Finite Element Dynamic Analysis of Subgrade Embankment Ballasted Railway under High Speed Train

Melaku Sisay Abebe

School of Transortation Wuhan University of Technology, 430063, Wuhan China
e-mail: fine_melak@yahoo.com

Hong Sheng Qiu

School of Transortation, Wuhan University of Technology, 430063, Wuhan Hubei, China
e-mail: qiuhhss@163.com

ABSTRACT

The impact of dynamic loading on ballasted railway track has become an important issue due to increased demand for high-speed freight and public transport, and because it leads to progressive deterioration and settlement of railway .In this paper, the LS-DYNA computer code is used to conduct finite element calculations for the dynamic analysis of a high-speed train running on ballasted railway track. The rails are modelled as beams of a plastic kinematic material, and the ballast and sub-ballast structure are modelled using rectangular prisms of an elastic material. The elastic beams representing the sleepers are placed 0.6 m apart. The load of a high-speed train is applied using a simplified finite element model. The commands RAIL_TRACK and RAIL_TRAIN LS-DYNA are applied to simulate the train's interaction with the track. The CONTACT_SINGEL_SURFACE and CONTACT_SURAFCE_SURFCE commands, which have not been applied in previous research, are used to model the contact between connected parts. The results indicate that the LS-DYNA program can be used to model a high-speed train running on ballasted railway track and to calculate stress–strain, deformation, and contact forces as well as sliding energy, which are crucial for in railway track maintenance and in designing new ballasted railway track.

Keywords: Dynamic analysis; ballasted railway; High-speed train; Finite element

INTRODUCTION

Improvements to running speeds on existing railway lines can economically improve rail transport, an increasingly important piece of the infrastructure given its efficiency and low environmental impact [1]. A modern rail network requires faster, more frequent, and heavier trains [2]. Such improvements can be challenging to effect, and depend on the existing track's geotechnical dynamics. The quality of the subgrade and track bed (and the dynamic loads on them) greatly influence the maximum safe running speed. Therefore, a deep understanding of the track dynamics and the track bed properties is necessary [3].

High-speed tracks can allow running speeds over 300 km/h, much faster than possible on conventional rail. The weight per axle of trains has also increased. Greater loads at higher speeds lead to higher stresses in the track, which can increase track deterioration, leading to passenger discomfort and safety problems. As a result, high-speed track is more costly to maintain than conventional track.

Accumulated experience from high-speed railways has shown that even if the trains have a relatively low axle load, their dynamic loading degrades the ballast and its subgrade, causing severe track settlement problems along the line. Such settlement will not stop until the tack is reinforced; left unmaintained, permanent deformations in the ballast, sub-ballast, and subgrade will follow with a severity depending on their quality and behaviour. As soon as the structure of ballasted track starts to degenerate, the variations of the dynamic train–track interaction forces increase, further promoting track deterioration. Commonly the ballast bed becomes unevenly distributed, resulting in loss of the full contact between the sleepers and the ballast bed, and leaving some sleepers suspended from the rails rather than resting on the ballast.

The finite element method is a powerful and well-used general method of structural analysis. It can be applied to various physical complex systems; the analysed problem can have arbitrary geometry, loads, and support conditions [4]. Also, the meshing process can mix elements of different types, shapes, and physical properties. This numerical method is useful when the problem is too complicated to be solved satisfactorily by classical analytical methods. Many finite element software programs are available for structural analysis: the LS-DYNA program is one of the most powerful and versatile. It is effective and efficient, especially for transient and impact load analysis, and combines the advantages of other finite element software. It can handle a wide range of element types and material models in every area of engineering [5].

Numerical modelling is crucial to the analysis of the dynamic responses of the combined system of a high-speed railway's ballast, sub-ballast, and subgrade—collectively called the track substructure. A typical profile of track resting on its substructure can be modelled, analysed, and simulated using LS-DYNA. Computational analytical parameters determined by selecting a relevant train load must be calculated at different time steps. The lateral distributions of vertical displacement, stress, strain, and vertical acceleration through the substructure must be analysed to model its dynamic response to the load[6].

Ballast is an essential component of the track structure due to its mechanical properties: its structure can deform and readily return to the undeformed state without suffering damage. It is also easy to construct and maintain. Track engineers, both practical and theoretical, tend to focus mainly on the track superstructure (i.e., the vehicle, rails, sleepers, and fasteners), and have devoted less attention to the substructure [7]

Operational expenditure on preventive maintenance of railway substructure has increased because of the difficulties arising from ballast fouling. Keeping the ballast as clean as possible is an essential part of maintenance to ensure its longevity. The processes of removing and cleaning ballast are costly, and such maintenance interrupts the regular use of the track. Ballast problems can allow vibrations to deform the railway track structure, and it is important ensure that the ballast functions well to minimise track vibrations.

