International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-9, Issue-12, December 2022

Fatigue Strength Analysis of the Bogie Frame for the CRH2 High-Speed Train in Consideration of Uncertainty Parameters

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Abstract: **The bogie frame is the base for carrying and transferring forces from many structural parts in the running gear of a train. Its reliability plays an important role in the safety and stability of train operations. However, during operation, uncertainty parameters affect its performance, and the evaluation of its structural reliability is essentially to check the structural strength and fatigue strength after facing uncertainty parameters. Those random parameters can cause fatigue failure, especially in a CHR2 high-speed train. Therefore, it is more important to accurately evaluate the fatigue strength of the frame due to uncertainty parameters than the structural strength. At present, the research on the fatigue strength of bogie frames is mainly based on two aspects: dynamics and statics. In dynamics-based research, the dynamic model of the multi-rigid-body system of the vehicle body is established by analyzing the irregularity of the track line, and the load history of the vehicle suspension system is obtained. On this basis, the dynamic analysis and stress evaluation of the bogie are carried out, and the fatigue life of the bogie is predicted according to the cumulative damage based on uncertainty parameters. In this study, three cases were considered for uncertainty parameters: suspension system, passenger weight, and wind force. The results show that the uncertainty of suspension systems has a shorter fatigue life cycle, which implies that it has more negative effects compared to other uncertainty parameters.**

Keywords: **Bogie frame, Fatigue strength, CHR2, Fatigue life, Uncertainty parameters**

1. INTRODUCTION

In general, a bogie frame of railway operated under tractive force, restoring force and propulsion receives fatigue load caused by repetitive vibration forces and landing during service. Moreover, in spite of low probability, unexpected parameters may be applied such as passengers' weight, wind force, track irregulates, coefficient of friction and suspension system [1],[2].

Thus, securing a sufficient structural strength that can endure not only static load but also fatigue load is required and it should be verified through a proper test and evaluation methods [3]. In terms of test and evaluation method for the bogie frame, UIC, EN or JIS Standards have well established methods to verify static and fatigue strength for wheel railway vehicles[4]. In case of CHR2, various analyses and test evaluation methods may be used to analysis the fatigue strength of bogie frame for commercial use, furthermore, the safety of bogie frame was verified by comparing with experimentally study [5],[6]. However, there are limits to apply the existing standards to a new developed CHR2 trains since its characteristics are different from a wheel train [7]. In addition to this, advanced companies disclose the related technologies restrictively so it is actually very difficult to find out proper test methods to evaluate the safety of bogie frame due to uncertainty parameters [8],[9].

2. BOGIE FRAME

The bogie is known as the wagon's movement system. The bogie frame is either casted or fabricated. The bogie frames are manufactured based on its working conditions [10]. It is the main component which takes the stresses. CRH2 coaches use 16.25t bogies which is an all-welded lightweight construction [11],[12]. Axles are located on the bogie by telescopic dash pot and axle guide assemblies Helical coil springs are used in both the primary and the secondary stages[13]. The axle guide device provides viscous damping across primary springs while hydraulic dampers are provided across the secondary stage [14], [15]. Dampers are protected against misalignment by resilient fittings. Isolation of vibration is affected by rubber pads in primary (also Hytrel and secondary suspension. Side bearers consist of lubricated metal slides immersed in oil baths[16].

No vertical weight transfer is affected through bogie pivot and pivot acts merely as a center of rotation and serves to transmit tractive/braking forces only [17][18].

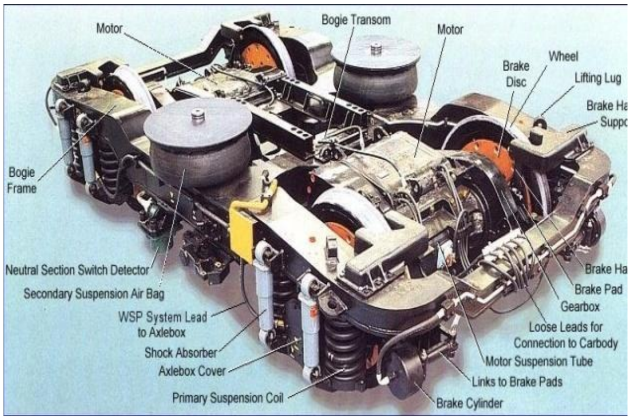

Fig 1: Details of Bogie [8]

3. FORCES CALCULATION AND MATERIAL PROPERTIES

According to the Power bogie frame's strength test method (TB/T2368-2005) [19], we must calculate the vertical load and transverse load in order to analyze the structure stress condition more comprehensive.

Vertical load applied to each side frame, based on the assumption of vehicles whose mass is evenly distributed between the two bogies and the body supported directly on each side frame.

$$F_z = [(m_a + m^+) + \text{Passengers weight}] \times \frac{g}{2} \qquad (1)$$

Where;

m_a – Weight of carbody = 35067kg

m^+ - Weight of bogie = 3630kg

g- Acceleration due to gravity = 9.81m/s^2

Average person weight is 70kg (80 people per carbody)

$$F_z = [(35067 + 3630) + (80\times70)] \times \frac{9.81}{2}$$

$$F_z = 217276.785\text{N}$$

Transverse load is applied to each axle

$$F_y = [0.5\times (Fz_1 + (0.5\times m^+ g))] \qquad (2)$$

Where;

$$F_{y1} = \frac{Fy}{2} = \frac{217276.785N}{2} = 108638.39\text{N}$$

m^+ - Weight of bogie = 3630kg

g- Acceleration due to gravity = 9.81m/s^2

$$F_y = 0.5\times [108638.39 + (0.5\times 3630\times9.81)]$$

$$F_y = 63221.77\text{N}$$

The materials used was SM490A [20], [21].

