Dynamic load modelling for tank containers with the frame of circle pipes and structurally improved fittings

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Abstract. Higher efficiency of bulked cargo transportation along international transport corridors can be achieved with a resource-saving tank container described in the study. A characteristic feature of a tank container is the use of circle pipes as the carrying elements of the frame. In order to decrease impact loads between fittings of the tank container and fitting stops of the flat wagon at shunting impacts, the authors suggest filling fittings with viscous or viscoelastic materials of dumping or anticorrosive properties. The study also deals with modelling dynamic loading for the suggested tank container. The accelerations obtained were considered in strength calculations for a tank container as components of the dynamic loading. It was determined that the maximum equivalent loads did not exceed the admissible loads. The research will promote designing new-generation tank containers of improved technical, economical and ecological properties, and improve the working efficiency of combined transportation.

1 Introduction

Higher efficiency of bulked cargo transportation along international transport corridors has necessitated introduction of specialized transport means.

At present oil products are transported by tank wagons and tank containers. And it should be mentioned that recent years have witnessed a clear tendency to transfer part of bulked cargo transported from tank wagons to tank containers due to the mobility of the latter. And in recent years transportation of bulked cargo by tank containers is already estimated at the level of 18% annually out of the total bulked cargo turnover and this rate is going to increase.

Therefore, on-time delivery of oil products needs new-generation tank containers. Some characteristic operational features should be taken into account as early as at the designing stage, particularly the structural loading for different means of transport.

One of the most difficult transportation in terms of power load on the carrying structure is transportation of tank containers by rail flat cars. It is taken that at shunting impacts of flat cars loaded with tank containers the rear stop of an automatic coupling is under a force of 3.5 MN [1-3]. It is considered that the tank container sustains an acceleration of 4.0 g. However, with displacements between fitting stops and fittings the acceleration value can considerably increase. It can harm tank containers in operation and require an unscheduled repair. Therefore, while designing tank containers, it is of primary importance to guarantee their constructional adaption to certain operational conditions and compliance with the strength and durability requirements

2 Analysis of recent researches

At present, problems of improved carrying structures of vehicles have been considered by many engineers and designers in Ukraine and other countries. However, a further development of technical, economical and operational characteristics of rail transport means requires an extensive search for new engineering solutions [4-7].

Thus, study [8] deals with transfer of a heat flow through the carrying structure of a container. It describes simulation of a heat flow through the multilayer plastic support.

The results of optimization of the carrying structure of a tank container are given in [9]. The study confirms the need to design and implement tank containers as transport means. An improved tank container for transporting light oils was designed.

Tests on metal and composite containers under low temperatures are described in [10]. The study identifies some types of containers advisable for transporting certain types of cargo with consideration of low ambient temperatures.

It should be mentioned that the studies under examination do not consider problems of designing resource-saving tank containers.

The results of the research into the stressed state of an ISO tank container by the finite element method with

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ABAQUS software suite are given in [11]. The calculation was made under the static loading according to ISO 1496-3. The objective of the calculation was to define deflections of the frame angles and vertical deflections of the reservoir.

An improved structure of the support platform on the tank wagon for fluid cargo is presented in [12]. The strength calculation was made by the finite element method in Lira software.

However, the studies examined do not pose the problem of optimization of the carrying structures of tank containers to minimize the material capacity.

Considering the analysis of literature resources, we can conclude that, by far, the problems of designing resource-saving tank containers are not sufficiently highlighted.

The purpose of the article. The purpose of the article is to highlight characteristics of modelling dynamic loads on tank containers with frame of circular pipes and structurally improved fittings.

3 Results and discussion

In order to decrease the material capacity of a tank container the authors suggest optimization with the minimal material capacity criterion. A TK25 tank container manufactured by VAT Zarechinskiy Plant of Chemical Machine Building (ISO: 1CC) was taken as a basic structure (Fig. 1).
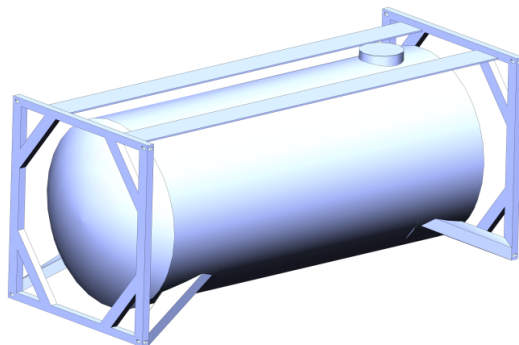

Fig. 1. A 1CC tank container

The tank container consisted of a frame (of rectangular cross-section pipes) and a tank; it was fixed on the flat wagon with corner fittings.

