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Approaches of Finite Element Analysis to Study Fatigue Analysis of Rail-Wheel Contact for Light Rail Transit

M. N. Tawfik[1], M.M Padzi[1], Shahrum[2], H. Hapaz[1], Mazli Zahar[3], M. Nur Firdaws[4]

[1]Department of Mechanical Engineering, MFI,
University Kuala Lumpur, 43650, MALAYSIA

[2]Department of Mechanical and Manufacturing Engineering,
Universiti Kebangsaan Malaysia, Bangi 43600, MALAYSIA

[3]Dept. of Train Ops,
Rapid Rail - Amp. Line, 5th Mile, PO Box 39, Jalan Ampang, 68000, MALAYSIA

[4]Dept. of Track Network Engineering,
Rapid Rail - Amp. Line. 5th Mile, PO Box 39, Jalan Ampang, 68000, MALAYSIA

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Abstract: Rolling contact fatigue (RCF) is one of the main rail failure due of repeated stresses at rail-wheel contact. The types of defects of RCF such as spalling, squat and head checking occur at surface of rail as possible lead to catastrophic for train derailment. As to reduce the cost of maintenance in using preventative maintenance than corrective maintenance where it crucial to predict the rail fatigue failure through simulation. The objective of this research paper was to predict the cracks at rail surface in 3-dimensional through finite element analysis and in compared results with Hertz theory, also to count circles of fatigue failure with 80000 N against rail. The rail profile selection was R260 as standard rail for light rapid transit. Results demonstrated that the highest von mises stress located at contact patch of rail-wheel, different percent of von mises stress & contact pressure and predicted the rail fatigue regards 339300 circles. Furthermore, this research study has not yet reported and discussed in previous studies for light rapid transit.

Keywords: FEA, rail-wheel contact, rolling contact fatigue, fatigue of rail, stress analysis

1. Introduction

Rail is a crucial component in railway track as permanent way to carry out the weight and to ensuring the direction movement of train from one place to another. It is origin from steel and typically involves in hot rolled steel for manufacturing process [1]. The reliable movement by rail-wheel contact, usually it has been created various stresses exist in rail-wheel contact as reports through many researches studies. According to [1] that the contact in between rails and wheel creates the small cracks may allow initially grow in critical manner and become large crack to lead till failure. The term of rolling contact fatigue (RCF) have been used in rail-wheel contact stress which popular words in today researchers. RCF defects can appear at surface or subsurface originated and rely on the types of materials and the stress distribution [1, 2]. The types of RCF defects such as spelling, head-checking, squats can lead to make failure at the rail. Many researchers have studied the fatigue failure that progressing continuously [2,3]. In today railway track, a lot of studies have been completing to investigates the rolling contact fatigue (RCF) and crack growth at the surface of rail

*Corresponding author: tawfik.badruddin@s.unikl.edu.my

through finite element analysis simulation (1,4 ,5). However, a recent suggest that the simulation as a tool for study the predict of failure and mathematic equation from Hertz theory might be compared to ensure each other verified. The main objective of this research study to predict the crack of rail surface and evaluate the fatigue failure of rail under static loads. In order to achieve these, the actual specimen and real dimension of rail given by rail company. The 3-dimensional of rail was modelling, performed and the total number of applied loads on rail have been counted. The results considered the stress distribution and fatigue life estimation. The following of Fig. 1 left and right for instance the defects of RCF.

a

b

Fig. 1 - (a) Head checking of gauge side by us department transportation (2015); (b) shelling / spalling defect cited by rapid rail [5]

2. Methodology

This section demonstrates in details from beginning to end for methodology process in this research study. The two approaches have been used that as first stage the Hertz contact theory of mathematics equation presented and second stage as the finite element analysis of rail under static loads both for predicting the failure of crack and fatigue at surface of rail.

2.1 Mathematics Equation of Hertz Contact Theory

In order to predict the RCF of rails, it vital to measure the accurate stress analysis for rail-wheel. Generally, the Hertz contact theory important to predict rolling contact stress, however sometimes this method has less accuracy for results of rolling contact stress when the plastic deformation develops in large number of stress.