Track can remain in good order by ensuring the quality and suitability of its individual components, here broadly categorized as the superstructure and the substructure. The superstructure thus includes all non-granular components of the track, while the substructure includes its granular components.

To withstand axle loads higher than 250 kN, rails need to be of high strength, joint less, and massive, preferably with a weight greater than 60 kg/m [3]It is therefore desirable to connect the rails using elastic fasteners to pre-stress or reinforced concrete sleepers or steel sleepers, which are more durable than traditional wooden sleepers. The ballast layer, for which the main functions are to ensure the train load is evenly distributes and to keep the sleepers in their required positions, needs to have a nominal thickness greater than 300 mm to provide sufficient resilience, strength, and energy absorption [8]. These structural criteria, however, have not yet led to a general consensus about the requirements of ballast materials.

Variations in the ballast's support condition and differences in its stiffness influence the risk of damage to the track and trains. There are several ways to measure the vertical stiffness of the substructure components [9].If stiffness is evaluated for a track system, it could be used as a parameter to optimize maintenance through allowing the identification of local weaknesses along the track and hanging sleepers.

GAP IN EXSITING RESERCH

Our literature search revealed no sufficiently in-depth report of the dynamic responses of ballasted railway track specifically studied using the LS-DYNA finite element computer code, a program capable of modelling the dynamic forces approximately as they occur in the real world. Most previous studies have focused on finite element simulations of static loads, and have not sufficiently addressed dynamic effects. Besides contact between the wheel and rail, rail and sleeper, the sleeper and the ballast and the sub-ballast and subgrade were not studied perviously. However, these forces can be considered using the LS-DYNA program, and this paper presents the first use of this program to model these forces.

PROBLEM STATEMENT

Increasing economic growth requires improving the transport infrastructure in a way that is environmentally sustainable with regard to factors such as noise and emissions. Railways are a promising means of transport in this respect, and railway owners have sought to increase the capacity of their networks through increasing the capacity of each train and/or making the train faster.

Railways require constant improvement and development to remain competitive against air, road, and sea transport. This calls for highly technical yet affordable technologies to allow faster trains to carry more goods and people efficiently, safely, and comfortably without requiring expensive maintenance or causing environmental damage [10].

Ballasted railway track settlement occurs as a result of the dynamic loading of high-speed trains and fatigue load. The dynamic loading of a train degrades and deforms the track substructure, leading to track settlement[11,13]. The severity of settlement depends on the quality and behaviour of the substructure components. Any initial degeneration of the track structure significantly increases the variations of the dynamic train–track interaction forces, thereby accelerating track deterioration.

The finite element method is a powerful and generally applicable method for structural analysis, being able to model and simulate nearly any engineering structural system. It is particularly useful for modelling structural analysis problems.

Finite element analysis is conducted using the LS-DYNA finite element computer code, which has the advantage of incorporating a wide range of element types and material models. This code is particularly effective for transient and impact load analysis. Explicit finite element methods were originally formulated to solve problems in wave propagation and impact engineering, but currently find many other engineering applications such as sheet metal forming, underwater simulations, failure analysis, glass forming, metal cutting, pavement design, and earthquake engineering .

Ballasted high-speed railway track generally requires a strong substructure to withstand the dynamic responses that can potentially cause its deterioration and settlement. The dynamic responses of the track should be considered during the design and feasibility studies of the ballasted structure, with numerical simulation using a finite element computer code such as LS-DYNA being potentially applicable for this purpose.

The objective of the paper is to perform a finite element simulation of a high-speed train load on ballasted railway track using the LS-DYNA computer code. The analysis models the stress and plastic strain state, vertical displacement, internal and kinetic energy, and sliding energy.

MATERIALS METHODS

Finite element method

The finite element method is a leading structural tool; however, several factors should be considered. First, the method is an approximate analytical procedure whose accuracy usually depends on the level of discretisation of the mesh. Second, the accuracy also depends on whether the major influences on the problem behaviour are included in the analytical idealization. Finally, the simulations must be properly interpreted to ensure the results are meaningful.

