Fatigue Strength Analysis of Bogie Frame Under Wheel Polygon

Tindiwensi edison[1], awel Mohammedseid[1,2]

1. African Railway Center of Excellence, Addis Ababa University, Ethiopia
2. School of Mechanical Engineering, Southwest Jiatong University, Chengdu 1003, China
E-mail address: tindiedison1@gmail.com and awel.mohammedseid@aait.edu.et

ABSTRACT

The development of the railway bogie includes analysis and testing of the bogie frame. The main purpose of the frame is to withstand or transfer vertical loads of the superstructure with payload. Many researchers have conducted research on wheel polygonal wear and bogie frame fatigue analysis. Several published papers have reviewed the research question of "what is the influence of different wear amplitudes on fatigue of bogie is being answered". Different review articles have been looked into and proper consideration has been put on and identified the research gap. The bogie could be improved by reducing variable frequency drive or wheel reprofiling that can revamp the system to its original or some acceptable working condition. Detailed data on the bogie frame has been collected from the kinds of literature. Then modelling of the bogie frame has been performed by using solid works and besides, and detailed sensitivity analysis has been performed by using different operating parameters (i.e., material properties and loading conditions). At normal loading conditions a stress of 83.56Mpa which is below the yield strength of steel was attained by the bogie frame and cycles of 10^{12},$10^{9}$and 10^{9} were calculated from 0.1mm,0.2mm and 0.3mm respectively. It indicated that an increase in wear amplitude increased contact forces which increased the fatigue on the bogie. Reducing wear amplitude would reduce contact forces hence reducing wear polygonisation and improving operation.

Therefore, this study aims at assessing the fatigue on the bogie due to different wear amplitudes which will maximize the energy losses and also improve the safety and operation of the whole system.

Keywords: CRH Bogie, dynamic modelling, FEM, stress analysis, Fatigue strength analysis of bogie frame, wheel polygonisation.

1. INTRODUCTION

The bogie, as the running part of the high-speed EMU, carries the car body, contacts the track, and traction and guides the vehicle to drive along the track, which has an important impact on the stability, smoothness and safety of the EMU operation. And the frame is its main bearing part, each part on the bogie must be installed in the frame and form a whole. Therefore, the bogie frame of the EMU must be strong enough to ensure the safety of train operation[1]

Wheel polygonisation, strongly influences the operational safety and quality of railway vehicles therefore this paper discuses the influence of different wear amplitudes on the fatigue of bogie frame.

This paper aims to develop a vehicle-track coupled dynamics model to investigate the effect of polygonal wear upon the dynamic performance of wear amplitude . Here the coupled effects from the wear amplitudes of the wheel are included, based on classical vehicle-track coupled dynamics theory and that of the TRB's dynamics. And, the interactions between the wheel and the rail, and guiding flange are modelled in detail. Based on this model,the dynamic response of the vehicle-track system is calculated under excitations of polygonal wheel wear and non-linear factors. Furthermore, the influence of the amplitude and the order of wheel polygonal wear on dynamic performance of the bogie frame are investigated in detail.

During train operation in Germany, a polygonisation phenomenon was observed to occur on the wheel tread, causing noise in the frequency range of 70–100 Hz and also resulting in medium-frequency structural vibration of the car body[2]. To reduce the wheel-rail rolling noise and vehicle structure vibration, solid wheels were replaced by rubber-sprung ones. The results of the accident investigation showed that the rubber wheels exhibited polygonisation with two harmonics around the wheel circumference. This can lead to a violently fluctuating wheel-rail contact load, and the wheel rim may fracture under alternating loads. Wheel polygonization is one of the major challenges in the field of wheel-rail interaction and can causewheel–rail impact vibration, and wheel–rail rolling and impact noise, thereby significantly reducing the vehicle ride comfort. The shock and vibration caused by the wheel polygon can be transmitted to the vehicle and track, causing fatigue failure of the vehicle and track components