4. MODELLING

The vehicle, track, and wheel/rail interaction submodels comprise the railway vehicle multibody dynamic model. The current study established and built a multibody 3D dynamic model for all three categories. The dynamic equation of motion for the vehicle can be stated in the form of a submatrix using the finite element program and vehicle-track coupling [22].

$$M_V\ddot{D}_V + C_V\dot{D}_V + K_V D_V = P_{vt} \qquad (3)$$

where $\ddot{D}_V$, $\dot{D}_V$, and D_V are the vectors of acceleration, velocity, and displacement of the vehicle subsystem, respectively. The subscripts V mean the vehicle dynamics and track of the subsystem, respectively; M_V, C_V, K_V, and P_{vt} is the subsystem matrices of mass, stiffness, damping, and external force, respectively.

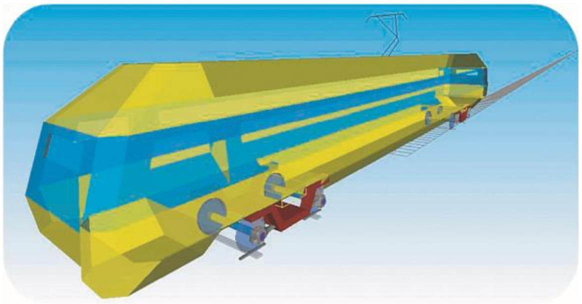

Fig 2: Designed rail vehicle

The 3D model of bogie frame modelled by Solidwork.

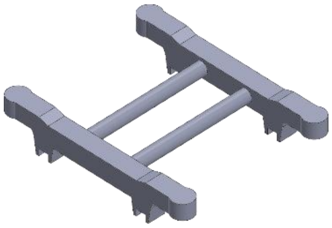

Fig 3: Designed Bogie frame

Table 1: Mean parameters of the CRH2 railway vehicles used in current research [22]

Parameters	Notation	Value	Unit
Car body mass	m_c	35067	kg
Car body roll moment of inertia	J_{cx}	119200	kgm^2
Car body pitch moment of inertia	J_{cy}	1711800	kgm^2
Car body yaw moment of inertia	J_{cz}	1615300	kgm^2
Frame mass	m_t	3630	kg
Frame roll moment of inertia	J_{tx}	2940	kgm^2
Frame pitch moment of inertia	J_{ty}	1990	kgm^2
Frame yaw moment of inertia	J_{tz}	3630	kgm^2
Wheelset mass	m_w	1794	kg
Wheelset roll moment of inertia	J_{wx}	900	kgm^2
Wheelset pitch moment of inertia	J_{wy}	220	kgm^2
Wheelset yaw moment of inertia	J_{wz}	950	kgm^2
Vertical stiffness of primary suspension per axle side	k_{pz}	980000	N/m
Lateral damping of primary suspension per axle side	c_{py}	5490	kNs/m
Vertical stiffness of primary suspension per axle side	k_{pz}	1176000	N/m
Vertical damping of secondary suspension	c_{pz}	20	kNs/m
Lateral stiffness of secondary suspension per bogie side	k_{sy}	192	kN/m
Lateral damping of secondary suspension per bogie side	c_{sy}	60	kNs/m
Vertical stiffness of secondary suspension per bogie side	k_{sz}	990.8	kN/m
Vertical damping of secondary suspension per bogie side	c_{sz}	9.8	kNs/m
Nominal wheel radius	r_o	0.43	m
Half of the lateral distance between wheel/rail contact points	l_t	1.25	m
Half of the lateral distance between primary suspensions of the two sides of the bogie	d_o		m

5. MODAL SIMULATION WITH UNCERTAINTY PARAMETERS

By using Monte Carlo simulation, which is used to represent the likelihood of various outcomes in a process that cannot be easily anticipated due to the presence of random factors. It is a technique for determining the impact of risk and uncertainty [23][24].

3 Parameters Weibull equation was used as

$$\mathrm{f(t)} = \frac{\beta}{\eta} \times \left(\frac{t-\gamma}{\eta}\right)^{\beta\text{-}1} \times e^{\left(\frac{t-\gamma}{\eta}\right)\beta} \tag{4}$$

where, β is the shape parameter η is the scale parameters and γ is the location parameter.

In this study, three cases were considered for uncertainty parameters i.e. suspension system U_{DS}, passenger weight U_{PW} and wind force U_{FW}. Table 2 to table 4 shows the uncertainty parameters vales for all cases.

