsible cause for train accidents in almost all types of track. However, in BBES the slab is designed with barrier to protect derailment as shown in figure 4.31. [14]

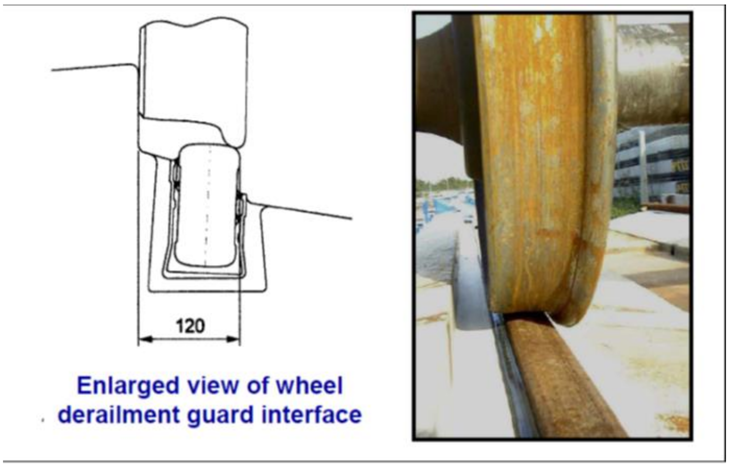


Figure 4-31: Derailment Protection of BBES [14]

Sound Reduction

Resilient fasteners, ballast mats, resiliently supported ties and some part the ballast itself plays the role of sound reduction in conventional ballasted track. [21] However, tests for sound pressure clearly shows sound reduction is better in BBES. The vertical and lateral continuous resilient pad in BBES has a very good sound reduction capacity so that sound pollution is reduced. [1], [14]. We can observe from figure 4.32 that BBES has better sound reduction capacity than that of ballasted track.

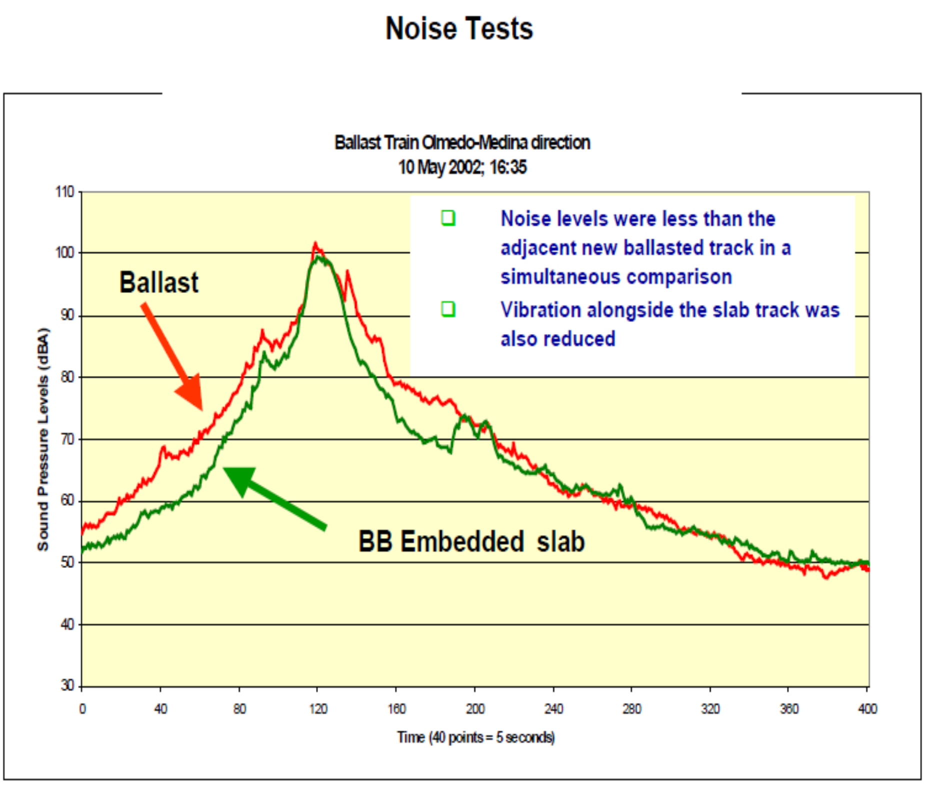


Figure 4-32: Sound reduction capacity of BBES compared

4.4 Balfour Beatty Embedded Rail Track System in Ethiopia Context

From the binging legacy steel sleeper track system to the recent under construction concrete sleeper track system, Ethiopia has experience of conventional ballasted track system except in short segments in tunnels and bridge. The rail, fastenings, bolts, rail pads and under sleeper pads are some of the components imported from abroad. It is well clear that importing most components have negative economic implication.