Many researchers have begun conducting research on wheel polygonal wear, and most scientific papers on wheel polygonal wear in the past decade have been published by Chinese scholars. Several reviews have been published in the past. Nielsen and Johansson 2000[3] summarized the causes of wheel corrugation and low-order polygonal wear and mitigation measures in 2003. Barke and Chiu 2005[4] reviewed the effect of wheel polygonisation on vehicle and track components in 2005. Many new studies on wheel polygonisation have emerged in the last decade. The objective of this literature survey is to describe the state-of-the-art research on wheel polygonisation. Kaper identified polygonal wear phenomena on train wheels when he conducted research on the noise of intercity trains and studied the relationship between polygonal wear and noise in the frequency domain [5]. Anon, Kaper and Wu reviewed the literature on wheel polygonal wear in 2000 and 2018, respectively, and in their review, they summarized numerical simulation models of polygonal wear and explanations of its initiation mechanism and development [5]–[7]. Morys developed a dynamics model of an ICE-1 high-speed Garman train to investigate the polygonal wear mechanism. In the model, the wheelset mass modelling included five parts (two wheels and three brake discs), and they were all regarded as rigid bodies [6], [8]. Meywerk established a coupling dynamics model that included an elastic wheelset and two elastic rails to study the formation of polygonal wear [9]. The results showed that flexible deformations of the wheelset and rails, caused by their interaction, resulted in the initiation and development of polygonal wear.Meywerk established a coupling dynamics model that included an elastic wheelset and two elastic rails to study the formation of polygonal wear[10]. The results showed that flexible deformations of the wheelset and rails, caused by their interaction, resulted in the initiation and development of polygonal wear. The first and second bending modes of the wheelset played an important role in initiating polygonal wear. This literature focused on the characteristics and mechanisms of low-order polygonal wear. Pan proposed a finite element model of a wheelset's rolling contact with two rails using commercial finite element software to research to identify the root cause of polygonal wear[11]. Pan suggests that the self-excited vibration of the wheel-rail system leads to polygonal wear at a frequency of 150 Hz. A suitable sleeper support stiffness or wheel–rail friction coefficient can be controlled to limit the development of polygonal wear. Pan conducted extensive measurements of polygonal wear on electric locomotive wheels with radii of 1050–1200 mm at an average operating speed of 80 km/h [11], [12]. The measurement results showed that the dominant orders of the polygonal wear of locomotive wheels were 18^{th}, 19^{th}, and 24^{th}, and depended on wheel diameter. Jin et al. 2012). Studied the mechanism of the ninth-order polygonal wear in wheels of metro trains with a linear induction motor using a detailed site test and observation[13]. They found that the resonant frequency of the first wheelset bending matched the exciting frequency of the ninth-order polygonal wear. When the first wheelset bending mode was excited, the period of lateral creepage and force between wheel and rail occurred. However, most of the research on the structure still focuses on strength checking and fatigue analysis at present, while few on its optimal design. Therefore, this paper intends to use SOLID WORKS and multi-body system dynamics software to study the CHRH bogie frame applied to the type of CRH380A EMU, carry out simulation analysis and analyse the effects of different wear polygons with reference to the design and optimization of the power bogie frame of the EMU.

The paper is organized into three parts. A procedure of collecting reviewed papers are elaborated in section two under review methodology. Next, a detail review of fatigue damage calculation are presented in section three. Analysis and discussion of FE models extracted from each study is presented in section four.Finally, Conclusion is drawn in section five.

2. RESEARCH METHOD

The first step of a dynamic load of bogie frame is preparing a 3D solid model and assembly for validation of the structural model. Next is a calculation of dynamic load according to UIC due to rollingstock movement on the track to get the loading value received by the bogie structure. To represent the static and dynamic load on the bogie model, the boundary conditions and free body diagram were defined. Then predicting the S-N diagram for bogie material as input of fatigue analysis. Fatigue simulation is run using ANSYS software [14]and validated using experimental results.

The bogie was then imported to the multi-body system dynamics (SIMPACK) and contact forces generated from the right and left pair wheels are extracted which are imported to Ansys software again and the corresponding boundary conditions are applied and their respective life and damage observed. From the calculated and simulated results obtained from the Ansys software, the results are validated using experimental and literature results.

