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Fatigue life assessment of high-speed train's bogie frame due to dynamic loads under the influence of wheel flat

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Abstract— A bogie frame is the most important railway vehicle's component that supports almost the weight of the system, and it is subjected to various excitations and loads that can result in the failure of the structure. The dynamic forces influenced by various excitations, both internal and external, can speed up the system's fatigue failure. This paper aims to analyse the impact of wheel flats on the life of a high-speed bogie frame. To accomplish this study, a Chinese railway high-speed (CRH2) bogie frame, has been chosen for the analysis. The required input data for CRH2 have been collected from literature; the wheel flat defect models under the wheel flat lengths of 20 mm, 40 mm, and 60 mm have been developed with a MATLAB tool, and the results have been inputted into a multibody model with the SIMPACK tool. The dynamic response loads for each case have been exported and applied to the finite element model in ANSYS, where stresses and strain have been used to estimate the fatigue life. The results from the study show that as the wheel flat length increases, it increases the dynamic forces and stresses that decrease the life of the bogie frame; thus, the influence of wheel flat should be considered in the life prediction of a bogie frame.

Index Terms— Fatigue life, Wheel flat, Finite element method, Multi-body system, High-speed bogie frame.

I INTRODUCTION

A railway bogie frame is the most important component that supports almost the weight of a train. Its reliability can affect the safe operation of the system [1]. The failure of a railway bogie frame can result in fatal incidents such as derailment, passenger discomfort, etc. The bogie frame can face with fatigue failure resulting from dynamic loads under the influence of various parameters. The various researches about fatigue failure of a railway bogie frame had been conducted. For instance, the studies on fatigue strength of a bogie frame under the influence of randomly distributed stresses had been conducted [2, 3]. The stress characteristics due to random loads affect significantly the fatigue strength of welded bogie structures [4, 5].

The future of railway operation is focused on increasing the speed as well as the safety performance of a train. China is one of the world's first countries to implement high-speed train operations capable of reaching speeds of up to 350 km/h. For instance, the Beijing-Tianjin railway line was established as the first high-speed line in China, followed by the long-distance Wuhan-Guangzhou high-speed line, which operated in 2009, and later the Beijing-Shanghai line, with the highest standard design, was established as a high-speed railway line in 2011 [6]. However, the development of high-speed trains

is accompanied by the effect of increasing the complexity of the dynamic responses [7]; which can influence severe vibrations and resonance due to variation of dynamic loads, which can increase fatigue failure of the high-speed train [6].

Fatigue life assessment of a railway bogie frame has been developed by various researchers till now. Zehsaz et al. [8] looked at the effect of increasing train speed on stress distribution on the bogie frame, and the findings showed that as train speed increased, so did the stress distribution on the bogie frame area, reducing the frame's life. Seo et al. [9] performed the full-scale test for fatigue life evaluation of a bogie frame under exceptional and service loading by adopting EN 13798 standard. Li et al. [10] and Xiu et al. [11] carried out research on various approaches used in the fatigue life prediction of a railway bogie frame. The prediction of fatigue damage of a metro bogie frame based on measured loads was conducted by Wang et al. [12]. Guo et al. [7] studied the fatigue life assessment of a powered bogie frame by considering the effect of internal excitation from gear meshing. During the operation of a high-speed train, almost all vehicle system components can experience severe vibration due to external excitations, and if these severe vibrations reach an unacceptable limit, they can immediately impact the safe operation and ride comfort of the railway system [6]. High vibrations can

force the track components to move downward and the vehicle components to rise, which can shorten the lives of those components [13, 14].

One of the wheel defects that is considered as an external excitation between the wheel and rail is wheel flatness. Wheel flats can occur as a result of improper brake application or a decrease in wheel-rail adhesion contact [15]. When a braking system of a railway vehicle is poorly applied, adjusted, or deteriorates, it may result in a braking force that is higher than the friction force between wheel and rail, hence becoming a barrier to the rotation of the wheelset and causing the sliding of a railway wheel [16]. The presence of contaminants such as lubricants, leaves, or snow on the rail surface can result in

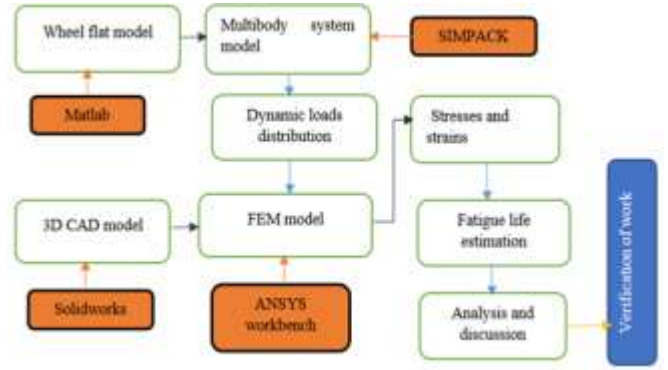
a decrease in the adhesion force between wheel and rail, hence hindering the rotation of wheelsets [17].