A prospective approach in achieving the objective is implementation of profiles, as the carrying elements of the frame, which provide lower metal structural capacity and meet the strength requirements. An analysis of prospective profiles for car building industry, and the experience gained by other machine building industries confirmed the importance of applying circular section pipes as the carrying frame elements [13].

The authors suggest replacing rectangular pipes for circular pipes as the elements of the carrying structure of a tank container.

The vertical pipe diameter was chosen on the basis of geometrical features of the fitting ($D = 152$ mm). The variation was made by changing the width of the wall S of

the pipe (3 – 5.5 mm). The inner diameter of the pipes changed within a range from 146.5 to 149 mm.

The basic sizes, static characteristics and mass of circular section pipes calculated are given in Table 1.

Table 1. The sizes, static characteristics and mass of a one meter long pipe.

Sizes of a pipe, mm		Cross-section area F, cm^2	Static characteristics for axes x and y		Mass of a one meter long pipe M, kg
Outer diameter, D	Wall width, S		Inertia moment of the section, cm^4	Modulus of section, cm^3	
152	3.0	14.04	389.87	51.30	11.02
	3.2	14.96	414.21	54.50	11.74
	3.5	16.33	450.35	59.26	12.82
	3.8	17.69	486.04	63.95	13.89
	4.0	18.60	509.59	67.05	14.60
	4.5	20.85	567.61	74.69	16.37
	5.0	23.09	624.43	82.16	18.13
	5.5	25.31	680.06	89.48	19.87

In order to optimize the tank container structure, spatial meta-models were built in SolidWorks software [14], the strength calculation was made with the finite element method [15-18]. The results of the research conducted are given in Table 2.

Table 2. The results of the strength calculation for the spatial models

Outer diameter D, mm	Wall width, mm	Stresses, MPa	Mass, kg	Deformations
152	3.0	318.32	1055.61	$1.701 \cdot 10^{-3}$
	3.2	316.466	1061.69	$1.726 \cdot 10^{-3}$
	3.5	315.482	1070.77	$1.758 \cdot 10^{-3}$
	3.8	314.525	1057.39	$1.790 \cdot 10^{-3}$
	4.0	313.639	1063.38	$1.858 \cdot 10^{-3}$
	4.5	311.555	1078.33	$1.927 \cdot 10^{-3}$
	5.0	311.664	1093.17	$1.948 \cdot 10^{-3}$
	5.5	310.8	1093.17	$1.983 \cdot 10^{-3}$
	5.5[1]	316.374	1075.17	$1.868 \cdot 10^{-3}$

[1] it is taken that the pipe has cross section along the whole vertical post for the tank container

To obtain the optimal frame structure (optimal structural geometric parameters of pipe sections to be used), the optimization research was made in the

following order: it was determined that optimization be made by the minimal material capacity criterion (*m*) with meeting the strength requirements (without exceeding the admissible stress values *σ*); on the basis of structural features, the limits at which variable values could change, i.e. the outer diameter of the pipe (*D*) and the wall width (*S*) were determined; it was determined that mathematical models of parametric variations (*m*, *σ*, *l*) were described with two-factor generalized mathematical models which were defined through nine experiments based on the corresponding spatial computer models; and the mathematical models were determined, on the basis of which an additional schedule was built and optimal geometrical parameters of pipes were defined.

At the first stage, the decision was taken to use a circular pipe along the whole height of the vertical post of the tank container. The results of the strength calculation demonstrated that stresses in the contact area between the support and the vertical post did not exceed the admissible values for the steel grade of the metal structure of the tank container. Therefore, while building a spatial computer model of the tank container it was considered that the vertical post of circular section was located on the special superstructure (Fig. 2) in the form of a truncated pyramid. In order to decrease the impact loads between the fittings of the container and the fitting stops of the flat wagon under shunting impacts, when the impact loads exceeded the friction force between the horizontal planes of the fittings and fitting stops, the authors filled the fitting stops with elastic (Fig. 3, a) or viscoelastic (Fig. 3, b) materials of dumping or anti-corrosion properties.
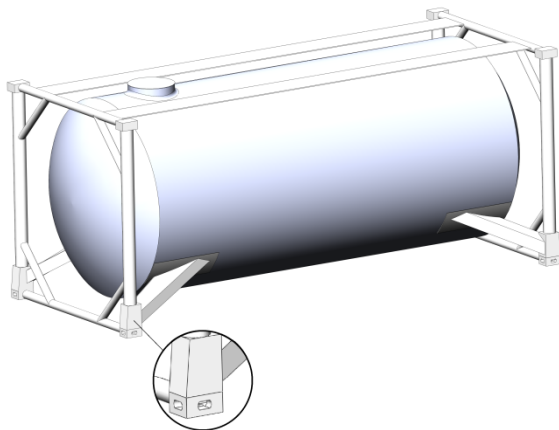

Fig. 2. The spatial model of an improved tank container.