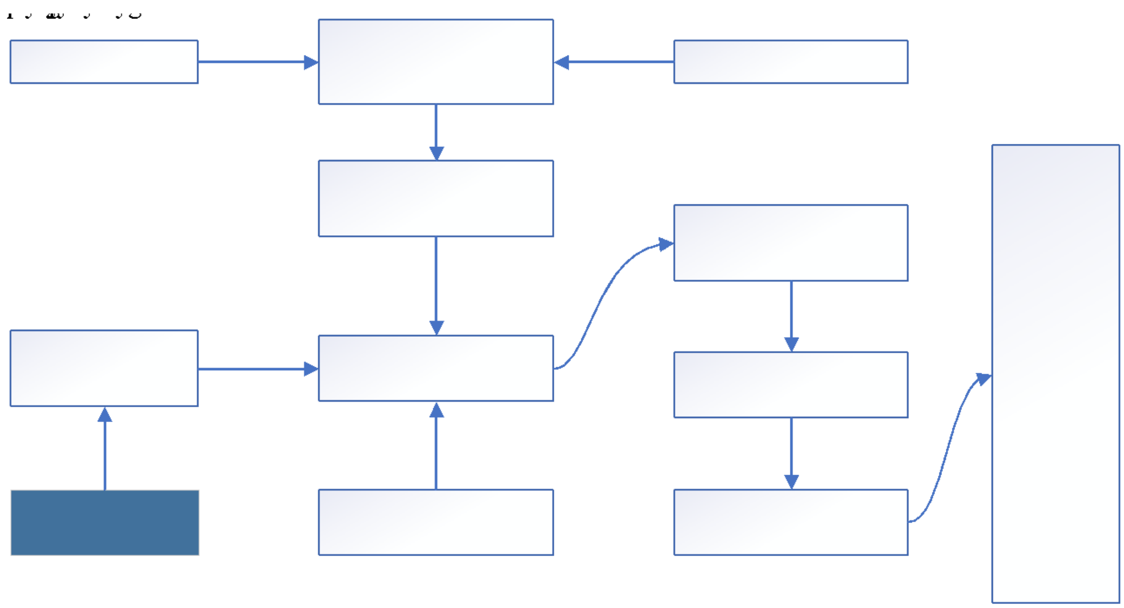

***Figure 1**. shows the methodology chart*

2.1: Basic Processing of 3D Model

Firstly, the solid model using CAD software was set up, and then the model was converted via the data interface of ANSYS and the finite element model was obtained through meshing and the load and boundary conditions were applied. The check for the convergence of mesh was conducted through contrast analysis. The calculation results are convergent when the element size was 7mm. The finite element model and the boundary condition of constraint are shown in Fig1.

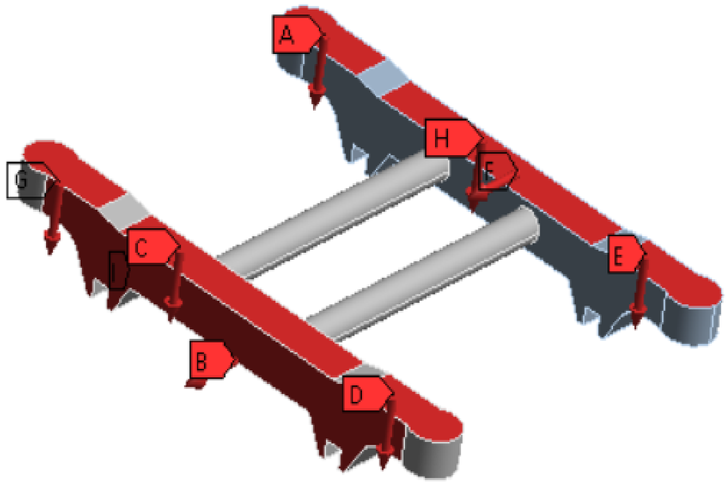

Figure 2. *shows the load conditions of the bogie frame*

2.2: Static Strength Load Calculation from Ansys Software

Table .1shows Properties of high-speed bogie

Parameter	Value
Mass of car (M_c)	35067kg
Mass of bogie frame (M_b)	3630kg
Mass of wheelset (M_w)	1794kg
Mass of passenger	70kg/person
Carrying capacity	80 persons

2.3: Load Calculation Under Simulated Operating Condition

2.3.1: Vertical loading

The vertical load acts on the left and right air spring support beams of the frame, and the calculation formula is as follows:

