Fatigue life prediction of wheels for CRH2 high-speed train due to flexible tracks

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ABSTRACT.

Wheels are some of the most vital components of a railway vehicle with respect to reliable and safe operations of the railway system. However, the wheels of the railway vehicle are routinely subjected to continuous excitations resulting from track flexibility and irregularities during the running action. Frequent subjection on the wheels results in repetitive loads and hence contributes to fatigue failure. Thus this study aims to propose a method of fatigue life prediction for wheels of high-speed trains dueto irregularities and flexibility of the track and conducts an investigation about the influence at different speeds. A study on the wheel was conducted using the finite element method, SIMPACK software for dynamic performance and Matlabfor irregularities.

An investigation was conducted at different speeds of operation to establish the effect on the wheels and the results indicated that as the speed of operation increases, the life of the wheels reduces significantly from $1.747 \times 10^9\ cycles$ to $1.093 \times 10^6\ cycles$. Hence irregularities and track flexibility are some of the most important factors which must be put into consideration to ensure a lasting service life of the wheels.

Keywords: *Wheels, Irregularities, Fatigue life, Flexibility, High speed.*

1. Introduction.

There is a wide use of railway vehicles throughout the world accounting for approximately 25 – 50 million wheels. The failure rate is estimated to be in the range of 1 in 1000 which implies that 25000 to 50000 wheels fail every year[1].In themajority of the failures, fatigue is one of the main damage mechanisms and thus it is imperative to consider it in order to have a strong design, enhance the performance of the wheels and prolong the fatigue lives of the wheels and the entire railway system. This study is based on CRH2, an Electric multiple unit having an operating speed of 200km/hrusing a digital track circuit train control system, a pantograph with low noise and is based on Shinkansen E2 series electric cars.

Higher axle loads combined with greater speeds of operation in recent days have left wheels exposed to larger forces during their operations. The wheels are constantly subjected to different types of loads during their movement[2].The rail vehicle operates on two parallel rails through the wheel/rail rolling contact. The contact at the wheel/rail interface is characterized by large contact stiffness due to the steel-made wheel and rail, and the size of the contact patch is similar to the dimension of the thumb. Therefore, the contact force of wheel/rail interaction is very sensitive to irregularities at the wheel/rail interface. These irregularities could be from either the wheel or the rail interface[19-21]. With regards to the safety of operations and increase in speed, the fatigue life of wheels is a vital factor for operators and manufacturers because it can result in catastrophic failure in the worst-case scenarios, cause damage to the suspension, rails and even derailments[3].Wheel damage due to fatigue may include rolling contact fatigue which takes place in the wheel tread and wheel rim, plain fatigue occurring in the disc of the wheel, fretting fatigue which is a result of tangential motion and compression and others. This is caused by the contact geometry and load magnitudes that result in contact stresses. The nucleation, growth and propagation of cracks in wheels can be further caused by thermal loads between the rail and the wheel, wheel material structural defects and wheel-brake block during the braking process. These are accelerated by an increase in speed and loads on the wheels. Fatigue cracks are initiated and continue to grow at points with high stress ratios eventually leading to damage, derailment and other failures[4].

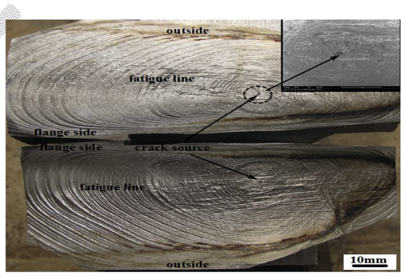


Figure 1*.shows macroscopic morphology crack of rim of the wheel*[5].

The wheels operate under conditions such as degraded infrastructure resulting from environmental conditions, discontinuities like switches and others. These imperfections result into extreme repeated loads having high frequencies and are transmitted to the wheels leading further to vibrations. The forces experienced by the wheels if not properly considered can contribute to fatigue failure for instance microcracks can be formed in the subsurface area of high-speed wheels at a distance of approximately 5-25mm below the tread[6]. Under this, the microcrack growth is accelerated by operating conditions like track irregularities and speed of movement leading to expansion[7]. This is due to the fact that fatigue damage largely occurs on both the subsurface and surface of the wheels under rolling contact fatigue.

A number of studies and research have been conducted by several individuals about the fatigue failure of wheels and have proposed different methods for high-speed trains.

Equivalent stress criteria such as dang van and Crossland has been used by Lindqvist et al., 1999 to carry out an analysis of fatigue initiation due to defects however, the influence of shape, quantity and size of the defect cannot well determined directly[8].

Numerical simulation tools play a key role in investigating the behaviourof the wheels during operations so that better designs can be achieved to prolong the service life of the wheels. They are fast and cost much less compared to experimental tests and therefore a suitable method to conduct the investigation. With the increase in the time of operation, deterioration of the operating conditions takes place and irregularities become more significant hence exposing the wheels to higher chances of fatigue failure.