Table 2: Uncertainty of suspension system as case 1

Parameters	Mean value	Std	Upper limit	Lower limit	Error	Units
Vertical stiffness of primary suspension/ axle side	980000	10%	980030	979970	3%	N/m
Lateral damping of primary suspension/ axle side	5490	10%	5520	5460	3%	kNs/m
Vertical stiffness of primary suspension/ axle side	1176000	10%	1176030	1175970	3%	N/m
Vertical damping of secondary suspension	20	10%	50	-10	3%	kNs/m
Lateral stiffness of secondary suspension per bogie side	192	10%	222	162	3%	kN/m
Lateral damping of secondary suspension per bogie side	60	10%	90	30	3%	kNs/m
Vertical stiffness of secondary suspension per bogie side	990.8	10%	1020.8	960.8	3%	kN/m

Vertical damping of secondary suspension per bogie side	9.8	10%	39.8	-20.2	3%	kNs/m

Table 3: Uncertainty of passenger's weight as case 2

Parameters	Mean value	Std	Upper limit	Lower limit	Error	Units
Passenger weight	8	10%	8.3	7.7	3%	tons

Table 4: Uncertainty of wind force as case 3

Parameters	Mean value	Std	Upper limit	Lower limit	Error	Units
Wind force	140	10%	143	137	3%	mph

For suspension system normal distribution method used, for passenger's weight extreme maximum distribution method used and for wind force extreme minimum distribution method used.

Normal distribution method

Probability density function (PDF)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{5}$$

Cumulative distribution function (CDF)

$$\mathrm{F(x)} = \frac{1}{2}[1+e^{-\frac{(x-\mu)^2}{2\sigma^2}}] \tag{6}$$

Hazard function (HF)

$$\mathrm{h(x)} = \frac{f(x)}{1-F(x)} \tag{7}$$

Maximum distribution method

Cumulative distribution function (CDF)

$$\mathrm{F(x)} = e^{-e^{-x}} \tag{8}$$

Probability density function (PDF)

$$\mathrm{f(x)} = e^{-x} e^{-e^{-x}} \tag{9}$$

Hazard function (HF)

$$\mathrm{h(x)} = \frac{e^{-x}}{e^{e^{-x}-1}} \tag{10}$$

Extreme maximum distribution method

Cumulative distribution function (CDF)

$$\mathrm{F(x)} = e^{-e^{\frac{-(x-\mu)}{\sigma}}} \qquad \infty - < x < \infty,\ \mu \text{Є} R,\ \sigma > 0 \tag{11}$$

Probability density function (PDF)

$$\mathrm{f(x)} = \frac{1}{\sigma} e^{-\frac{(x-\mu)}{\sigma}} \times e^{-e^{-\frac{(x-\mu)}{\sigma}}} \qquad \infty - < x < \infty \tag{12}$$

Hazard function (HF)

$$\mathrm{h(x)} = \frac{\frac{1}{\sigma} e^{-\frac{(x-\mu)}{\sigma}} \times e^{-e^{-\frac{(x-\mu)}{\sigma}}}}{1-e^{-e^{-\frac{(x-\mu)}{\sigma}}}} \qquad \infty - < x < \infty \tag{13}$$

where:

$f(x)$ = probability density function

F(x) = cumulative distribution function

h(x) = hazard function

x = value of the variable (suspension system, passenger weight, wind force)

μ = mean

σ = standard deviation

σ^2 = variance

6. RESULTS

The following results obtained after mathematical calculation, dynamic and numerical simulation in this study.

6.1 Dynamic Response

Three cases were considered, after dynamic simulation, the following results were obtained.