Using the factor values obtained (*m*, *σ*, *l*), the authors approximated them in the form of second-order polynomials:

$$Y = f(x_{t_1}, x_{t_2}, x_{t_3}, x_{t_a}) = a_0 + a_1 x_{t_1} + a_2 x_{t_2} + a_3 x_{t_3} + a_4 x_{t_a} + a_{11} x_{t_1}^2 + a_{11} x_{t_1}^2 + a_{22} x_{t_2}^2 + a_{33} x_{t_3}^2 + a_{44} x_{t_a}^2 + a_{12} x_{t_1} x_{t_2} + a_{13} x_{t_1} x_{t_3} + a_{14} x_{t_1} x_{t_a} + a_{23} x_{t_2} x_{t_3} + a_{24} x_{t_2} x_{t_a} + a_{34} x_{t_3} x_{t_a},$$
(1)

where Y – the controlled value, x_{t_a} – the control parameters, a_i – the coefficients of a generalized mathematical model, the numeric values of which were defined through solving an equation system with the data obtained.

Generalized mathematical models and an additional schedule for the optimal pipe parameters of the tank container's frame were developed in a software suite.

The generalized mathematical models obtained have the following form:

$$m = -70130 + 924.3D + 542.416S - 3D^2 + 2.048S^2 - 3.6DS,$$
(2)

$$s = 22383.3 - 286.18D - 181.77S + 0.928858D^2 + 1.1853S^2 + 1.1146DS,$$
(3)

$$l = -0.4537 + 0.00591D + 0.0038S - 1.916D^2 - 0.000023S^2 - 0.00002DS,$$
(4)

where D – the outer diameter of the pipe, mm, S – the pipe wall width, mm, m – the structure mass, kg, l – the deformations in the structure, σ – the stresses in the structure, MPa.
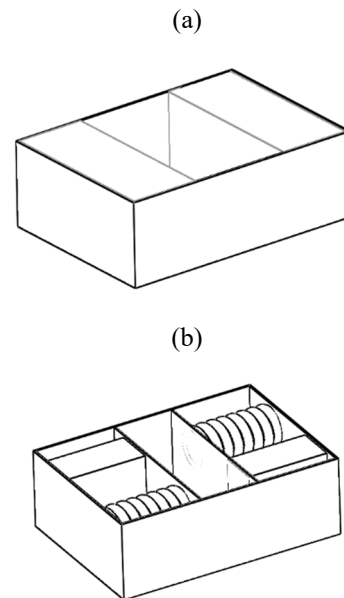
(a)

(b)

Fig. 3. The fittings of the tank container: (a) with viscous linkage, (b) with viscoelastic linkage.

The mathematic model verification (2 – 4) was made by the mean square error value [19, 20]:

$$\sigma = \sqrt{\frac{\sum_{j=1}^{m-k}(Y_j - Y_{jp})^2}{m-k}},$$
(5)

where k – the number of coefficients a_i of the generalized mathematical model; m – the number of mathematic modes.

The calculations conducted confirmed the efficiency of the generalized mathematical models obtained [21-23]. And the mean square error value did not exceed 3%.

In order to decrease the impact loads between fittings of the container and fitting stops of the flat wagon under shunting impacts, when the dynamic load P_d exceeds the friction force F_{FR} between horizontal planes of fittings and fitting stops, the authors suggest installing viscous or viscoelastic elements in the fittings of the container.

In order to define the dynamic loading of the container in shunting impacts considering the improvements, a mathematical model (6) was built; the model took into account displacements of the container placed on the flat wagon.

$$\begin{cases} M_{FC}^{gw} \cdot \ddot{q}_1 = P_l - \sum_{i=1}^{n} \left(F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2) + \beta_v (\dot{q}_1 - \dot{q}_2) \right), \\ M_C \cdot \ddot{q}_2 = \sum_{i=1}^{n} (F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2) + \beta_v (\dot{q}_1 - \dot{q}_2) + \\ + M_M \cdot l \cdot q_3), \\ I_m \cdot \ddot{q}_3 = M_M \cdot l \cdot \ddot{q}_2 - g \cdot M_M \cdot l \cdot q_3, \end{cases} \quad (6)$$

where M_{FC}^{gw} – the gross weight of a flat wagon; P_l – the value of longitudinal force on the automatic coupling; F_{FR} – the friction force between fitting stops and fittings; M_C – the tank container mass; β_v – the viscous resistance coefficient in the container's fittings; M_M – the mass of the pendulum imitating displacements of bulked cargo in the tank container; l – the length of the pendulum suspension; I_m – the inertia moment of the pendulum; q_1, q_2, q_3 – the coordinates indicating displacements of flat wagon, tank container and bulked cargo, respectively, relative to the longitudinal axis.