Even though multiple studies have been concluded about wheel failure, few and rarely have studies been carried out about the influence of speed, and irregularities in combination with track flexibility to better estimate the fatigue life of the wheels since they are vital components in ensuring that safe and stable operations are achieved.

Hence this study is to investigate how the fatigue life of the wheels is affected by the flexibility of the track and irregularities and their effect on the dynamic performance. It is conducted using finite element and multibody dynamic SIMPACK software and the results describe a detailed understanding of the behavior and how possible solutions can be devised to overcome problems.

1.1 Representation of the wheel geometry.

This is a circular component that rotates about the axis of an axle shaft supporting the mass of the train and facilitating its movement. The wheel of the train is mostly made of steel and is in constant contact with the rail during its rolling motion. The figure below shows the different parts that make up the wheel.

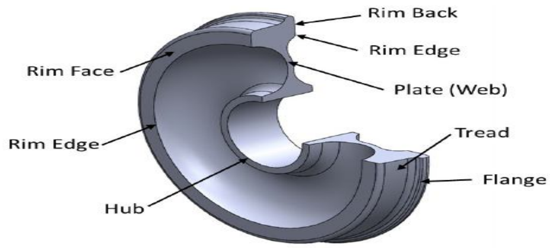


Figure 2.*parts of the wheel*[9].

2. Materials and Methodology.

3D modelling of the wheel for high-speed train was done using Solidworks CAD software. An IGS file format was exported to ANSYS workbench for static analysis and validation of results was done using Mansion-coffin equation. Dynamic simulations using SIMPACK software were done at different speeds as indicated in table 4 and the contact force history at the rail wheel contact was obtained for fatigue analysis using ANSYS nCode. Irregularities of the track were modelled using Matlab software and linked to SIMPACK. A straight track is considered and thus the lateral forces on the vehicle are ignored. The forces extracted were then applied on the wheel in Ansys workbench to obtain themaximum stresses and strain experienced by the wheel at different speeds and for further determination of the fatigue life using ncode.

The high-speed wheel under consideration is for CRH2 constructed from high-speed ferrite-pearlite steel having material properties of ER8 and a profile of LMA type. The material is suitable because of its strength and high ductility properties[10][11].Below is the table that shows the mechanical properties of the wheel.

Table 1.*shows mechanical properties of ER8*[12][13].

HB	E	σ_f'	ε_f'	b	c	Yield strength	Tensile

						(MPa)	strength(MPa)
254 ± 7	2.1×10^{5}	840	0.304	-0.09	-0.56	540	$860-980$

Where $\varepsilon_f^{'}$ is the fatigue ductility coefficient, c is the fatigue ductility exponent, $\sigma_f^{'}$ is the fatigue strength coefficient, b is fatigue strength coefficient, E and HB are modulus of elasticity and hardness value respectively.

2.1 Static structural analysis.

Table 2*.Shows parameter values of the vehicle applied in the analysis*[14].

Parameter	Mass(kg)
Carbody,M_C	35067
Bogie,M_b	3630
Wheelset, M_w	1794

The following formula is used to calculate forces for static analysis. Hence the total vertical force, F_y, acting on the wheels.

$$(M_c + 2M_b + 4M_w)g \qquad \text{Eqn (1)}$$

2.2 Geometric modelling and structure of the wheel.

A 3D model of the wheel is made using Solidworks software and constructed of high-speed ferrite pearlite with LMA profile and ER8.

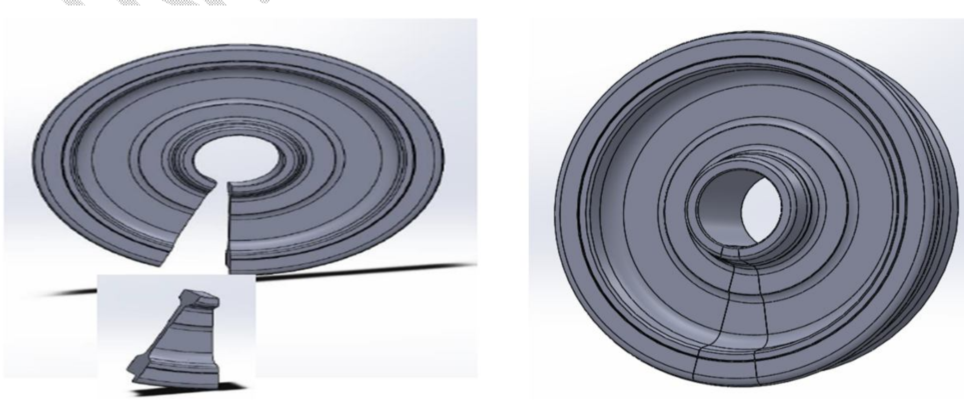


Figure 3*.shows 3D model of the wheel.*

The total vertical load is determined as indicated in eqn (1).The following force has been calculated using eqn (1) and was applied on the wheel for static analysis.

