Determination of the strength of the containers fittings of a flat wagon loaded with containers during shunting

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Abstract. The article presents the results of the dynamic loading and strength study of the fittings for containers of a flat wagon loaded with containers during shunting. It has been found that with impact interaction of corner castings with fittings, there are increased stresses, both in structural components of a flat wagon and in containers. To provide the strength of the fittings of a flat wagon and corner castings of containers, it has been proposed to install elastic-viscous linkage between them. This solution is implemented by installing elements having appropriate properties in the corner castings. Mathematical modeling has been performed to determine the dynamic loading of the flat wagon and containers. The obtained values of dynamic loads were taken into account when determining of the strength indexes. It has been established that, the maximum equivalent stresses in the fittings and corner castings are within acceptable parameters taking into account the proposed solutions. The studies will contribute to provide the strength of the structural components of flat cars and containers during shunting, to reduce the cost of their unscheduled repairs, as well as to create recommendations for design of rolling stock with improved technical and economic indexes.

1. Introduction

The creation of foreign economic relations between the Eurasian states determined putting into operation of intermodal transport systems. At present container transportation is one of the most common transportations, owing to containers intermodality as vehicles.

Containers are transported by flat wagons equipped with fittings for container with respect by main tracks. The study of regulatory documents standardizing the containers dynamic loading in operation allows for the conclusion that one of the most loaded modes is a shunting collision of a flat wagon with containers placed on it. In this case, both the corner castings damage and the flat wagon container fittings damage may occur (fig. 1).

To improve the efficiency of container transportation and reduce the cost of unscheduled flat wagons and containers repair types, at the current stage of the transport industry development it is important to introduce new alternative solutions for the design features of vehicles, their interaction patterns, and so on [1-3].
2. Analysis of recent research
Requirements for the supporting structures of modern rolling stock, in particular freight wagons, are described in a paper [4]. These requirements are proposed to be applied at the stage of new wagons designs manufacturing, as well as those ones that are untitled to modernization.

![Figure 1](image1.png)

**Figure 1.** Damage to corner castings and container fittings: a) corner casting misalignment; b) container post break; c) cracks in the container fitting; d) damage to the fastening element of the container fitting to the frame.

However, attention to the issue of the wagons dynamic loading studying during shunting is not paid.

Features of pressure sintering of materials with alternating current are given in a paper [5]. It is found that the materials after this procedure have increased hardness and some elasticity. Prospects for the use of this nanomaterial in wagons designs to reduce their dynamic loading in operation are not described in a paper.

Determination of the dynamic loading of flat wagons loaded with containers during shunting is carried out in an article [6]. The results obtained by mathematical modeling are proved by computer simulation. It has been found that there are increased values of dynamic loads of supporting structures when moving the casting corners relative to the container fittings of flat wagons.

It is important to note that measures to reduce the dynamic loading of flat wagons and containers during a shunting collision have been not proposed in the paper.

Features of mathematical modeling of spatial oscillations of the subframe – track system are described in an article [7]. The calculation is carried out using the finite element method in the Ansys software. Measures to improve the rolling stock design to reduce the dynamic load in operation are not given in the paper.

The dynamic loading study of the wagon body bearing structure during its transportation by a railway ferry is carried out in papers [8, 9]. The results of mathematical modeling are confirmed by computer simulation.

The issues of wagons supporting structures improving to reduce the dynamic loading during shunting are not considered in the articles.
Possible versions of improving the rolling stock technical and economic indexes are considered in a paper [10]. In this case, the paper does not describe possible measures to reduce wagons dynamic loading.

The analysis of innovative rolling stock designs constructed by "Uralvagonzavod" (Russia) for 1520 mm gauge is described in a paper [11]. Issues for the rolling stock and its components modernization to improve operating efficiency are considered. Measures to reduce the dynamic loading of the wagons bearing structures during a shunting collision are not considered.

The analysis of the BCNHL freight wagons designs is carried out in a paper [12]. Possible ways of improving the technical and economic indicators of wagons to improve the efficiency of their operation are determined.

The results of the freight wagon structural-elemental analysis are described in a paper [13]. The calculation has been carried out using the finite element method. Studies have been conducted on the example of an open wagon type "BOXN25", which is operated on the Indian railway. Determination of wagons dynamic loading and measures of its reduce during a shunting collision is not carried out in these works.

