PART 2
STRENGTH OF THE BEARING STRUCTURE OF A UNIVERSAL FLAT WAGON

2.1 Analysis of forces on the bearing structure of a flat wagon in operation

The main forces acting on the flat wagon in operation are [15–17]:

– dead weight of the flat wagon (tare weight) and the freight weight;

– inertia forces that appear during oscillations; and

– oscillatory or impact forces, as well as those that appear in the horizontal longitudinal plane at different modes of train movement and shunting operations.

For calculations and in wagon designing these forces are considered as follows:

– vertical load: static and dynamic;

– lateral load;

– longitudinal load;

– combined self-balanced forces; and

– the load acting on the flat wagon through the fitting stops.

<u>Vertical loading</u>

The main vertical load consists of the tare weight, payload and vertical dynamic load.

The vertical force caused by the tare weight and the payload is called the vertical static load and determined by the formula:

$$P_v^{st} = \frac{P_{br} - P_{wp}}{m}, \tag{2.1}$$

where P_{br} is the gross weight of the wagon;

P_{wp} is the weight of the wagon parts (those that are calculated) from which the load is transferred to the rail track;

m is the number of similar concurrent parts.

The gross weight of the wagon is determined by the formula:

$$P_{\text{br}} = (P + T) \cdot g \,, \qquad (2.2)$$

where P is the load capacity of the wagon;

T is the tare weight;

g is the free fall acceleration.

The vertical dynamic load is calculated by the formula:

$$P_v^d = P_v^{st} \cdot k_{dv} \,, \qquad (2.3)$$

where k_{dv} is the coefficient of vertical dynamics calculated as:

$$k_{dv} = \frac{\overline{k}_{dv}}{\beta} \cdot \sqrt{\frac{4}{\pi} \cdot \ln\left(\frac{1}{1 - P(k_{dv})}\right)} \,, \qquad (2.4)$$

where $\overline{k}_{\text{dv}}$ is the mathematical expectation;

β is the distribution coefficient, for freight wagons β = 1.15;

$P(k_{dv})$ is the probability of the coefficient of vertical dynamics, $P(k_{dv}) = 0.97$.

$$\overline{k}_{dv} = a + 3{,}6 \cdot 10^{-4} \cdot b \cdot \frac{V - 15}{f_{\text{st}}} \,, \qquad (2.5)$$

where a is the dimensionless coefficient depending on the type of an assembly, $a = 0.05$;

b is the axiality factor, calculated by the formula:

$$b = \frac{n' + 2}{2 \cdot n'} \,, \qquad (2.6)$$

where n' is the number of axles in the bogie or in a group of bogies under one end of the wagon, $n = 2$;

V is the design speed, $V = 33$ m/s;

f_{st} is the static deflection of the spring suspension, $f_{st} = 0.45$ m.

The centrifugal force is calculated by the formula:

$$H_c = P_{br}^b \cdot \eta \,, \qquad (2.7)$$

where η is the coefficient for freight wagons, $\eta = 0.075$.

Lateral loading

The wind load is determined as:

$$H_w = \omega_w \cdot F_s, \tag{2.8}$$

where ω_w is the specific wind pressure, ω_w = 0.5 kN/m^2;

F_s is the side projection area of the loaded body.

The lateral forces of dynamic interaction between the wagon and the track (frame force) are determined as:

$$H_p = \overline{H}_p \cdot \sqrt{\frac{4}{\pi} \cdot \ln\left(\frac{1}{1\text{-P}(\text{H}_\text{p})}\right)}, \tag{2.9}$$

where $\overline{H}_p$ is the mathematical expectation of the frame force;

$P(H_p)$ is the frame force probability, $P(H_p)$ = 0.97.

Then, the mathematical expectation of the frame force is equal to:

$$\overline{H}_\text{p} = q_0 \cdot b \cdot \sigma \cdot (5 + V), \tag{2.10}$$

where σ is the coefficient depending on the type of running gears, σ = 0.003;

q_0 is the axial load.