$$F_v = \left(M_c + M_b\right) + passenger\ weight \times \frac{g}{2}$$

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

$$F_v = 217276.758N$$

2.3.2: Transverse loading

$$F_y = 0.5\times\left(F_z + 0.5m \times g\right)$$

$$F_z = \frac{F_v}{2} = \frac{217276.785}{2} = 108638.3925$$

$$F_y = 0.5\times(108638.3925 + 0.5\times3630\times9.81)$$

$$F_y = 63221.77125N$$

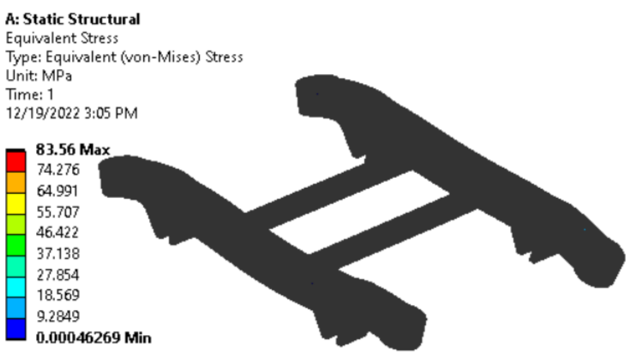

Figure 3 shows von-misses stress

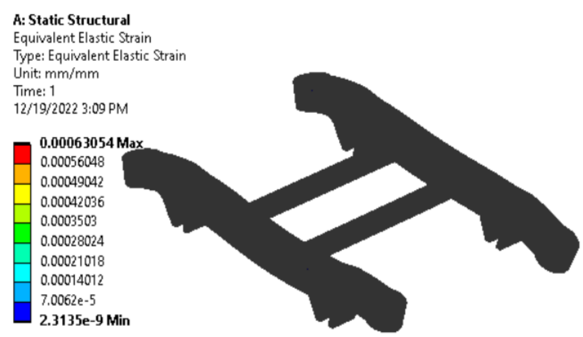

Figure 4 shows equivalent strain

3. Fatigue Damage Calculation

The counting method described above is independent of fatigue damage parameters, being based on hysteresis deformation behaviour. Being unrelated to material properties, it can be integrated with any multiaxial fatigue damage model. If the counted reversals are non-proportional, a fatigue damage parameter that accounts for non-proportional straining effects is required. The path-independent damage parameter proposed by Wang and Brown (19) has been shown to provide good correlation for several materials under proportional and non-proportional loading

3.1: Calculation of Damage in terms of strain

Using the Smith-Watson-Topper/Bannantine ((0=90 degrees only) [15]

Material properties for fatigue analysis

Table 2 shows Material properties for fatigue analysis

$\sigma^{i}_{f}(Mpa)$	v	$\varepsilon^{i}_{f}(\%)$	$E(Gpa)$	b	c
840Mpa	0.3	0.304	210×10^{3}	-0.18	-0.65

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \left(\frac{\left(\sigma^{i}_{f}\right)^{2}}{E}\right)\left(2n_{f}\right)^{2b} + \sigma^{i}_{f}\varepsilon^{i}_{f}\left(2n_{f}\right)^{(b+c)}$$

$$n_{f} = design\, life\, , b = -\, 0.09, c = -\, 0.56, HB = 335$$

$$\sigma^{i}_{f} = 4.25(335) + 225 = 1648.75Mpa$$

$$\varepsilon^{i}_{f} = \frac{0.3(HB)^{2} - 487(HB) + 191000}{210\times10^{3}}$$

$$\varepsilon^{i}_{f} = \frac{4.25\times335 - 487\times335 + 191000}{210\times10^{3}}$$

$$\varepsilon^{i}_{f} = 0.34$$

$\sigma_{max} = 83.56Mpa$ from Ansys

$$83.56\frac{0.01233}{2} = \left(\frac{(1648.75)^{2}}{210\times10^{3}}\right)\left(2\times10^{6}\right)^{-0.18} + 1648.75\times0.304\left(2\times10^{6}\right)^{-0.65}$$

$$\Delta\varepsilon = 0.023653$$

4: DYNAMIC LOADS CALCULATIONS

Case 1 0.1mm,

Using mansion coffin coefficient

$$\sigma_{max} = 59.856Mpa$$

$$\Delta\varepsilon = 0.0046518Mpa$$

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \left(\frac{\left(\sigma^{i}_{f}\right)^{2}}{E}\right)\left(2n_{f}\right)^{2b} + \sigma^{i}_{f}\varepsilon^{i}_{f}\left(2n_{f}\right)^{(b+c)}$$

$$59.856\frac{0.00046518}{2} = \left(\frac{(840)^{2}}{210\times10^{3}}\right)\left(2\times10^{6}\right)^{-0.18} + 840\times0.304\left(2\times10^{6}\right)^{-0.65}$$