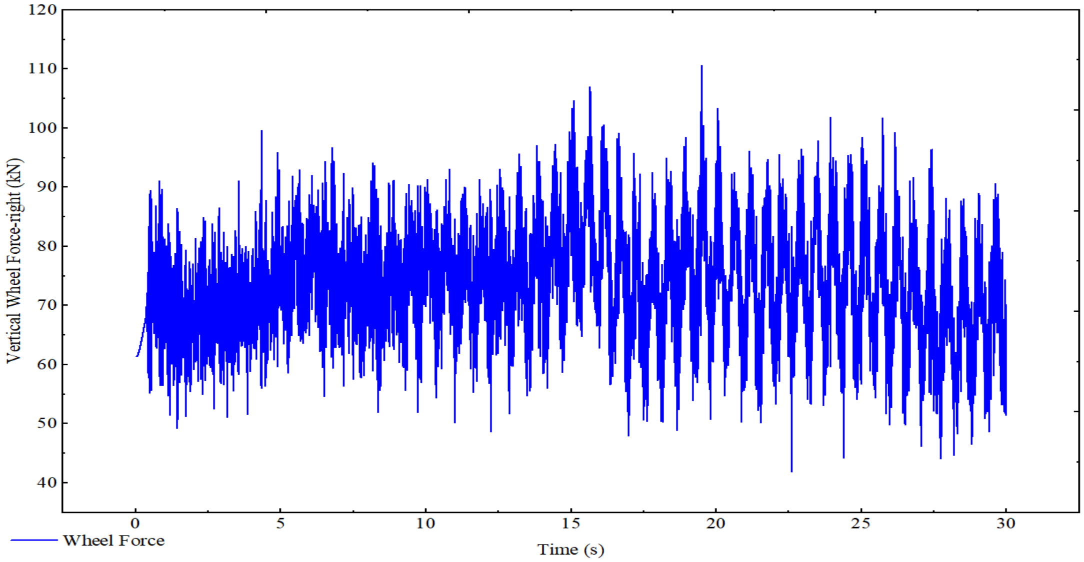

Fig 4: Vertical wheel force for case 1

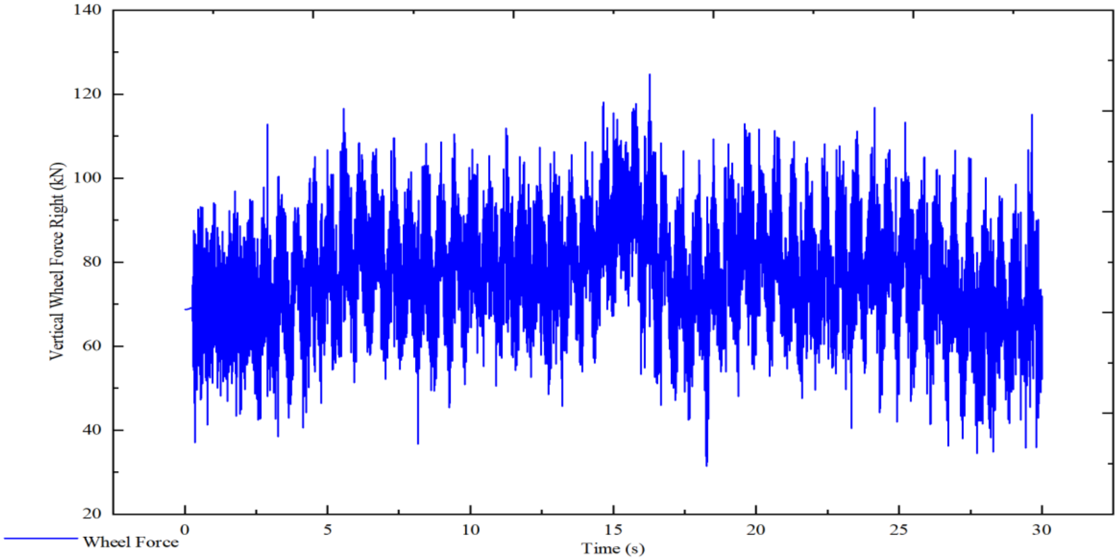

Fig 5: Vertical wheel force for case 2

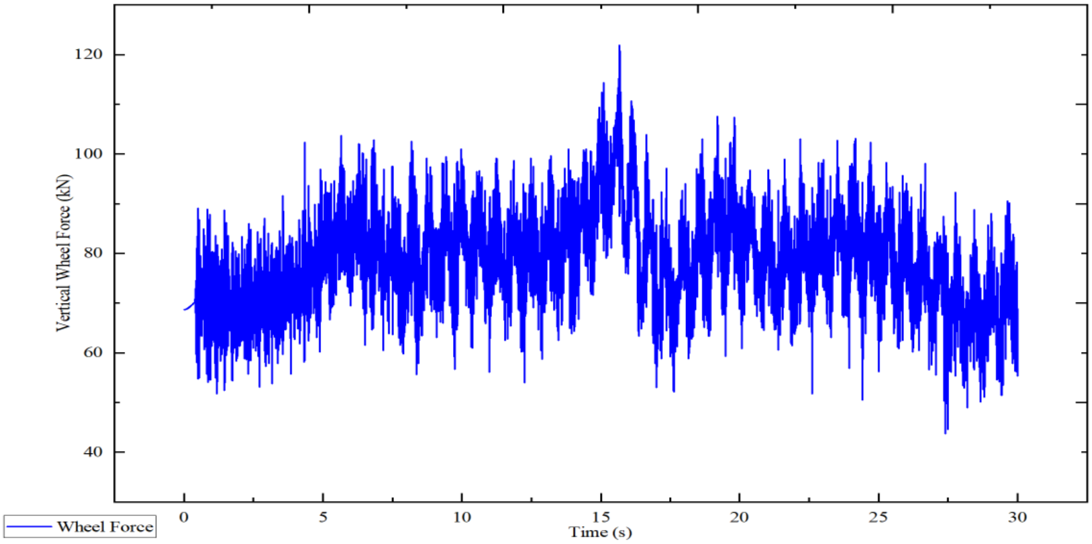

Fig 6: Vertical wheel force for case 2

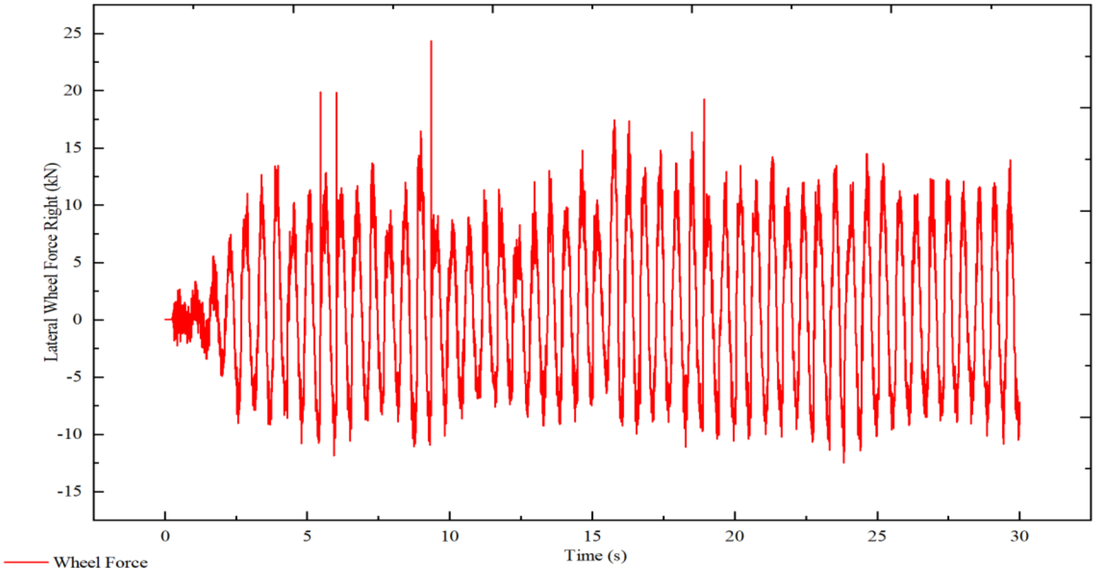

Fig 7: Lateral wheel force

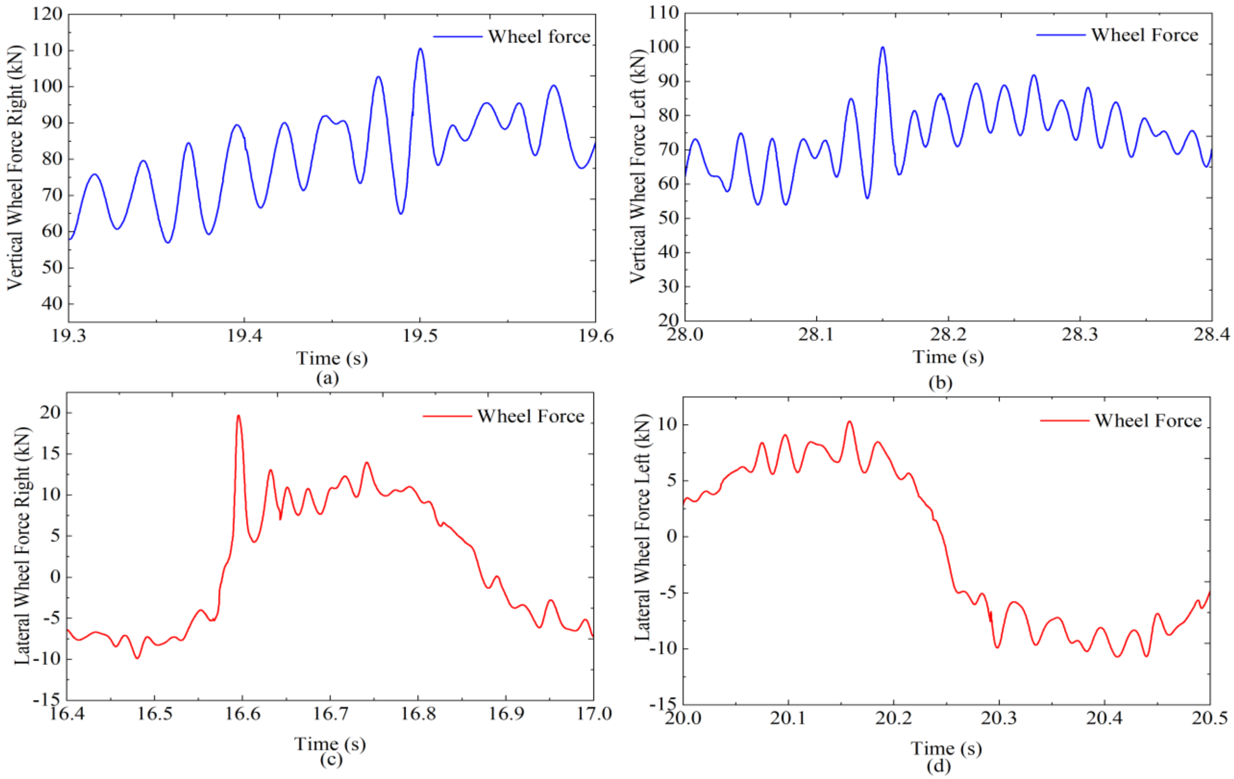