The inertial loads are calculated as:

$$N_i^{\text{куз}} = N \cdot \frac{m}{M_\text{br}}, \tag{2.11}$$

where N is the normalized longitudinal load applied to the coupler;

M_{br} is the gross weight of the wagon;

m is the body weight.

The vertical force caused by lateral forces is calculated as:

$$P_v^s = \frac{H_c \cdot h_\text{c} + H_w \cdot h_\text{w}}{m' \cdot b'}, \tag{2.12}$$

where H_c, H_w are the centrifugal load and the wind load, respectively;

h_c, h_w are the vertical distances from the point of force application to the point of additional loading/unloading;

m' is the number of similar concurrent assemblies;

b' is the horizontal distance between the points of additional loading/unloading.

The vertical force applied to the draft lugs is determined by:

$$P_{\text{v}}^{\text{y.a.}} = \pm N \cdot \frac{l}{2a}, \tag{2.13}$$

where N is the normalized longitudinal force;

l is the difference in the axle levels over the couplers;

a is the design body length of the coupler (if compressed a = 1 m, if extended a = 0.9 m).

The lateral forces acting on the wagon through the automatic coupler are

– when braking:

$$P_N = N \cdot \left(\frac{\delta \cdot L}{l_{\text{s}}^2} \cdot \left(1 + \frac{L}{a} \right) \cdot \frac{L_C}{R} \right) \cdot \frac{l_s}{L}, \tag{2.14}$$

where N is the normalized longitudinal force;

δ is the potential unilateral displacement of the bolster section of the body due to the gaps between the wagon elements;

L is half the distance between the rear draft lug surfaces;

L_C is half the length of the wagon over the couplers;

l_s is half the wagon base;

R is the design curve radius.

<u>Longitudinal loading</u>

Longitudinal loads are tensile and compressive forces (quasi-static and dynamic) arising from the interaction of wagons and from the interaction of a wagon and the locomotive at various operating and shunting modes, as well as the inertia forces perceived by the wagon units.

The tensile and compressive forces are applied to the front and rear draft lugs. For design modes their values are taken as normative and given in Table 2.1.

Table 2.1 – Longitudinal forces on a flat wagon in operation

Longitudinal force, MN			
Design modes			
I		III	
Quasi-static force	Impact, jerk	Quasi-static force	Impact, jerk
−2.5 +2.0	−3.5 +2.5	−1.0 +1.0	−1.0 +1.0

The '+' sign indicates tension and jerk, while the '−' sign indicates compression and impact. The time of impulse forces (impact, jerk) is taken 0.3 sec.

The following diagrams of longitudinal forces are considered:

– quasi-static tension or compression applied to the draft lugs on both wagon ends; and

– impact or jerk forces applied to the draft lugs on one end of the wagon and balanced by the inertia forces of the wagon masses.

2.2 Stress-strain state of the bearing structure of a flat wagon

The first stage of the study into improvements of an existing flat wagon included the strength calculation of its bearing structure. A flat wagon mod. 13-401 was chosen as a prototype.

The stress-strain state of the bearing structure of the flat wagon was investigated by means of its spatial model built in SolidWorks (Figure 2.1) [7, 18–20].

The finite element model (FEM) of the flat wagon is shown in Figure 2.2. The optimal number of mesh elements was determined using the graphical analytical method. Thus, the number of mesh elements is 368,732, and the nodes – 14,938. The maximum size of the mesh element is 235.62 mm, and the minimum is 47.12 mm, the maximum aspect ratio of the elements is 332, the percentage of elements with a side ratio of less than three is 24.6, more than ten – 31.5.

