

AN INNOVATIVE METHOD FOR STRESS ANALYSIS OF Y25 BOGIE UNDER OSCILLATING LOADS DUE TO TANK WAGON FLUID SLOSHING

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Freight wagons carry higher axle loads and may travel along tracks of lower quality. This can be interpreted as higher dynamic loading of freight bogies especially for tanker cars that are subjected to sloshing loading. Rail irregularities, particularly during braking and running on curved tracks initiate the fluid sloshing. This article is about introducing an innovative method for analyzing bogie stresses of tanker cars while in travel and under critical circumstances. The effect of the vehicle speed of travel, its liquid filling ratio, track quality and fluid density are also investigated in terms of stress results of bogies.

Keywords: Y25 bogie, dynamic modeling, FEM, stress analysis, longitudinal sloshing

1. Introduction

Bogies are major parts in the configuration of railway vehicles that directly interact with the rail and track irregularities. While in motion bogies tolerate severe dynamic loadings. Fatigue in bogie axles, center bowls and frames is unavoidable. As a consequence of fatigue, safety in travel is jeopardized and the cost of maintaining the fleet increases. There are a few research papers concerned with the issue of fatigue in bogie frames. Most of such researches are focused on passenger coaches. The reason for that is higher speed of travel in passenger trains. There is also the need to improve safety aspects of the trip. This leads to higher forces and impact loads on bogie frames.

Kim (2006) reported a research on high speed passenger trains in Korea. Kim and Kim (2005) and Kim (2005) also reported on fatigue life estimations of articulated bogies according to UIC615-4. Park (2006) examined the fatigue life of passenger bogies with the finite element method. Younesian *et al.* (2009) estimated the fatigue life of passenger bogies MD36 and MD523 in both time and frequency domain by introducing an innovative method. They also determined sensitivity of the frame fatigue life on the track quality.

Although freight bogies travel at lower velocities, but the higher axle loads lead to higher levels of static stresses. Locovei *et al.* (2010) examined fatigue of axles in tank wagons with the finite element method considering thermal effects and the residual stresses in the axle box in both tangent and curved tracks. However, the effect of sloshing was ignored. The tanker wagons carrying fluids are subjected to fluid sloshing while this does not exist for other types of freight wagons.

Liquid sloshing can be examined with analytical, experimental and numerical methods in order to calculate the forces due to liquid-solid interactions. Simulation of the sloshing mostly falls into two groups (Badran *et al.*, 2012; Cherna *et al.*, 2012). The first group considers a continuum medium for the fluid (finite element) while the latter focuses on the discrete equivalent dynamic model. Aliabadi *et al.* (2003) studied a 3D sloshing of a tank vehicle in braking with the finite element model. By using 250 000 hex elements, they modeled an elliptic tank at the speed of travel of 10 m/s and braking acceleration of 0.2g. Lateral sloshing was also modeled with the equivalent pendulum and finite element. Comparisons between the outcomes of the

two methods prove good agreement. However, the amplitude of the oscillations predicted by the pendulum method is higher.

The modeling tools such as the ADAMS/RAIL engineering software were used in order to study the derailment behavior of a tanker wagon along a curved track. The effects of the parameters such as the fluid density, vehicle speed of travel and track irregularities were considered. Lateral sloshing was also considered by using the assumption of the equivalent pendulum. The effects of sloshing on other directions were neglected. 18% and 25% differences in the results for the derailment and unloading of the wheel at the presence of the lateral sloshing were reported (Younesian *et al.*, 2010).

Vera *et al.* (2005) also simulated a dynamic model of 4 tanker wagons in SIMPACK. They modeled the longitudinal sloshing by using the equivalent mass – the spring model, and an equivalent pendulum was used for the lateral sloshing. In the longitudinal model both braking and acceleration was studied and the results were examined in couplers. They also considered 4 simple baffles inside the tankers. Beside many tasks have been done on sloshing, many scientists worked on ways to avoid failures caused by sloshing (Koh *et al.*, 2013; Biswala and Bhattacharayab, 2010).