Fig 8: Maximum wheel force for case 1

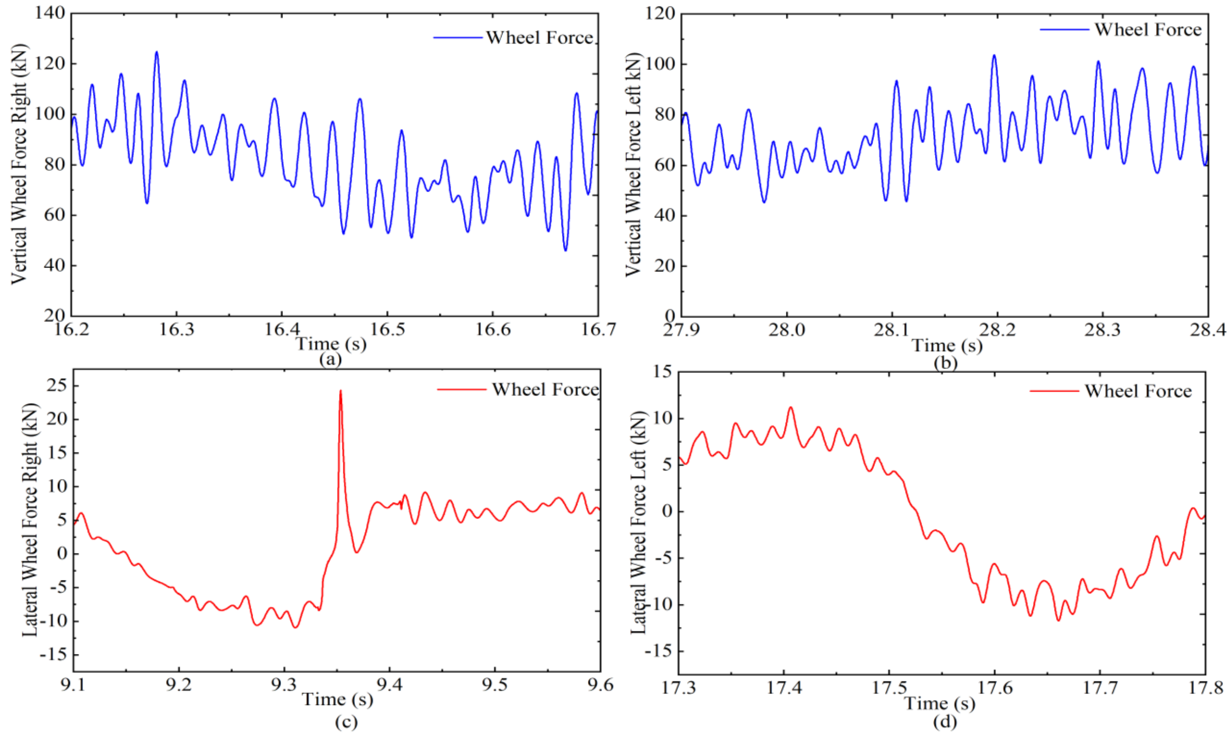

Fig 9: Maximum wheel force for case 2

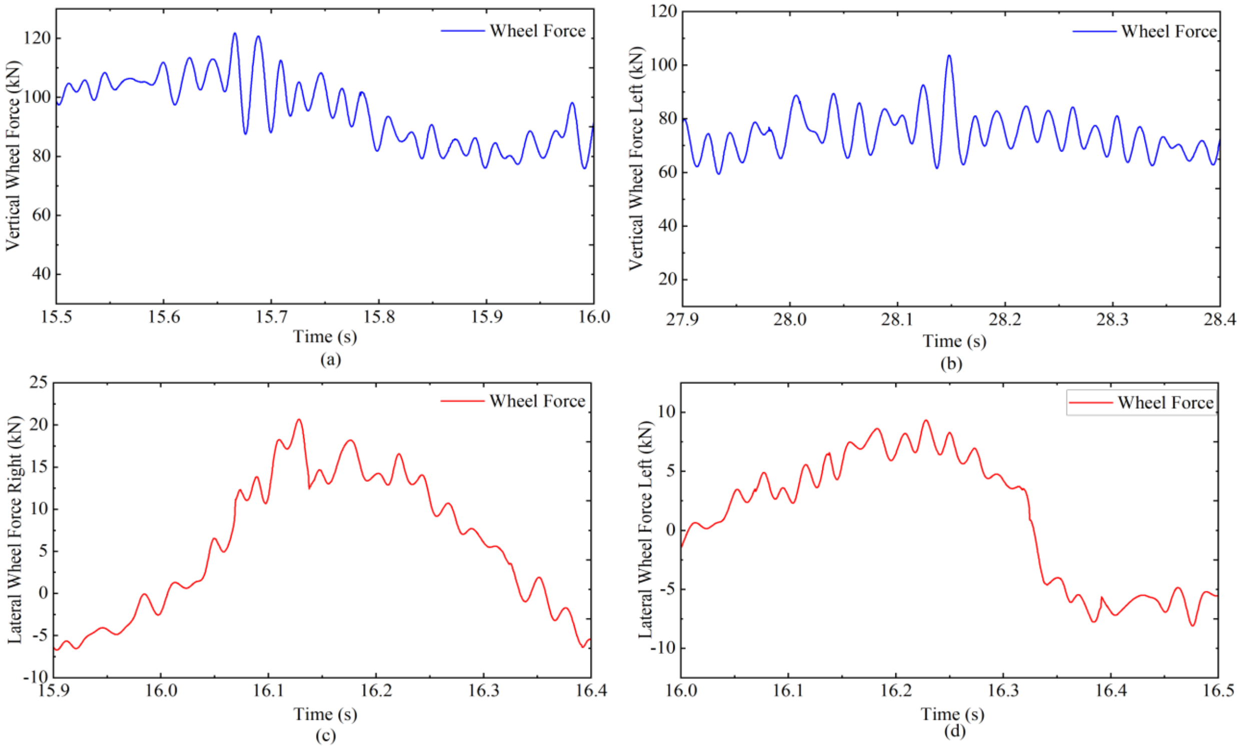

Fig 10: Maximum wheel force for case 3

Figure 8 to 10 are the maximum wheel forces for both vertical and lateral cases obtained from dynamic response in all three cases as tabulated below;

Table 5: Maximum wheel force

Maximum wheel force	Case 1	Case 2	Case 3
Vertical right (kN)	110.6	124.8	121.8
Vertical left (kN)	100.1	103.7	103.7
Lateral right (kN)	19.7	24.3	20.6
Lateral left (kN)	10.3	11.2	9.3

Table 5 shows that the case 2 has high maximum wheel force (71.967MPa) compared to case 1 and case 3.

