

Fatigue life estimation of MD36 and MD523 bogies based on damage accumulation and random fatigue theory[†]

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Abstract

Bogies are one of the multifunctional parts of trains which are extremely subjected to random loads. This type of oscillating and random excitation arises from irregularities of the track including rail surface vertical roughness, rail joints, variance in super-elevation, and also wheel imperfections like wheel flats and unbalancy. Since most of the pre-mentioned sources have random nature, a random based theory should be applied for fatigue life estimation of the bogie frame. Two methods of fatigue life estimation are investigated in this paper. The first approach which is being implemented in time domain is based on the damage accumulation (DA) approach. Using Monte-Carlo simulation algorithm, the rail surface roughness is generated. Finite element (FE) model of the bogie is subjected to the generated random excitation in the first approach and the stress time histories are obtained, and consequently the fatigue life is estimated by using the rain-flow algorithm. In the second approach, the fatigue life is estimated in frequency domain. Power spectral density (PSD) of the stress is obtained by using the FE model of the bogie frame and the fatigue life is estimated using Rayleigh technique in random fatigue theory. A comprehensive parametric study is carried out and effects of different parameters like the train speeds and level of the rail surface vertical roughness on the estimated fatigue life are investigated.

Keywords: Damage accumulation; Fatigue life; Monte-Carlo simulation; Rain-flow algorithm; Random vibration.

1. Introduction

Bogies are one of the main parts of trains which not only carry static loads due to the body weight but also dynamic loads due to the rail surface roughness and imperfect wheels. Bogie frames are always subjected to dynamic random loads and consequently fatigue phenomena. Fatigue always deals with two main objectives in bogies: safety and excessive maintenance cost.

A few researches have been recently done to evaluate or improve fatigue life of the bogie frames. Kim [1] has evaluated fatigue life of bogies used in high-

speed lines of Korea using an experiment based on UIC615-4 standard. Park [2] has estimated fatigue life of some types of bogie frames using FEM. He has also optimized the bogie weight based on the genetic algorithm. A web-based automation of fatigue durability analysis for a welded bogie frame of railway vehicle has been investigated under the multi-agent based engineering framework using JADE software by Bang [3]. Fatigue strength evaluation for the bogie frame of a Korean tilting train was carried out by Kim and Kim [4]. They showed that the bogie frame of the tilting train is exposed to more severe loadings compared with the conventional one because of the tilting of the car-body and the high-speed curve negotiation. An automation technique was proposed by Han et al. [5] in order to do fatigue durability analysis for welded bogie frames according to the LJIC-code proposed by

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using the Model-Center, which enables several tools used in fatigue durability analysis to be integrated. A new method to predict fatigue lifetime based on the combination of frequency domain and time domain calculations, which allows lifetime prediction with reduced computational effort is given by Dietz et al. [6]. The benefits of the new approach are demonstrated by application to the bogie of a freight locomotive.

Kim [7] has assessed fatigue strength of the bogie frame for the Korean tilting train. For evaluation of the loading conditions, multi-body dynamic analyses have been carried out and strength analysis has been performed by FE analyses.

MD36 and MD523 bogies are widely used in passenger trains with moderate to high speed range (Iwnicki [8] and Lari et al. [9]). Fatigue life estimation of these types of bogies is studied in this paper. FE model of the bogies is generated by ANSYS software. FE models are then validated using existing results in the literature and provided by supplier. Two approaches for fatigue life estimation are taken into account. The first approach is based on the damage accumulation theory. Rail surface roughness is generated using Monte-Carlo simulation. The generated random excitation is then applied to the FE model as its base motion. The time history of the stress is obtained with ANSYS-LSDYNA software. The next step is to count stress cycles using the rain-flow algorithm. Finally, damage fraction is obtained and the damage accumulation index is calculated. The second approach is based on the random fatigue theory. PSD of the rail surface vertical roughness is applied to the FE model. PSD of the stress as well as its various moments are then calculated. Finally, the fatigue life is estimated by using Rayleigh technique in random fatigue theory. A comprehensive parametric study is carried out for different types of tracks with different levels of rail surface vertical roughness and different train speeds.