In this study, by combination of the method introduced by Younesian *et al.* (2009) and implementing longitudinal sloshing into it, the effects of the longitudinal sloshing generated during the braking process and its effect on the structural stresses of the bogie frame is studied. It needs to be reminded that simultaneous application of track irregularities and oscillatory loads due to fluid sloshing have severe effects on the freight bogie stresses. This was not considered in prior researches. The Y25 bogie is the subject of interest for this research. Initially, in order to determine the dynamic forces, the model for the selected wagon is developed in ADAMS/RAIL engineering software. In this part, sloshing is modeled with the equivalent mass – a spring. In the next step, the dynamic forces and the track irregularities are applied to the model in LS-DYNA, and the stress history of the critical points is extracted. This time signal gives a very important required data for further analysis.

2. The Y25 bogie and its characteristics

The freight bogies in Iranian railway are mainly divided into two groups of solid and three pieces frames. The bogies with solid frames are used for axle loads up to 20 tonnes and the three pieces bogies are used for axle loads of up to 23.5 tonnes. The bogies with solid frames have more stable behavior during operation. Besides, the limit tolerances in these bogies prevent warping during operation. The wagon union bogie type Y25 is of the solid frame type. It is equipped with the primary suspension and can carry the axle load of 20 tonnes. Y25 is widely in use for freight transportation throughout the world. Figure 1 is for a tank wagon equipped with Y25 bogies manufactured by WAGON PARS in Iran.



Fig. 1. Tank wagon equipped with Y25 bogies

While in motion, the common problem with such tanker cars is the change in the axle load due to longitudinal sloshing during braking that can increase the axle load of the bogies. This phenomenon has a negative effect on the fatigue life of bogies. In this paper, by using the dynamic model of a tank wagon on Y25 bogies, the dynamic forces are calculated. These forces are used in the stress analysis of the FE model of the frame and, finally, the effect of the longitudinal sloshing in generating the structural stresses is studied.

3. The modeling of Y25 bogie

This bogie consists of a solid frame and the primary suspension that includes helical springs and friction elements. The friction elements cause non-linear behavior of the bogie. This non-linearity is modeled by using the hysteresis loop reported by Molatefi *et al.* (2006). The schematic of such a loop is presented in Fig. 2.

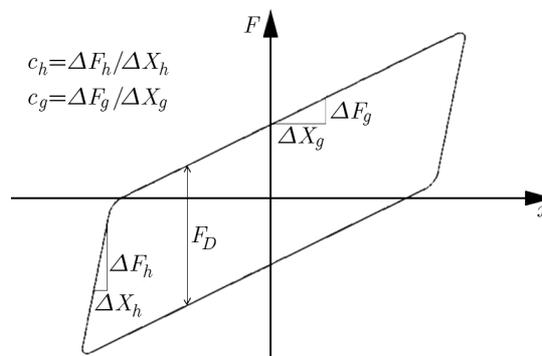


Fig. 2. Schematic of the hysteresis loop modeled for the primary suspension system of Y25 bogie (Molatefi *et al.*, 2006)

The specifications for the primary suspension and the hysteresis loops are presented in Table 1.

Table 1. Parameters of the primary suspension system of Y25 bogie (Molatefi *et al.*, 2006)

Vertical direction			Lateral direction			Longitudinal direction		
C_h	C_g	F_D	C_h	C_g	F_D	C_h	C_g	F_D
[N/m]	[N/m]	[kN]	[N/m]	[N/m]	[kN]	[N/m]	[N/m]	[kN]
$1.3 \cdot 10^7$	$8.9 \cdot 10^5$	2.5	$2.2 \cdot 10^6$	$4.3 \cdot 10^5$	5.0	$1.7 \cdot 10^7$	$8.5 \cdot 10^5$	4.0

The schematic of the center bowl and its friction components that are also used for the modeling purposes are presented in Fig. 3. The side bearers are also modeled.