At the given viscous resistance in the container's fittings, the acceleration was approximately 40 m/sec^2 (≈ 4 g) and did not exceed the normalized value [24].

Besides, the total viscous resistance to displacements of one tank container should be within a range from 9 to 54 kN·sec/m.

At viscoelastic linkage between fittings and fitting stops, the mathematical model has the form:

$$\begin{cases} M_{FC}^{gw} \cdot \ddot{q}_1 = P_l - \sum_{i=1}^{n} (F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2) + C_v(q_1 - q_2) + \\ + \beta_v(\dot{q}_1 - \dot{q}_2), \\ M_C \cdot \ddot{q}_2 = \sum_{i=1}^{n} (F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2) + C_v(q_1 - q_2) + \\ + \beta_v(\dot{q}_1 - \dot{q}_2) + M_M \cdot l \cdot q_3), \\ I_m \cdot \ddot{q}_3 = M_M \cdot l \cdot \ddot{q}_2 - g \cdot M_M \cdot l \cdot q_3, \end{cases} \quad (7)$$

where C_v – the rigidity of the elastic elements in the tank container's fittings.

The rigidity of an elastic element was taken 480 kN/m, and the viscous resistance coefficient – 30 kN·sec/m. The maximum acceleration was about 40 m/sec^2 (≈ 4 g) and did not exceed the normalized value.

The acceleration values obtained were considered in strength calculations for the tank container.

The strength calculation was made with the finite element method in SolidWorks software suite [25-27]. When designing the finite element model of the tank container, isoparametrical tetrahedrons were used; the optimal number of them was determined with the grapho-analytical method.

The basic characteristics of the finite-element model for the optimized tank container are given in Table 3.

Table 3. The basic characteristics of the finite-element method of the optimized tank container

Parameter	Value
The number of Jacobian points	4
The number of units	376555
The number of elements	1162350
The maximum size of an element, mm	20
The minimum size of an element, mm	4
The minimum number of elements in a circle	10
Ratio of an element size expansion	1.7
Maximum side ratio	177.52
Percent of elements with a side ratio less than 3	36.7
Percent of elements with a side ratio more than 10	0.939

While designing the strength model for the tank container, it was considered that the structure was effected by vertical static loads P_v^{st}, pressure of bulked cargo P_p, longitudinal pressure on the bottom P_l, horizontal pressure on the fitting stop P_{hp} conditioned by the force P_n, and vertical load on the fitting P_v conditioned by P_v^{st} (Fig. 4).
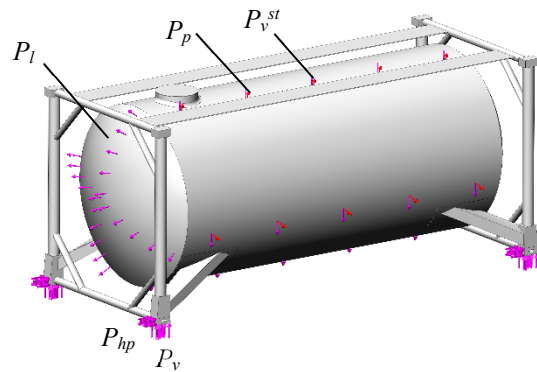

Fig. 4. The design diagram of the tank container.

The tank container was fixed in the areas where the flat wagon rested on fitting stops. The 09G2C steel was used as a construction material.

The maximum equivalent stresses were 294.1 MPa (Fig. 5, 6). The maximum displacements were concentrated in the area of the access door and accounted for 7.24 mm (Fig. 7, 8), the maximum deformations were 2.79·10^{-3} (Fig. 9, 10).
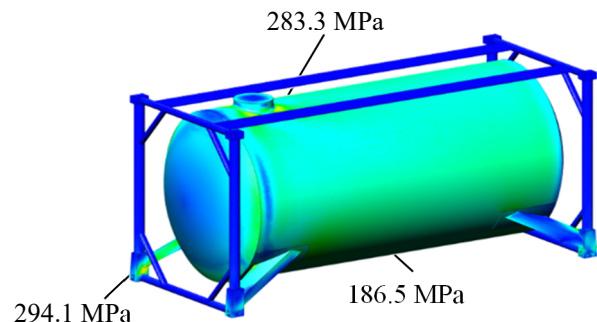

Fig. 5. Stressed state of the tank container.