3. The purpose and tasks of the study

The purpose of the article is to determine the strength of the container fittings of a flat wagon loaded with containers during shunting. To achieve this goal, the following tasks are defined:

1. To investigate the flat wagon dynamic loading taking into account the improved interaction scheme of container fittings with corner castings by means of mathematical modeling;
2. To investigate the flat wagon dynamic loading taking into account the improved interaction scheme of container fittings with corner castings by using computer simulation;
3. To calculate the strength of the flat wagon, taking into account the improved interaction scheme of container fittings with corner castings.

4. The main part of the study

To reduce the dynamic loading of the flat wagon loaded with containers during a shunting collision, in the case when there is a shock interaction of fittings with corner castings, it is proposed to place elastic, viscous or elastic-viscous couplings in the corner castings. Modeling of the container dynamic loading, taking into account the presence of elastic couplings in the corner castings, made it possible to conclude that this solution does not fully compensate for the container dynamic loading.

With a viscous and elastic-viscous coupling, the maximum accelerations acting on the container during flat wagon shunting do not exceed the permissible ones.

To determine the flat wagon dynamic loading during a shunting collision, taking into account the presence of a viscous linkage between the fittings and corner castings, a mathematical model (1) has been compiled.

\[
\begin{align*}
M_{fw} \ddot{q}_1 &= P_{imp} - \sum_{i=1}^{n} (F_{fr} \cdot \text{sign}(\dot{q}_i - \dot{q}_e) + \beta_f (\dot{q}_i - \dot{q}_e)), \\
M_c \dot{q}_2 &= (F_{fr} \cdot \text{sign}(\dot{q}_i - \dot{q}_e) + \beta_f (\dot{q}_i - \dot{q}_e)),
\end{align*}
\]

where \(M_{fw}\) – is the flat wagon gross mass; \(P_{imp}\) – is the value of the longitudinal force acting on the automatic coupling; \(n\) – is the number of containers placed on the flat wagon; \(F_{fr}\) – is a friction force between container fittings and corner castings; \(M_c\) – is a container weight; \(\beta_f\) – is a coefficient of viscous resistance in the corner castings; \(\dot{q}_i, \dot{q}_e\) – are coordinates that determine displacements, respectively, of the flat wagon and the container relative to the longitudinal axis.

The flat wagon model 13-401M has been chosen as the prototype wagon. Studies have been conducted in relation to the container size 1CC.
The forces scheme acting between the flat wagon and the container during a shunting collision taking into account improvement measures is shown in fig. 2.

![Diagram](image)

**Figure 2.** Scheme of the longitudinal forces action on the flat wagon with containers placed on it

- \( P_{\text{imp}} \) – impact force acting on the flat wagon;
- \( P_d \) – dynamic force acting on the container;
- \( P_{\beta} \) – viscous resistance force to the container movement.

When compiling the model, the dry friction force arising when moving the corner castings relative to the horizontal surfaces of the container fittings [14] is taken into account. The study was conducted using plane coordinates.

When compiling the model, it was assumed that the container was loaded with a conditional load using the maximum allowable load capacity.

The solution of the mathematical model (1) has been implemented in the MathCad software [15, 16]. At the same time, it was reduced to the normal form of Cauchy \( \dot{y}(t) = Q(t, y) \) [17, 18]. Where

\[
\begin{align*}
q_i &= y_i; \\
q_2 &= Y_2; \\
q_3 &= y_3; \\
q_4 &= y_4.
\end{align*}
\]

\[
Q(t, y) = \begin{bmatrix}
y_1 \\
y_2 \\
y_3 \\
y_4
\end{bmatrix}
\begin{bmatrix}
P_{\text{imp}} - \sum_{i=1}^{n} (F_{ri} \cdot \text{sign}(q_i - q_{i,\text{sign}}) + \beta_i (q_i - q_{i,\text{sign}})) \\
M_{ri} \\
F_{ri} \cdot \text{sign}(q_i - q_{i,\text{sign}}) + \beta_i (q_i - q_{i,\text{sign}}) \\
M_e
\end{bmatrix}
\]

\[
Z = rkfixed (Y0, tn, tk, n', Q),
\]

where \( Y0 \) – is a vector containing the initial conditions, \( tn, tk \) – are the quantities that define the initial and final integration variables, \( n' \) – is a fixed number of steps, \( Q \) – is a symbol vector.

In this case, the viscous resistance to the movement of the container was taken in the range of \( 10 - 50 \) kNꞏs/m. On the basis of the calculations, accelerations, acting on the flat wagon taking into account the viscous coupling between corner castings and container fittings during a shunting collision, have been obtained (fig. 3). This acceleration value was about \( 40 \) m/s\(^2\) (4g), that is, it does not exceed the standard value [19, 20].