Geometry

The track geometry is constructed in two main parts: the superstructure and the substructure. Of the superstructure components, each rail is considered as a prismatic beam element as per Timoshenko beam theory; the sleepers are modelled as rectangular prisms, and are considered as elastic beam elements; the fasteners and rail pads are considered as discrete spring and damper elements. The substructure comprises ballast and sub-ballast modelled as rectangular prisms that transfer the load toward the subgrade foundation, another rectangular prism Figure1 Train load on ballasted railway track

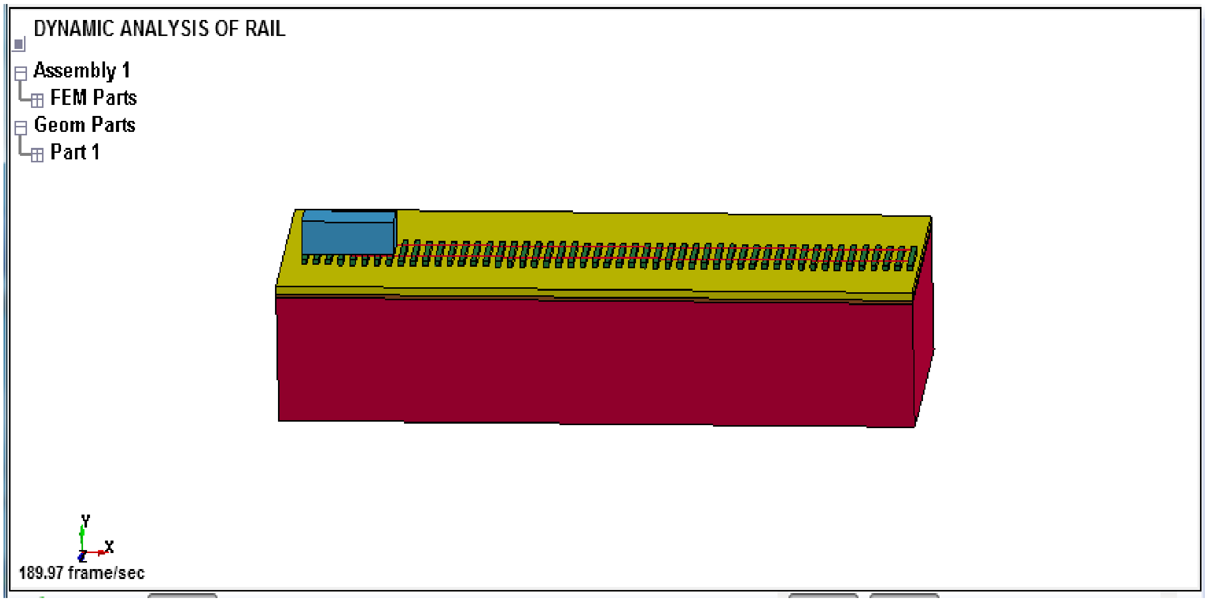

Figure 1: Train load on ballasted railway track

Material Model

Finite element analysis of a high-speed train on ballasted track is performed in the LS-DYNA code, with a focus on the load distribution along successive sleepers and the underlying substructure. The material model includes two parallel rails as prismatic beam elements of a plastic–kinematic material deformable in flexure and shear. The sleepers, spaced at 0.6 m, are modelled as rectangular prismatic elastic beams vibrating only vertically and laterally using beam finite elements and respective constraints. The ballast and sub-ballast are each modelled as a rectangular prism of linearly elastic material bounded by unrotatable and unmovable side and bottom boundary conditions. Soft subgrade soil is considered as a rectangular prism of linearly viscoelastic material bounded by unmovable side and bottom boundary conditions. The train is modelled as a rigid body. Table 1 lists the material properties of each component.

Table 1. Material properties of each component of the high-speed railway model

Component	L(mm)	W(mm)	D(mm)	Density($\frac{g}{mm^3}$)	Young modulus(MPa)	Poison ratio
Rail	30000	150	176	7850	$2*10^5$	0.25
Sleeper	2525	250	243	$24*10^{-3}$	70	0.3
Ballast	30000	10000	350	$16*10^{-4}$	150	0.35
sub ballast	30000	10000	150	$19*10^{-4}$	80	0.35
Subgrade	30000	10000	5500	$20*10^{-4}$	10	0.4
Train (rigid)	4500	1500	2000	$7.67*10^5$	$2.1*10^5$	0.25

Note: These are raw data for the Yujiatou ballasted railway track from the Hubei Design and Construction Limited Company.