6.2 Stress analysis

Stress obtained from ANSYS after applying the maximum wheel force to the bogie are presented in figures below.

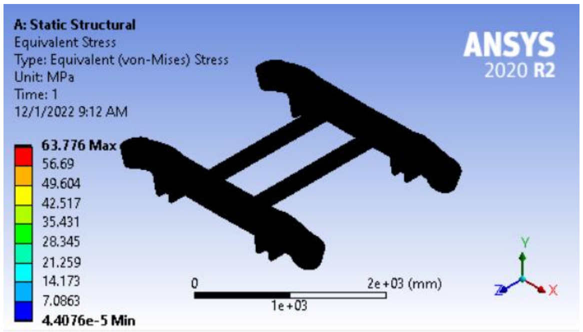
A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
12/1/2022 9:12 AM

Fig 10: Equivalent stress for case 1

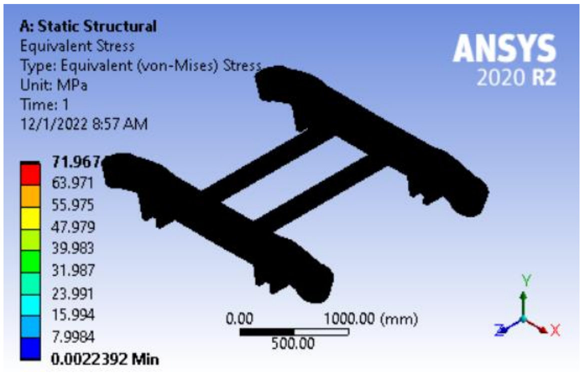
A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
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Fig 11: Equivalent stress for case 2

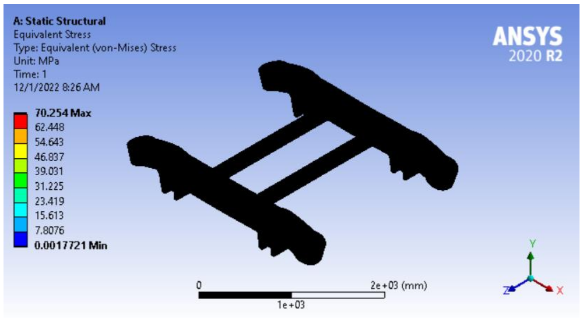

Fig 12: Equivalent stress for case 3

Case 2 has high equivalent stress compared to case 1 and case 3.

6.3 Fatigue Analysis

By using Manson-Coffin equation

$$\sigma_{\max} \times \frac{\delta\varepsilon}{2} = \frac{(\sigma_f)^2 \times (2N_f)^{2b}}{E} + \sigma_f{}' \times \varepsilon_f{}' \times (2N_f)^{b+c} \tag{14}$$

Where, $\sigma_{\max}$ is the maximum stress, $\delta\varepsilon$ is the maximum normal strain, $\sigma_f{}'$ is the N_f is the fatigue life cycles, E is the young modulus, $\varepsilon_f{}'$ is the b and c are constants.

Table 6: Fatigue life for three cases

Case	Fatigue life (N_f)
1	3.2248×10^6
2	4.3171×10^6
3	3.4812×10^6

According to the study done by Kang et al. in 2009 [25] and Seo et al. in 2017 [9], the results of this study were validated.

Conclusion

Uncertainty of suspension have more negative effects compared to other uncertainty parameters. Uncertainty of passenger's weight have less negative impact compared to other uncertainty parameters.

Conflict of Interests Declaration

There are no potential conflicts of interest with regard to the research, authorship, and/or publication of this paper, according to the authors.

Acknowledgments

The authors would like to thank the World Bank (WB) for funding railway engineering studies at Addis Ababa University's African railway center of excellence (ARCE). The authors would like to thank ARCE administration for allowing us to be a part of this intellectual adventure, as well as the anonymous reviewers for their constructive remarks that improved the paper and acknowledge the incorporation of some of their suggestions.

References

[1] Y. Lu, P. Xiang, P. Dong, X. Zhang, and J. Zeng, "Analysis of the effects of vibration modes on fatigue damage in high-speed train bogie frames," *Eng. Fail. Anal.*, vol. 89, no. November 2016, pp. 222–241, 2018, doi: 10.1016/j.engfailanal.2018.02.025.

[2] Y. Li, Q. Qin, Y. Wang, and M. Hu, "Welded joint fatigue reliability analysis on bogie frame of high-speed electric multiple unit," *J. Shanghai Jiaotong Univ.*, vol. 22, no. 3, pp. 365–370, 2017, doi: 10.1007/s12204-017-1845-1.

[3] C. K. V. B. D. Bharadwaj, "Stress Analysis of Bogie Frame Structure," *Yüksek Lisans Tezi*, pp. 17–20, 2007.

[4] W. Zhai, P. Liu, J. Lin, and K. Wang, "Experimental investigation on vibration behavior of a CRH train at speed of 350 km/h," *Int. J. Rail Transp.*, vol. 3, no. 1, pp. 1–16, 2015, doi: 10.1080/23248378.2014.992819.

[5] Y. Zakaria, "Analyzing a bogie frame behavior by using the experimental method and ansys simulations," *UPB Sci. Bull. Ser. D Mech. Eng.*, vol. 76, no. 4, pp. 149–164, 2014.