Table 3.*shows calculated force.*

Load		Calculated force(N)	Force on each wheel(N)	Formula
Vertical	F_{ymax}	485624.43	60703.05	(1)

3. Railway vehicle multibody dynamic model.

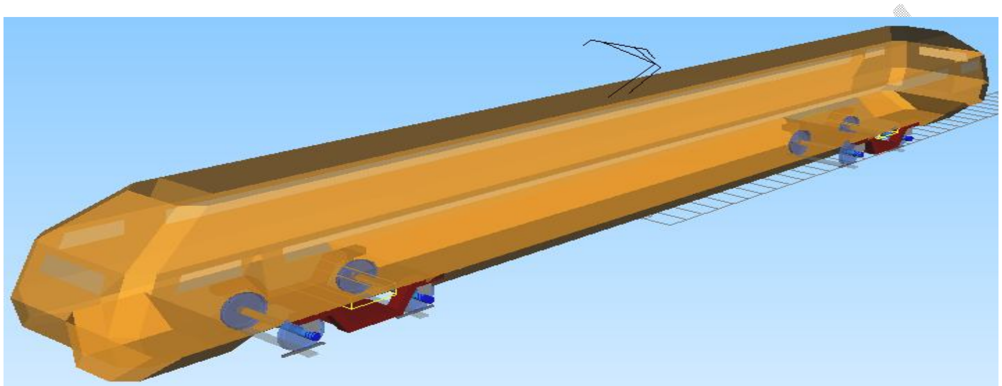


Figure 4.*shows railway vehicles modelled in SIMPACK.*

The railway vehicle was modelled with the help of SIMPACK multibody dynamic software to conduct an analysis of the effect of various operating speeds combined with irregularities and track flexibility on the fatigue life of the wheels. In general, the vehicle consists of the car body, the bogie, wheels and axles and both primary and secondary suspension which absorb shocks and vibrations to ensure comfortable movement by the passengers. The peak vertical forces at the rail-wheel contact region were extracted and considered for analysis. Below is the rail track equation of equilibrium during the motion of the vehicle.

$$M_V \ddot{D}_V + C_V \dot{D}_V + K_V D_V = F(t) \qquad \text{Eqn (2)}$$

Where $\ddot{D}_V$, $\dot{D}_V$ and D_V are acceleration, velocity and displacement vectors respectively. The subscript v represents the subsystem track and vehicle dynamics. K_V, C_V, M_V and $F(t)$ are damping, stiffness, mass and external force respectively.

3.1 Flexible Track Model.

This incorporates the design of the track combined with irregularities defined by particular design parameters. The situation considered in this analysis takes intoconsideration the flexibility of the track and irregularities. The track is usually considered to be rigid however, it shows a small extent of flexibility as a result of poorly supported sleepers, small deformations and rotations[15].The rails of the track and sleepers are modelled using Euler-Bernoulli beam elements and the foundations and pads are represented by elements of the spring-damper as shown in figure 5. The irregularities of the track can be grouped according to the wavelength and categorized as medium wavelength, short wavelength and long wave type of irregularities. The dynamic response of the track is taken to be linear under the normal operating conditions and each node constitutes six degrees of freedom.

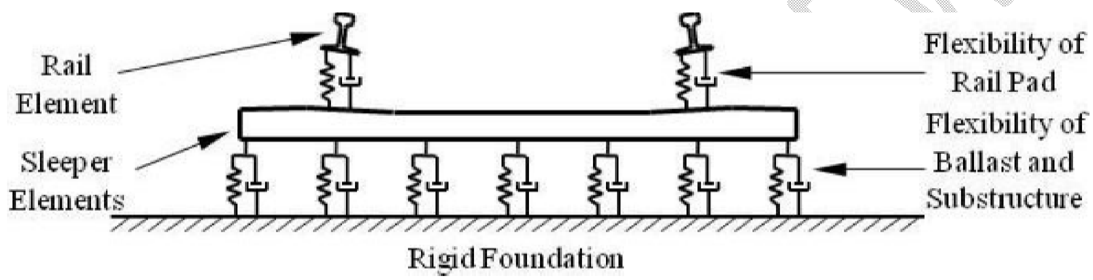


Figure 5*.a cross-section view of a flexible track*[16].

4. Results and Discussion.

4.1 Dynamic response results.

A railway vehicle with the same wheel profile was modelled in SIMPACK dynamic software and simulated for a distance of 6.6km putting into consideration the irregularities and flexibility of the track to obtain the peak vertical forces acting on the wheels. The simulations were conducted at various speeds whichis 200k/hr, 250km/hr and 300km/hr and the corresponding vertical forces in the time domain are obtained in Table 4.