Finite element model

The LS-DYNA code can simulate a model as close to the actual physical system as possible. Here, a three-dimensional finite element model of a high-speed train on ballasted railway track is created using solid brick elements to represent the substructure components and beam elements to represent rails. As an initial step, all finite element analysis requires meshing of the model, whereby the model is divided into a number of small elements. After loading, stress and strain are calculated at integration points of these small elements. Selecting an appropriate mesh density is important. A mesh size of 10 mm is used here, as it has previously provided more satisfactory results than other mesh sizes. Figure 2 shows the three-dimensional finite element model of the ballasted railway track, including the boundary conditions and a moving train.

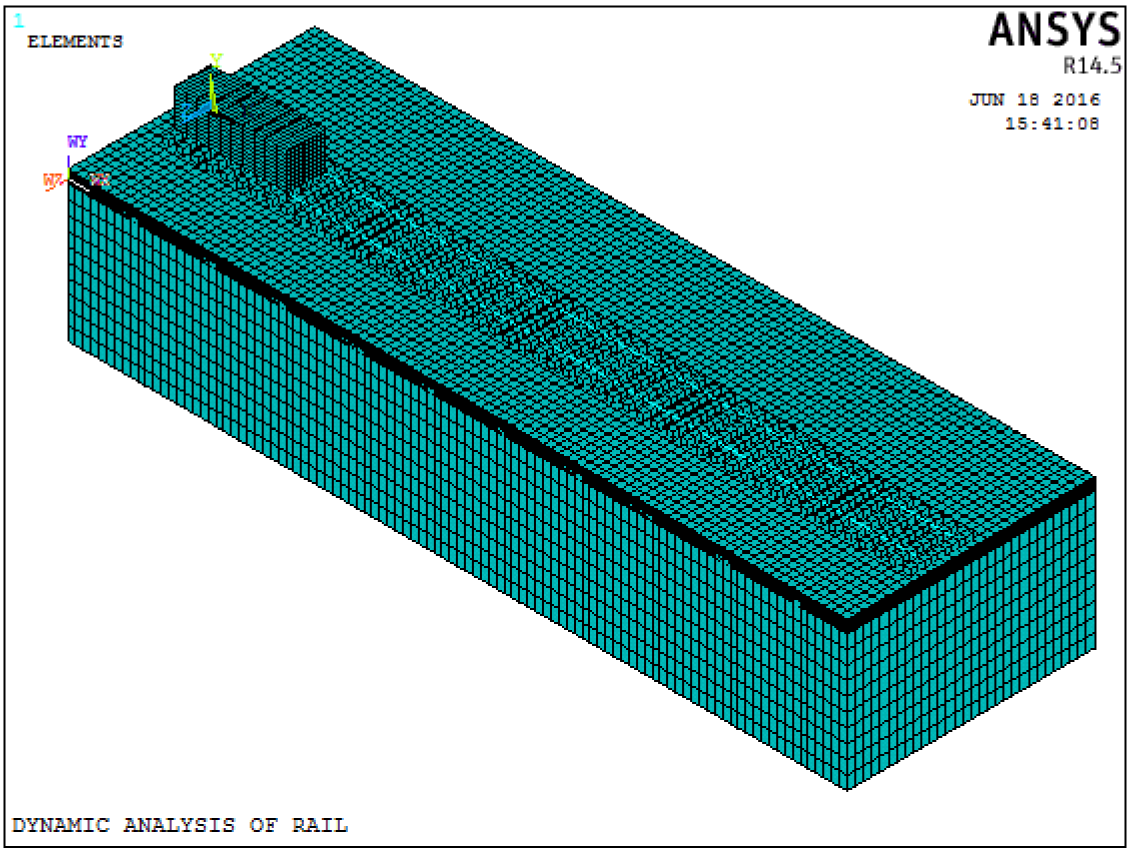

Figure 2:Three-dimensional finite element model of ballasted railway track.=

Boundary Conditions

Modelling boundary conditions is often the most critical factor in achieving sensible, reliable data from a finite element analysis (LS-DYNA Keyword User's Manual, 2014). To ensure a good representation of the physical conditions, several tools are used to provide proper boundary conditions, such as fixing the ends to be unmovable. The load application is also important and is discussed in detail

Load application

The dynamic load on the track component is modelled using the prescribed motion rigid finite element LS-DYNA computer code, and the static load component of the train–rail contact is modelled as an axial load node set command. Details of the prescribed motion and static axial load protocol are discussed here. For both the dynamic and static load, the displacement direction and rotation are restrained in the X-, Y-, and Z- axes.

