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Structural Improvements in a Tank Wagon with Modern Software Packages

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Abstract

For transportation of dangerous goods rail transport uses tank wagons. Structural changes can contribute to reduction in the maximum stresses, and as a result, to improvement in technical and economic characteristics of a tank wagon. In order to investigate the stress-strain state of a tank wagon the finite element model was built, its adequacy having been checked by results of analytical calculations and experiments. It has been applied for numerous researches to find the most effective bracket support structure by comparing it to the existing structure. The laws of stiffness change in radial direction and the laws of contact pressure change have been demonstrated. The improved structure has been checked by a load spectrum according to normative documents.

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Keywords: tank wagon, barrel, finite element method, support structure, stress-strain state, equivalent stresses, contact pressure

1. Introduction

Dangerous goods are transported in tank wagons which provide safe and high-quality delivery of petroleum products to customers [1, 2]. Operational environment of transport modes requires high standards in capacity of

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existing and new tank wagon structures. The forecasting and elimination of vulnerable zones and a longer life cycle of tank wagons should take into account new achievements in capacity, reliability and durability researches [3, 4].

The researches provided by leading companies in the field of rolling stock testify that stresses exerted by support pressure amount to 70–90% out of the maximum stresses in the tank of tank wagons [5–7]. The observations have shown that cracks on the surface of liquid tanks in support areas begin to intensively appear after 10–12 years of operation [8, 9]. Typically, the cracks are of fatigue nature.

At present the wagon structure has taken full advantage of width and height, therefore a further increase in body space is only possible due to extension that results in increased tare weight and decreased carrying capacity at the same axial loads.

$$P \leq q_o m_o - T , \tag{1}$$

where P is the wagon carrying capacity; q_o is the admissible axial load of the wagon; m_o is the number of wagon axles, T is the tare weight.

As $q_o m_o$ can not exceed its maximum value, a further increase in carrying capacity is only possible due to a lower tare weight.

Structural changes aimed at re-distribution of loads and stresses in vulnerable zones can contribute to reduction in the maximum stresses and, as a result, to improvement of technical and economic characteristics of a tank wagon.

2. Development of the computational finite element model of a tank wagon

Nowadays the finite element method is one of the most efficient multiple methods of research into capacity and stress-strain behaviour of tank wagons [10, 11]. A computational finite element model was developed for investigation into stress-strain state of tank wagons. The tank was built by rotating a generatrix around the axle through the centers of heads. The tank hatch is a cylindrical surface and the hatch cover is a circular plate. An outlet for the drainage device is built by rotating the generatrix around the axle through the tank centre in vertical plane. To calculate hollow cases one can use a number of simple lamellar quadrangle finite elements. Yet these elements cannot be used to describe the geometry of compound profile structures, so triangular elements are used. Application of triangular elements makes it possible to clearly describe the geometry of a compound profile structure. Therefore, to build a computational model it is necessary to use triangular finite elements in the tops of heads and hatch covers, in places where the hatch and outlet for drainage device join with the tank shell. For every basic frame element one can notice that the thickness of an element is much smaller than its basic dimensions, thus it is reasonable to design the frame's supporting parts with flat finite elements. Thus, each beam of the frame, bracket support and middle mounting foot are made of sheets the thickness of which correspond to the dimensions of the elements. The wooden beams of the bracket supports are presented as octagonal three-dimensional elements. In places where the compound frame elements cross and join, triangle finite elements are used. In places where the tank rests on the wooden beams binodal finite elements were introduced, namely, a one-sided linear connection for simulating free movement of the tank relative to the beams in the plane perpendicular to the generatrix and a one-sided frictional element for sliding the tank along the generatrix. Furthermore, in the place where surfaces touch and friction appears the union of movements is applied for all nodes in pairs in all directions except the direction of sliding. By the finite element method the computational diagram was obtained by dividing the model into three-dimensional eight-nodal lamellar quadrangular and triangular finite elements [12]. This division generated 86174 elements and 82479 nodes (Fig. 1).

LIRA software was used for calculation by static and impact loads.

In order to check the adequacy of the method the calculation results were compared to analytical and experimental data [13, 14]. The inaccuracy of the results obtained for the model and experimental results does not exceed 10–12%.