Table 4*.peak vertical forces obtained from SIMPACK software.*

	Peak Vertical force(N)	
Speed(km/hr)	Left	Right
200	75490.5	84036.4
250	89924.8	117501
300	253546	258965

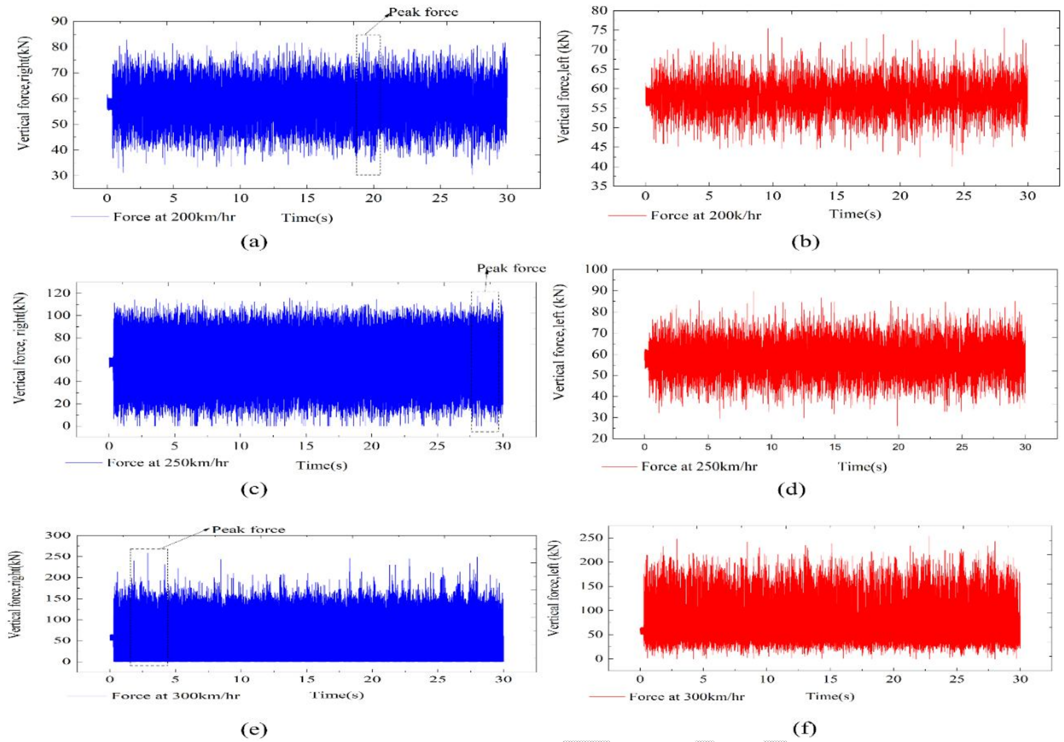


***Figure 6**.graphs of vertical forces obtained at different speeds.*

The results from SIMPACK dynamic software indicate that the highest forces are experienced on the right side of the rail vehicle wheels at all speeds. The figures below show enlarged views of the peak vertical forces experienced at the rail wheel contact region at different speeds.

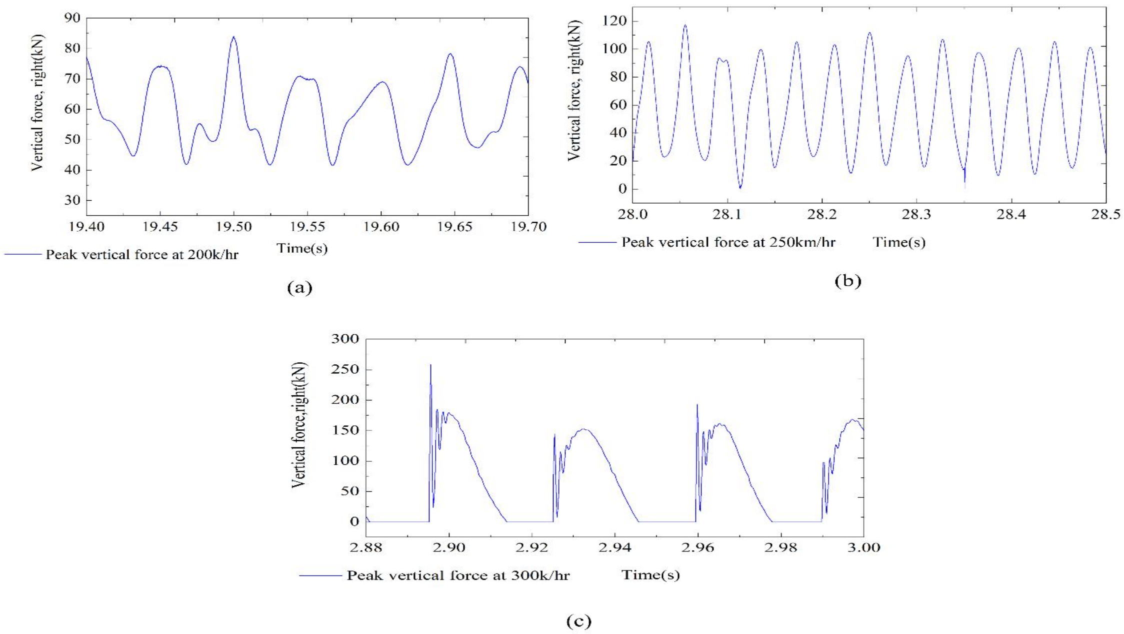


***Figure 7**.magnified views of the peak vertical forces at different speeds.*

Effect of speed and track irregularities.