Static load

The static train load is applied to the wheel–rail contact. Each axel comprises two wheels sets (an axle with two wheels). The total load on both axles is equivalent to 320 ton, distributed equally at the four wheels (i.e., 80 ton per wheel). The load is defined and prescribed in LS_DYNA as the LOAD_NODE SET command. Figure 3 shows the distributed static load with respect to time.

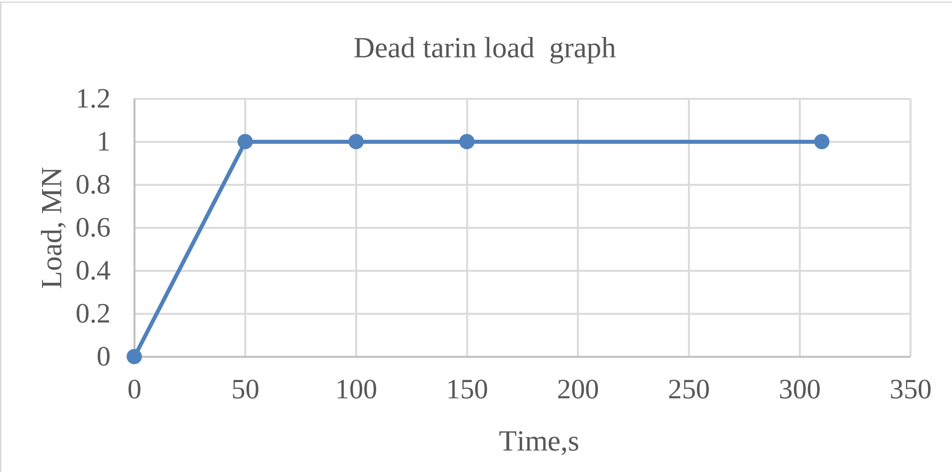

Figure 3: Plot of train load with respect to time.

Dynamic load

The dynamic load is prescribed by the LS-DYNA software in its BOUNDARY_ PRESCRIBED_MOTION command. The finite element model in LS_DYNA defines the movement of the train in terms of displacement with respect to time. A maximum permissible static axle load of 160 kN is assumed throughout. The train is moving at 350 km/h. The axle spacing and bogie wheelbase, as well as the train speed, corresponded to the dimensions of the track model, particularly the 0.6 m sleeper spacing, to ensure that each wheel set is located exactly above a sleeper at each considered moment of time. Figure 4 depicts the train velocity in terms of its displacement with respect to time.

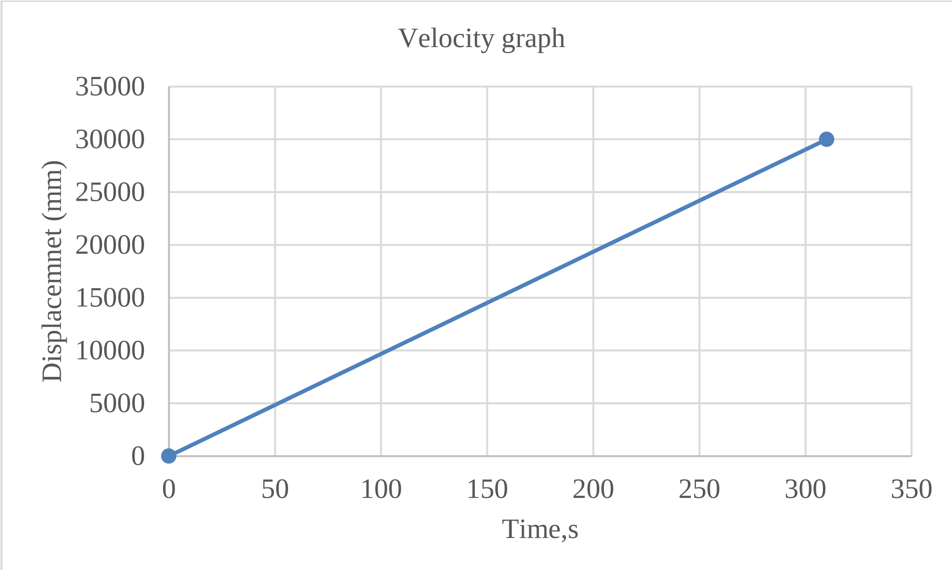

Figure 4: Plot of the train's displacement with respect to time.

RAIL_TRACK and RAIL_TRAIN codes

The contact between the vehicle and the track is important in the simulation, and LS_DYNA is the only software appropriate for this. Its RAIL_TRACK and RAIL_TRAIN commands are used here.