3.1. The dynamic modeling

In order to estimate the sloshing loads, the dynamic model of Y25 bogie is modeled in ADAMS/RAIL engineering software. Some details for the bogie are provided in Tables 1 and 2 from the report by Molatefi *et al.* (2006). The model is presented in Fig. 4. The calculated inertial properties for different parts of this bogie are presented in Table 2.

The index x denotes the longitudinal axis, y lateral and z represents the vertical axis. The liquid in the tank is subdivided into two components including a fixed mass m_o and a moving mass m_{fluid} (Abramson and Silverman, 1966), see Fig. 5. There is no sloshing in the fixed mass. Sloshing happens within the moving mass. The mass-spring system is used for the modeling of the longitudinal sloshing of the liquid in the tank.

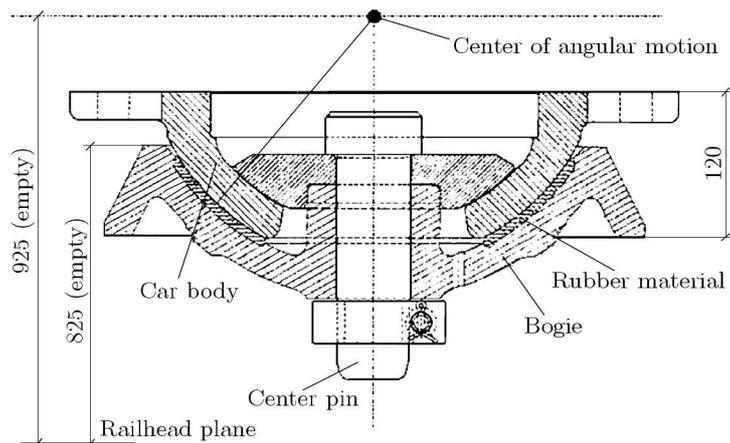


Fig. 3. The center bowl of Y25 bogie (Molatefi *et al.*, 2006)

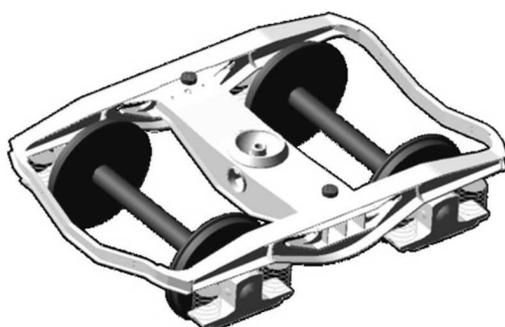


Fig. 4. The 3D dynamic model of Y25 bogie in ADAMS/RAIL

Table 2. Inertial properties of Y25 bogie

Body	M [kg]	I_{xx} [kg m ²]	I_{yy} [kg m ²]	I_{zz} [kg m ²]
Bogie frame	1990	1188	1484	2582
Axle box	20	5	5	5
Side bearer	25	10	10	10
Wheelset	1.380	902	108	906

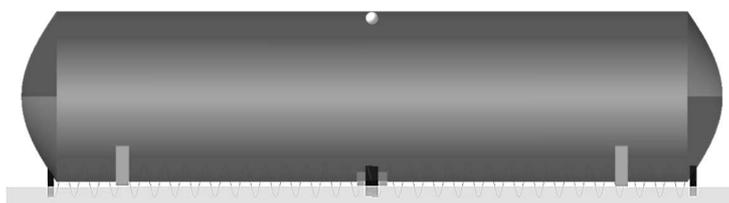


Fig. 5. Modeled tank wagon with longitudinal sloshing in ADAMS/RAIL

The specifications for the mass-spring system for partially filled tanks containing water of different filling percentages are calculated and presented in Table 3.

Later on in this article, the sulfuric acid that is 1.83 times denser than water is also considered as the content of the tank.