The combination of wheel flat defects, high vehicle speed, and large axle loads influence high impact vibrations and dynamic forces, which can increase the rate of failure for both track and vehicle components [18]. The high-impact loads and vibrations between the wheel and rail can be transferred to various components like rails, sleepers, and soon, reducing the life cycle of those components due to fatigue failure [19]. In addition to that, wheel flats induce thermal conditions that can initiate cracks on the wheel tread rolling surface, which affects the wheel life [15]. Repairing a wheel defect increase the maintenance cost of a railway operation system and affect the effectiveness of the system [20]. The availability of wheel flats can be recognized when the dynamic force provided by the wheel on the rail exceeds the predetermined thresholds [21]. Railway wheel defects can influence a higher rate of accidents than any other components of the vehicle [22]. A study on the dynamic behaviour of a train under the influence of wheel flat defects using a 3D vehicle-track coupled system was analysed by Uzzal et al. [23]. A study on wheel flat impacts under the influence of contact geometry was carried out [17, 24].

Even though several types of research have been developed on the fatigue life of a bogie frame under the influence of various parameters, no detailed study has explained the impact of wheel flats on the life of a bogie frame. Therefore, further studies on the impacts of wheel flat defects on various vehicle components are still needed. The main objective of this paper is to analyze the effect of wheel flat excitation on the fatigue life of a high-speed bogie frame, CRH2. The study has been accomplished by combining the multibody vehicle system model with finite element numerical simulations under the influence of wheel flats. The model has been validated by comparing the simulation results and analytical results from the study with previous results from the literature.

II MATERIALS AND METHODOLOGY

In this study, the integration of finite element and multi-body dynamic system simulation methods has been used because it is among the most cost-effective techniques in the analysis of railway vehicle dynamic behavior. As shown in Figure 1, this study is based on simulation analysis with the



help of various design and simulation software packages such as SOLIDWORKS, MATLAB, SIMPACK, and ANSYS Workbench tools. SOLIDWORKS has been used in the 3D design of the CRH2 bogie frame, Matlab code has been used to provide a wheel flat model, SIMPACK has been used to provide a multibody vehicle system model and provide dynamic response on the bogie for various wheel flat lengths, and finally, ANSYS Workbench has been used to analyze stresses and strains distribution on the bogie frame for selected cases of wheel flat lengths with finite element method (FEM) and to estimate the life of the CRH2 high-speed bogie frame.

Figure 1. Fatigue life assessment analysis methodology

III DYNAMIC SYSTEM OF A RAILWAY VEHICLE

The general railway vehicle dynamic system equation can be expressed in the form of a submatrix as appear in [25] as follows:

$$[M_v]\ddot{D}_v + [C_v]\dot{D}_v + [K_v]D_v = [F_{vt}] \quad (1)$$

Where $[M_v]$, $[C_v]$, $[K_v]$, and $[F_{vt}]$ are matrices for mass, damping, stiffness, and external force, respectively; \ddot{D}_v , \dot{D}_v , and D_v are acceleration, velocity, and displacement vectors of the vehicle subsystem, respectively. The subscripts v and t refer to the vehicle and track of the subsystem, respectively.

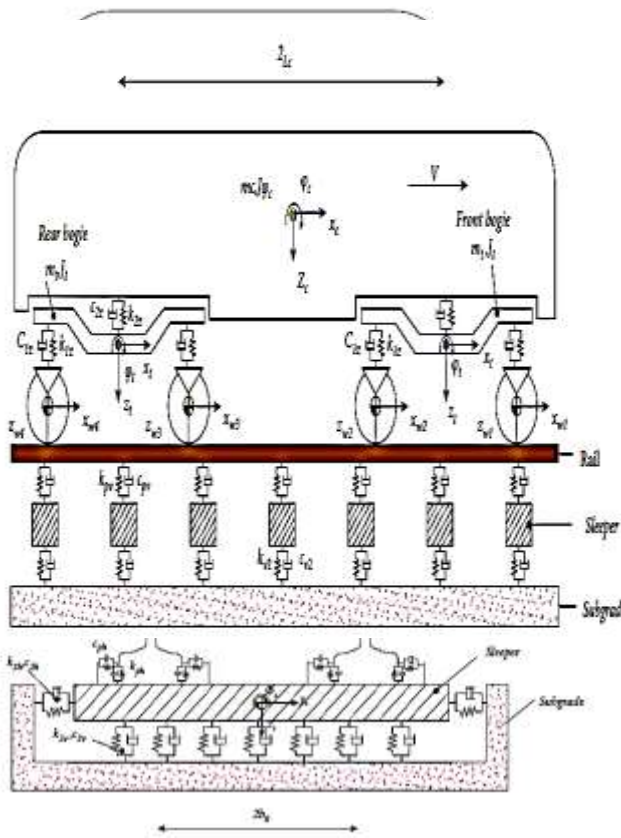


Figure 2. Side view of vehicle dynamic model for railway [25]