2. Fatigue life estimation in time domain

Finite element models of the two bogie frames are illustrated in Fig. 1 and Fig. 2. Power spectral density of the rail surface vertical roughness is assumed to have general form of (Younesian et al. [10], Wu and Yang [11])

$$S(\Omega) = \frac{A_v \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \tag{1}$$

in which $\Omega (=2\pi/\lambda)$ denotes the spatial frequency (rad/m), λ is the wavelength of rail surface vertical roughness (m) and A (m), Ω_1 (rad/m) and Ω_2 (rad/m) are relevant parameters indicated in Table 1. This spectrum is based on the measurements made on the railways of the USA. Using Monte-Carlo algorithm random surface of the rail is generated by (Lutes, Sarkani [9], Ansari et al. [14])

$$r^d(x) = \sum_{k=1}^N a_k \cos(\omega_k x + \phi_k) \tag{2}$$

$$a_k = 2\sqrt{S(\omega_k)\Delta\omega} \quad k = 1, 2, \dots, N$$

Table 1. Track PSD Model Parameters (Younesian et al. [10], Wu and Yang [11]).

Track Class	4	5	6
A (m)	2.39*10 ⁻⁵	9.35*10 ⁻⁶	1.5*10 ⁻⁶
Ω ₁ (rad/m)	2.06*10 ⁻²	2.06*10 ⁻²	2.06*10 ⁻²
Ω ₂ (rad/m)	0.825	0.825	0.825

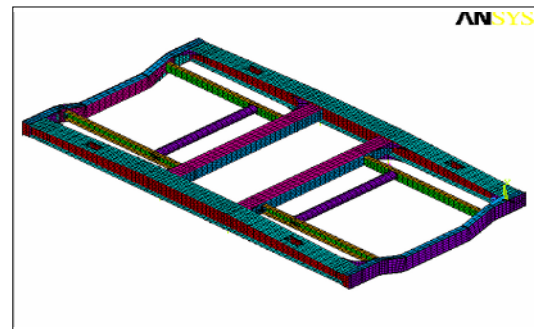


Fig. 1. FE model of MD36 bogie.

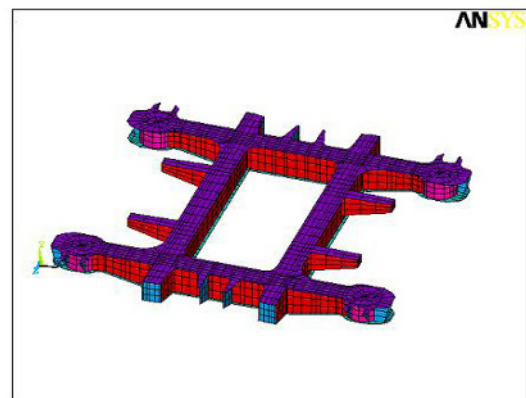


Fig. 2. FE model of MD523 bogie.

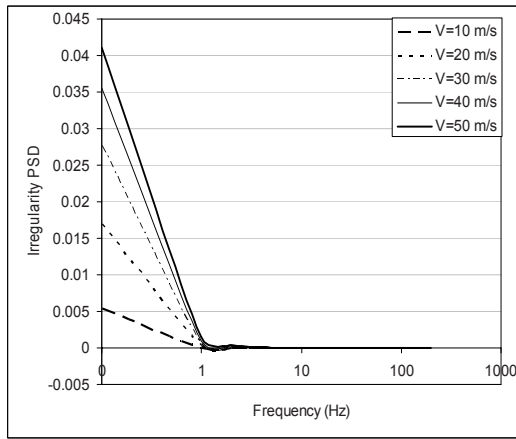


Fig. 3. Random excitation generated for the rail class 4 in frequency domain.