In order to verify the dynamic model, the hunting velocity of the vehicle is also calculated. The result is presented in Fig. 6. The calculated hunting velocity is equal to 17.7 m/s. It is

Table 3. Mass and stiffness of the longitudinal mass-spring system (water content)

Filling ratio	30%	50%	80%
m_{fluid} [kg]	$1.3857 \cdot 10^4$	$2.2684 \cdot 10^4$	$3.4803 \cdot 10^4$
m_o [kg]	$3.3983 \cdot 10^3$	$6.0748 \cdot 10^3$	$1.1210 \cdot 10^4$
K [kN/m]	$6.3291 \cdot 10^3$	$1.6961 \cdot 10^4$	$3.9926 \cdot 10^4$
h_{fluid} [m]	0.0017	0.0079	0.0319
h_o [m]	1.6762	2.5861	3.5294

comparable to the hunting velocity of 17 m/s for the same vehicle that was reported by Molatefi *et al.* (2006). The difference comes from the effect of neglecting structural clearances. It is concluded that the dynamic model is reliable and can be used for further processing.

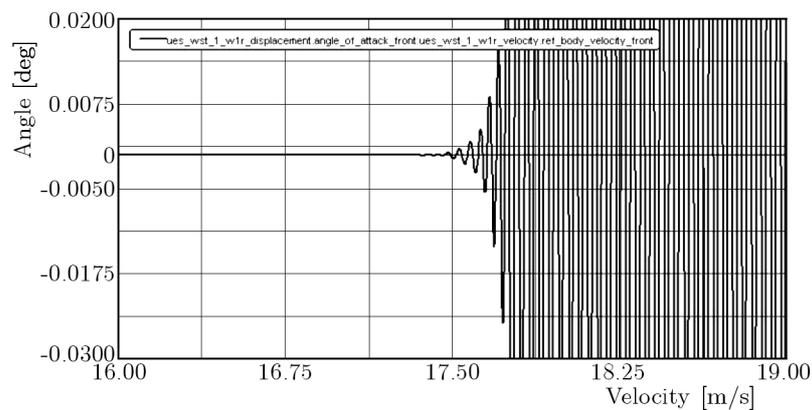


Fig. 6. Non-linear hunting velocity of Y25 bogie (output from ADAMS/RAIL)

3.2. The analysis

The Iranian freight tankers have been equipped with Wagon Union (Y25) bogies since 1982 (Reports on the Technical Specifications of the Freight wagons, Freight Division, 2010). The wheel profile for the fleet running over Iranian National tracks is S1002. The track inclination angle is 1:20. With the simulated model provided in the prior sections of this article, the partially filled tanker cars were tested during the braking process. It is assumed that the vehicle decelerates at 1 m/s^2 . Three scenarios including the tanker cars with 30%, 50% and 80% filling ratios are examined. The results of the simulation for the vertical forces on the bogie centre bowl are presented in Fig. 7. It is observed that during braking, the amplitude of fluctuation of the vertical loads on the bogie decreases as the filling ratio increases.

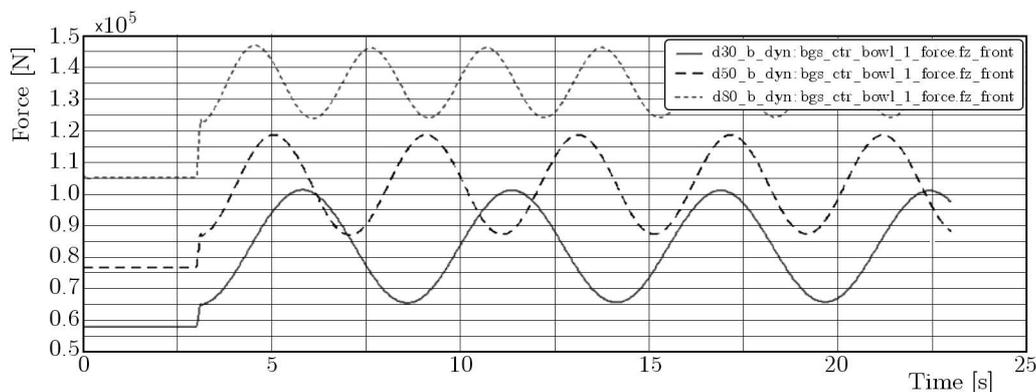


Fig. 7. A comparison of the vertical forces on the bogie centre bowl during braking