Contact algorithms

The contact algorithm is unique to LS_DYNA. It models the contact between parts, segments, and nodes. It is defined and applied here for the first time on ballasted railway track. This contact algorithm is defined as the commands CONTACT_AUTOMATIC_SINGEL SURFACE, CONTACT SURFACE_SURFACE and CONTACT TRANDUCER PENALITY, which are identified here as being applicable to model the contact between the rail, sleeper, ballast, sub-ballast, and subgrade. The algorithm uses a penalty method to model the contact interface of the different track components.

RESULT AND DISCUSSION

Ballasted railway track deformation

The finite element analysis results for a high-speed train on ballasted railway track are calculated and presented here. They yield interesting information regarding the global and local dynamic responses of the track to the load.

In general, implicit methods have the form

$$U^{n+1} = f(\acute{u}^{n+1}, \acute{u}^{n+1}, u^{n}, \ldots.) \quad (1)$$

and therefore the computation of the current nodal displacements requires knowledge of the time derivatives, which are unknown, meaning that simultaneous equations need to be solved.

On the other hand, explicit methods have the form

$$U^{n+1} = f(u^n, \dot{u}^n, \ddot{u}^n, u^{n+1}, \dots \dots) \quad (2)$$

Meaning the current nodal displacements in the model can be determined completely from the previous known displacements and their time derivatives.

The total track deformation is calculated in LS-DYNA along successive sleepers, as shown in Figure 3. The maximum deformation due to the dynamic train load is 0.3 mm. The calculated results suggest that the train causes significant track settlement, and thus regular track maintenance is required. Dynamic loading degrades only the ballast and underlying layers if the track is suitably maintained, and the damage can thus be controlled. Otherwise, settlement follows from permanent deformation of the ballast and the underlying soil, and is detrimental to the railway. Of course the severity of the settlement depends on the quality and behaviour of the substructure components, and any damage mitigation plan must consider these factors. Once the track structure starts to degenerate, the variations in the dynamic train–track interaction forces increase, accelerating the deterioration. Very often the ballast bed becomes unevenly distributed, which, because the sleepers are fastened to the rails, results in the loss of full contact between the sleepers and the ballast, leaving some sleepers hanging from the rails. The occurrence of hanging sleepers can be investigated by finite element analysis. Overall, the dynamic interaction of a high-speed train with ballasted track significantly deteriorates and deforms the track.

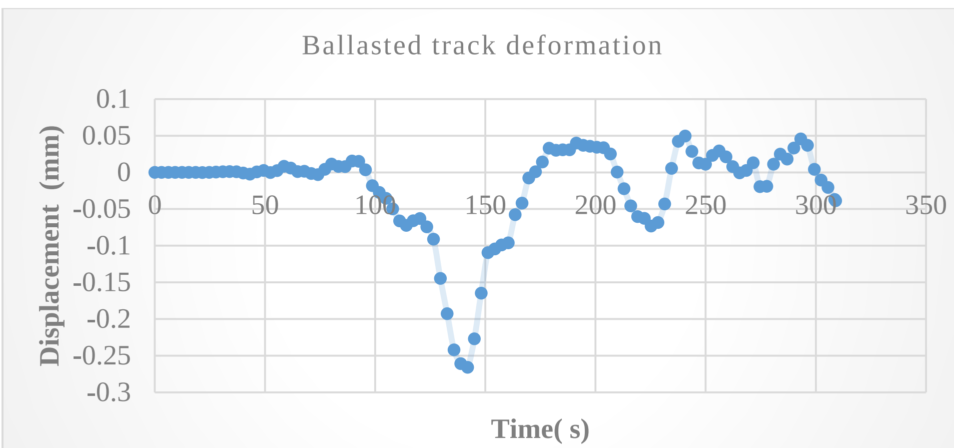

Figure 5: Track displacement due to the dynamic load of a high-speed train.

Stress–strain state of the track

Modelled contours of the stress and plastic strain are presented in Figure 6(a) and (b), respectively. They give information about the behaviour of the track and the stress–strain state of the foundation under a dynamic load.