Three different speeds that are 200km/hr, 250km/hr and 300km/hr were proposed to examine the effect of speed on the fatigue life of the wheel.

As indicated by the results, an increase in speed is inversely proportional to the fatigue life of the wheel. The maximum vertical force experienced by the wheel increases from 84.036kN to 258.965kN for 200km/hr and 300km/hr respectively. As the speed of the railway vehicle increases, a threat is posed to the wheel and track integrity which has an integral influence on the operation of the train. Track flexibility and irregularities lead to vibrations whose effect becomes more pronounced at greater speeds and thus higher vertical force generation at contact points. This is because they tend to alter the dynamic interaction of the rail and the wheel contact region during its movement.

4.2 Finite Element Analysis.

Static analysis results.

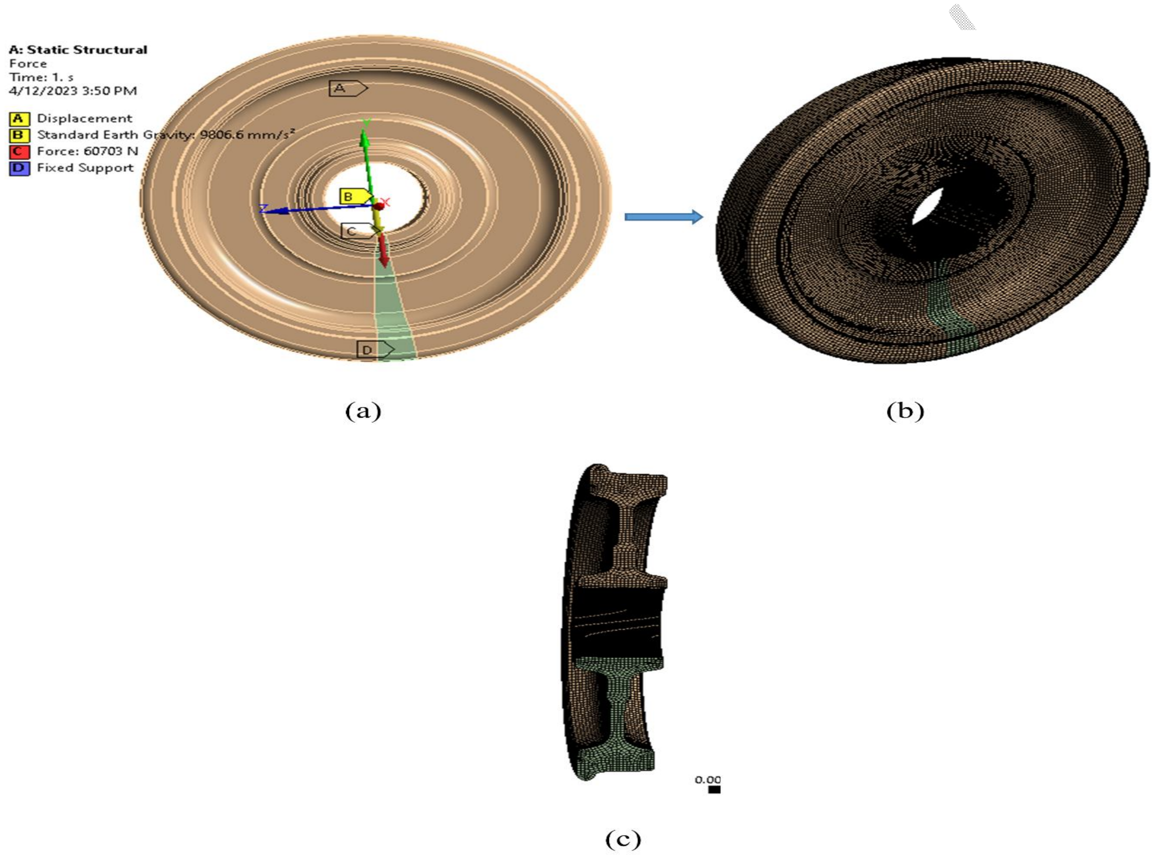
The wheel was analysed in Ansys workbench using the calculated force in Table 3 and the equivalent stress, life and strain obtained as shown in figure 8 below. The simulated fatigue life was compared with the calculated fatigue life of the wheel using the Mansion-coffin equation. In this equation, the strain-life estimation method is applied through the combining of strain and equivalent stress[17][18].

$$\sigma_{\max}\frac{\Delta\varepsilon}{2}=\frac{(\sigma_f^{'})^2}{\mathrm{E}}(2N_f)^{2b}+\sigma_f^{'}\varepsilon_f^{'}(2N_f)^{b+c} \quad \text{Eqn (3)}$$

Where c and $\varepsilon_f^{'}$ are fatigue ductility exponent and fatigue ductility coefficient respectively. b and $\sigma_f^{'}$ are fatigue strength exponent and fatigue strength coefficient respectively.

