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ANALYSIS OF THE STRESS STATE IN THE FRAME OF THE Y 25 CS BOGIE AT RUNNING IN CURVES

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Rezumat. *Pentru compensarea forţei centrifuge care acţionează asupra vehiculelor feroviare în timpul circulaţiei în curbe, la construcţia liniilor de cale ferată se execută supralărgirea căii şi supraînălţarea firului exterior. În prezenta lucrare analizăm influenţa vitezei de circulaţie în curbă cu raza de* 500 m *la un vagon Eacs echipat cu boghiuri Y25Cs, asupra tensiunilor din cadrele boghiurilor*

Abstract. *In order to compensate the centrifugal force that appears in railway vehicles during running in curves, overwidening of the track and superelevation of the external rail are executed. In this paper, we analyze the influence of the cruising speed on the stress state in the frames of the bogie, in a turn with a radius of* 500 m *of an Eacs car, equipped with Y25 Cs bogies.*

Keywords: Y 25 Cs bogie, circulation in turn, stress, finite element analysis

1. Introduction

In order to diminish the effect of the centrifugal force that acts on the railway car in curves and to ease the entrance in a curve, the tracks are overelevated and overwidened. The lateral centrifugal acceleration of a vehicle when running in a curve is given by the equation [4]:

$$a = v^2 / R \tag{1}$$

where: v - the speed of the vehicle [m/s], R - radius of the curve [m].

In Figure 1 are depicted the accelerations that act on a vehicle which runs in a curve of radius "*R*" and superelevation "*h*" of the external rail. In such a case, the uncompensated value of the acceleration is given by the relationship [4]:

$$a_d = \frac{v^2}{R} - \frac{gh}{s} \tag{2}$$

The ideal case during running in a curve is the one when the uncompensated value of the acceleration is $a_d = 0$, and the resultant acceleration between $a = v^2 / R$ and gravity g is perpendicular to the track.

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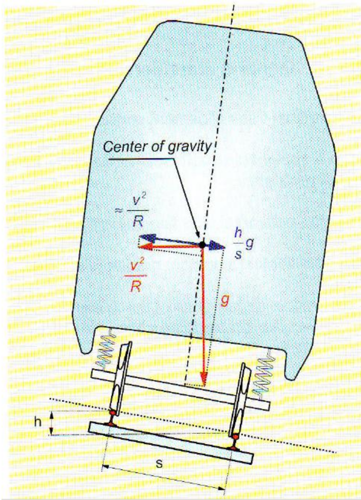


Fig. 1. Accelerations in a curve.

From (1), the value of the ideal superelevation results as:

$$h_{id} = \frac{v^2 s}{gR} = \frac{11{,}8\,V^2}{R} \tag{3}$$

where: v - speed of running [m/s], V - speed of running [km/h]; R - radius of the curve [m], g = 9.81 m/s^2 is gravity, h - superelevation [mm], s = 1500 mm - distance between the rails (for tracks with normal track gage). Since both freight cars and passenger cars travel on the railway and they have different maximum speed, two situations may appear in practice: lack of superelevation and excess of superelevation. The lack of superelevation h_d is given by the difference between the ideal superelevation and the existent superelevation and can be calculated with the formula:

$$h_d = \frac{v^2 s}{gR} - h = \frac{11{,}8\,V_{\max}{}^2}{R} - h \tag{4}$$

The uncompensated acceleration when lack of superelevation occurs is:

$$a_d = \frac{g}{s} h_d \tag{5}$$

When speed of running is smaller than the maximum speed for which superelevation was calculated, an excess of superelevation appears, whose value is given by:

$$h_e = h - \frac{11{,}8\,V_{\min}{}^2}{R} \tag{6}$$

During running in curves, apart from the quasi-static accelerations given by the centrifugal force, dynamic accelerations that depend on the quality of the track appear. The variation of the quasi-static and dynamic accelerations at running in curves is shown in Figure 2 [4].