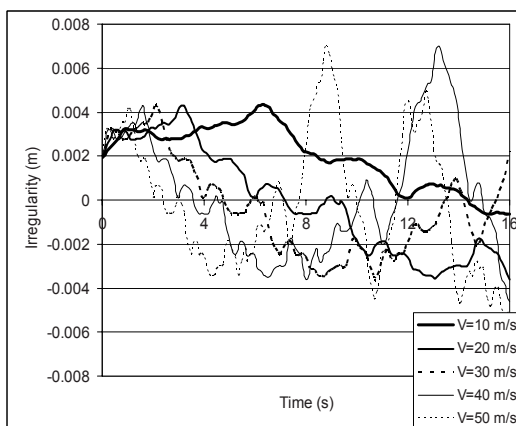


Fig. 4. Random excitation generated by Monte-Carlo simulation for the rail class 4 using MATLAB.

in which ϕ is random phase with normal probability distribution. A computer code has been provided in order to randomly generate the rail surface roughness (Younesian et al. [11]). Typical random excitations for different train speeds are illustrated in Fig. 3 and 4, respectively, in frequency and space domain. Generated random excitation is then applied to the FE models as the base motion and time history of the stress is obtained for the whole structure.

Fig. 5 illustrates the loading condition as well as the geometric constraints of the bogie frame. The main dead load arises from the body weight and the main dynamic excitation comes from the base motion $Z(t)$ due to the rail surface corrugation. Combinational differential equations of motion including the body, bogie frame and elements of the primary and second-

Table 2. Mechanical properties of bogies.

MD523	Body Mass	M = 45000 kg
	Secondary Suspension Stiffness	K = 422690 N/m
	Secondary Suspension Damping	C = 23000 N.s/m
	Primary Suspension Stiffness	K = 507228 N/m
	Primary Suspension Damping	C = 9000 N.s/m
MD36	Secondary suspension Stiffness	K = 16256 N/m
	Secondary Suspension Damping	C = 26700 N.s/m
	Primary Suspension Stiffness	K = 590340 N/m
	Primary Suspension Damping	C = 12300 N.s/m

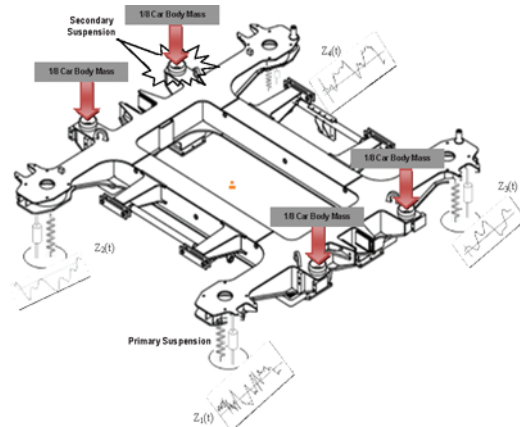


Fig. 5. Schematic model of loading and constraints for the MD523 bogie.

ary suspension systems are simultaneously solved by the FEM package. In some papers, for simplification, dynamic loads of the suspension system are initially obtained by using a rigid model and then applied to an elastic model. This leads to a modeling error arising from the effects of elasticity of the structure on the dynamic forces. In our model, displacements of the wheels are taken as the dynamic input, and the dynamic forces are then obtained by using the combinational model including both the rigid body motions and elasticity of elements. Mechanical properties of the primary and secondary suspension system are listed in Table 2.

To validate the finite element model and verify the stress analysis, an experiment was arranged and the achieved experimental data were compared with those obtained by the finite element model. The experiment was set in the Central Overhaul Workshop- Raja Passenger Trains Company. Figure 6 illustrates how the hydraulic actuators are exerting vertical loads to the

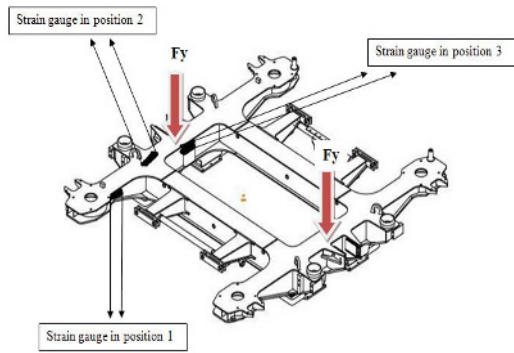


Fig. 6. Position of strain gauges and loading condition.