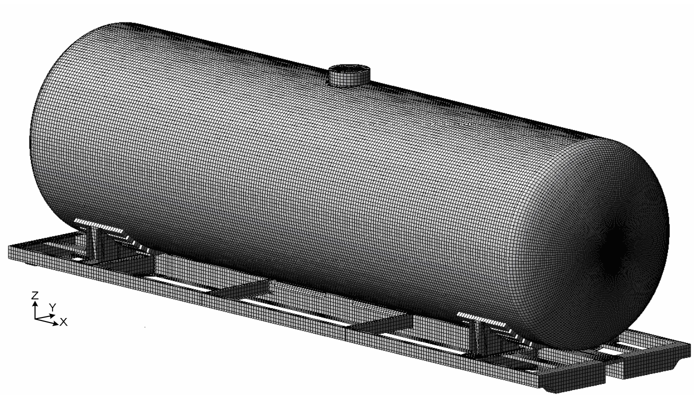

Fig. 1. Computational finite-element model of the tank wagon.

3. Rationale for selection of the bracket support structure

In Ukraine tanks are fixed on the frame in the middle and end parts of tank wagons. At the ends the tank rests on wooden bars located inside the ledgers of the end support structures on the bolster beams. The bolster beams are made as a box-type construction of adjustable length. The supports for ledgers are a welded construction of metal sheets which looks like an open box, the vertical sheets being connected in the middle of the diaphragm for rigidity [15]. The supporting structures made from low-alloy structural steel.

Contact pressure from the support structure on the shell directly depends on stiffness change in radial direction. For a more rigid support one can witness “tearing away” of the surface in the midsection and, thus, the loading transfers to the support’s ends in radial direction. The support’s stiffness (contact pressure) will decrease from the midsection to the ends in radial direction.

The solution of the assigned task required a search for the optimal support structure. The first stage dealt with patent-bibliographic analysis of engineering solutions, finding advantages and disadvantages. The disadvantage of the existing support is its stiffness. Structurally, the support has three horizontal belts reinforced with two vertical ones. The scheme is rather rigid regardless of thickness of the sheets used. Under loading vertical and horizontal sheets of the support structure are under stresses which are considerably lower compared with ones appeared in zones where the bolster beam joins with the center sill, and the channel beams join with the vertical diaphragms. Besides, there is a small so-called “working area” where the tank rests on the support. The width of the area corresponds to the distance between vertical diaphragms. The diaphragms are located perpendicular to the generatrix of tank, so in the support zones stress concentrators appear. Due to high stresses in tanks of tank wagons one can witness deviations from the regular geometry – dents – in the support zones. Sometimes these dents are so large that bracket part of the surface can lower and touch the center sill [16].

On the base of research [17–19] new construction variants have been proposed and the most efficient construction has been determined [20]. The second stage included determination of the optimal parameters: a target function was built, limitations were introduced, and approximation of the target functions and limitations as polynomials were obtained. The third stage embraced multiple realizations of function optimization and determination of optimal parameters of the structure graphically. The results of the methods coincided [21–23]. As mentioned above, stiffness of the support element will gradually reduce from the midsection to the ends. Therefore, the deformation analysis of structural variants was conducted, namely the existing structure and the most effective structure were compared (Fig. 2) by the stress-strain analysis.

In order to determine the law of support pressure distribution from the support on the tank of a tank wagon, some changes in the computational finite element model were made. In zones where the shell contacts with the support beams, binodal rod finite elements were introduced between them. In calculation of the tank wagon model the values of longitudinal forces in rod elements were obtained, and on the base of it the dependencies of forces in rods on their location in circumferential direction were built (Fig. 3).

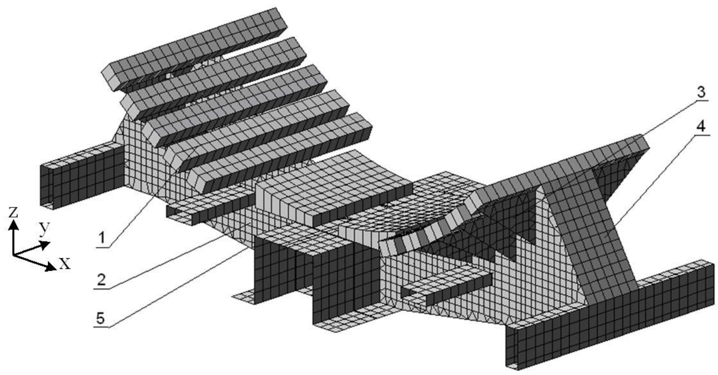

Fig. 2. Diagram of the bracket support structure: 1 – support element; 2 – diaphragm; 3 – stiffening rib; 4 – inclined sheet.