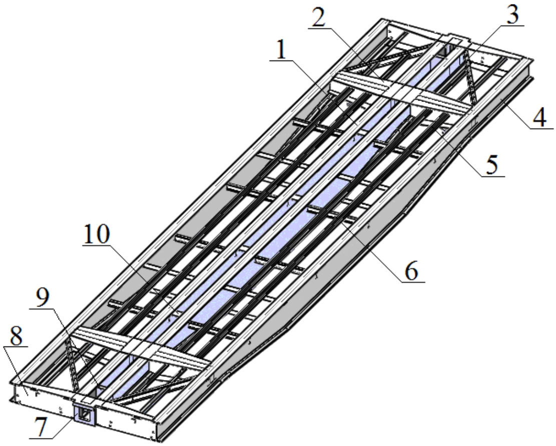


Figure 2.1 – Spatial model of the flat wagon
1 – centre sill; 2 – bolster beam; 3 – brace; 4 – main longitudinal beam; 5 – intermediate longitudinal beam; 6 – cross bearer; 7 – striker and front draft lug; 8 – front plate; 9 – rear draft lug; 10 – diaphragm

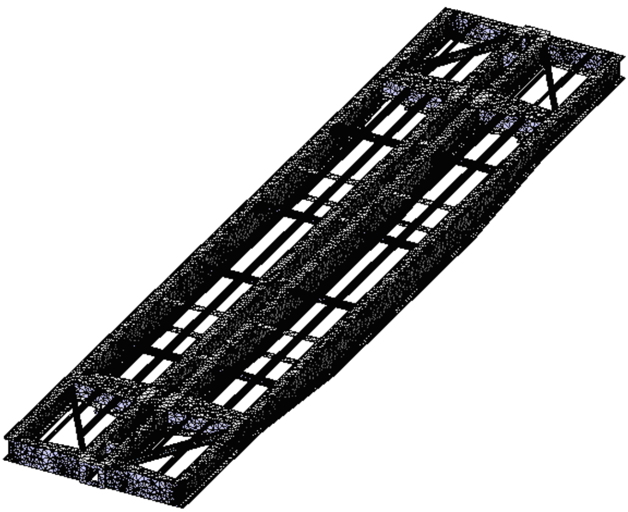


Figure 2.2 – FEM of the flat wagon

The design diagram of the bearing structure of a flat wagon at design mode I is shown in Figure 2.3.

The model's limitations are the lack of difference in the levels of couplers interacting with each other. The model is secured to the centre plates and side bearings of the bolster beams of the bearing structure of the flat wagon.

The strength of the loaded flat wagon at the impact/compression mode was studied when the longitudinal force was applied to the rear draft lug of the coupler. When modelling the strength of the flat wagon at the torsion/jerk mode, the longitudinal force was applied to the front draft lugs on one end of the flat wagon.

The results of the strength calculation for the bearing structure of the flat wagon at design mode I (impact) are shown in Figure 2.4.

The maximum equivalent stresses occur in the lower area of interaction between the bolster beam and the centre sill and amount to about 306 MPa, which is lower than permissible values [20, 21]. The maximum displacements in the structural units are in the middle of the frame and are 7.6 mm, the maximum deformations are $2.4 \cdot 10^{-3}$.

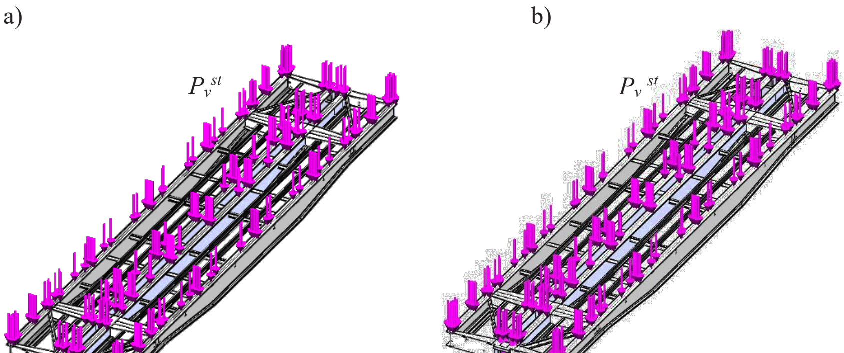
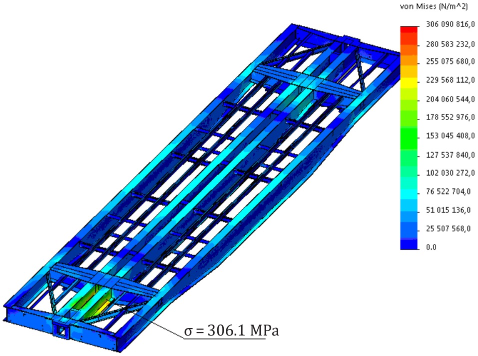