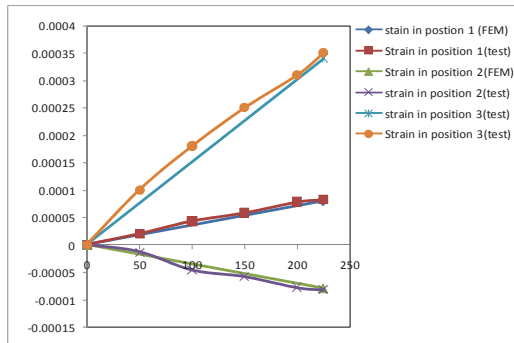


Fig. 7. Comparison between the experimental and FEM results.

bogie MD523 frame totally up to 22.5 tons correlated with half of the body mass. Strains at the three directions shown in Fig. 7 are being measured by use of TML-YEFLA-5 and TML-FLA-5 type strain gauges and logged by TML-TMR-200 Data Logger. The achieved experimental data are compared with those obtained by the FE model and a very good correlation between the results is observed. Figures 8 and 9 illustrate the stress contours due to the dead load of body weight, respectively, for two types of bogies. It has been achieved that in both case, spring seats of the secondary suspensions are critical position in sense of stress concentration.

Using one of the cycle counting algorithms (rain-flow in this paper (Lutes, Sarkani [9])), one can obtain stress cycles for each element. Damage fraction of each cycle is then calculated and the damage index is obtained for each element using the damage accumulation approach. The critical node and element are then specified and their fatigue life is taken into account as the fatigue life of the bogie frame. The prescribed procedure has been done for two bogies and critical

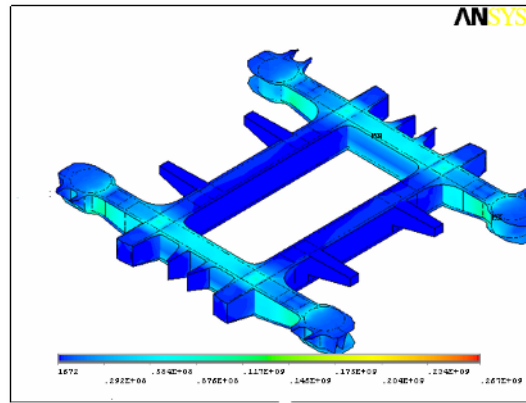


Fig. 8. Stress contour for the MD523 bogie frame.

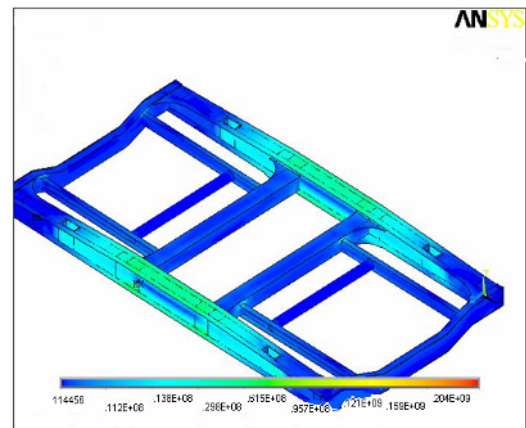


Fig. 9. Stress contour for the MD523 bogie frame forming process design.

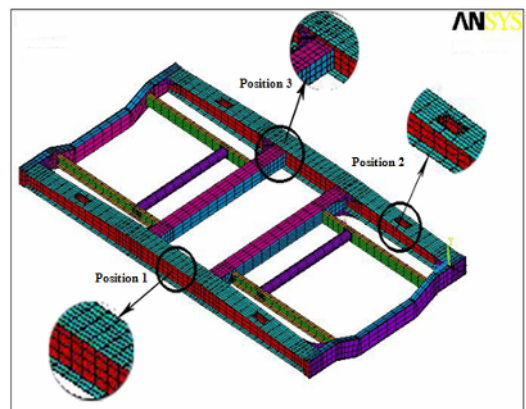


Fig. 10. Critical points in MD36 bogie.

positions have been obtained. It has been proved that mainly there are three critical positions (Fig. 10 and Fig. 11) in the sense of fatigue strength. A typical

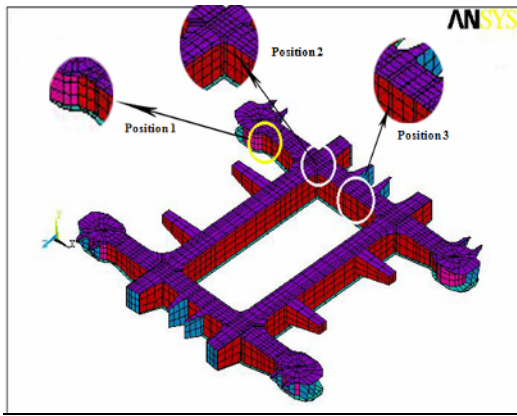


Fig. 11. Critical points in MD523 bogie forming process design.