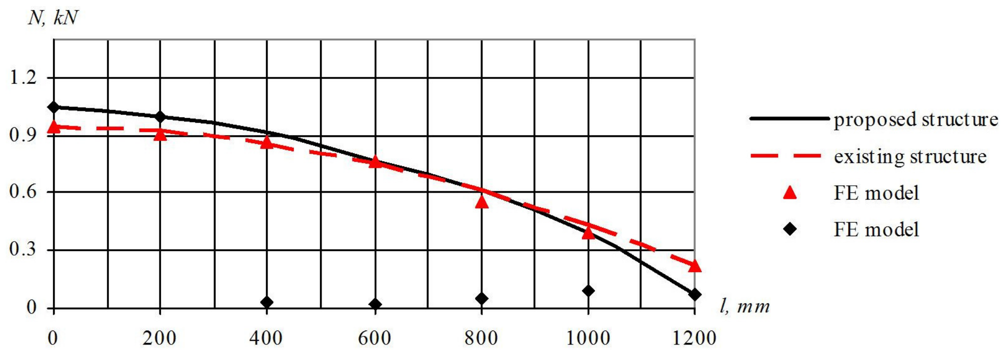

Fig. 3. Dependency of forces in the rods on their location in circumferential direction.

The law of support pressure distribution in the midsection of the support structure in the direction of the generatrix of tank of the tank wagon was built. The laws of stiffness change in radial direction and the laws of contact pressure change were demonstrated. In the proposed variant, they decrease more to their ends, which positively influences the stress-strain state of the tank.

4. Analysis of the strain-stress state of a tank wagon

The improved structure [24] was checked by loads according to design modes I and III [25]. In operation mode I corresponds to back-ins and starts of freight rolling stock, impacts of wagons during marshalling operation, and also emergency brake application in trains running at low speeds. The main requirement in capacity calculation by this mode is to exclude appearance of residual deformations of the tank's elements. By mode III a relatively frequent potential combination of considerable loads, which is typical for a regular operation of the wagon in a running train, was considered. The main requirement in calculation by this mode is to exclude fatigue damages in a node or detail. Analysis of the results demonstrates that the maximum stresses do not exceed the limit ones [25, 6].

The designing of every type of wagon requires consideration of main design forces influencing the wagon during its repair. Results of the calculation for the structure proposed show that the maximum equivalent stresses (Fig. 4) do not exceed the limit values, and the highest do not exceed 250 MPa (Fig. 4c).

For calculation by dynamic loads a mathematical model in MATHCAD was designed on the base of developed models [26–28]. In order to simplify the model it was taken that the barrel is fully loaded with liquid. The value of the maximum amplitudes was taken as depending on the track condition. By results of the calculations the diagrams presenting dependencies of accelerations of the body on time were built.