Figure 3. Front view of vehicle dynamic model for railway [25]

SIMPACK simulation for the three selected wheel flat lengths of 20 mm, 40 mm, and 60 mm has been applied to the finite element model to provide stresses and strain distribution for each case on the bogie frame. Finally, the fatigue life estimation for each case has been calculated using

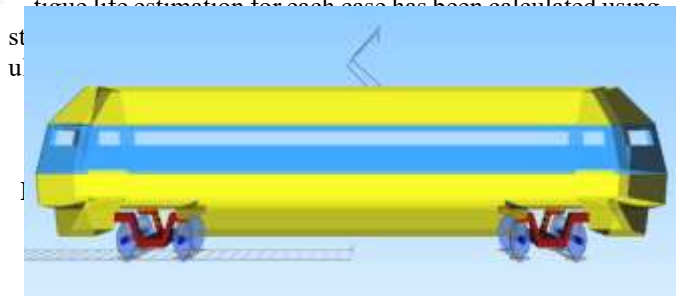


Figure 5. Multibody system model in SIMPACK

IV Results and discussion

A. Dynamic response from SIMPACK at various wheel flats

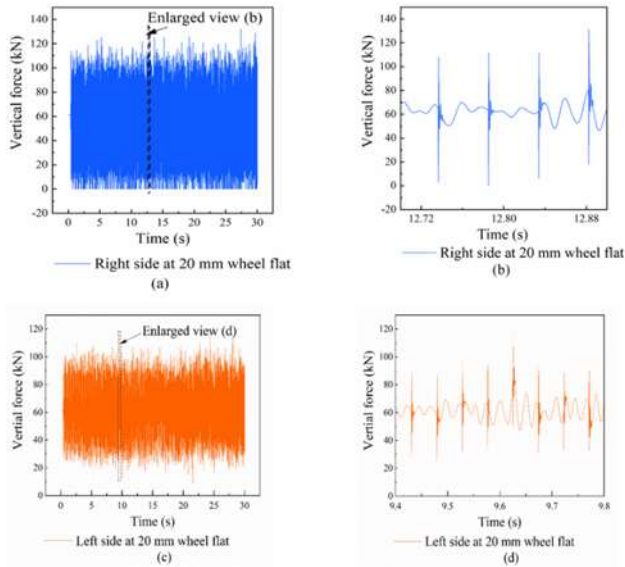
1. Dynamic response results for 20 mm wheel flat

The dynamic response load history when a wheel flat length of 20 mm is considered is shown in figures 6 and 7 for the vertical and lateral forces, respectively. Figures 6 (a), (b), (c), and (d) represent vertical forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively; while figures 7 (a), (b), (c), and (d) represent lateral forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively. The result shows that the wheel flat affects the

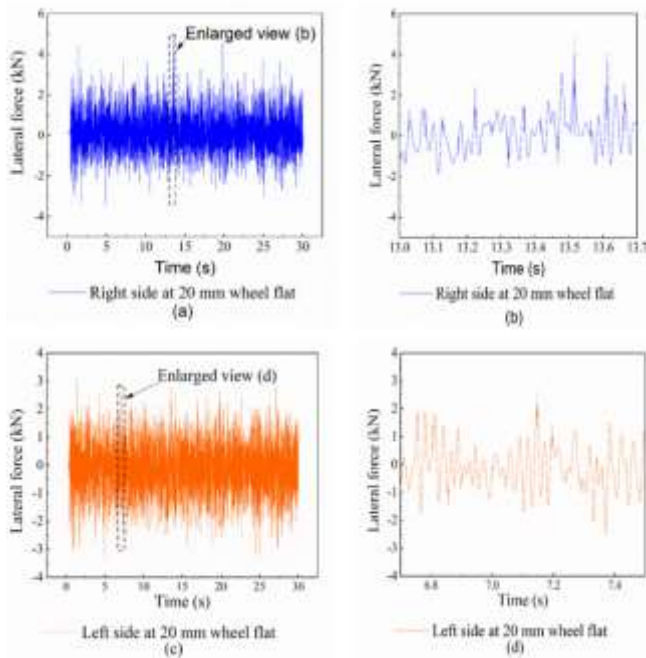
A. Modelling and simulation

The main objective of this study is to analyze the influence of wheel flats on the fatigue life of the high-speed bogie frame case of the CRH2. The aim has been accomplished through the design and simulation of the model with the help of various software. As shown on the flow chart methodology used in the study, the wheel flat model has been provided by using MATLAB code and integrating it with the multibody vehicle system model in SIMPACK as shown in Figure 4, where dynamic load history responses for different wheel flats have been recorded. Also, the SOLIDWORKS tool has been used to design the 3D CRH2 bogie frame model, and its IGS file has been imported into ANSYS to form a finite element model as shown in Figure 3. The extracted load history from

right side more than the left side because, during the simulation, the wheel flat was considered on the right-side wheels. In general and at normal condition for straight track consideration the behaviour of left side and right side are assumed to be equal (Symmetric) during simulation you might consider



both sides but in terms of computational time it is better to consider input on one side which in turn provide the generalization on whole system, this is the reason behind of one side's consideration. The maximum vertical loads in this case have been recorded as 132.167 KN and 116.962 KN for the