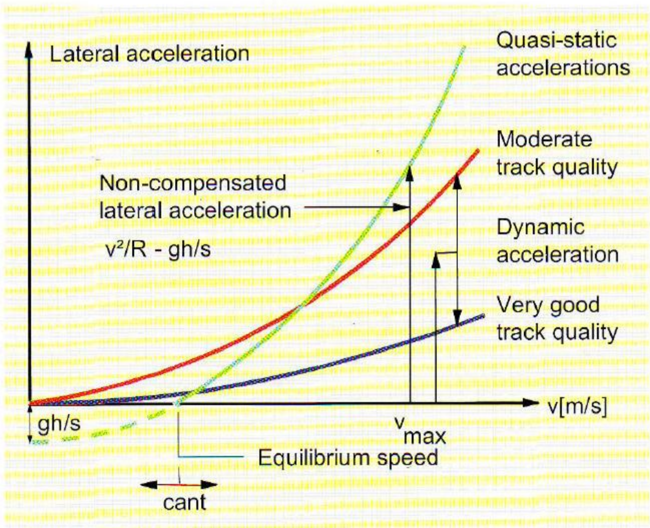


Fig. 2. Accelerations in curves.

2. Loads acting on the bogie frame

Several types of loadings can act on different elements of a railway vehicle, depending on the loading state, position of ride and running regime, as follows, [1]:

a) Loadings given by the quota of the weight of the vehicle sub-assemblies, including own weight;

b) Loadings that appear in different exploitation regimes:

- Vertical dynamic loads that appear during running due to the passing of the wheels over irregularities of the rail and oscillation of the vehicles leaning on springs;

- Loadings that appear at running in curves and that stress supplementary the frame of the bogie and of the car. Such loadings are given by the centrifugal force, the force that appears due to the pressure of the wind and reaction forces in the rail;

- Loadings that appear at braking, due to horizontal inertia forces and reaction forces transmitted by the brake system;

- Longitudinal loads that appear at collision between vehicles when maneuvers are performed in order to assembly or disassembly the set of cars or during towing or braking, especially in the case of long and heavy freight cars;

- Service load given by the weight of the transported goods or passengers.

2.1. Vertical static loads

Vertical static loads are transmitted from the frame of the car to the frame of the bogie either through central supports (center bowls) or through central or lateral supports. Static vertical loads from bogies are taken by the axle boxes, axle necks and traversing wheels through the suspension.

In Figure 3 it is shown the transmission of the vertical static load between different elements of a railway car with two bogies, each bogie having two axles. In this figure, G_c is the weight of the box, including the aggregates mounted on it (for freight cars, this weight is the sum of the own weight of the box G_{pc} and the service load or charge G_u), G_b - the total weight of a bogie, G_o - the unsuspended weight of a mounted axle, G_{sb} - the suspended weight of a bogie, n_{ob} - the number of axles of a bogie and $2Q$ is the static load acting on an axle (the vertical load transmitted by an axle to the rail).

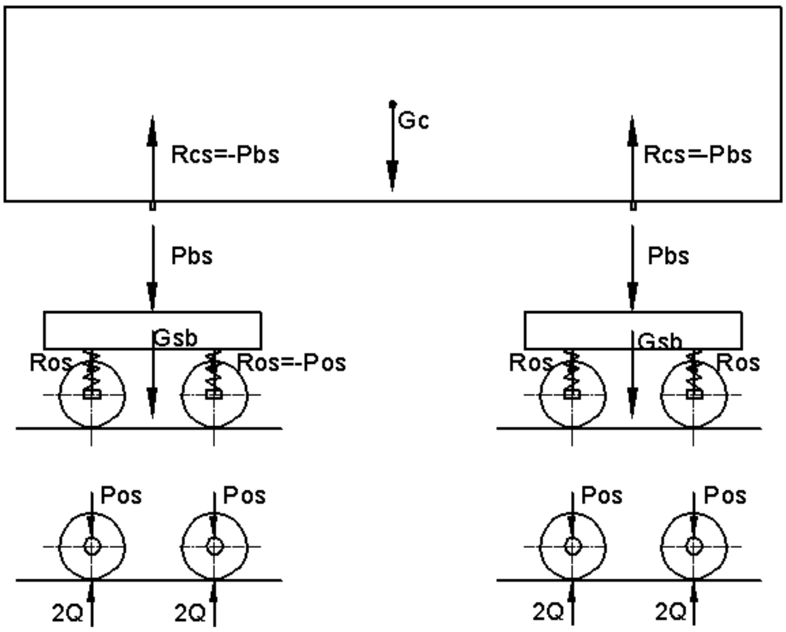


Fig. 3. Loads acting on the elements of a railway car.