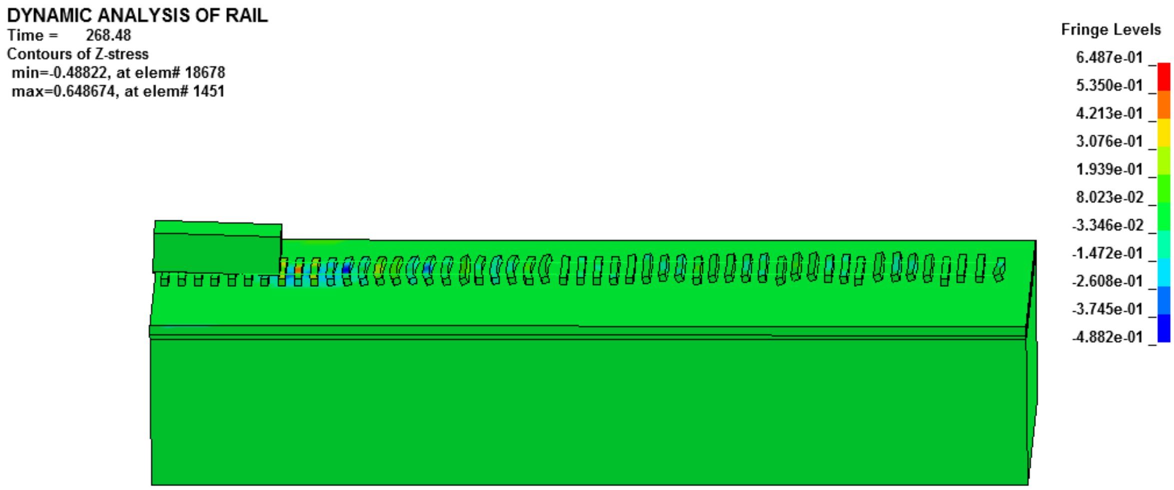

Figure 6(a). Stress state of ballasted railway under high-speed train load.

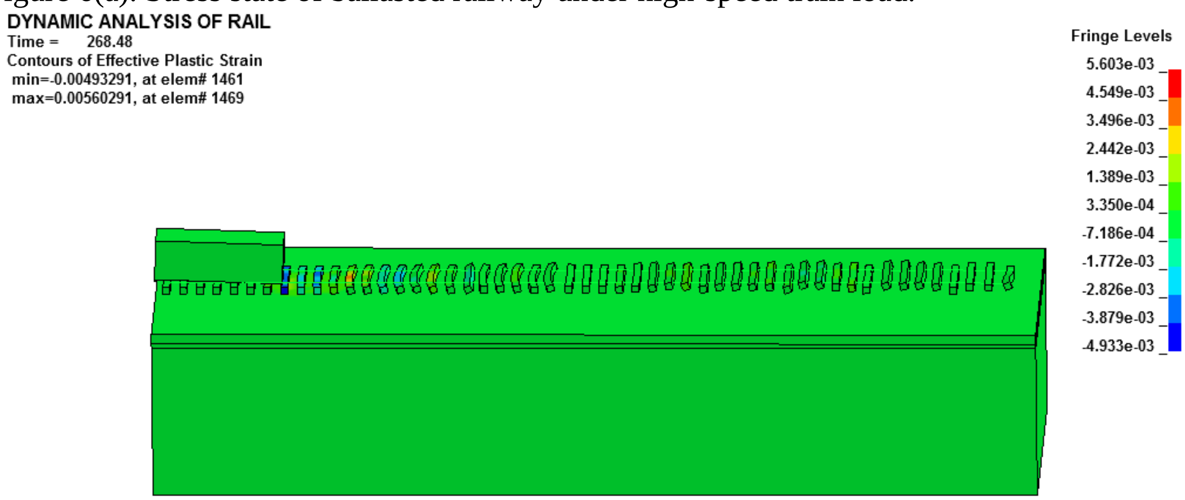

Figure 6(b). Plastic strain state of ballasted railway under high-speed train load.

Sliding energy

The sliding energy measures the penetration of one part into other components. Figure 7 depicts the calculated sliding energy and shows positive values, which means that the system is properly designed and modelled without any of the components penetrating each other.