The calculated forces and track irregularities applied to a model of the frame in Ansys-LS-DYNA FEM engineering software. To speed up the calculations, the frame model is divided into several smaller parts. Consequently, the new parts are meshed by using 350243 Hexa meshes. Figure 8 (right) illustrates the bogie centre bowl that is meshed monotonously.

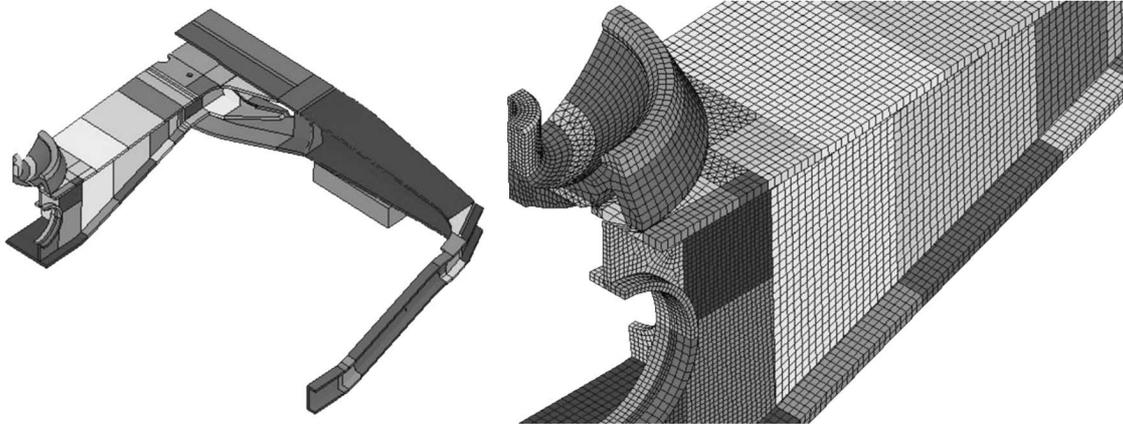


Fig. 8. Partitioning of the bogie to smaller parts (left), meshed view of the bogie in FEM software (right)

In order to consider the effect of track irregularities on the bogie structure, the suspension system is modeled by a set of the damper and spring. Irregularities act as displacements on the end of the suspension system (Frýba, 1996; Wiriyachai *et al.*, 1982).

The power spectral density (PSD) functions were used to generate track irregularities with random nature. The Federal Railroad Administration of US (FRA) classifies the railway tracks from 1 (the worst) to 6 (the best) in view of surface irregularities. The following PSD functions provided by FRA represent $S_{c,g}$ cross and gauge and $S_{e,a}$ elevation and alignment irregularities.

$$S_g(\Omega) = \frac{A\Omega_2^2}{(\Omega^2 + \Omega_1^2)(\Omega^2 + \Omega_2^2)} \quad S_e(\Omega) = \frac{A\Omega_2^2(\Omega^2 + \Omega_1^2)}{\Omega^4(\Omega^2 + \Omega_2^2)} \quad (3.1)$$

$S(\Omega)$ is the PSD of irregularities versus wavelength ($\Omega = 2\pi/(v\omega)$), while v is the wagon speed of travel and A , Ω_1 and Ω_2 are constant coefficients shown in Table 4.