When elastic-viscous interaction of corner castings with container fittings are used, the mathematical model for determining of the flat wagon dynamic loading will be:
\[
M_{f_{w}}^{\text{full}} \ddot{q}_{i} = P_{\text{imp}} - \sum_{i=1}^{n} \left( F_{s_{i}} \cdot \text{sign}(\dot{q}_{i} - \dot{q}_{i}) + C_{c_{i}} (q_{i} - q_{i}) + \beta_{i} (\dot{q}_{i} - \dot{q}_{i}) \right),
\]
\[
M_{c} \ddot{q}_{z} = \left( F_{s_{k}} \cdot \text{sign}(\dot{q}_{k} - \dot{q}_{k}) + C_{c_{k}} (q_{k} - q_{k}) + \beta_{k} (\dot{q}_{k} - \dot{q}_{k}) \right).
\]

where \(C_{c_{i}}\) is the stiffness of the elastic elements in the corner castings.

**Figure 3.** Acceleration acting on a flat wagon with viscous interaction of corner castings with fittings.

Then,

\[
Q(t, y) = \frac{y_{i} \quad y_{a}}{M_{f_{w}}^{\text{full}} \left( F_{s_{k}} \cdot \text{sign}(\dot{q}_{k} - \dot{q}_{k}) + C_{c_{k}} (q_{k} - q_{k}) + \beta_{k} (\dot{q}_{k} - \dot{q}_{k}) \right)}
\]

The calculations results showed that when the elastic element stiffness is 20 kN/m and the viscous resistance coefficient is 30 kN\cdot s/m, the accelerations acting on the flat wagon are about 40 m/s\(^2\) (4g) (fig. 4), and are in limits of allowed values [19, 20].
To study the flat wagon dynamic loading with the elastic-viscous interaction of corner castings with container fittings, computer simulation has been carried out using the finite element method, implemented in the CosmosWorks software [21, 22].

Spatial isoparametric tetrahedras were used as finite elements, the optimal elements number is determined by using the graphic analytical method. The number of mesh nodes is 285189 and the number of elements is 853256. The maximum element size is 100 mm, and the minimum one is 20 mm. The minimum number of elements in a circle is 9, the ratio of increasing the elements size in the mesh is 1.7. The maximum aspect ratio is 306.67, the percentage of elements with an aspect ratio of less than 3 is 29.6 and the percentage of elements with an aspect ratio of more than 10 is 21.2.

The design scheme of a flat wagon with containers during a shunting collision is shown in fig. 5. It is taken into account that a horizontal load $P_h$ is acting on the corner castings, caused by the impact force $P_{imp}$ action on the vertical surface of the rear draft lugs, as well as vertical load $P_v$ is acting in the bearing areas of the corner castings on the container fitting. At the same time, the load effect on container walls is not taken into account. The container was fixed in the areas of its bearing on the flat wagon. It is taken into account that when a horizontal load $P_h$ is applied to corner castings, it is moved relative to the initial position by 30 mm.
When modeling the container dynamic loading, taking into account the presence of viscous coupling in corner castings, the total viscous resistance to displacement of one container was taken to be 50 kN∙s/m. To simulate the viscous coupling in the CosmosWorks software, the spring-damper option has been used. In this case, the stiffness value was set close to zero.

The material of the construction is steel 09G2S with the corresponding values of strength and yield point [19, 20]. The calculation results are shown in fig. 6.

The maximum accelerations acting on the container, taking into account the viscous interaction of corner castings with container fittings, arise in the end walls on the cantilever parts of the flat wagon frame and are about 20 m/s².

The material of the construction is steel 09G2S with the corresponding values of strength and yield point [19, 20]. The calculation results are shown in fig. 6.

In the middle part of the container, the accelerations amounted to almost 15 m/s². The smallest acceleration occurs in the end walls of the container over the center of the flat wagon frame and is about 8 m/s².

The maximum accelerations acting on the flat wagon supporting structure occur in the cantilever parts and are about 38 m/s², and are about 30 m/s² over the bolster cross-sections of the frame. The accelerations are 21.4 m/s² in the middle part of the center girder. The smallest accelerations occur in the middle parts of the main longitudinal beams of the flat wagon frame and are 7.2 m/s².