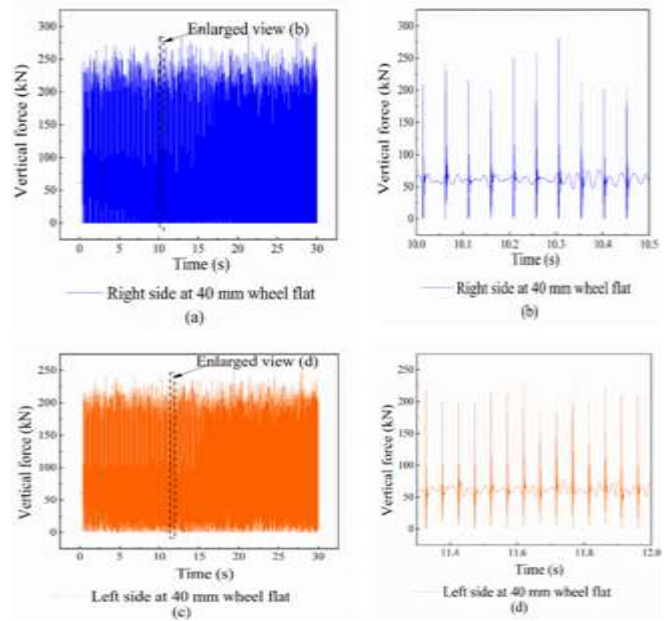
right and left sides, respectively, and the lateral forces are 4.911 KN and 3.067 KN.

Figure 6. Vertical dynamic response at wheel flat of 20 mm: (a) right side, (b) enlargement of (a), (c) left side, and (d) enlargement of (c).

Figure 7. Lateral dynamic response at wheel flat of 20 mm: (a) right side, (b) enlargement of (a), (c) left side and (d) enlargement of (c).

2. Dynamic response results for 40 mm wheel flat

The dynamic response load history for the case of a 40 mm wheel flat, is shown in Figures 8 and 9 for the vertical and lateral forces, respectively. Figures 8 (a), (b), (c), and (d) represent vertical forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively, while figures 9 (a), (b), (c), and (d) represent lateral forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively. The results also show that the wheel flat affects the right side more than the left side, as in the case of the 20 mm wheel flat. The max-



imum vertical loads in this case have been recorded as 292.622 KN and 254.297 KN for the right and left sides, respectively, and the lateral forces are 12.951 KN and 5.498 KN. From these results, it is clear that the dynamic loads for the 40 mm wheel flat are higher than those for the 20 mm wheel flat, which means that as wheel flat length increases, induced dynamic forces increase.

Figure 8. Vertical dynamic response at wheel flat of 40 mm: (a) right side, (b) enlargement of (a), (c) left side and (d) enlargement of (c).

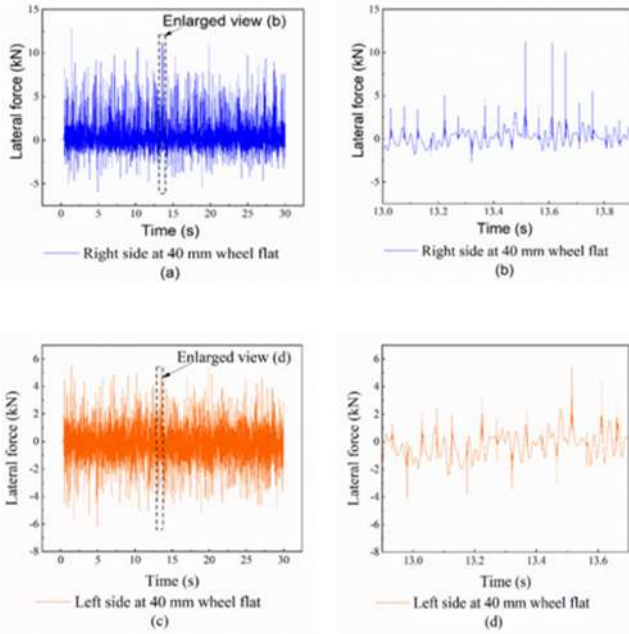


Figure 9. Lateral dynamic response at wheel flat of 40 mm: (a) right side, (b) enlargement of (a), (c) left side and (d) enlargement of (c).