[6] W. Tang, W. Wang, Y. Wang, and Q. Li, "Fatigue Strength and Modal Analysis of Bogie Frame for DMUs Exported to Tunisia," *J. Appl. Math. Phys.*, vol. 02, no. 06, pp. 342–348, 2014, doi: 10.4236/jamp.2014.26041.

[7] N. Zhu, S. Sun, Q. Li, and H. Zou, "Theoretical research and experimental validation of elastic dynamic load spectra on bogie frame of high-speed train," *Chinese J. Mech. Eng. (English Ed.*, vol. 29, no. 3, pp. 498–506, 2016, doi: 10.3901/CJME.2016.0308.027.

[8] Amol B. Sapkal and Saurabh S. Sirsikar, "Static and fatigue strength analysis of bogie frame," *Natl. Conf. Appl. Sci. Humanit. (NCASH 2016)*, vol. 1, no. March, pp. 129–134, 2016.

[9] J. W. Seo, H. M. Hur, H. K. Jun, S. J. Kwon, and D. H. Lee, "Fatigue Design Evaluation of Railway Bogie with Full-Scale Fatigue Test," *Adv. Mater. Sci. Eng.*, vol. 2017, 2017, doi: 10.1155/2017/5656497.

[10] E. Andersson, R. Persson, V. Engineering, and B. Transportation, "on the Optimization of a Track-Friendly Bogie," pp. 1–13.

[11] A. N. Savoskin, A. A. Akishin, and D. Yurchenko, "Dynamics and optimization of a new double-axle flexible bogie for high-speed trains," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 232, no. 5, pp. 1549–1558, 2018, doi: 10.1177/0954409717737879.

[12] Sunqi and Liminzhi, "Researching on CRH2 type's moving train operation simulation's compared the single-mass-string model in the high-speed railway special passenger line of China," *2011 3rd Int. Conf. Adv. Comput. Control. ICACC 2011*, no. Icacc, pp. 39–43, 2011, doi: 10.1109/ICACC.2011.6016362.

[13] S. Baek, X. Song, M. Kim, and J. Kim, "Multiobjective Optimization of Beam Structure for Bogie Frame Considering Fatigue-Life Extension," *J. Electr. Eng. Technol.*, vol. 16, no. 3, pp. 1709–1719, 2021, doi:

10.1007/s42835-021-00662-3.

[14] B. Hwa Park, N. Po Kim, J. Seok Kim, and K. Yong Lee, "Optimum design of tilting bogie frame in consideration of fatigue strength and weight," *Veh. Syst. Dyn.*, vol. 44, no. 12, pp. 887–901, 2006, doi: 10.1080/00423110600737106.

[15] S. Huang, H. Hemida, and M. Yang, "Numerical calculation of the slipstream generated by a CRH2 high-speed train," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 230, no. 1, pp. 103–116, 2016, doi: 10.1177/0954409714528891.

[16] K. Daher and Ali, "Strength and fatigue analysis of composite bogie frame," 2017.

[17] B. Xing, J. Zhang, and Y. Xu, "Simulation and optimization design of CRH380A Emu bogie frame," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 790, no. 1, 2020, doi: 10.1088/1757-899X/790/1/012117.

[18] L. Kou, Y. Qin, L. Jia, and Y. Fu, "Multistate Reliability Evaluation of Bogie on High Speed Railway Vehicle Based on the Network Flow Theory," *Int. J. Softw. Eng. Knowl. Eng.*, vol. 28, no. 4, pp. 431–451, 2018, doi: 10.1142/S0218194018400053.

[19] "Analysis of methodologies for fatigue calculation for railway bogie frames. A.Cera 1 , G.Mancini 1 , V.Leonardi 1 , L.Bertini 2," 2006.

[20] S. Joshi, R. Arindom, T. Dikshit, B. Anish, A. G. Deep, and P. Pallav, "Optimization of Bogie Frame," *Indian J. Sci. Technol.*, vol. 8, no. 12, pp. 83–89, 2019, doi: 10.17485/ijst/2015/v8i.

[21] S. C. Yoon, Y. S. Kim, J. H. Ryu, S. H. Park, and G. S. Park, "A study on the characteristics of bogie frame materials," *Appl. Mech. Mater.*, vol. 420, pp. 144–148, 2013, doi: 10.4028/www.scientific.net/AMM.420.144.

[22] A. Momhur, Y. X. Zhao, W. Q. Li, Y. Z. Sun, and X. L. Zou, "Flexible-Rigid Wheelset Introduced Dynamic Effects due to Wheel Tread Flat," *Shock Vib.*, vol. 2021, pp. 13–23, 2021, doi: 10.1155/2021/5537286.

[23] Q. An, H. Zhao, P. Li, and M. Fu, "Fatigue strength analysis of bogie frames under random loads," *Adv. Mech. Eng.*, vol. 11, no. 9, pp. 1–13, 2019, doi: 10.1177/1687814019878018.

[24] P. Rail, E. Safety, and S. W. Group, "Design and Construction of Passenger Railroad Rolling Stock," 2020.

[25] K.-W. Kang, B.-C. Goo, J.-H. Kim, D.-K. Kim, and J.-K. Kim, "Experimental investigation on static and fatigue behavior of welded sm490a steel under low temperature," *Int. J. Steel Struct.*, vol. 9, no. 1, pp. 85–91, 2009, doi: 10.1007/bf03249483.

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