$$n_{f} = 8.9441\times10^{12}$$

Case 2 0.2mm

$$\sigma_{max} = 118.31Mpa$$

$$\Delta\varepsilon = 0.00091423Mpa$$

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \left(\frac{\left(\sigma^{i}_{f}\right)^{2}}{E}\right)\left(2n_{f}\right)^{2b} + \sigma^{i}_{f}\varepsilon^{i}_{f}\left(2n_{f}\right)^{(b+c)}$$

$$118.31\frac{0.00091423}{2} = \left(\frac{(840)^{2}}{210\times10^{3}}\right)\left(2\times10^{6}\right)^{-0.18} + 840\times0.304\left(2\times10^{6}\right)^{-0.65}$$

$$n_{f} = 4.6283\times10^{9}$$

Case 3 0.3mm

$$\sigma_{max} = 136.5Mpa$$

$$\Delta\varepsilon = 0.0010346Mpa$$

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \left(\frac{\left(\sigma^{i}_{f}\right)^{2}}{E}\right)\left(2n_{f}\right)^{2b} + \sigma^{i}_{f}\varepsilon^{i}_{f}\left(2n_{f}\right)^{(b+c)}$$

$$136.5\frac{0.0010346Mpa}{2} = \left(\frac{(840)^{2}}{210\times10^{3}}\right)\left(2\times10^{6}\right)^{-0.18} + 840\times0.304\left(2\times10^{6}\right)^{-0.65}$$

$$n_{f} = 1.060017\times10^{9}$$

Table 3 shows the numerical and simulated results from Ansys software

Load conditions	Calculated cycle	Simulated cycles
Case 1	$n_f = 8.9441 \times 10^{12}$	1×10^{12}
Case 2	$n_f = 4.6283 \times 10^{9}$	1.7482×10^{11}
Case 3	$n_f = 1.060017 \times 10^{9}$	1.0405×10^{11}

Simulated results.