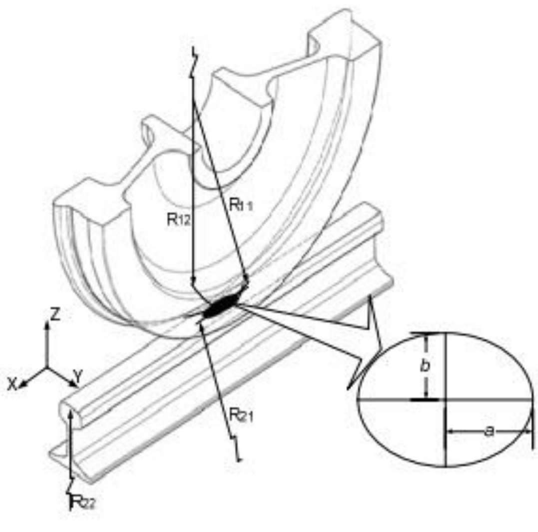

Fig. 2 - Rail-wheel contact of elliptical [15]

In order to calculate a number of contact area and pressure distribution that it essential to understanding the main formula by Hertz theory [2]. Kim (2014) [2] mentioned that the theory of Hertz contact considers the radius of curvature of rail and wheel profiles in contact with assumed as the constant and no plastic deformation in contact area. Fig. 2 shows the elliptical rail-wheel contact with labelled dimension x,y,z axis. To find the value of normal pressure distribution p(x,y) expressed as below [6, 7, 8]:

$$P = p_o\sqrt{\left(1-\frac{x^2}{a^2}-\frac{y^2}{b^2}\right)} \tag{1}$$

the representative of formula as follows:
a= x longitudinal direction for half width contact area
b= y lateral direction for half width contact area

$$a = m(\frac{3\pi}{4} * p\frac{K_1+K_2}{(A+B)})^{1/3} \tag{2}$$

$$b = n(\frac{3\pi}{4} * p\frac{K_1+K_2}{(A+B)})^{1/3} \tag{3}$$

To calculate the contact areas of rail-wheel, it essential to obtain the real measurement of geometric constants for being used above mathematics formula. The following the combinations of curvature as follows [6, 7, 8]:

$$A+B = 0.5*(\frac{1}{R_{11}}+\frac{1}{R_{12}}+\frac{1}{R_{22}}+\frac{1}{R_{21}}) \tag{4}$$

$$B-A = 0.5*[(\frac{1}{R_{11}}-\frac{1}{R_{12}})^2+(\frac{1}{R_{22}}-\frac{1}{R_{21}})^2 \quad +2(\frac{1}{R_{11}}-\frac{1}{R_{12}})(\frac{1}{R_{22}}-\frac{1}{R_{21}})^2*\cos 2\varphi]^{1/2} \tag{5}$$

The value of A and B as constants, where the R_{11}: is the wheel curvature of rolling radius of, R_{12}: is the wheel profile of radius, R_{21}: is the radius of runaway of infinity and $R_{22:}$ is rail curvature of the radius of in the cross section [6].

In order to calculate stresses of principal at the surface of rail-wheel contact are as under:

$$\sigma_1 = -2\mu p_0 - (1-2\mu)p_0\frac{1}{R_{11}}+\frac{1}{R_{12}}+\frac{1}{R_{22}}+\frac{1}{R_{21}}) \tag{6}$$

$$\sigma_2 = -2\mu p_0 - (1-2\mu)p_0\frac{1}{R_{11}}+\frac{1}{R_{12}}+\frac{1}{R_{22}}+\frac{1}{R_{21}}) \tag{7}$$

$$\sigma_3 = -p_0 \tag{8}$$

$$\sigma_{von-mises} = \sqrt{(\sigma_1-\sigma_2)^2}+\sqrt{(\sigma_2-\sigma_3)^2}+\sqrt{(\sigma_3-\sigma_1)^2}*[\frac{1}{2}] \tag{9}$$