Table 4. Railway track characteristics specified by FRA

Irregularity	Parameter	Unit	Track class		
			1	3	6
Elevation	A	10^8 m^3	15.53	4.92	0.98
	Ω_1	10^3 m^{-1}	23.3	23.3	23.3
	Ω_2	10^3 m^{-1}	13.1	13.1	13.1
Gauge	A	10^8 m^3	9.83	3.15	0.59
	Ω_1	10^3 m^{-1}	29.2	29.2	29.2
	Ω_2	10^3 m^{-1}	23.3	23.3	23.3

Using a Monte Carlo algorithm, the irregularities $r(x)$ are calculated for the rail classes of 1, 3 and 6

$$r(x) = \sum_{k=1}^N \alpha_k \cos(\omega_k x + \varphi_k) \quad (3.2)$$

where α_k is the amplitude and ω_k is the frequency in the range of (ω_1, ω_2) . The calculations were carried out in these intervals. φ_k is a random value with normal distribution in the range

of $(0, 2\pi)$. X and N are the position on the track and the number of the divided intervals, respectively. The values of α_k and ω_k are calculated as

$$\alpha_k = 2\sqrt{S(\omega_k)\Delta\omega} \quad \omega_k = \omega_1 + \left(k - \frac{1}{2}\right)\Delta\omega \quad k = 1, 2, \dots, N$$

$$\Delta\omega = \frac{\omega_2 - \omega_1}{N}$$
(3.3)

The vertical and horizontal components of the irregularities calculated for the railway tracks of 1, 3 and 6 classes are presented in Fig. 9.

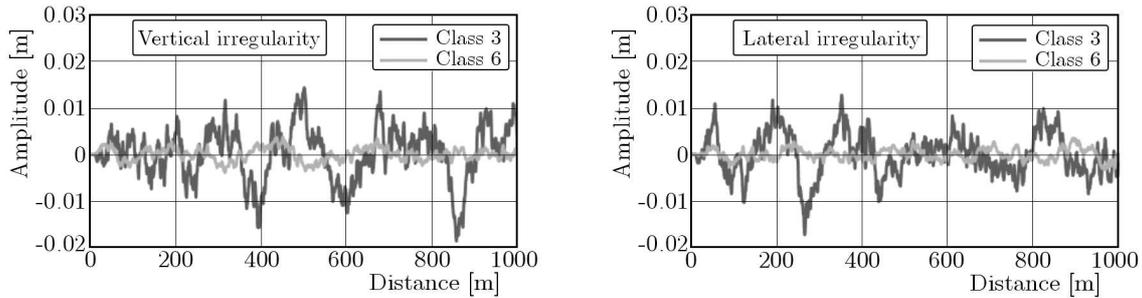


Fig. 9. Vertical and horizontal components of the rail track irregularities

It is intended to identify the critical points within the bogie structure while it is under the influence of track irregularities of statistical nature. The size and the history of the stresses on such points are extracted. The most critical point lies on the bogie centre bowl. The stress contour for this zone is indicated in Fig. 10. This case belongs to a filling ratio of 50%, the initial velocity of 20 m/s, the track of class 6, and the fluid content is water. All the results are plotted for this point.