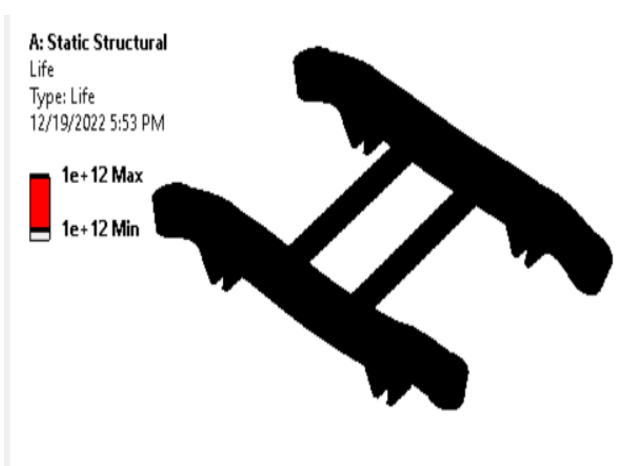

Figure 5. *shows 0.1mm polygon wear amplitude*

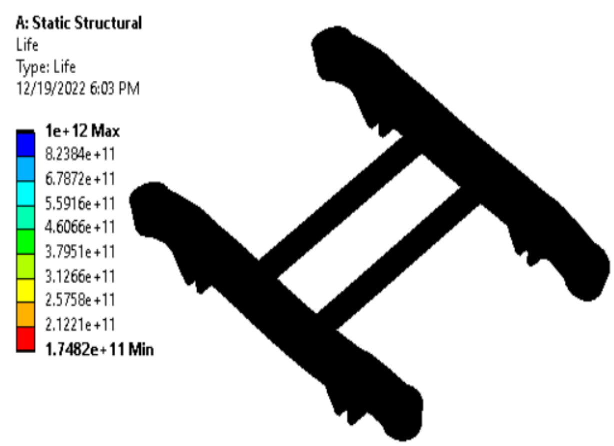

Figure 6. *shows 0.2mm polygon wear amplitude*

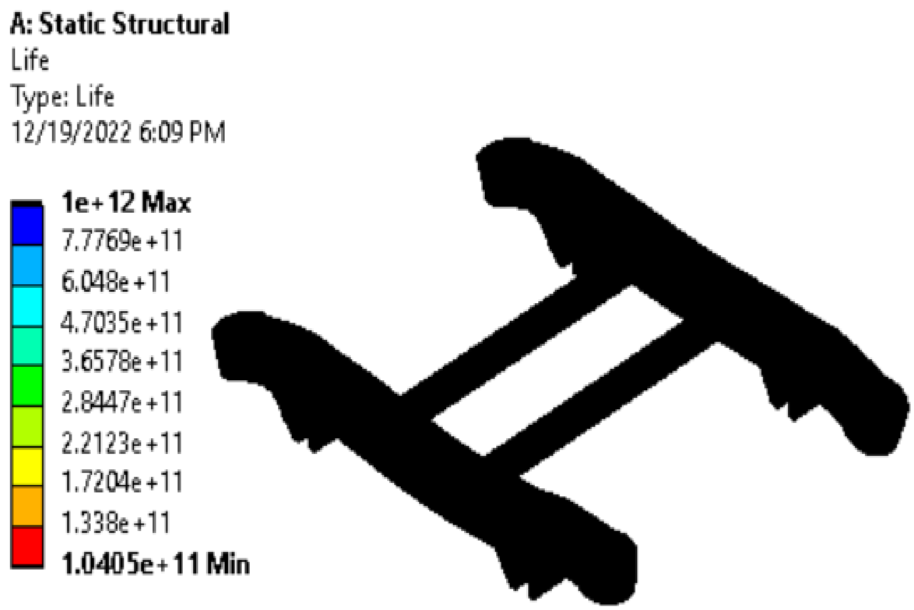

***Figure 7**. shows 0.3 mm polygon wear amplitude*

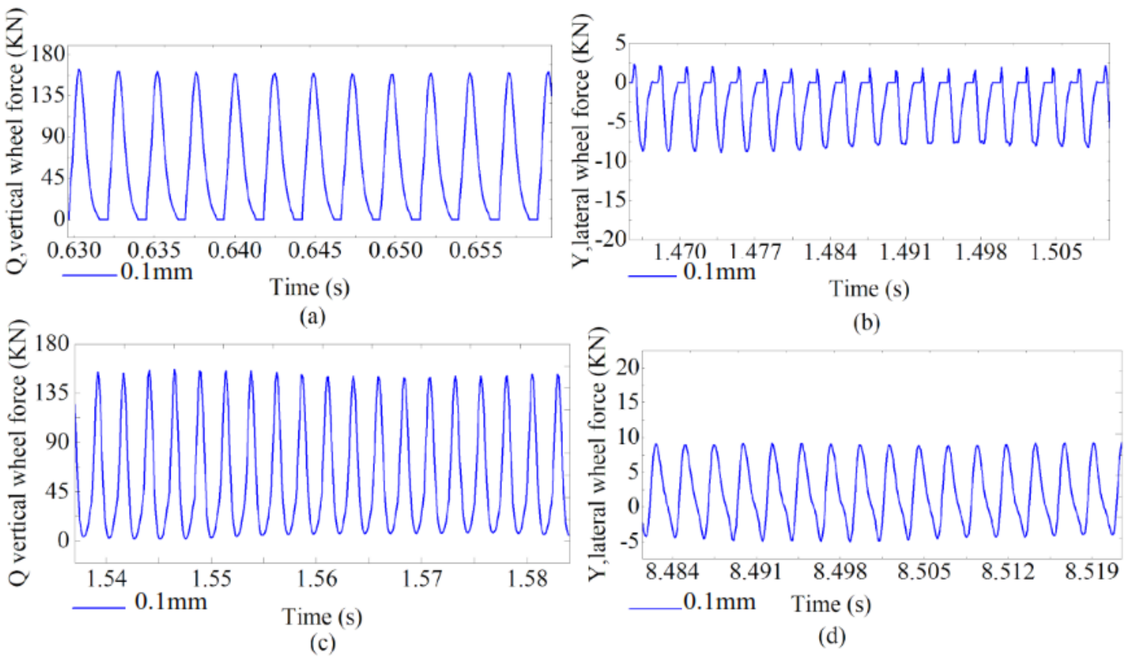

Figure 1. *Shows 0.1mm vertical and lateral wheel forces vs time for right and left wheel pairs.*