2.1.1 Fatigue Analysis

This section demonstrates that fatigue analysis results with referred on the FEA. The fatigue crack life usually can be pillars into 3 phases with covering initial of crack and growth. First phase the shear stress occurs at the surface, second phase - the growth of crack behaviour and final phase -subsequent shear crack growth and tensile. The crack starting with repeated of rolling contact surface may occur when complete at phase 1. To determine the fatigue life, the formula have been introduced by Jiang [9] as under

$$FP = <\sigma^{max}> (\Delta\varepsilon * 0.5) + J\Delta\tau\Delta\gamma) \tag{10}$$

The mathematics formula for fatigue life on plane can be used as follows Eq. (11) as set the material properties in Fig. 4.

$$FP_{max} = < \sigma^{max} > (\Delta\varepsilon * 0.5) + J\Delta\tau\Delta\gamma)_{max} \quad (11)$$

2.2 Finite Element Analysis for Rail

In order to complete the static load on FEA, it important to design the rail with real dimension in 3-dimensional for analysis in according to specimen and rail profile given from urban LRT company. The preloading of 80000 N in considering of 80% stress numbers with minimum count as of 1.5 value factor of safety. The contact interactions in between rail and wheel were following with using surface to surface discretization of contact and slave surface identified each contact pair [10]. The advantages of contact formulation method were successfully to provide 95% accurate stress and strain results compared with other method and prevents large of nodes on main surface [10]. To predict the high stress and fatigue failure on rail, it pivotal to understandings the rail-wheel contacts interaction when two contact patches might be presented in rail-wheel contact as Fig. 3 [10]. A loading in 3-dimension model were applied 80000 N as in z-axis down ward at rail surface when wheel can be moving and rotation along at rail, in this case that rotation have been ignored due of makes no different rail stress determination because to study steady state analysis. The geometrical model was meshed with 2mm, total elements and nodes were 4786 and 8959, respectively and the boundary conditions were setup at bottom of rail as fixed and a static load of 80000 N was imposed as z-axis in the direction of loading. The type of rail was R260 as steel as standard rail in this research. Table 1 shows the material properties of rail and wheel. On the stress distribution reveals that a critical area with highest stress as known the stress hotspot.

Table 1 - Material properties of rail and wheel

Properties	Rail	Wheel
Standard	EN 13674	SSW-Q35
Material Type	R260	JIS E 5402
Young's modules, *E*	210 X 10^3 MPa	210 X 10^3 MPa
Yield stress, σ	528 MPa	500 MPa
Ratio of Poisson's ,*V*	0.27	0.27

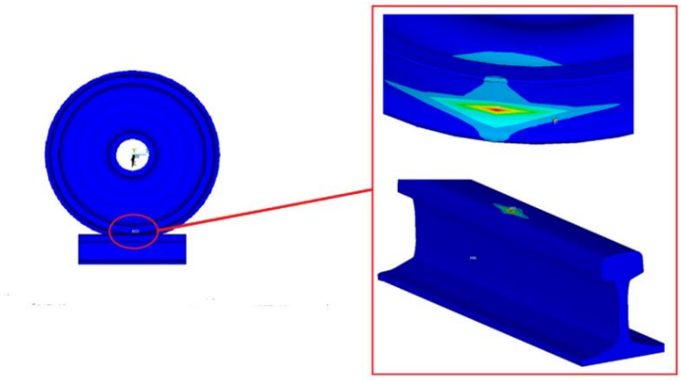

Fig. 3 - The contact patch of rail-wheel contact [1]

3. Results and Discussions

Fig. 4 (left) indicates the contour of von-mises stress distribution, obviously the highest stress and critical in contact patch in the rail surface of 80kN under static analysis in ranges 82MPa on red contour display, second layer of orange-66.02MPa max as high stress less than red and yellow contour display contour less high stress than orange contour. The total deformation was subjected of rail as rely on the value of stress and factor of safety of rail may be decreased, when increasing of value for vertical load. The factor of safety considered was of 1.5 value as safe as Fig. 4 (right). This result similar with the Zulkifli [11] and Sayed [8] reported that the contact patch occurs the highest stress.