4.4.1 Potentials

From the properties and other features of the components of BBES, it can be assessed as in Table 4.3 if there are potential capabilities to manufacture in Ethiopia so that no need of foreign currencies. This assessment is done by comparing required qualifications of BBES components and experiences of companies in Ethiopia to produce products of nearly similar properties. Maximum modifications of the companies to produce the components of BBES shall be proper mix design, ambient temperature, and proper molds.

Table 4-3: BBES components manufacturing potential in Ethiopia [1], [12]

Components	Required specification	Potential Producer company	Row material	Previous experience
Pad Production	• U shaped elastomeric, 2m length. • Stiffness range from 10KN/mm/650mm upwards. • Tolerance +/-25mm. • Varied densities and base dimensions according to spring coefficient needed • 7mm thickness is commonly used	Any rubber manufacturing companies E.g. Horizon Addis Tier Factory	High quality foamed polyurethane , Rubber, chemicals	Horizon Addis Tier Factory well experienced in any mix ratio with any required conditions
Shell production	• Fiber Reinforced plastic (FRP) composite, • manufacturing tolerance of +/- 0.25mm,	Any rubber manufacturing companies E.g. Horizon Addis Tier Factory	Fiber, plastic composite	Horizon Addis Tier Factory well experienced in fiber reinforced tier production
Rail Production	• BB14072 profile, head surface geometry (radii, width @ gauge, etc) identical to CEN 60/UIC 60 rail. • Hot rolled in a rolling mill in any length, manufacturing tolerance +/- 0.3mm. • Designed Based on (European standard BS/EN/13674-1:2003 vingole Railway rails 46kg/m and above.) • Weight 74kg/m	Kality Metal Factory Metal Engineering Corporation		Have experiences of producing metals in different molds. Eg. Sledge Hammer

Slab & Grout preparation	• Non-shrink, cementitious • 28 days strength about 30% higher than surrounding concrete. • about 50mpa strength, • 6m long, • 2.15m wide and • 0.35 m deep.	Any 1st level Contractor	Reinforcement fiber or steel, Aggregates, Cement,	Well Experienced

4.4.2 Limitations

Limitations of BBES are as follows:-

- Needs high class of professional due to its small tolerance of manufacturing components
- It needs robust gantries
- Not possible to run the geometry recording trolley when muntries are installed
- Institution of curve with high cant value to control the rail inclination is uneasy
- Supply of rail with this new type is rear
- Maintenance requires specific techniques, provision of dedicated equipment, and extensive training of the maintenance staffs.
- No vertical adjustment is possible to allow for rail wear or settlement
- Doesn't provide any possibility of geometry adjustment is an inconvenient
- Accommodation of signaling device bonded on rail would be difficult

5 CONCLUDING REMARKS

5.1 Conclusion and Recommendations

This thesis aims to investigate dynamic performance of Balfour Beatty Embedded Rail Track System (BBERS) using Finite Element analysis method. Conclusion about the results and suggestions for future research are presented below.

5.1.1 Conclusion

The dynamic performance of a Balfour Beatty Embedded track System has been studied by means of numerical simulations in the frequency domain. In addition different cone and prone of the track system are also discussed. Typical model have been constructed in order to study the three dimensional dynamic phenomena at different frequencies using of systematic methodologies and standard tools offered in a commercial ABACUS software. Dynamic performance and economic benefits of BBES is also presented comparing with that of traditional ballasted track.

From the modeling and analysis results presented from previous chapters we can conclude the following remarks.

- From the modal dynamics it can be concluded that lower modes of vibration can represent and explain the dynamic response of the structure. The first 30 modes are with high value of most dynamic responses i.e. Mass participation both in lateral and vertical direction, kinetic energy and vertical& lateral slab displacement. The rail displacement however continues it's up and down amplitudes through all modes. The lateral deflection start to vibrate first and the vertical continue.
- From the frequency domain dynamics the model shows that the first 500Hz frequency range is responsible for most dynamic responses maxima as shown in the response spectra which implies it is at longer period the track vibrates so that dynamic effects on the track will not have serious problem.
- The model shows the rail pad stiffness affects the flexibility of the track that the softer rail pad deflects more so that decrease the dynamic effect.
- Comparing with the RC slab the BBES rail has larger vibration which comes from direct contact with the excitation load and the flexible rail pad support.
- From the comparison of the dynamic performance of BBES and ballasted track we can conclude that the continuous rail pad of BBES play a role in decreasing the dynamic effect by increasing the flexibility more than that of the pin-pin support of ballasted.
- Performances of BBES shows that it has European and British Standard acceptances.
- The study also shows that there is a potential to manufacture different components in Ethiopia that fulfil all the dynamic and other criteria even though it needs further investigations.