3. Dynamic response results for 60 mm wheel flat

The dynamic response load history for the case of a 60 mm wheel flat, is shown in figures 10 and 11 for the vertical and lateral forces, respectively. Figures 10 (a), (b), (c), and (d) represent vertical forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively; while Figures 11 (a), (b), (c), and (d) represent lateral forces on the right side of the bogie frame and its enlargement, and the left side and its enlargement, respectively. The results from this third case simulation also show that the wheel flat affects the right side more than the left side, as in previous cases, because the defect was considered on the right wheels of the system during the simulation. The maximum vertical loads in this case have been recorded as 508.55 kN and 447.941 kN for the right and left sides, respectively, and the lateral forces are 25.139 kN and 9.923 kN. From the results of both three cases of multibody simulation in Simpack, the general trend can be taken as if the wheel flat increases and influences the increase of dynamic forces in both the vertical and lateral directions of the frame.

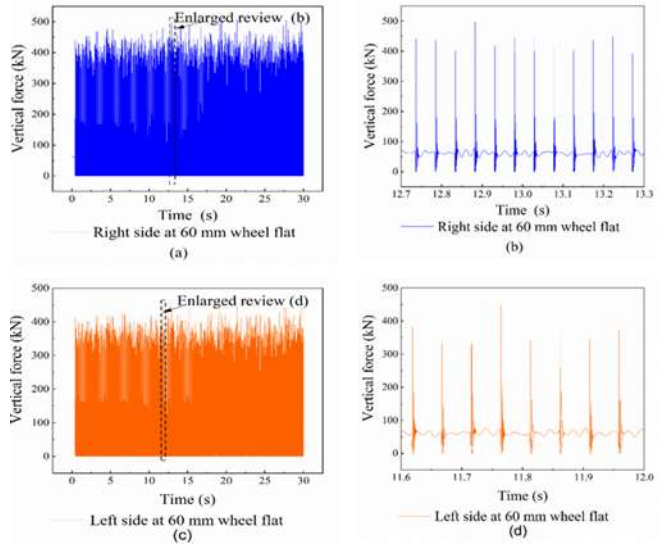


Figure 10. Vertical dynamic response at wheel flat of 60 mm: (a) right side, (b) enlargement of (a), (c) left side and (d) en-largement of (c).

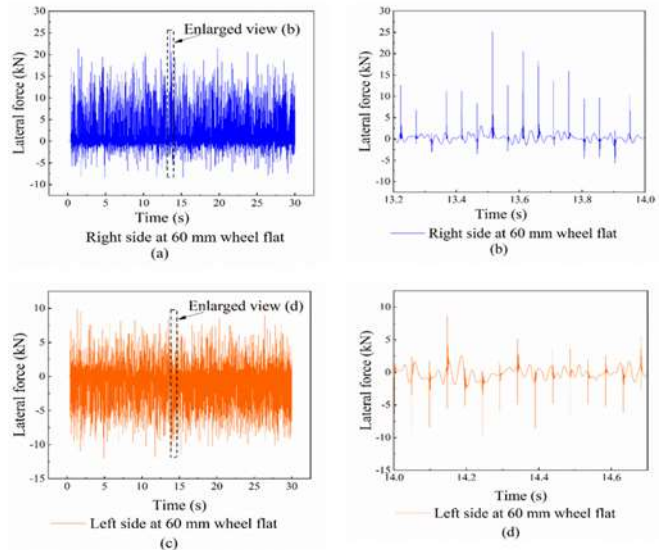


Figure 11. Lateral dynamic response at wheel flat of 60 mm: (a) right side, (b) enlargement of (a), (c) left side and (d) en-largement of (c).

4. Variation of the vertical load as a function of the variation in the size of the wheel flat length

The figures 12 and 13 show the variation in the maximum values of the vertical load as a function of the variation in the size of wheel flat for the right and left side respectively. The results show the general trend as the vertical load increases as the size of wheel flat increases. In addition to that the figures show clear change at wheel flat length of 40 mm, this indicates that at 40 mm wheel flat, the critical response will start due to the gradually increasing of wheel damage. Beyond this value the fit line of the graph is too slop than below 40 mm

this means that at the wheel flat length which is great than 40 mm the rate in the variation of vertical load is too high. Further explanation on this phenomenon about critical response due to variation in wheel flat length were provided in study done by Momhur et al., 2021 [25]

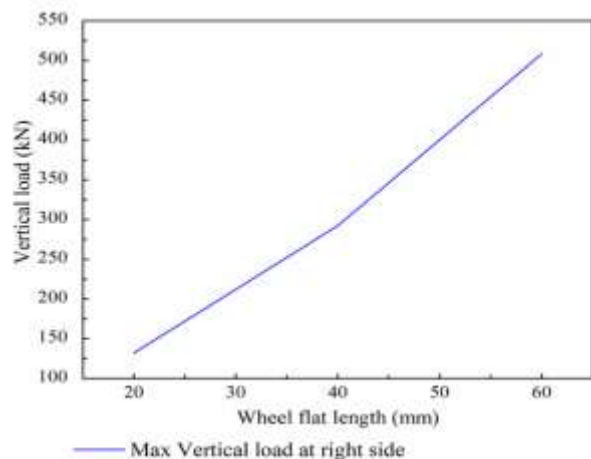


Figure 12. The variation of maximum vertical load in function of wheel flat length at the right side.