Fig. 4 - Left: Maximum von mises stress distribution; Right: Factor of Safety for rail surface

Table 2 - The variation of effect for rail profile on von mises stress and contact pressure with based on FEA and analytical [6]

R22	Von Mises Stress		Contact Pressure		Different (%) Von Mises Stress	Different (%) Contact Pressure
	FEA MPa	Analytical MPa	FEA MPa	Analytical MPa	FEA vs Analytical	FEA vs Analytical
280	335.3	356	1222	1269	6%	4%
290	342.6	353	1240	1261	3%	2%
300	350.1	349	1254	1253	1%	0.09%
310	358.3	345	1263	1246	4%	2%
320	364.38	342	1266	1239	6%	3%
330	346.12	338	1269	1232	3%	3%

Table 2 presents the two results of FEA and Hertz theory about the von mises stress and contact pressure in comparing each other were similar with no significant difference as under 7% diversion. It was supported recent report by [12] in cited of Germany experiment that they have completes the laboratory test and well-compared with theory of Hertz Theory that the results similar. Fig. 5 above demonstrates the fatigue analysis of rail-wheel contact from the FEA. The results from stress analysis imported to the fatigue analysis with loading 80000 N and guided by simulation handbook. It was indicating the highest possibility to RCF defects on the red contour with 339300 number of circles to failure and the blue contour show the highest high circles with no significant effect of force. The range of fatigue failure starting with low circles 3.393E05 until 9.167E09 highest circles.

4. Conclusions

In this research paper, the objectives were successfully achieved for predicting the crack and fatigue failure of rail with using finite element analysis and Hertz theory as modern tool for contact stress, modelling and simulation in improving the traditional approach about stress impact from wheel to the rail. It can be summarizing that as below:

1) Results demonstrate the von Mises stress on the rail as above than yield point.
2) The plastic deformation and failure damage can appear on the rail surface if total loading is more than 85 kN.
3) The calculation from FEA and Hertz theory were similar in comparing the results of rail-wheel
4) The fatigue of rail can be failure after 339300 circles by simulation

The current findings high important as fundamental knowledge in informing the researchers for investigating the material properties of rail in relation to influences the factor of stress analysis, wear, fatigue and corrosion for future research.

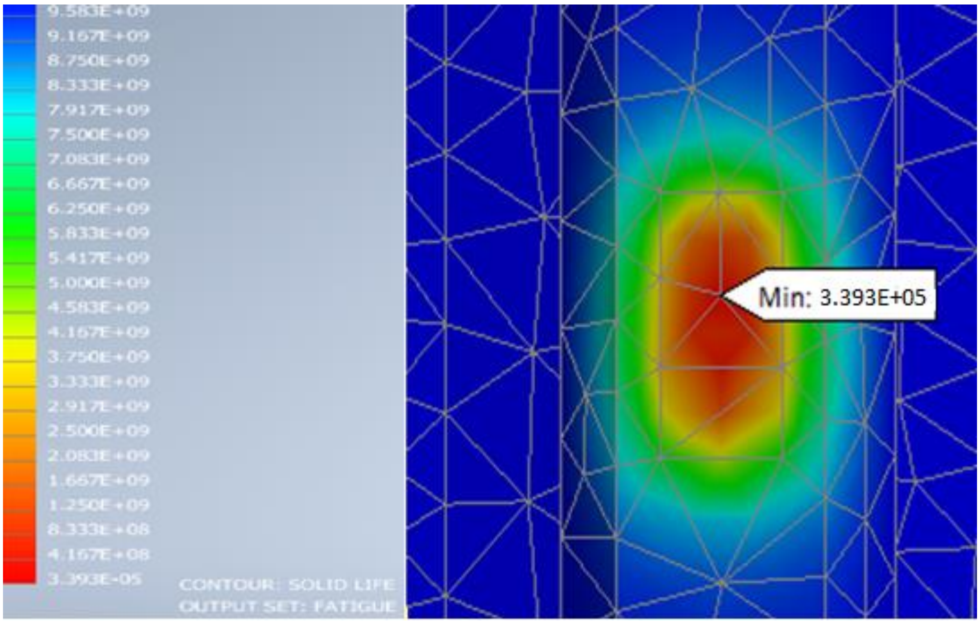

Fig. 5 - The contour of fatigue life for rail at top view

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