Boundary conditions.

A 3D model of the geometry is imported to ANSYS software and meshed with rectangular elements well refined to display the stress distribution on the application of the various forces. A total of 489984 nodes and 107622 elements are realised after meshing and the material is assumed to be homogenous, linear, elastic and isotropic.



***Figures8**.show (a) boundary conditions on the wheel,(b)meshed wheel and (c)crossection of a meshed wheel.*

Results.

Using the calculated force in table 3, the following results were obtained after carrying out finite element analysis.

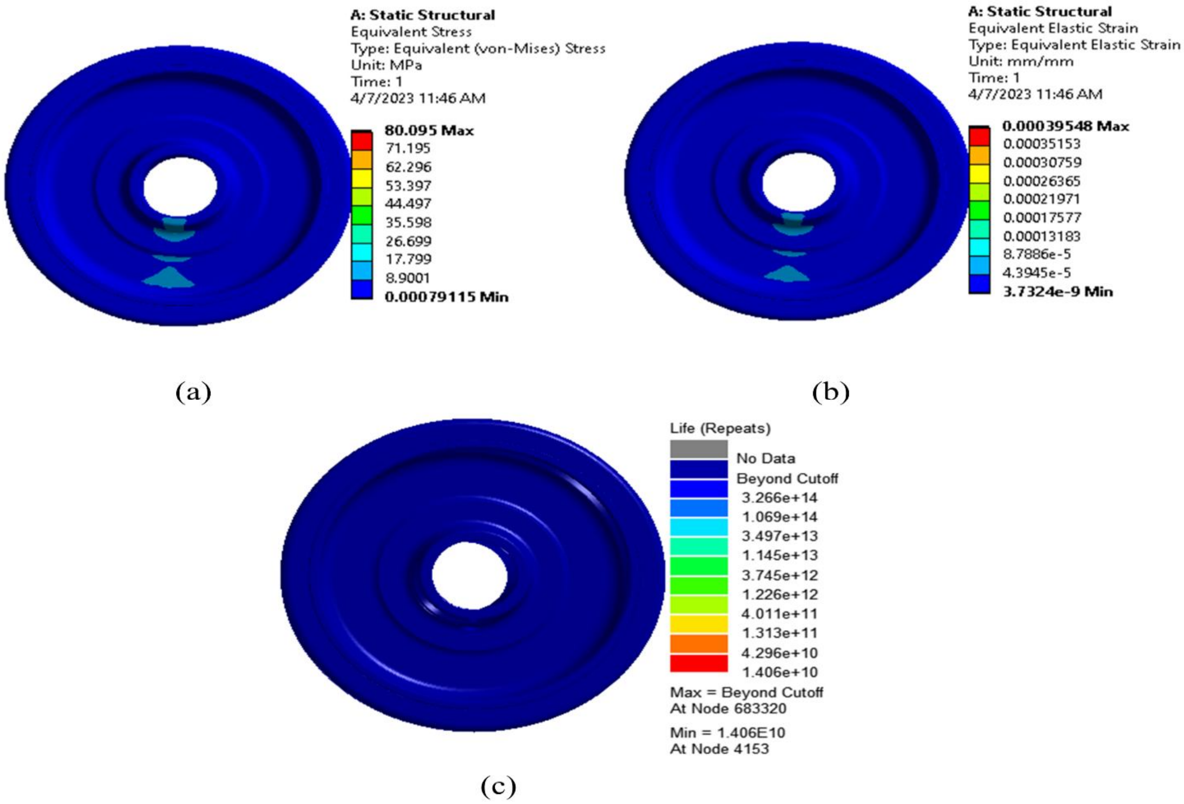


Figure 9*.shows (a) Meshed wheel, (b) Equivalent stress, (c) Strain and (d) life values obtained during static analysis.*

Calculation of fatigue life.

The fatigue life of the wheel was determined using Mansion-coffin equation as indicated in eqn (3).

Table 5. *Shows results from static structure analysis.*

Equivalent stress(MPa)	**Strain**	**Number of cycles(N_f)**	
		Simulated	Calculated
80.095	0.0003954	1.406×10^{10}	4.27×10^{12}

Finite element results from dynamic response.

The vertical forces realized from dynamic simulations were applied in the finite element analysis to determine the stresses, strain and life of the wheel at different speeds of operation of the railway vehicle as indicated in the figures below.