Figure 2.3 – Design diagram of the bearing structure of the flat wagon at design mode I

a) impact/compression; b) tension/jerk

P_v^{st} is the vertical static force; P_l is the longitudinal force

a)



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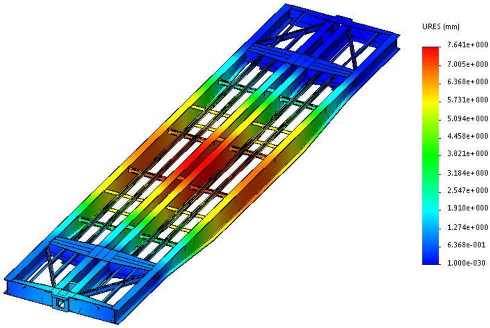

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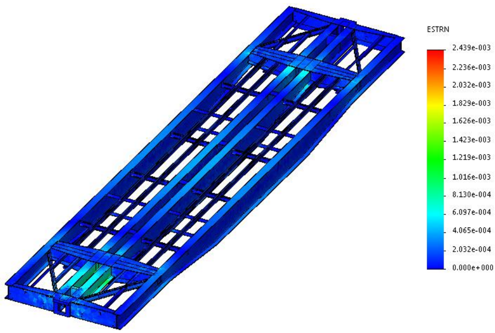


Figure 2.4 – Results of the strength calculation of the bearing structure of the flat wagon at design mode I (impact)
a) stress state; b) displacements in structural units;
c) deformations

The results of the strength calculation for the bearing structure at design mode I (jerk) are shown in Figure 2.5.

The maximum equivalent stresses occur in the lower area of interaction between the bolster beam and the centre sill and amount to about 242.8 MPa; the maximum displacements in the structural units are 7.6 mm, the maximum deformations are $2.4 \cdot 10^{-3}$.

The design diagram of the bearing structure of the flat wagon at design mode III are shown in Figure 2.6.

The results of the strength calculation of the bearing structure of the flat wagon at design mode III (impact) are shown in Figure 2.7. The lateral loads acting on the flat wagon in operation are considered as transverse reactions in the centre plate arrangements. The vertical dynamic force acting on the bearing structure of the flat wagon when moving on the rail track is taken into account in quasi-statistics.

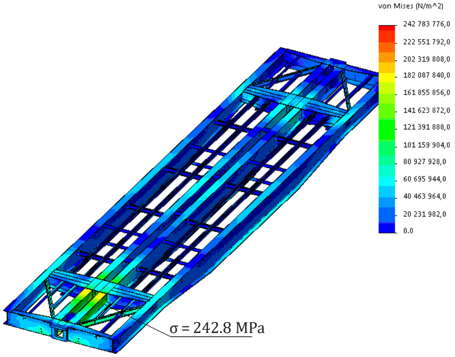
Thus, the maximum equivalent stresses are about 224 MPa, the maximum displacements in the structural units are 78.2 mm, and the maximum deformations are $3.3 \cdot 10^{-3}$.

The results of the strength calculation of the bearing structure of the flat wagon in design mode III (impact) are shown in Figure 2.8.

Thus, the maximum equivalent stresses are about 230.8 MPa, the maximum displacements in the structural units are 6.8 mm, and the maximum deformations are $5.67 \cdot 10^{-3}$.