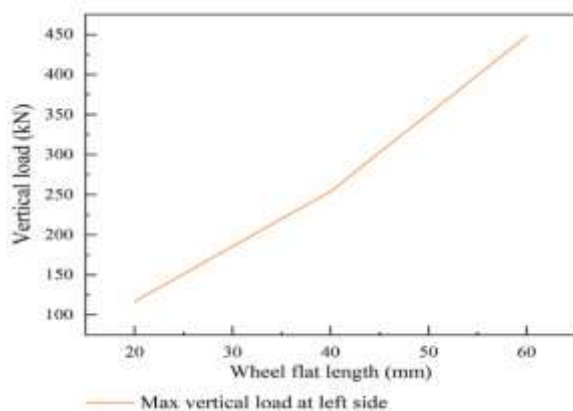


Figure 13. The variation of the maximum vertical load in function of wheel flat length at the left side

V Finite element simulation results

As shown from the methodology flow chart used in this study, the dynamic forces from SIMPACK simulations have been exported and applied to the finite element model in the ANSYS tool; to understand the distribution of stresses and strains on the bogies frame for each wheel flat length considered in this study, which has been used in the calculation of the fatigue life cycles of the bogies frame. In addition to that, the fatigue life cycles for each case have been recorded using the fatigue tool in ANSYS. The results from ANSYS software simulations are shown in Figures 14, 15 and 16 for stress distribu-

tion at 20, 40, and 60 mm wheel flats, respectively, while Figures 17, 18 and 19 show estimation fatigue life cycles for 20, 40, and 60 mm wheel flats, respectively. The figures 20 and 21 show the variation of life cycles versus wheel flat length and maximum von mises stress versus wheel flat length, respectively. The general trend from the simulation results shows that as the wheel flat length increases, stresses increase while fatigue life cycles decrease.