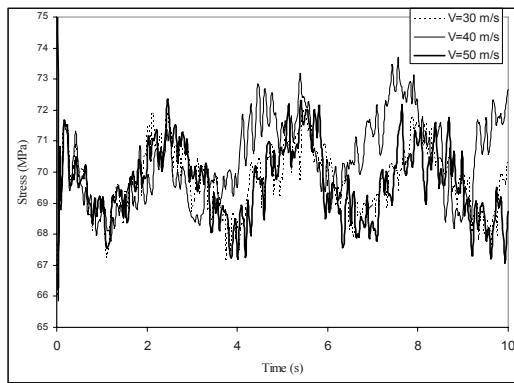


Fig. 12. Time history of the Von-Mises stress at position 1 for the rail class 4, (MD23).

sample for the time history of von-Mises stress for position 1 is illustrated in Figure 12. As it is seen, not only the maximum stresses but also the RMS values are both very sensitive with respect to the traveling speed. For the three critical positions in MD36 bogie, variation of the fatigue life versus the train speed is illustrated in Fig. 13. As can be seen, the critical region (positions 1) is proved to be very close to the spring seat position between the body and the frame.

This result is very well matched with those reported by the user companies [13]. Moreover, it is seen that fatigue life is a decreasing function of the operational speed, but its negative gradient is larger at lower speed range.

Effects of the track quality on fatigue life of an MD36 bogie are illustrated in Fig. 14. As illustrated, rail surface vertical roughness can dramatically (even up to 5 times) reduce fatigue life of the bogie frame. Similar results have been obtained for the MD523

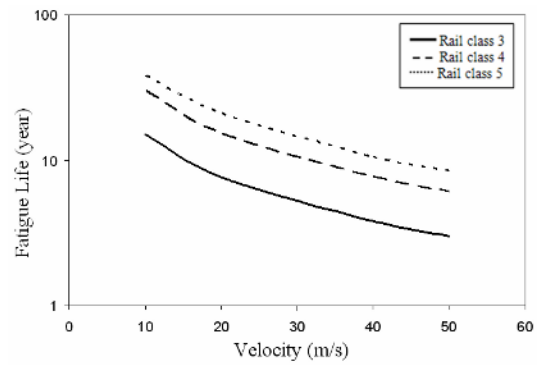


Fig. 13. Fatigue life in different position (MD36 Bogie, Rail Class 4).

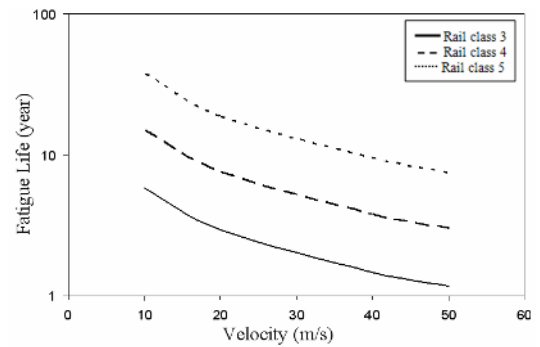


Fig. 14. Fatigue life for different rail classes (MD36 Bogie, Position 1).

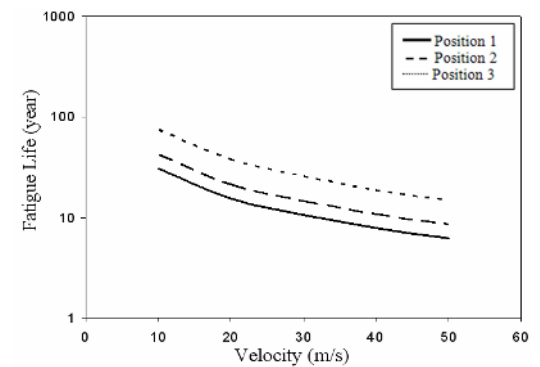


Fig. 15. Fatigue life in different position (MD523 Bogie, Rail Class 4).

bogie. Results are shown in Fig. 15 and Fig. 16. A comparison between the results obtained for the two bogies, shows that generally fatigue life for the MD523 bogie is larger than for the MD36. It is also seen that the sensitivity of the fatigue life with respect to the rail quality is almost the same for the two types of bogies.