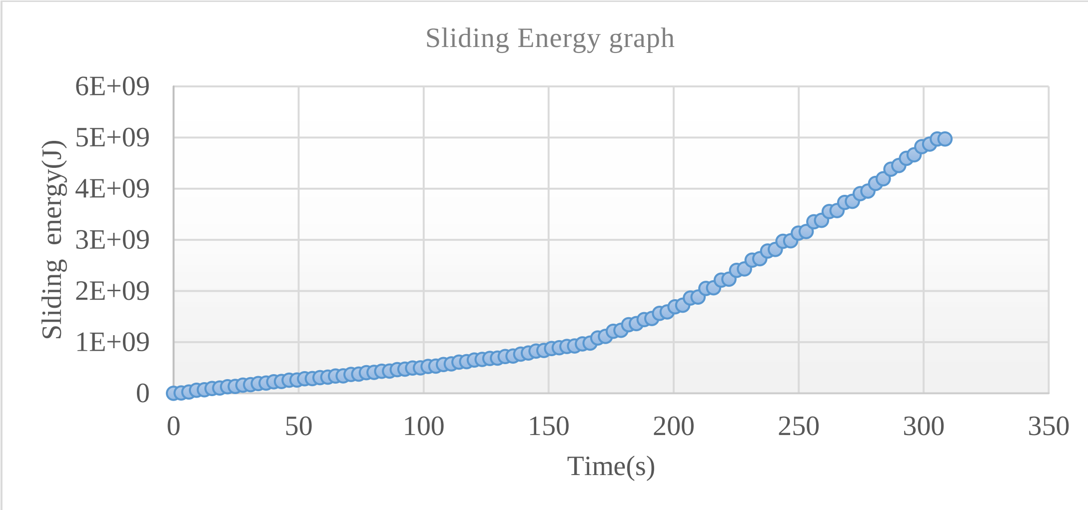

Figure 7: Sliding energy.

Contact forces

Contact modelling by finite element analysis in LS-DYNA uses commands including CONTACT_ AUTOMATIC_SINGELSURFCE,CONTACT_SURFACE_SURFCE,andCONTACT_TRANDUCR PENALITY Successful contact modelling by this method, as displayed in Figure 8, has not been attempted in other works. Therefore, the present results demonstrate a method of finite element modelling that might interest other researchers.

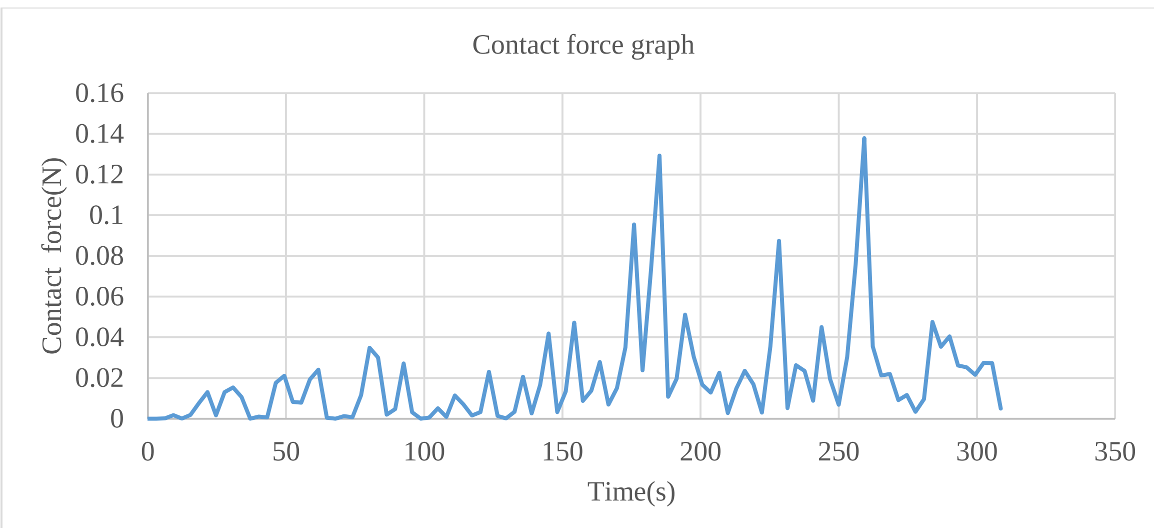

Figure 8: Contact forces.

CONCLUSIONS

This work selected and analysed a finite element model to simulate the dynamic response of a high-speed train on ballasted railway track. A typical track profile was modelled in the LS-DYAN program using 3D finite elements. The dynamic load of the train on the rail was also simulated in this program. Computation parameters were determined using a rational trainload and appropriate material properties. The distribution of vertical displacement, stress, strain, contact forces, and sliding energy directly beneath the train load were also analysed to give the full dynamic response of the train–track system.

(1) The dynamic response to the train load resulted in the substructure showing the greatest stress and ground vibration. It bore the majority of the vertical displacement, stress, strain, and shear failure.

(2) Equivalent stress and minimum principal strain occurred at the edge of the bearing plate of the super face of the ballast structure, where they were most likely to generate stress concentration, resulting in plastic deformation and thus damage to the track.

Overall, most ballasted high-speed railway track requires a high-strength substructure to resist the dynamic response of passing trains, which can potentially degrade the track and cause it to settle. This dynamic response should be considered and given more attention during design and feasibility studies. One such method to do this is numerical simulation using finite element computer code such as LS-DYNA.

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