$$G_{sb} = G_b - n_{ob} \cdot G_o \tag{7}$$

In order to obtain a uniform repartition of the vertical static load on the axles, the weight of the box should act equally on each bogie. For a two bogie vehicle, the vertical static load transmitted by the box to each bogie is:

$$P_{sb} = \frac{Gc}{2} \tag{8}$$

Each point of support of the box on the bogie takes a vertical static load equal to:

$$P_{1bs} = \frac{P_{bs}}{n_{rb}} = \frac{G_c}{2n_{rb}} \tag{9}$$

where n_{rb} is the number of support points of the box on the vertical direction, on a bogie. The vertical static load taken by an axle mounted on the bogie frame through the axle boxes is:

$$P_{os} = 2Q - G_o \tag{10}$$

On each axle neck, acts a load equal to:

$$P_{1s} = \frac{P_{os}}{2} = \frac{2Q - G_o}{2} \tag{11}$$

In the points where the vertical loads are transmitted from the bogie frame to the axle, a resultant reaction force on the bogie frame appears, having the value:

$$R_{os} = -P_{os} \tag{12}$$

The reaction force on the bogie frame in such a point is:

$$R_{1s} = \frac{R_{os}}{2n_{ro}} = \frac{2Q - G_o}{2 \cdot 2n_{ro}} \tag{13}$$

where n_{ro} is the number of points through which the vertical load is transmitted from the bogie frame to an axle box.

This number is given by the type of suspension and has usually a value of 1 or 2. The sign minus of the reaction force R_{1s} in equation (6) shows the sense of action of this force (upward).

2.2. Vertical dynamic loads

The vertical dynamic loads appear during running of the vehicle due to passing of the wheels over the irregularities of the rail and due to oscillation of the vehicles leaning on springs.

One considers that such loads act in the same areas where the static vertical loads appear. The values of the vertical dynamic loads P_{id} are obtained by multiplication of the vertical static loads P_{is} with a dynamic vertical coefficient k_{vd}:

$$P_{id} = k_{vd} P_{is} \tag{14}$$

A value $\beta = 0.3$ of the dynamic vertical coefficient for freight cars is reported in [6], [7]. The vertical dynamic load is considered as statically applied and the stresses yielded by such load are summed with those given by the static load.

2.3. Forces that act at running in curves

During running of the vehicle in curves, supplementary forces appear, yielding loadings on the box of the vehicle and on the elements of the bogie. Such forces can be divided in the following categories:

- Lateral forces (centrifugal force, force given by the wind and reaction forces of the rail);
- Longitudinal forces (longitudinal components of the friction forces between wheels and rail);
- Vertical forces given by lateral forces.

2.3.1. Lateral forces

The uncompensated transversal acceleration of the car, taking into consideration the supplementary tilt of the car box given by the suspension, is [2]:

$$\gamma_t = (\frac{V^2}{3,6^2 R} - g\frac{h}{2s})(1+S) \tag{15}$$

The centrifugal force of the box, unbalanced by the supplementary superelevation of the external rail is:

$$C_c = G_c \gamma_t \tag{16}$$

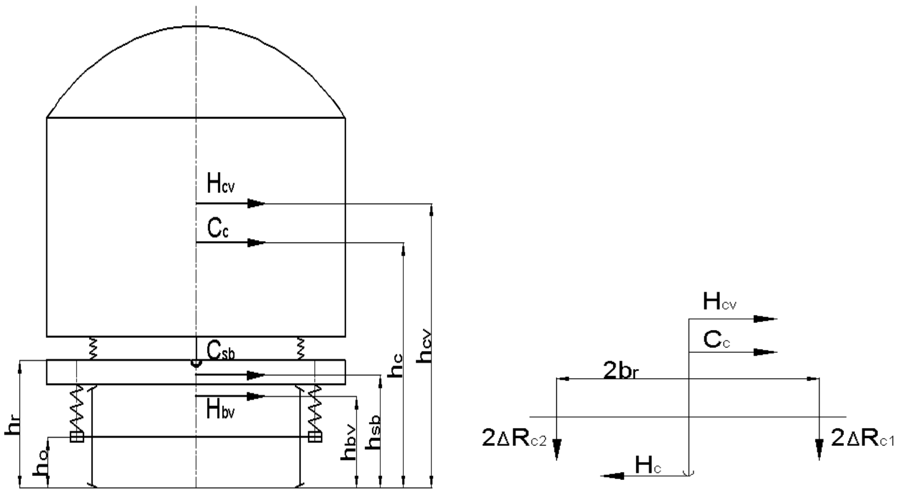
where: v - maximum speed allowed in a curve of radius R_c; h - overelevation of the external rail; G_c - mass of the box; S - slenderness coefficient; $2s$ - distance between the planes of the rolling circles of a mounted axle. A value $\alpha = 0.2$ is given in [6], [7] for a distance $2b_r = 1700$ mm between side bearings. The centrifugal force C_c is applied in the centroid of the box, at a height h_c from the rolling surface of the rail. The force given by the pressure of the wind H_{cv}, acting on the box is:

$$H_{cv} = S_c w \tag{17}$$

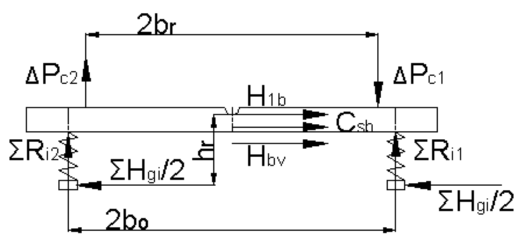
where: S_c - lateral area of the box [m^2], w - specific pressure of the wind, taken as $w = 50$ daN/m^2 [1], [2]. This force is applied in the center of the lateral wall of the box, at a height h_{cv} from the rolling surface of the rail. The force H_{bv} given by the pressure of the wind and acting on the bogie frame can be calculated as:

$$H_{bv} = S_b w \tag{18}$$

where: S_b - lateral area of the bogie [m^2]; w - specific pressure of the wind. In strength calculations of the railway vehicle, the composed action of the centrifugal force and wind force is considered for the most unfavorable situation, that is when wind blows perpendicular to the lateral surface of the vehicle. Depending on the connection system between the box of the car and the bogie, the forces $C_{1c} = C_c/2$ şi $H_{1c} = H_{cv}/2$ taken by a bogie are transmitted to it through the central support and the lateral side bearings (Fig. 4.a). The lateral forces $H_{1b} = C_{1c} + H_{1c}$ are transmitted to the bogie from the box, acting at a height h_r from the rolling surface of the rail (Fig. 4.c). The forces C_c and H_{cv} create a turn-over couple of the box with respect to the longitudinal axis of the vehicle, loading thus the lateral side bearings on each bogie and unloading the center bowl with the vertical forces ΔP_{cj} (Fig. 4.c). The lateral forces C_c and H_{cv}, acting on the box of the vehicle are equilibrated by the lateral reaction force $H_c = H_1$ from the elements that take the lateral load and by the vertical reactions $\Delta R_{cj} = -\Delta R_{cj}$ (Fig. 4.b). The lateral forces (H_{1b}, C_{sb}, H_{bv}) acting on the bogie are transmitted to the axles through the guideways and axle boxes. The forces H_{1b}, C_{sb}, H_{bv} and ΔP_{bj} yield a turn-over couple of the bogie with respect to the longitudinal axis of the bogie which loads the suspension springs on each axle neck on the external part of the bogie and unload those from the interior of the curve with the forces P_{ij}.



a. Lateral forces acting on a car b. Forces acting on the box



c. Forces acting on the bogie

Fig. 4. Forces acting on a car.

Forces acting on the bogie (Fig. 4.c) are equilibrated by:

- The lateral reactions from the guideways of the axle boxes:

$$H_{gi} = -H_i \tag{18}$$

- The vertical reaction forces in the points of support of the bogie frame on the suspension of the axle

$$R_{ij} = -P_{ij} \tag{19}$$

- The longitudinal reaction forces R_{hij}.

2.3.2. Vertical forces acting on the bogies with spherical center bowl

During running in curves, due to the fact that the centroid of the vehicle is located at a greater height that the one of the lateral supports, the turn-over couples of the box and bogie lead to a redistribution of the vertical loads on the lateral supports of the box and on the springs of the suspension at the axle (the springs being located on the two sides of the bogies).