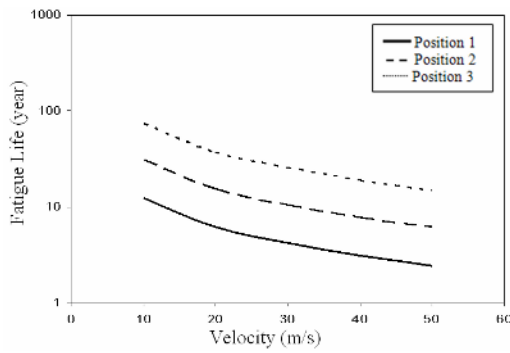


Fig. 16. Fatigue life for different rail classes (MD523 Bogie, Position 1).

3. Fatigue life estimation in frequency domain

Using the power spectral density defined in Eq. (1) as the PSD of the base motion, a spectral analysis has been carried out by means of FE models of two bogies. PSD of the stress as well as its different moments are obtained by ANSYS-LSDYNA. Using Rayleigh formula in random fatigue theory, i.e., (Lutes, Sarkani [9])

$$E(T) = \frac{2\pi\sigma_x}{E(\Delta D)\sigma_x} = \frac{2\pi}{E(\Delta D)} \sqrt{\lambda_0} \quad (3)$$

in which:

$$\begin{aligned} \text{Zero order moment: } \lambda_0 &= \int_{-\infty}^{\infty} S_{xx}^2(\omega) d\omega, \\ \text{Second order moment: } \lambda_2 &= \int_{-\infty}^{\infty} S_{xx}^2(\omega) \cdot \omega^2 d\omega, \\ \text{Stress PSD: } S_{xx}(\omega) & \end{aligned} \quad (4)$$

One can numerically obtain the fatigue life for each element. The presented procedure has been done for two bogies, and variations of the fatigue life with respect to the train speed are obtained. A typical sample for the PSD of von-Mises stress for position 1 is illustrated in Figure 17. A modal analysis has been carried out using the FE model and the first four natural frequencies of the two bogies are listed in Tables 3 and 4. The first natural frequency of the bogie is mainly matched with vertical rigid body motion. A short look at the Fig.12 reveals that the main peaks of frequency response are correlated with some vertical and bending natural frequencies. These peaks arise from this fact that the rail surface vertical roughness

Table 3. Natural frequencies of the bogies.

Bogie Type	Mode Number	Natural Frequency (Hz)
MD523	1th	1.4426
	2th	53.716
	3th	98.843
	4th	178.92
MD36	1th	1.4337
	2th	52.794
	3th	76.13
	4th	133.83

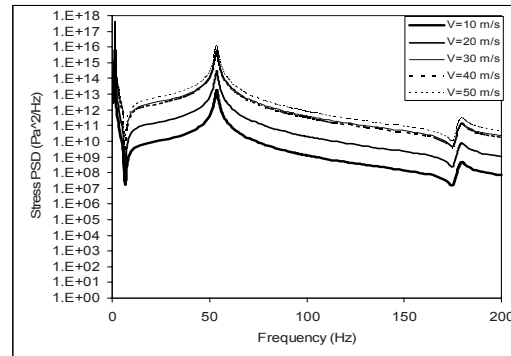


Fig. 17. PSD of the von-Mises stress at position 1 for the rail class 4, (MD523).