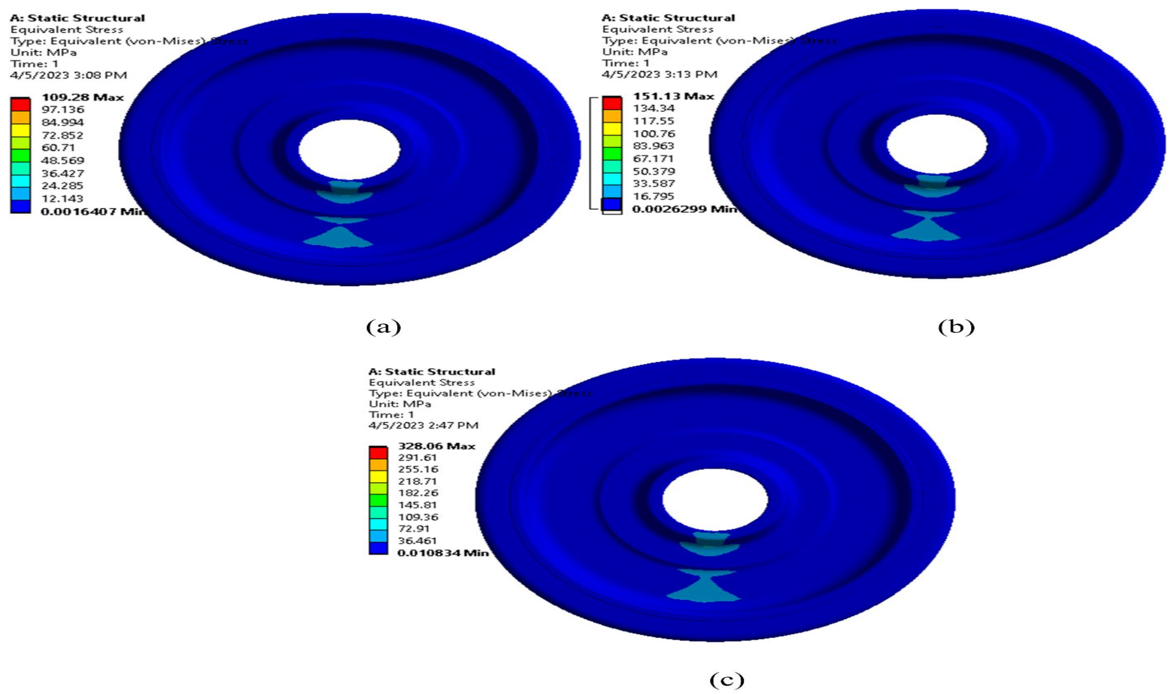
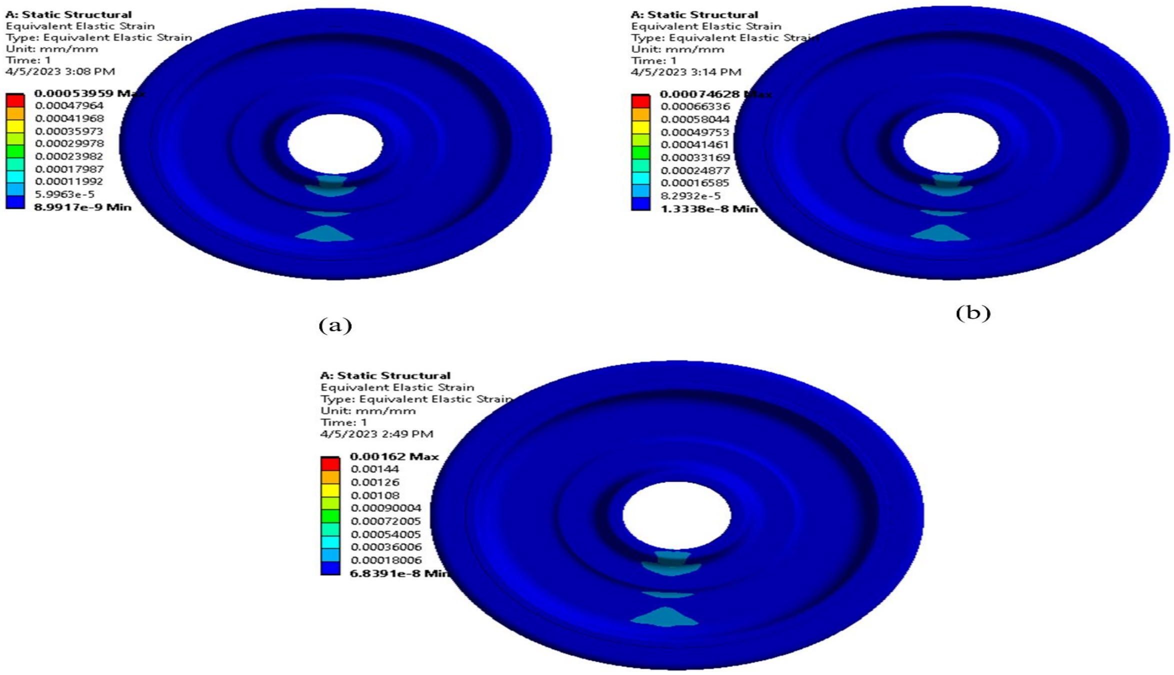


Figure 10.*shows equivalent stress values at (a) 200km/hr, (b) 250km/hr,(c) 300km/hr.*



(c)

***Figure11**.shows equivalent strain values at (a) 200km.hr,(b) 250km/hr and (c) 300km/hr.*

Fatigue life from simulated results.