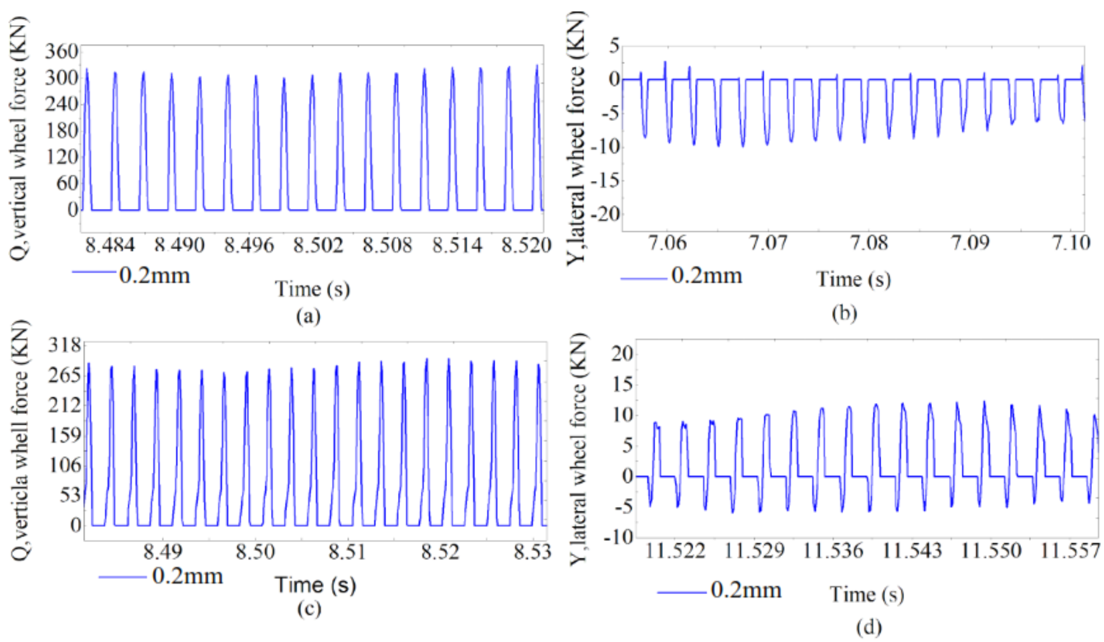

Figure 2. *shows 0.2mm vertical and lateral wheel forces vs time for right and left wheel pairs*