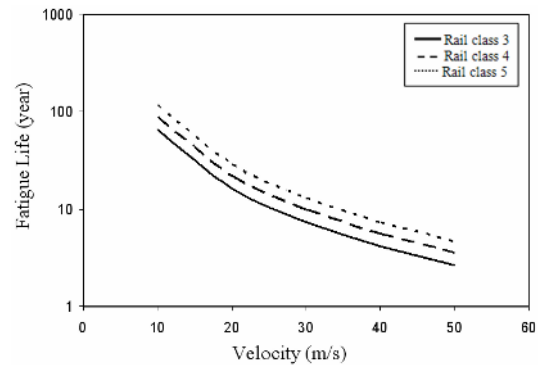


Fig. 18. Fatigue life for different rail classes (MD36 Bogie-Rayleigh method).

excitation has a broad-band nature and contains a wide range of frequencies and consequently stimulates most of the natural modes. Since the load nature of such an excitation is more matched with vertical motion and bending modes, the modal magnification factor of such modes is larger in frequency responses. The same critical positions were recognized in the frequency domain analysis as well. Between the three points

shown in Figs. 10 and 11, again position 1 has a critical situation. Variation of the fatigue life versus the operating speed is illustrated in Fig. 18 for the MD36 bogie. The same trend, i.e., rapidly decreasing of the fatigue life at lower speeds is again achieved. The slope of decreasing is then reduced in the high speed range. Similar results are achieved for the MD523 bogie (Fig. 19). Frequency domain analysis also confirms that the MD523 bogie has larger fatigue life than the MD36.

The numerical results obtained by the two different approaches, i.e., rain-flow technique in time domain and Rayleigh technique in frequency domain, are compared for the two bogies in Fig. 20. Comparison of the results shows that for the same rail corrugation PSD, rain-flow technique in time domain estimates smaller fatigue lives than Rayleigh technique in frequency domain. In other words, the rain-flow technique yields to with larger safety factors in design of bogie frames. It is also found that results of the two approaches are merged in higher speed range ($V > 120$ km/hr).

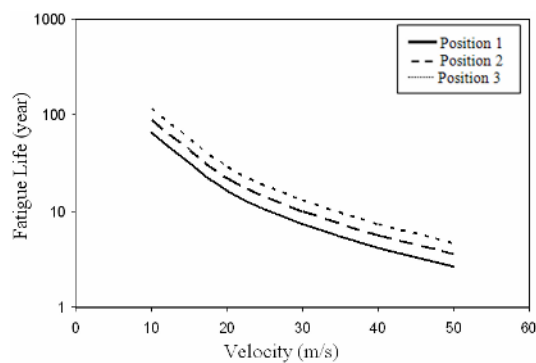


Fig. 19. Fatigue life for different rail classes (MD523 Bogie-Rayleigh method).

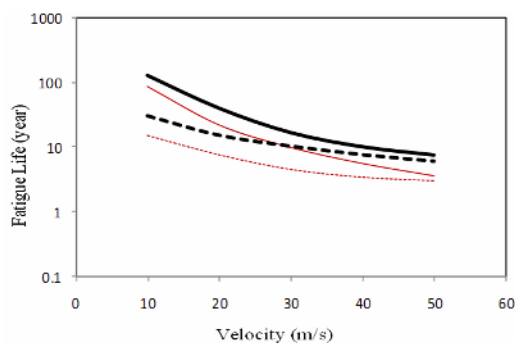


Fig. 20. Comparison between the results of different techniques.

4. Conclusions

Fatigue life of two bogies, namely MD36 and MD523, was estimated in this paper. Two approaches, rain-flow technique and Rayleigh method, were utilized respectively in time and frequency domains. Finite element model of two bogies was constructed. A combinational (MATLAB-ANSYS-LSDYNA) computer code was provided based on the two approaches. Critical regions in the sense of weakness against fatigue were obtained and proved to be well matched with the reports provided by user companies. It was found that the gradient of fatigue life reduction versus operational speed becomes smaller in the high-speed range. Comparison of results obtained for the two bogies showed that the MD523 bogie has larger strength against fatigue with less sensitivity with respect to the speed increasing. It was also found that rail surface roughness can dramatically reduce fatigue life of bogies. For instance, fatigue life for track class 5 is about five times larger than that of track class 3. Comparison of the obtained results also showed that for the same rail surface vertical roughness PSD, the rain-flow technique in time domain estimates smaller fatigue life than Rayleigh technique in frequency domain. In other words, the rain-flow technique yields to larger safety factors in design of bogie frames. In the sense of fatigue life, it was found that any 10 m/s increasing of the operational speed is almost correlated with 1 unit decrease in rail class. In other words, improving the quality of track from class 2 to class 4, one can have 72 km/hr increase in operational speed with the same fatigue life for the bogie frames.

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