The results demonstrate that the maximum equivalent stresses in the bearing structure of the flat wagon occur at design mode I (impact/compression). Regarding the frame components, the maximum equivalent stresses are lower than permissible ones and have a sufficient safety factor [20, 21], which makes it possible to increase the operational efficiency of international transport corridors.

a)



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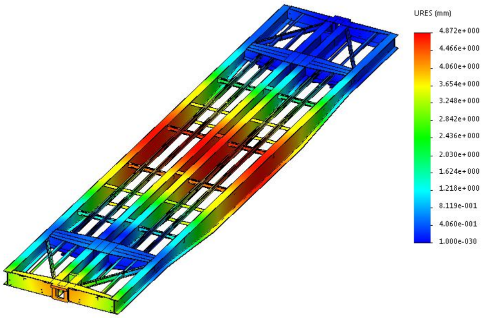

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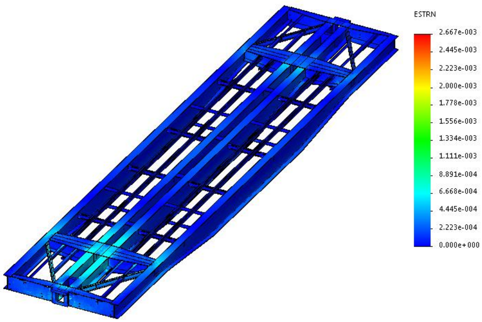
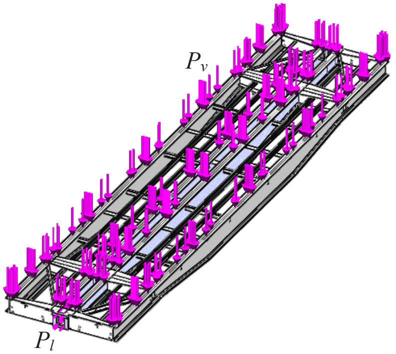


Figure 2.5 – Results of the strength calculation of the bearing structure of the flat wagon at design mode I (jerk)
a) stress state; b) displacements in the structural units; c) deformations

a)



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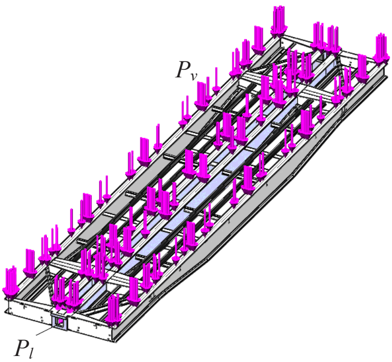

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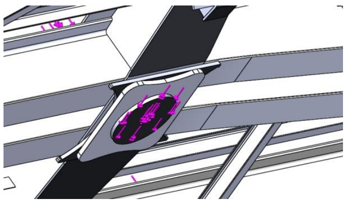


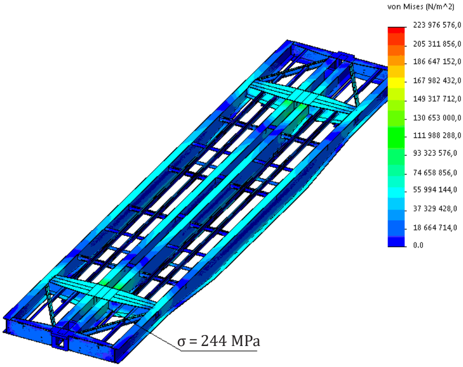
Figure 2.6 – Design diagram of the bearing structure of the flat wagon at design mode III

a) impact/compression; b) tension/jerk; c) transverse force on the centre plate

P_v is the vertical force (static and dynamic);

P_l is the longitudinal force

a)



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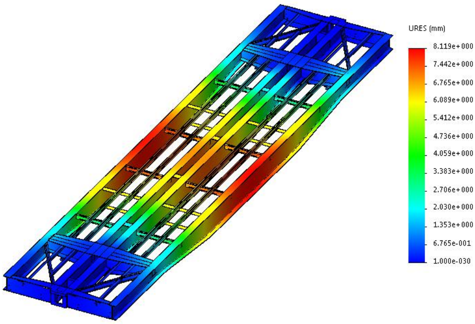