The lateral forces yielded by the centrifugal force C_c and the force H_{cv} given by the wind pressure are taken by the center bowls of the two bogies (Fig. 5.a); the turn-over couple of the box is:

$$M_{cx} = C_c\left(h_c - h_s\right) + H_{cv}\left(h_{cv} - h_r\right) \tag{20}$$

This couple loads the bogies through the lateral supports (lateral side bearings) from the exterior of the curve and unloads the two center bowls.

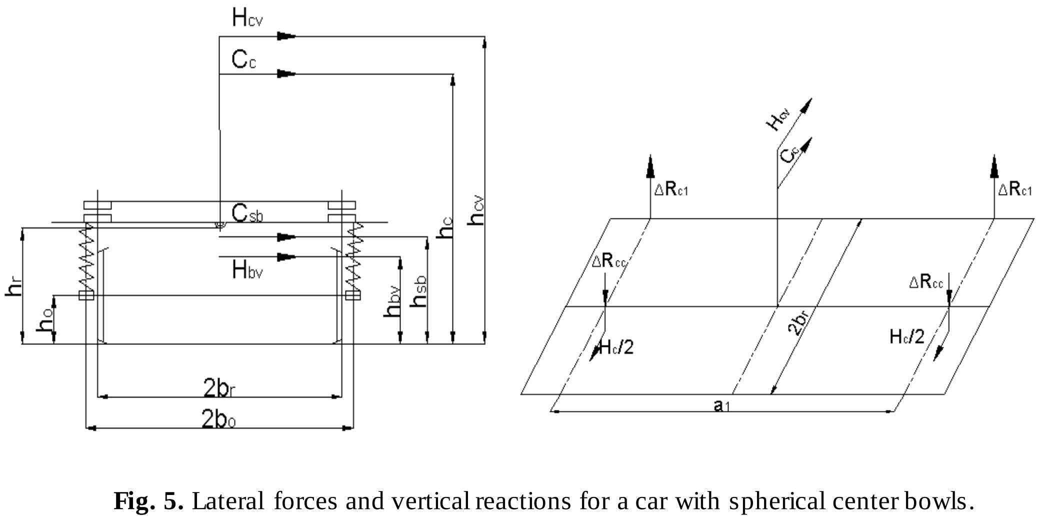


Fig. 5. Lateral forces and vertical reactions for a car with spherical center bowls.

a. Lateral forces acting on a car. b. Forces acting on the box.

From the condition of equilibrium, one can find the reaction force ΔP_{c1} from the lateral support of a bogie and the reaction force ΔR_{cc} from a center bowl (Fig. 5.b):

$$\Delta R_{c1} = -\frac{M_{cx}}{2b_r} \text{ şi } \Delta R_{cc} = \frac{M_{cx}}{2b_r} \tag{21}$$

The sign (–) shows that the force ΔR_{c1} acts upwards. The vertical force ΔP_{c1} that loads the lateral support of a bogie is $\Delta P_{c1} = -\Delta R_{c1}$, and the vertical force ΔP_{cc} that unloads the center bowl is $\Delta P_{cc} = -\Delta R_{cc}$ (Fig. 5.b).

3. Analysis of the stress state in the Y25Cs bogie frame at running in curves

The following section is dedicated to the numerical analysis of the stress state in an Eacs car, equipped with Y25Cs bogies, and which runs in a curve with radius of 500 m. The maximum speed of the car is 100 km/h. In order to have a null noncompensated acceleration, one can calculate the value of the ideal superelevation using equation (4):

$$h_{id} = \frac{v^2 s}{gR} = \frac{11.8\,V^2}{R} = \frac{11.8 \cdot 100^2}{500} = 232\,\text{mm} \tag{22}$$

Since the maximum value of the superelevation is limited to 150 mm [2], [4], one can establish the equilibrium (nominal) speed for which the uncompensated acceleration is zero, using relationship (1.2): $V = \sqrt{\frac{hR}{11.8}} = 79.7\,\text{km/h}$. When the car runs with a speed greater than 79.7 km/h, a lack of superelevation appears and for a speed lower than 79.7 km/h an excess of superelevation occurs.