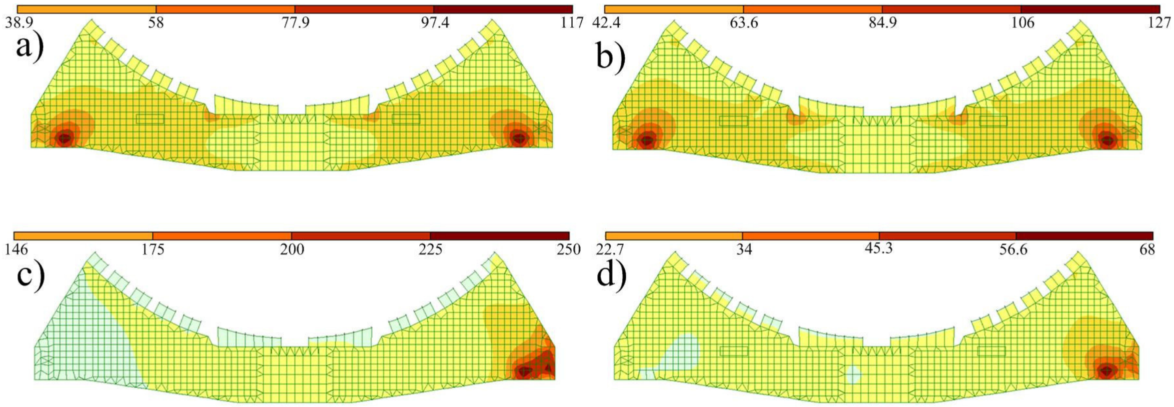

Fig. 4. Results of equivalent stresses in the bracket support at various supports of the tank wagon's frame:
a) lifting the loaded wagon by the bolster beam's ends at one side of the wagon frame; b) lifting the loaded wagon by the bolster beams' ends at both sides of the wagon frame; c) lifting the loaded wagon by one end of the bolster beam; d) lifting the empty wagon by the ends of the bolster beams located diagonally.

To consider inertial components from vertical oscillations of the wagon's masses (the body of the tank wagon) in calculation, design characteristics by dynamic efforts were specified in LIRA software. The name of the action "accelerogram" is chosen and the data from the diagram of dependency of the acceleration of the body in the center of mass on time are input. After calculation the program chooses the oscillation form when stresses are the highest. The following step is the option which sums up the stresses from static and dynamic loads, and as a result, one can obtain the total equivalent stresses (Fig. 5). Analysis of the results shows that the maximum stresses do not exceed the limit ones.

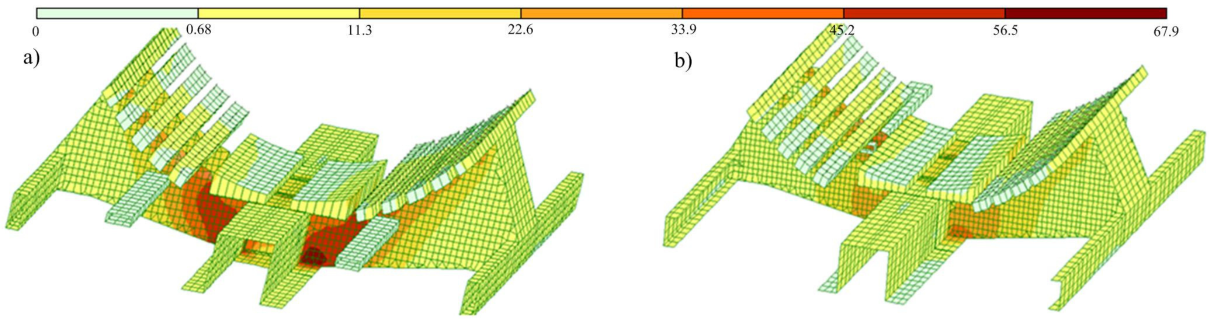

Fig. 5. Isofields of equivalent stresses in the end support considering the dynamic action in the vertical plane under the loaded body and a speed of 100 km/h: a) side view; b) view from the wagon's middle part.

Fatigue calculation was done. The design value of the dynamic stress amplitude for a conditional fully symmetric cycle is defined by the maximum equivalent stress amplitudes obtained on the computational finite element model. Results of the calculation show that the values of the maximum fatigue safety factor do not exceed the limit values.

5. Conclusions

1. The most vulnerable points in the construction of liquid tank wagons have been identified; they emerge as failures due to leakage and deformation of tanks. One of these weaknesses in service is the support zone.
2. A computational finite element model of the light oil tank wagon has been developed. Its adequacy has been checked by results of the analytical calculation and experiments; the discrepancy does not exceed 12%, which confirms suitability to use it for capacity calculation.

3. A prospective trend in improvements of technical and economic characteristics of a tank wagon is enhanced end support structures according to results of the research regarding the impact of contact pressure and stiffness of end structures on stress-strain states of tank wagons.
4. The mathematical formulation of the optimization design problem by the minimum material capacity criterion for the support structure of a tank wagon has been done and used for the structure proposed. Results of the calculations have shown that mass of the support structure at optimal values is $m^{proposed}$ = 415 kg which is 13% lower in comparison with the existing structure.
5. The structure with proposed improvements by a load spectrum according to normative documents has been checked.
6. Results of the research and the proposed and substantiated support structure of a tank wagon have been recommended for practical use by "The V. M. Bubnov Head Specialized Designing Car Building Bureau" Ltd.

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