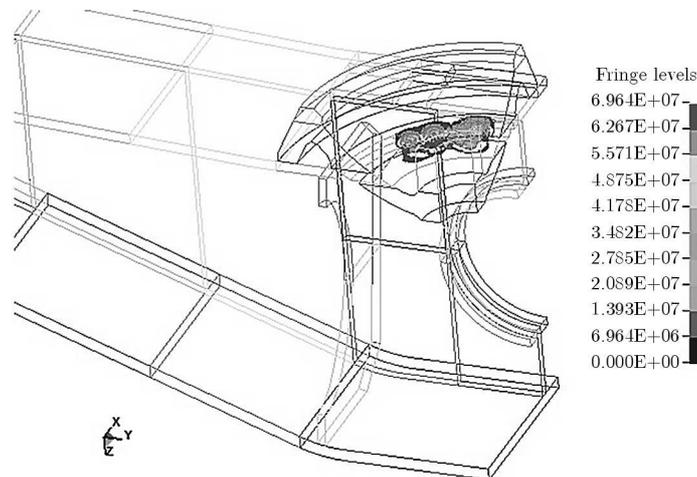


Fig. 10. Stress concentration in the bogie centre bowl

3.3. The effect of vehicle speed of travel on the bogie stresses

In Fig. 11, it is shown that by varying the vehicle speed of travel from 20 to 30 m/s, the stresses in the bogie center bowl grow approximately by 1.5%. By further increasing the speed, the amplitude can grow by more than 10%. The maximum stresses at the speed of 20 and 30 m/s are 93.7 and 94.5 MPa, respectively.

It is observed that there are two types of fluctuations in the calculated stress histories. The track irregularities cause fluctuations in the forces with smaller amplitudes and higher

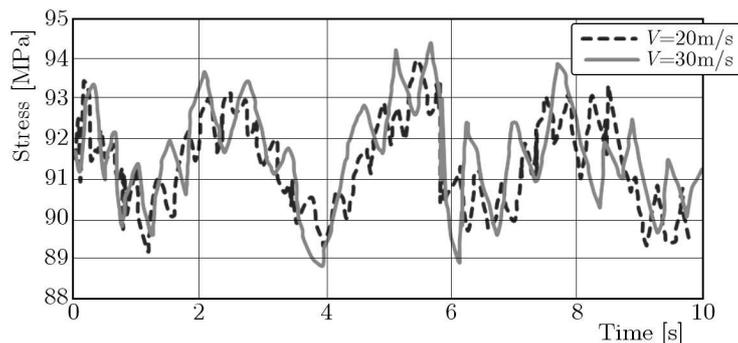


Fig. 11. Calculated stresses in the bogie centre bowl at different speeds of travel (rail irregularity type 3)

frequencies. The oscillating loads due to sloshing cause fluctuations with higher amplitudes and smaller frequencies.

3.4. The effect of track irregularities on the bogie stresses

Figure 12 indicates the effects of quality of the railway track on stressing out the bogie structure. As the quality of the track worsens, the amplitude of the corresponding stresses increases. The maximum stresses in tracks of the 1st, 3rd and 6th classes are 95, 93.6 and 92.8 MPa, respectively.

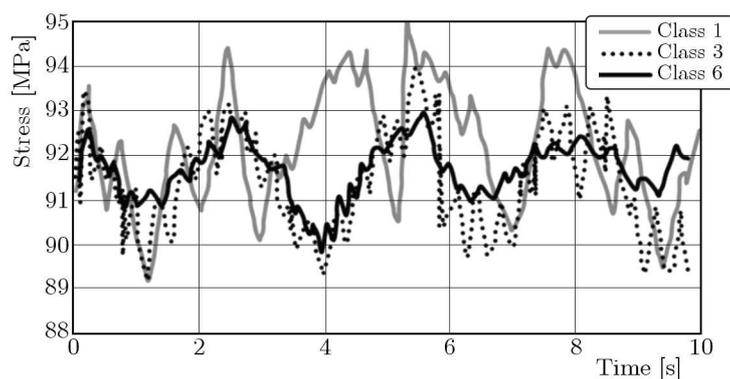


Fig. 12. The maximum calculated stresses in the bogies versus different classes of tracks

3.5. The effect of the fluid tank filling ratio on the bogie stresses

Clearly, as the liquid filling ratio increases, the vehicle axle load raises. Consequently, the average stress loaded on the bogies grows. Figure 13 illustrates the stress loading on the bogie at different filling ratios. The maximum stresses at the filling ratios of 30%, 50% and 80% are 90.5, 94.1 and 96.5 MPa, respectively. It is worth to notice that the stresses at the filling ratio of 50% rather than others are highly sensitive to track irregularities. This can be associated with the larger free surface at such a filing ratio.