Table 1. Forces and pressures acting on the side bearings and center bowl

Speed [km/h]	Turn-over couple M_{cx} [N·mm]	Force on the glider ΔP_{c1}	Force on the center bowl P_{zc}	Pressure on the glider $p_{\Delta Pc1}$ [N/mm^2]	Pressure on the center bowl p_{Pzc} [N/mm^2]
15	-72897554	-85762	403647	4.04	3.18
30	-66883991	-78687	410722	4.11	2.91
45	-56861385	-66896	422513	4.22	2.48
60	-42829737	-50388	439021	4.39	1.87
75	-24789046	-29164	460245	4.60	1.08
79.7	18268677	21493	467916	0	4.89
90	33798166	39763	449646	4.50	1.47
100	50725234	59677	429732	4.30	2.21

The analysis of the stress state is done for the most unfavorable situation, when the dynamic effect of the jump movement appears on the bogie, the centrifugal force acts and the force of the wind acts in the same sense in which the box of the car inclines. In the following analysis, the longitudinal forces, the quasistatic rolling effect given by the inclination of the box suspended on springs and the effect of torsion of the rail were not taken into account. The maximum vertical load acting on the bogie is:

$$P_z = 1.3\frac{\text{Gc}}{2}g = 489409\,N$$

Using equations (8), (16), (17) and (21), one can calculate the forces ΔP_{c1}. These forces will be applied as pressures both on the glider and on the center bowl. The support area of the glider is S_g = 27000 mm^2, and the support area of the center bowl is S_c = 100023 mm^2. The values of the forces and pressures acting on the glider and center bowl are given in Table 1. The sign minus from the turn-over couple and from the force acting on the glider shows that the resultant of the uncompensated acceleration is oriented towards the center of the curve.

3.1. The finite element model

From the structural point of view, the bogie frame is made of: lateral stringers, center bowl beam, brake linkage stringers, assembled through welding. The bogie frame is made of beam, plate and 3D elements. The finite element code Ansys 10.0. was used to model the bogie frame with shell elements, in a Cartesian coordinate system [3], [5]. The origin of the system was chosen in the center of the center bowl.

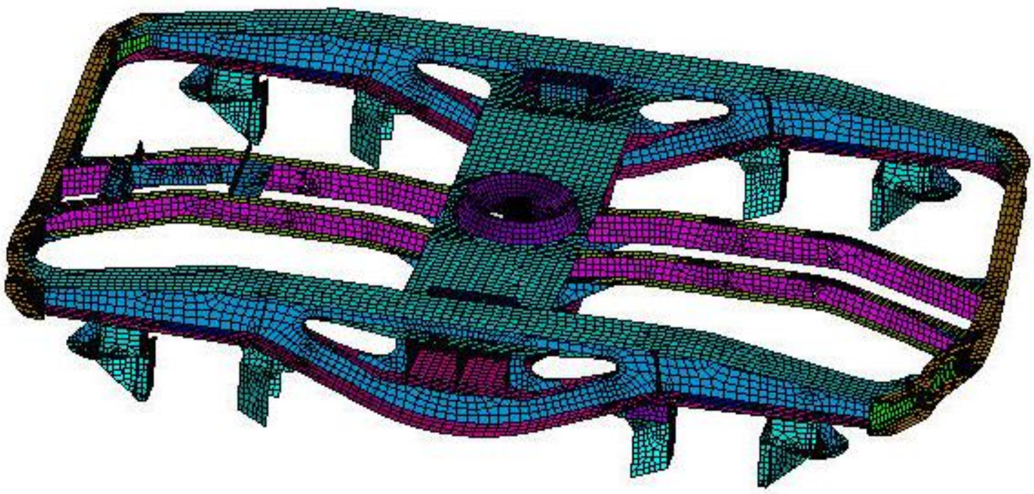


Fig. 6. The finite element model for the frame of the Y 25 Cs bogie.

The frame of the bogie is made of steel, having the following elastic constants: Young's modulus $E = 208000$ N/mm^2 and Poison's ratio $\nu = 0.3$. The finite element Shell 63 was chosen to mesh the structure with an imposed element side of 20 mm. The finite element model, having 23428 nodes and 23251 elements, is shown in Figure 6.