When modeling the flat wagon with containers dynamic loading, taking into account the presence of elastic-viscous coupling in the corner castings, the stiffness of the elastic element is assumed to be 20 kN/m and the viscous resistance coefficient is assumed to be 30 kN∙s/m.

The calculation results made it possible to conclude that the maximum accelerations acting on the supporting structure of the container located on the flat wagon were 19.7 m/s² and 38.4 m/s², respectively.

Studies made it possible to conclude that the maximum accelerations acting on the container, taking into account the elastic-viscous coupling between the corner castings and the container fittings, do not exceed the allowable ones [19, 20].

In order to verify the developed models, Fisher's criterion has been applied [23]. The calculations showed that the adequacy hypothesis is not rejected.

The obtained accelerations are taken into account in the strength analysis of flat wagon container fittings (fig. 7). It is taken into account that the impact force $P_{imp}$ acts on the flat wagon bearing structure, and the vertical load $P_v$ from containers and the horizontal load $P_h$ caused by the displacement of the corner castings relative to the container fittings act on the container fittings (fig. 8). The strength analysis has been carried out by using the finite element method.

Figure 6. The design scheme of the flat wagon with containers during a shunting collision.
Spatial isoparametric tetrahedras have been used as finite elements. The number of mesh nodes is 311601 and the number of elements is 932166. The maximum element size is 80 mm and the minimum one is 16 mm. The minimum number of elements in a circle is 9, the ratio of the increase in the size of mesh elements is 1.7. The maximum aspect ratio is 470.8, the percentage of elements with an aspect ratio of less than 3 is 41.5, and the percentage of elements with an aspect ratio of more than 10 is 8.17.

The calculation results are shown in fig. 9-13. It has been found that with the viscous interaction of corner castings with fittings during a shunting collision, the maximum equivalent stresses are about 270 MPa (fig. 9, 10) and are concentrated in the zone of interaction between the center girder and the bolster beam. Maximum displacements occur in the middle parts of the main longitudinal beams of the flat wagon frame and are 12.1 mm (fig. 11).
Using elastic-viscous interaction of corner castings with container fittings during flat wagon shunting, the maximum equivalent stresses are about 260 MPa (fig. 12, 13) and are concentrated in the zone of interaction between the center girder and the bolster.

The maximum displacements also occur in the middle parts of the main longitudinal beams of the flat wagon frame and are about 11,0 mm (fig. 14).

The proposed measures to improve the interaction scheme of the flat wagon with containers allow to reduce the maximum equivalent stresses acting in containers fittings almost three times (fig. 15), and in corner castings almost seven times (fig. 16).
Figure 11. Moving in the nodes of the flat wagon bearing structure with the viscous interaction of corner castings with container fittings.

Figure 12. The stressed state of the flat wagon bearing structure with the elastic-viscous interaction of corner castings with container fittings (side view).

Figure 13. The stressed state of the flat wagon bearing structure with the elastic-viscous interaction of corner castings with container fittings (bottom view).
5. Conclusions
Based on the research we can draw the following conclusions:
1 The dynamic loading of the flat wagon has been investigated taking into account the improved scheme of interaction of container fittings with corner castings using mathematical modeling. Mathematical models have been designed taking into account the presence of viscous and elastic-viscous couplings between fittings and corner castings. It has been established that the maximum
accelerations acting on the flat wagon are about 40 m/s² (4g), that is, they are within the allowable range;

2 The dynamic loading of the flat wagon has been investigated taking into account the improved scheme of interaction of container fittings with corner castings by using computer simulation. The finite element method, implemented in the CosmosWorks software, has been used in a calculation. The dislocation areas of accelerations acting on the flat wagon supporting structure with containers placed on it are determined. Verification of the designed models is made by the Fisher method;

3 The flat wagon strength has been calculated taking into account the improved scheme of interaction between container fittings and corner castings. It has been established that in case of viscous interaction of container fittings with corner castings during flat wagon shunting, the maximum equivalent stresses are about 270 MPa and are concentrated in the zone of interaction between the center girder and the bolster beam. Maximum displacements occur in the middle parts of the main longitudinal beams of the flat wagon frame and are 12.1 mm.

When using elastic-viscous interaction of fittings with corner castings during flat wagon shunting, the maximum equivalent stresses are about 260 MPa, the maximum displacements are about 11.0 mm. The research will contribute to improving the efficiency of container transportation, reducing the cost of unscheduled flat wagons and containers repair types, as well as creating recommendations for designing of modern rolling stock.

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