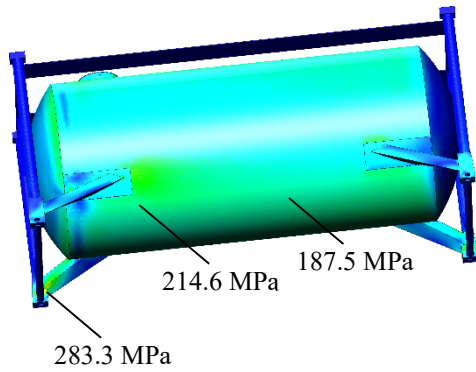Thus, the research conducted confirmed the efficiency of decisions taken during designing the tank container.

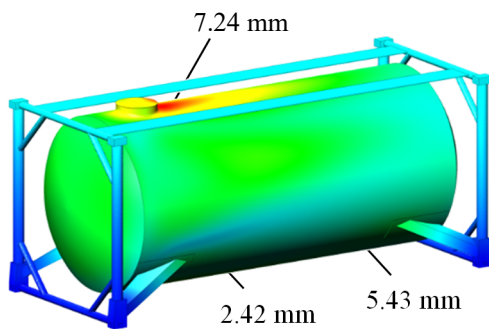**Fig. 6.** Stressed state of the tank container (bottom view).

Fig. 7. Displacements in the tank container.
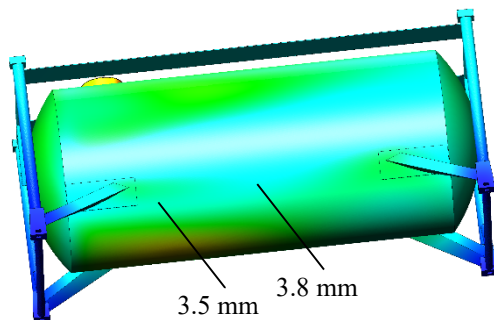

Fig. 8. Displacements in the tank container (bottom view).
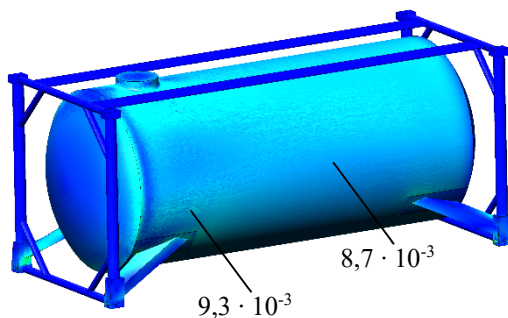

Fig. 9. The deformations in the tank container.

4 Conclusions

The following conclusions can be made on the basis of the research:

1. The carrying structure of the tank container was optimized with circular pipes for the frame. The vertical post of the frame was located on the special superstructure in the form of a truncated pyramid. It was determined that the mass of the optimized frame was less than that of a typical one by about 20%;

2. In order to decrease the impact loads between the fittings of the container and fitting stops of the flat wagon under shunting impacts, when the impact loads exceeded the friction force between the horizontal planes of fittings and fitting stops, the authors suggested filling fitting stops with elastic or viscoelastic materials of dumping or anti-corrosion properties.
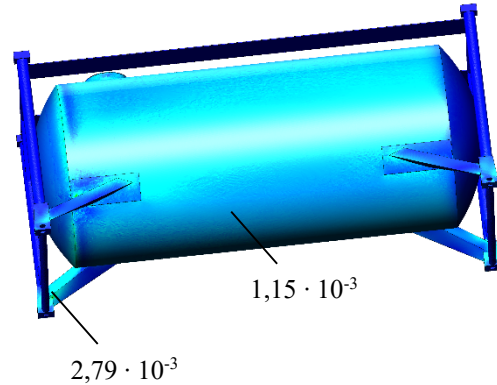

Fig. 10. The deformations in the tank container (bottom view).

The optimized structure of the tank container was calculated for strength. The maximum equivalent stresses were 294.1 MPa. The maximum displacements were concentrated in the area of an access door and accounted for 7.24 mm, the maximum deformations were $2.79 \cdot 10^{-3}$. The research conducted will promote designing new-generation tank containers, thus improving the efficiency of rail transportation along international transport corridors.

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