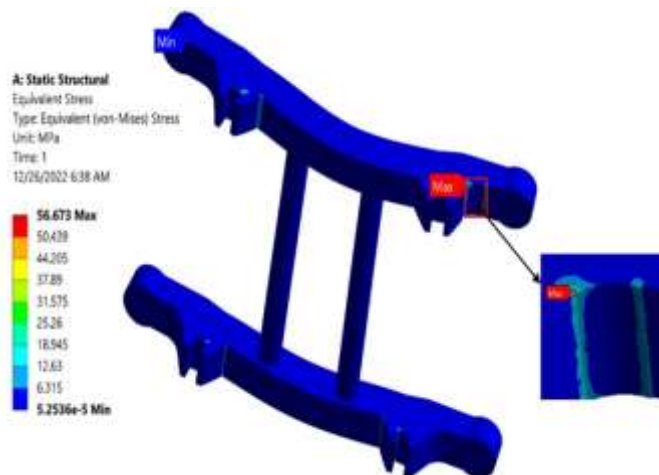


Figure 14. Stresses distribution on the bogie frame at 20 mm wheel flat length

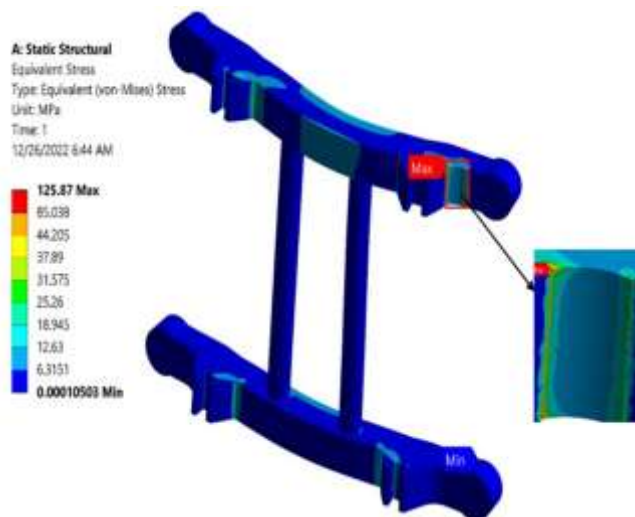


Figure 15. Stresses distribution on the bogie frame at 40 mm wheel flat length

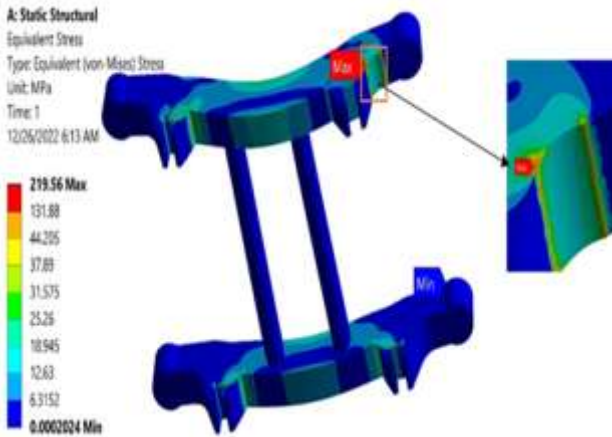


Figure 16. Stresses distribution on the bogie frame at 60 mm wheel flat length



Figure 19. Fatigue life cycles from the simulation at 60 mm wheel flat length

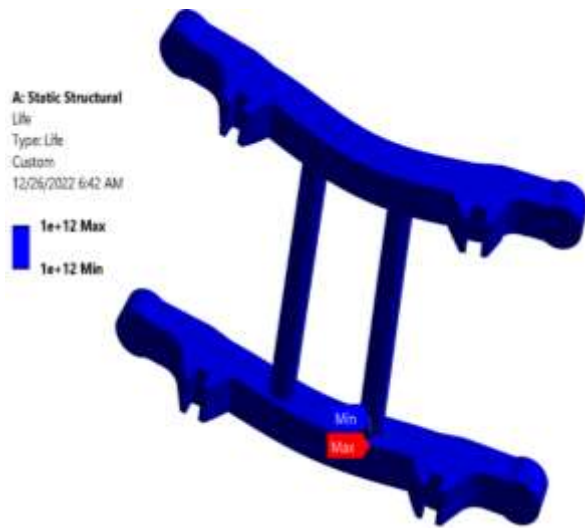


Figure 17. Fatigue life cycles from the simulation at 20 mm wheel flat length

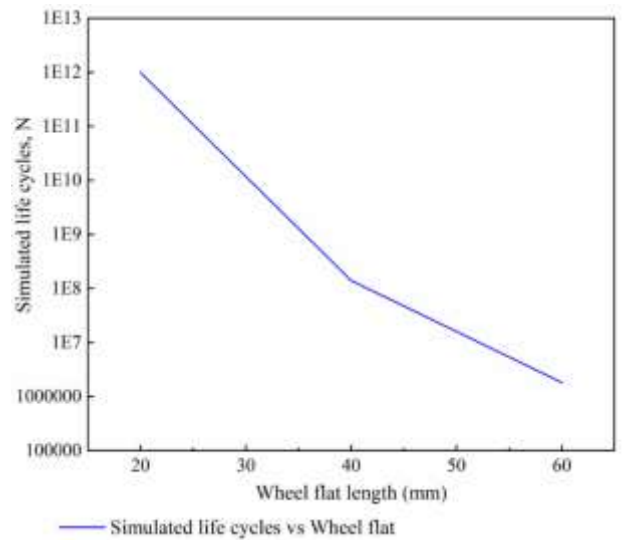


Figure 20. Simulated life cycle Versus Wheel flat length



Figure 18. Fatigue life cycles from the simulation at 40 mm wheel flat length

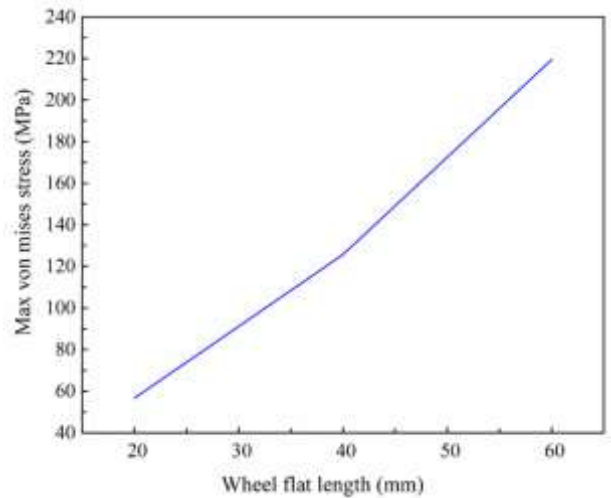


Figure 21. Maximum Von mises stress versus Wheel flat length

A. Fatigue life calculation

In this study, the fatigue life prediction has been performed based on the better approach of the Smith-Watson-Topper (SWT) modified approach of Manson-Coffin, which takes into consideration both stresses and strains induced in the structure. The expression for this SWT fatigue approach is shown in equation (2) [26].

$$\sigma_{\max} \frac{\Delta \varepsilon}{2} = \frac{(\sigma'_f)^2}{E} (2N_f)^{2b} + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \quad (2)$$

Where the symbols ε'_f , σ'_f , c and b explain the various fatigue characteristics; standard for, respectively, the fatigue coefficient of ductility, fatigue coefficient of strength, fatigue exponent of ductility and fatigue strength exponent. While σ_{\max} , $\Delta \varepsilon/2$, N_f and E means maximum stress, strain amplitude, fatigue life cycles and modulus of elasticity, respectively.