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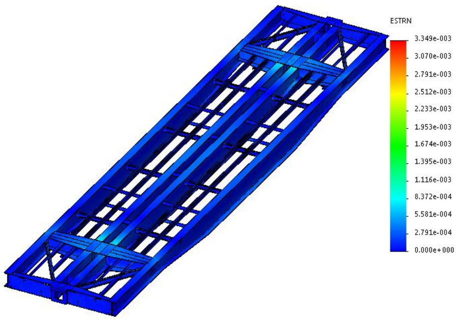

Figure 2.7 – Strength calculation of the bearing structure of the flat wagon at design mode III (impact)
a) stress state; b) displacements in the structural units; c) deformations

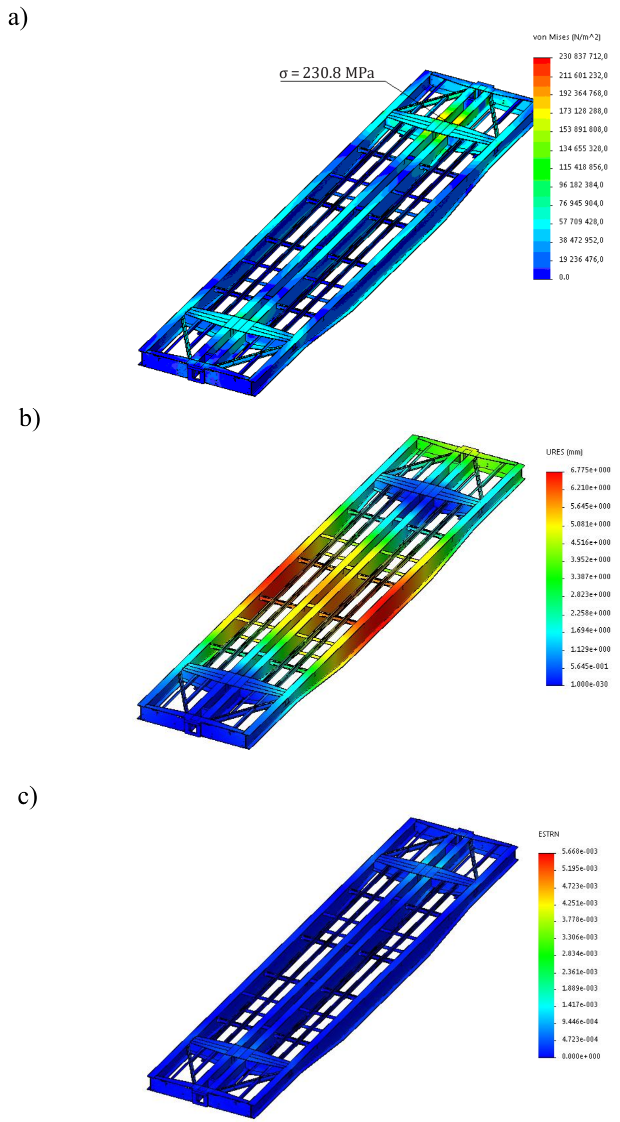

Figure 2.8 – Strength calculation of the bearing structure of the flat wagon mod. 13-401 at design mode III (jerk)
a) stress state; b) displacements in the structural units; c) deformations

Conclusions to Part 2

1. The analysis of forces acting on the bearing structure of the flat wagon in operation is carried out; the method applied is also given. It is also used for determining the forces acting on the bearing structure of a flat wagon mod. 13-401 manufactured by the Dnipro VahonMash company (Ukraine) for calculating the main strength characteristics of the flat wagon.

2. The stress-strain state of the bearing structure of the flat wagon is investigated. The calculation is carried out in SolidWorks Simulation using the finite element method. The main strength indicators of the bearing structure of the flat wagon are determined. It is found that the maximum equivalent stresses occur at design mode I (impact); they are close to the yield strength of the structural material of the flat wagon, however do not exceed the permissible values. The maximum equivalent stresses are concentrated in the interaction areas between the centre sill and the bolster beams.

The calculation is also carried out for other design loading diagrams.