3.6. The effect of fluid density on the bogie stresses

The simulated model of the vehicle was also used to study the effect of density of the liquid content of the tanker car on the stresses generated within the bogie. Water was replaced with sulfuric acid that is 1.83 times denser. As a result, the average stresses in the bogie structure increased. The maximum calculated stress in the case of water is 93.8, and in the case of sulfuric acid is 95 MPa, Fig. 14.

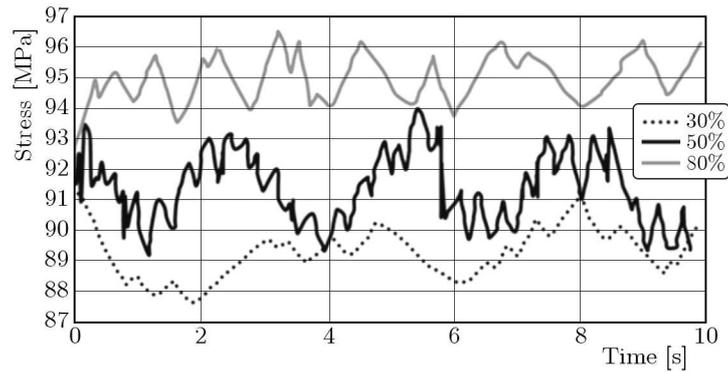


Fig. 13. The maximum calculated stresses in the bogies versus different filling ratios

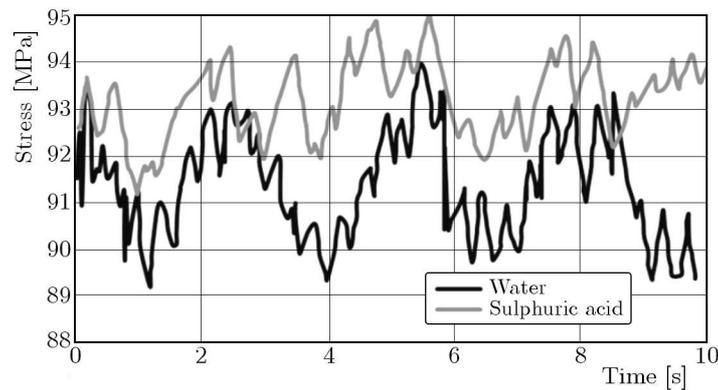


Fig. 14. The maximum calculated stresses in the bogies versus different liquids

4. Conclusions

This paper by employing a new combined method, presents the stress behavior of Wagon Union type Y25 bogie in the tanker wagon subjected to random and oscillating loads due to track irregularities and by liquid sloshing. Using a number of numerical models, including the Finite Element Method and the multi body dynamic techniques, the following important conclusions are drawn:

- The study of the stress history of the bogie indicated two types of fluctuations. Irregularities of the track cause stresses with smaller amplitudes at higher frequencies. The liquid sloshing causes stresses of higher amplitudes and smaller frequencies.
- By increasing the speed of travel from 20 to 30 m/s, the peak stresses rise up. At higher speeds, the stress amplitude grows by more than 10%. The maximum stresses at 20 and 30 m/s are 93.7 and 94.5 MPa, respectively.
- The type of the track has a noticeable effect on the stress amplitude within the bogie structure. As the quality of the track worsens, the amplitude of the stress increases. In this case, the maximum stresses for the tracks of the 1st, 3rd and 6th classes are 95, 93.6 and 92.8 MPa, respectively.
- The maximum stresses in the case of tanker wagons with 30%, 50% and 80% filling ratios are 90.5, 94.1 and 96.5 MPa, respectively. In addition, the stress at the 50% filling ratio, rather than others, is highly sensitive to track irregularities. This can be attributed to the larger free surface that becomes available for this case.
- At similar filling ratios, the maximum calculated stresses are 93.8 and 95 MPa, while carrying water or sulfuric acid, respectively.

- The discussed/developed methodology could apply to any type of bogie under live or random loads in order to extract stress history signals of the critical points.

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