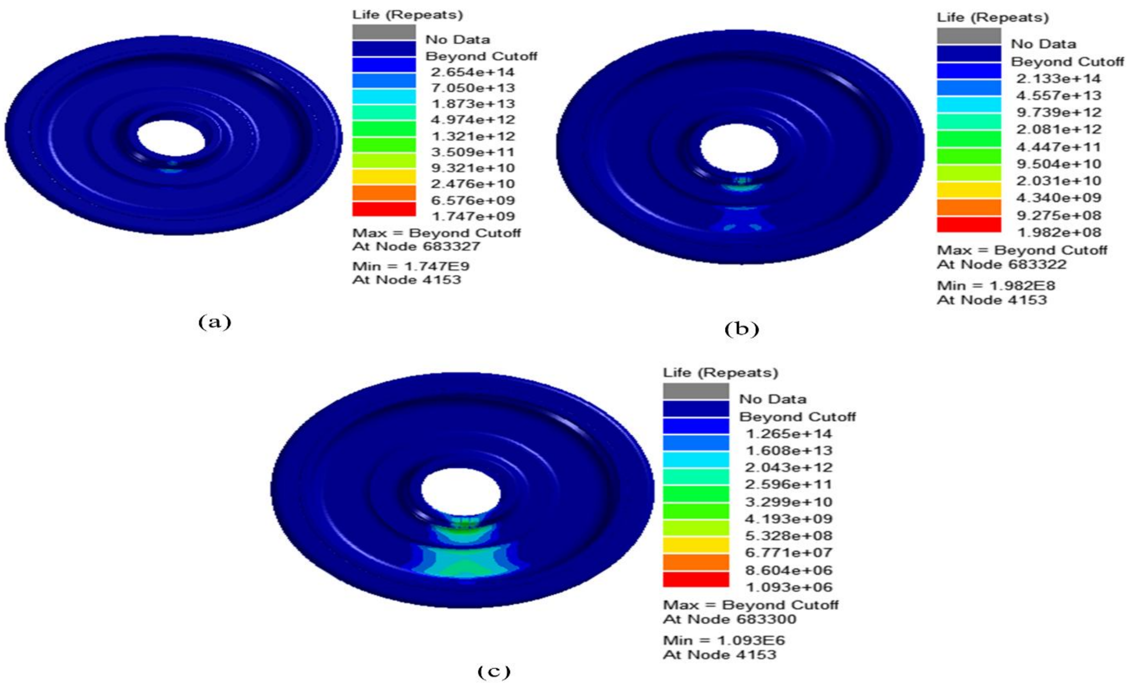


Figure 6*.the life of the wheel at speeds (a) 200km.hr, (b) 250km/hr and (c) 300km/hr.*

5. Fatigue life calculation.

The fatigue life of the wheel is calculated according to the Mansion-coffin equation as indicated in eqn (3) and a comparison is conducted against the simulated life values.

Table 6*.shows fatigue life in terms of cycles at different speeds.*

Speedkm/hr.)	Number of cycles(N_f)	
	Simulated	**Calculated**
200	1.747×10^9	1.333×10^{11}
250	1.982×10^8	3.670×10^9
300	1.093×10^6	1.021×10^6

It can be noted that the both simulated and calculated values of cycles are close to each other which implies that the methods can be applied in conducting analysis and deterring the life of wheels. Wheels are vital components of railway vehicles and thus better designs need to be effected to ensure that that fatigue failures and other unknown and uncertain factors are tolerated during the operations.

Conclusion.

In this paper, a method to help in predicting the life of high-speedwheels has been proposed. Through the consideration of irregularities and track flexibility, the analysis focused on the estimation of conditions close to the actual operating ones. The following conclusions are drawn from the study.

1. The life of the wheels of a train is greatly dependent on the conditions of the track. The loads induced by the track onto the wheel are also affected by the geometry of the track and the overall condition. Thereforeit is of great importance to conduct inspections and maintenance of the rails to ensure reliable and safe operation of high-speed trains and increase the longevity of the wheels.
2. The forces at the rail-wheel area of contact increase with the increase in the train speed and as the conditions of the track change from good to bad.
3. With the deterioration of the track conditions at greater speeds, the overall service life of the wheels is reduced and consequently the entire railway vehicle.

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