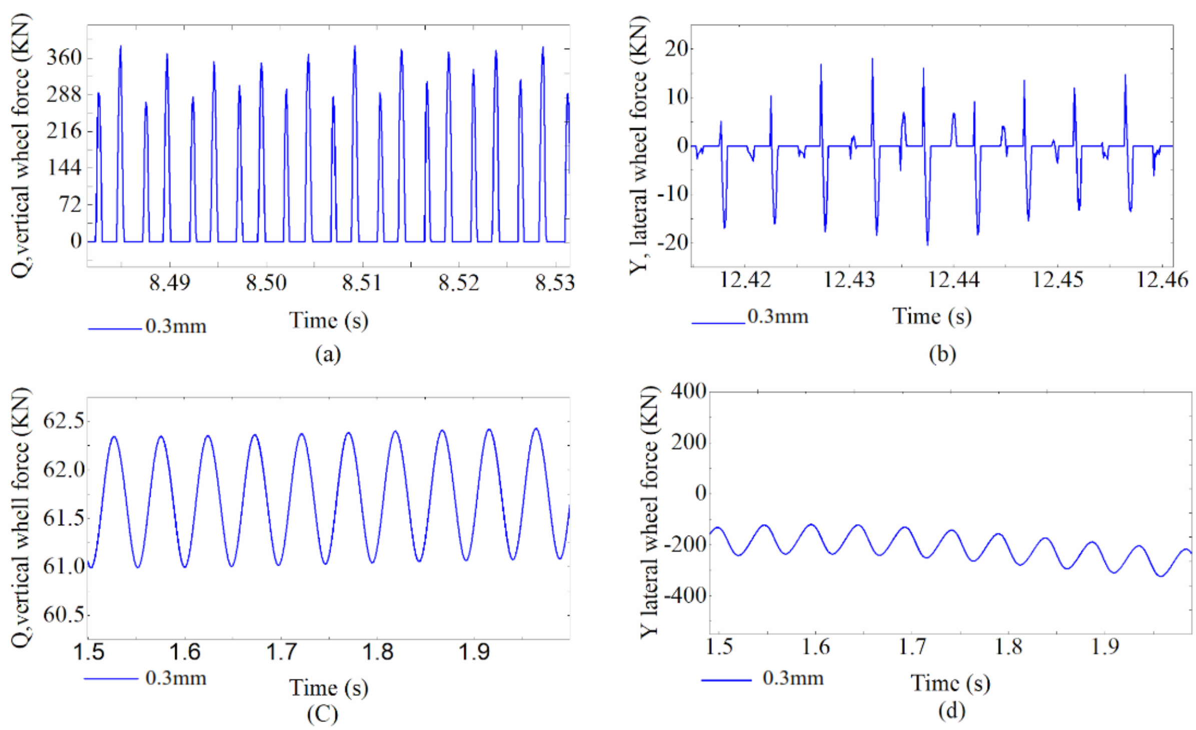

***Figure 3**. Shows 0.3mm vertical and lateral wheel forces vs time for right and left wheel pairs*

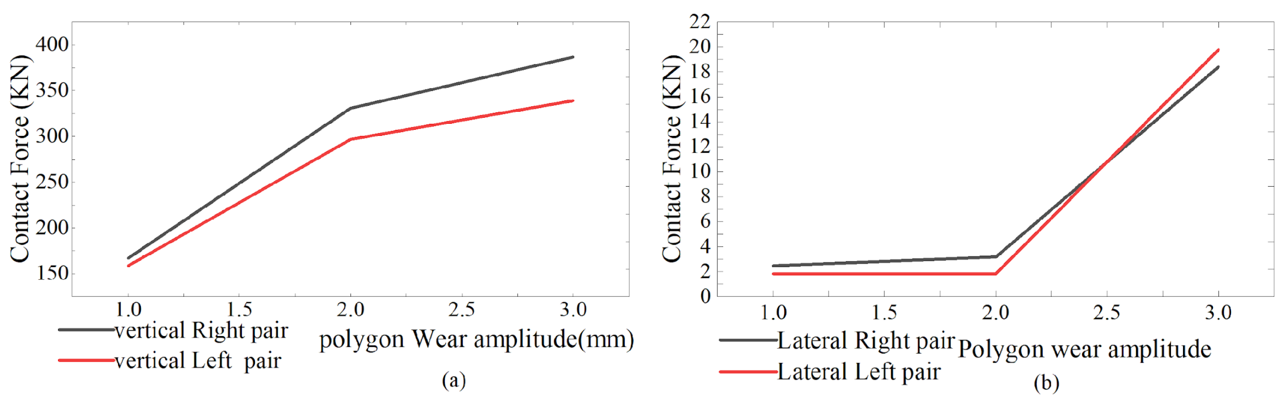

***Figure 11**. shows (a) the Contact force of the vertical right and left pair, (b) the contact force of the lateral right and left pair.*

5: RESULTS AND DISCUSSION

Figure 11 illustrates the contact forces on the wheel and the wear amplitude due to different polygon sizes ranging from 0.1mm,0.2mm and 0.3mm under the measured polygonal wear at 200 km/h. It can be seen that the contact forces of the polygon wheel in (a) in the vertical right and left pair increase as the wear amplitude increase this is attributed to the different characteristics of the system under differentwheel–rail contact states. 385.6KNWhen comparing a wheel with lower order polygonal wear geometry with that of a normal wheel with no wear, then the maximum amplitude of the contact force is 19.8 KN. Moreover, it can be seen that the contact force offers little variation within a harmonic order ranging from 1 to 3. When considering higher-order polygonal wear, the peak value of the contact force reaches 385.6kN. However, the high-order wheel polygonal wear has a greater influence on the contact force than the lower-order due to the higher wheel-rail forces. Therefore, the influence of high-order wheel polygonal wear on polygonisation of highspeed trains should be considered in regard to design, operation and maintenance

6: CONCLUSION

In this paper, to evaluate the fatigue strength of the bogie frames under polygon wear, static load analysis, and fatigue load analysis were performed. The load conditions under the static test were compared with different experimental results. The characteristics of stress history in the fatigue loads and static loads were evaluated and various fatigue life numerical evaluation methods were applied and the following conclusions were obtained:

Since the stresses that occurred as a result of the static load on the bogie frame were within the yield strength of the materials, the bogie frame satisfies the requirements for static strength safety.

The stresses that occur on the bogie frame are multiaxial and under nonproportional load, according to their locations. Therefore, to evaluate the fatigue strength of the bogie frame, it is determined that appropriate fatigue evaluation methods should be applied, depending on the locations and stress conditions.

It’s observed that increase in the wear amplitude increases the contact forces which in turn increases wear polygonisation and its related problems like vibrations, and increase in power consumption

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