Therefore, at low and mid frequencies, up to a few hundred Hz, and when the effects of the parametric excitation are not important, very simple, are seen to be entirely satisfactory for the study of dynamic performance. The frequency ranges and vibration modes indicate that the track can sustain strong vibrations. This is due to the presence of continuous rail pad support. The performance, the few number of components and the better dynamic capacity of the track contribute to low life cycle cost comparing with the conventional ballasted track.

5.1.2 Recommendation

From previous study and discussion, BBES has been found more attractive and sound alternative than ballasted tracks. There are huge technical savings during construction and in-service maintenance as compared to conventional ballasted track. The technical are the less number of components and their precast and prefabricated nature which simplifies the design and construction quality of the track with fast construction duration. The life cycle (LCC) cost of the track is much less than that of the conventional ballasted track since has less frequency of maintenance during service period. In addition to economic benefit, dynamic response of the track is found to be attractive.

The author recommends this track type for Ethiopian Railway projects due to the following reasons and advantages.

- The components could be manufactured in Ethiopia from local raw materials with local companies even though it needs further research
- Due to less maintenance requirement it is highly recommended
- Short construction period it needs
- The technology can be easily adapted without very complicated technologies since components are mold based works.

5.1.3 Future Research

- The Balfour Beatty Embedded Rail Track System has different components which can be manufactured in Ethiopia. Therefore manufacturing and optimization of each component needs to be studied.
- Full scale dynamic modeling of the track to know the effects of track bed and subgrade on the dynamic performance is needed.
- The speed effect of the train shall be studied on dynamic performance.
- The track should be studied how to accommodate the utilities.
- Dynamic Comparison of BBES and Other Embedded Rail Track Systems

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APPENDIX

ABAQUS INPUT FILE KEYWORD SAMPLE

```
*Heading
** Job name: Job-steadystate Model name: BBES model
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name="BBES Rail"
*Amplitude, name=Amp-1
0.,     0.,     0.05,   0.31,   0.1,    0.59,   0.15,   0.81
0.2,    0.95,   0.25,   1.,     0.3,    0.95,   0.35,   0.81
0.4,    0.59,   0.45,   0.31,   0.5,    0.,     0.55,   -0.31
0.6,    -0.59,  0.65,   -0.81,  0.7,    -0.5,   0.75,   -1.
**
** MATERIALS
**
*Material, name=BBES
*Density
2400.,
*Elastic
3.91e+10, 0.22
*Material, name=Rail
*Density
7850.,
*Elastic
2.1e+11, 0.33
** ----------------------------------------------------------------
**
** STEP: frequency
**
```

```
*Step, name=frequency, nlgeom=NO, perturbation
*Frequency, eigensolver=Lanczos, acoustic coupling=on, normalization=displacement
, 1., 1000., , ,
**
** BOUNDARY CONDITIONS
**
** Name: BC-Slab BTM Type: Displacement/Rotation
*Boundary
Set-155, 1, 1
Set-155, 2, 2
Set-155, 3, 3
Set-155, 4, 4
Set-155, 5, 5
Set-155, 6, 6
** Name: BC-Slabraillong Type: Displacement/Rotation
*Boundary
Set-156, 3, 3
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, RF, RM, RT, TF, U, UR, UT
VF
*Element Output, directions=YES
E, EE, ER, ESF1, IE, MISES, NFORC, NFORCSO, S, SE, SF
*End Step
** ----------------------------------------------------------------
**
```

```
** STEP: steady state
**
*Step, name="steady state", nlgeom=NO, perturbation
*Steady State Dynamics
1., 1000., 20, 3.
*Modal Damping, definition=FREQUENCY RANGE
1000., 0.6
**
** LOADS
**
** Name: Load-1   Type: Concentrated force
*Cload, amplitude=Amp-1, real
Set-153, 2, -125000.
** Name: Load-2   Type: Concentrated force
*Cload, amplitude=Amp-1, real
Set-154, 2, -125000.
**
** OUTPUT REQUESTS
**
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Node Output
A, AR, AT, CF, RF, RM, RT, TA
TF, TU, TV, U, UR, UT, V, VF
VR, VT
*Element Output, directions=YES
BF, CENTMAG, CENTRIFMAG, CORIOMAG, E, EE, ESF1, GRAV, HP, LE, MISES, NE, NFORC, NFORCSO, P, PS
ROTAMAG, S, SF, TRNOR, TRSHR, VS
**
** HISTORY OUTPUT: H-Output-1
```

**

*Output, history, variable=PRESELECT

*End Step