3.2. Forces and reactions

The finite element simulation, the values of the loads and the constraints were applied using the rules from [6], [7]. The load applied on the bogie frame was inserted as a pressure, distributed on the corresponding support surfaces.

3.3. Numerical results

The frame was subjected to successive loads corresponding to different cruising speeds and presented in Table 1. The wind was considered to act towards the center of the curve for speeds between 15 km/h and 79.7 km/h and towards the exterior of the curve for speeds greater than 79.7 km/h. In Figure 7, the distribution of the von Mises equivalent stress is shown for a speed of 15 km/h. One can see that, in this case, the stress has a maximum value in the lateral stringer of the bogie.

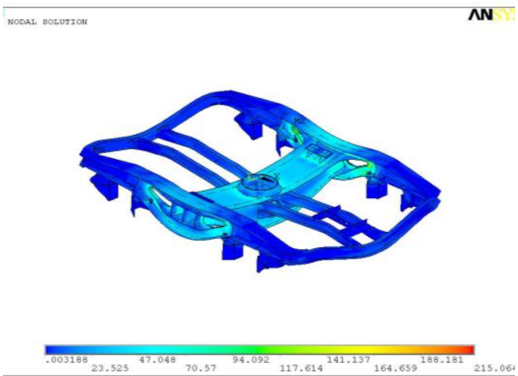


Fig. 7. The distribution of the von Mises stress for a speed of 15 km/h.

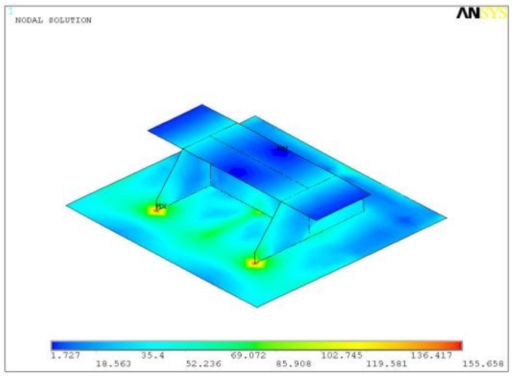


Fig. 8. The distribution of the von Mises stress in the area of the glider for a speed of 15 km/h.

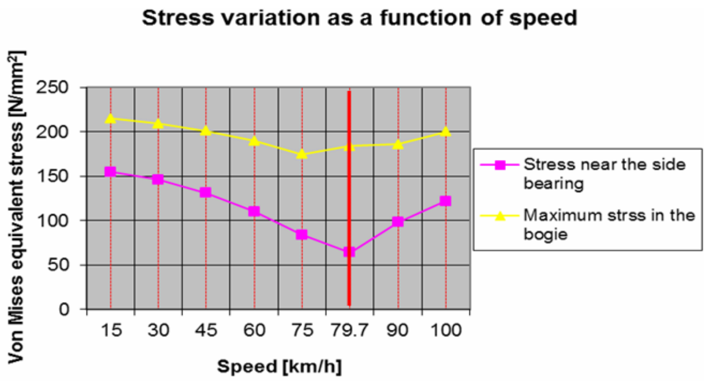


Fig. 9. Variation of the von Mises stress in the bogie as a function of the cruising speed.

The maximum stress is of 215 N/mm^2 and appears at the junction between the lateral stringer and the center bowl beam (Fig. 7). The value is greater than the maximum allowed stress 160 N/mm^2 for dynamic loads but greater than the yield limit of the considered steel - 280 N/mm^2. In this case, elevated stresses appear also in the top flange of the center bowl beam, in the area of the lateral loaded glider (Fig. 8). The value of the stress is 155 N/mm^2, at the limit of the allowable stress. For other speed values, we found similar distribution of the stress, only the maximum values being different. In Figure 9, the variation of the maximum stress in the frame and in the top flange of the center bowl beam in the area of lateral side bearings is presented.

Conclusions

Analyzing the obtained results, one can conclude that, when the cruising speed is different from the equilibrium value of *79.7 km/h*, the values of the equivalent stress in the bogie frame increase with the decrease of the cruising speed. Since the exploitation of the railways and especially of the industrial ones is not adequate, the solution of reduction of the cruising speed leads to overloading of the railway cars due to the excess of superelevation of the track in curves.

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