Estimated fatigue properties constants for bogie frame structural steel used in this study have been referenced from [27] as the following:

$\sigma'_f = 903.3$ MPa, $\varepsilon'_f = 0.288$, $b = -0.102$ and $c = -0.499$ and the modulus of elasticity for high-speed bogie frame steel can be taken as $E=215$ MPa [7].

From ANSYS simulation results $\sigma_{\max} = 56.673$ MPa, $\Delta \varepsilon/2 = 1.7483 * 10^{-4}$ for case 1 of 20 mm wheel flat, $\sigma_{\max} = 125.87$ MPa, $\Delta \varepsilon/2 = 3.8818 * 10^{-4}$ for case 2 of 40 mm wheel flat and $\sigma_{\max} = 219.56$ MPa, $\Delta \varepsilon/2 = 6.768 * 10^{-4}$ for case 3 of 60 mm wheel flat. By replacing the above data into equation (2), the estimation values for fatigue life cycles of the high-speed bogie frame are $2.3081 * 10^{12}$ cycles, $9.8757 * 10^8$ cycles and $6.4041 * 10^6$ cycles for 20, 40 and 60 mm wheel flat respectively.

B. Comparison between simulation and calculation results

The fatigue life cycles from simulation and calculation at various wheel flat lengths can be compared by referring to table 1 and figure 22. The results show that the simulation approach is approximately equal to the calculation; the difference might come from the mesh size used during the simulation of the finite element model, where better results are obtained with a fine mesh but computational time increases.

Table 1. Comparison between simulated and calculated life cycles

flat length (mm)	Simulated life cycles	Calculated life cycles
20	$1 * 10^{12}$	$2.3081 * 10^{12}$
40	$1.3962 * 10^8$	$9.8757 * 10^8$
60	$1.8317 * 10^6$	$6.4041 * 10^6$

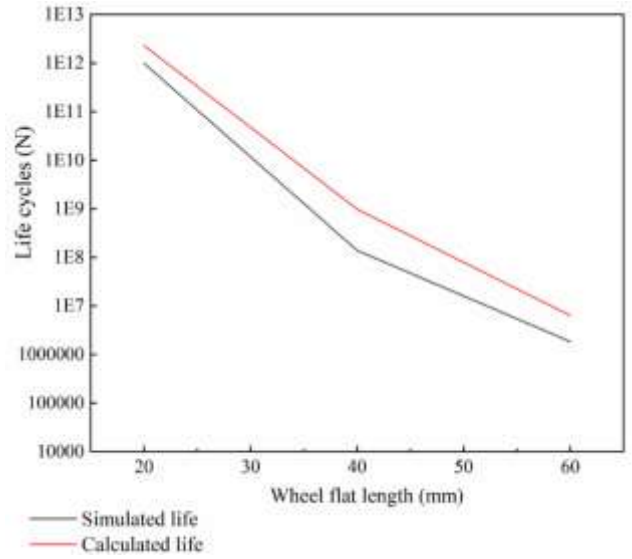


Figure 22. Effect of wheel flat for life cycles

With reference to paper [7] the design mileage for a high-speed bogie in china can be 10.8 million km and from paper [28] the fatigue life design is about 10^7 cycles; This indicates that, from Table 1 of the results for the cycles obtained, at 60 mm wheel flat, the bogie frame will start to operate below the designed fatigue life, which may result in a reduction in life. It is clear from figure 22 that an increase in wheel flat length decreases the life cycles for both simulation and calculation approaches.

VI CONCLUSION

In this paper, the influence of wheel flats on the fatigue life of a high-speed bogie frame has been analyzed. The dynamic response load histories and stress distributions were obtained for various wheel flat lengths. Finally, the fatigue life prediction and its analysis for bogie frame under the influence of wheel flats have been conducted. From the study, the following conclusions can be drawn:

1. The wheel flat excitation influences the increase in dynamic forces for the bogie frame in both vertical and lateral directions, which in turn increase the stress distribution on a bogie frame.
2. The increase in stresses and strains from the fatigue life calculation approach, like the well-known Smith-Watson-Topper (SWT) approach, causes the decrease in fatigue life cycles.
3. The relationship between wheel flat length and dynamic loads, stresses and strains is non-linear due to the impact from wheel-rail Hertzian contact.
4. As the wheel flat increases in length, it causes significant increase in stress distribution that minimizes the life of the bogie frame. For example, as shown in the study the fatigue life cycle of the frame at 20 mm wheel flat is $2.3081 * 10^{12}$ while at 40 mm is $9.8757 * 10^8$ this is about decreased by 99.9 % and the life cycle at 60 mm wheel flat is decreased about

99 % compared to that at 40 mm wheel flat.

5. At wheel flat length of 40 mm and above, the system experience the significant critical response where the rate in variation of dynamic forces is high which influence the fatigue failure due to high impact loads.
6. It is recommended to consider the effect of wheel flat excitation during the prediction of the fatigue life of the bogie frame. The further study based on real measured wheel flats for better understanding of the effect of wheel flat on the fatigue life of a bogie frame and how to mitigate it is required.

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