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DEVELOPMENT OF A DESIGN-EXPERIMENTAL METHODOLOGY FOR THE PREDICTION OF RELIABLE EXPLOITATION OF FREIGHT RAILWAY CARS

Summary. The article is devoted to the front burner problem of effective exploitation of industrial tank-wagons with the presence of residual operation time. The procedure of valuation of tank-cars' residual operation time for liquid gas transportation was proposed first. Key technical and exploitation parameters of the tank-wagon model 15-1408-10 according to testing loads that simulate loads in real exploitation were approved. The calculation, which, as against existent ones for valuation of universal freight cars' residual operation time, allows to calculate equivalent stress using test results that rely on a change of internal pressure activity during drainage and filling operations, and the most unfavorable combination of simulation of active loads on a tank-wagon was proposed. The proposed procedure can be adapted for use during valuation of freight cars' residual operation time, or for other means of transport and machineries.

1. INTRODUCTION

Currently, Ukraine has large centers in the chemical industry. Manufacturers of mineral fertilizers comprise the basis of the chemical complex, their share exceeding 60% of the country's entire chemical industry output. The facilities for manufacturing mineral fertilizers allow producing up to 8 million tonnes of products per year. These enterprises operate a fleet of freight cars, the bulk of which consists of tank-wagons for liquid gas and other products' transportation. The requirements for exploitation of such freight cars are much stricter than those for exploitation of universal freight cars. When securing safe railway traffic, carrying dangerous cargo is the most important aspect of the problems that the railway transport system is facing, as, in the case of an accident, the consequences ensuing could be dangerous for vital human activities.

The results of the analysis of railway tank-wagons' functioning at one of the chemical enterprises (Public company «Азот» Cherkassy city, Ukraine) allowed arriving at a conclusion that the tank-wagon fleet reduces gradually and that their future exploitation is impossible.

It is necessary that the process of transportation be carried out by the required number of tank-wagons to ensure enterprise functioning at a high level. That number is beginning to diminish according to enterprises' facts (these facts have been taken from the enterprise's database, which contains facts on tank-wagons' technical dossiers, routes etc.). The main purpose of this process is extending the technological lifespan. The designated repair works help to renew this resource, it being economically justified. The shortage of railway tank-wagons originates because lifespans of some cars are already terminated and their renewal is not economically justified; hence, the fleet of tank-wagons will have to be replenished by purchasing new ones.

Limitations of exploitation of any rolling stock in Ukraine, Russia and CIS countries are specified in the corresponding documents. According to such rules railway cars must be exploited only within the framework of the existing planned precautionary maintenance and repairs.

Enterprise car building – that is, launching new products – together with the customer involves developing technical requirements for the product and, accordingly, developing and coordinating design documents. After that, a prototype (for example a railway tank-wagon) has to undergo preliminary testing with the objective of determining correspondence of the technical parameters with standard technical documentation. Technical parameters are proved by the existent method, which has found its return in [1] and is used by experimental machinists. A test-engineer mission is to justify whether or not these technical parameters are met during tests.

Thus, when you create railway cars, a back-up life operation is provided, in which the estimated durability of the structure is slightly above that specified in the technical documentation for each product.

Therefore, we may come to a working hypothesis of our investigation: the lifespan resource of railway cars can differ at the moment of its expiry. Then, a question arises: how can the residual operation time of railway cars be measured and, consequently, how can the problem of rational exploitation of each railway car be solved? The essence of the answer is that rational exploitation depends on the actual technical state of railway cars. You should not become attached to the norms and standards that demand stopping of exploitation after expiry of the specified exploitation term [2].

Theoretical substantiation of exploitation of the railway car according to its actual condition, which is backed by a strong experimental basis, is the requirement of interested parties in the transportation process. The main problem that the owners and operatives of such rolled stock are facing is to use the railway tank-wagons with the highest efficiency during its operational life [3].

The work of such renowned scholars like M.B. Kelrikh, A.V. Tretyakov, A.P. Abramov, and A.A.Bitutskiy et. al. [4 - 7] are dedicated to finding solutions to the problems of reliability and evaluation of the rolling stock design. These problems agitate scholars not only from Ukraine and Russia, but also those from countries of the former Soviet Union and non-CIS states, such as K.Yauheni, A. Boiko, and M. Kassner [8 - 12]. Questions, which were devoted to the prediction strength of structural components of machines and mechanisms based on results of simulation of dynamics, taking into account real exploitation conditions, found their return in [13].

The procedure of carrying-out tests is well-known and is employed extensively during testing of new freight cars or carriages in [14, 15].

Following the analysis of mentioned publications, a conclusion was arrived at that, at present, there are no methods for evaluating exploitation opportunities for railway cars operating under severe conditions (carrying high pressure cargo). Such methods would allow for a principle to control their further life cycle. Consequently, a solution to this important problem is connected with the necessity of developing a design-experimental methodology, based on the results of technical diagnostics. The methodical approach to a solution for this problem is represented in [16]. Also, it is important to mention the research of such scholars as Spiryagin [17], pertinent to new generation of tests on rolling stock.

Thus, the objective of this work is to develop a design-experimental methodology for prediction of the term of railway freight cars' reliable exploitation.

2. DETERMINATION OF CRITERIA BEFORE DEVELOPING A DESIGN-EXPERIMENTAL METHODOLOGY

Work to extend the serviceable life of freight cars was widely carried out in recent times [18]. The serviceable life for a railway car of a particular model is indicated in the technical specifications for the production in the section "reliability". This means some calendar serviceable life at the end of which the operation of the railway car needs to be terminated regardless of its true condition. The purpose of the establishment of serviceable life is to provide the forced early termination of the use of the freight car on purpose, based on the conditions of operation, security, feasibility, performance, and durability [18].

When the serviceable life of a railway car expires, depending on its designation, exploitation conditions, technical state, and other factors, it either can be written off or a decision can be made regarding a possibility to prolong the exploitation.

Operational life of the railway car depends on the intensity of use, i.e., the operational life is the working of the railway car during the period from the beginning of its operation before transition to the ultimate state.

The article proposes a design-experimental methodology for determination of the residual operation time, according to which:

1) The residual operation time is determined for railway tank-wagons, the specified life span of which has expired;
2) The residual operation time is determined on the basis of the analysis of exploitation conditions and results of examination of the technical state of each railway car.
3) The methodology includes a refined allocation of the underlying mechanical stress test loads [19, 20].
4) Determination of residual operation time is suggested to be done according to several criteria:

- the value for excess stress in structural elements at load combinations, specified in "Norms …" [20]. According to this criteria equivalent stresses are calculated by test results compared with admissible stress. The procedure for determination of residual operation time based on this criterion is properly explained in chapter 3.
- accumulation of damages before fatigue failure [19]:

$$\sigma^{m} N = const \quad , \tag{1}$$

where σ is stress while loading; N is loading cycles; m is a degree of an amplitude of dynamic stress.

If loads are forced there is a smaller number of loading cycles required. Thus, we can get the number of loading cycles faster before the fatigue failure.

3. EVALUATION OF TANK-WAGONS' RELIABILITY ACCORDING TO THE CRITERION OF EXCESS STRESSES IN THE ELEMENTS OF DESIGN

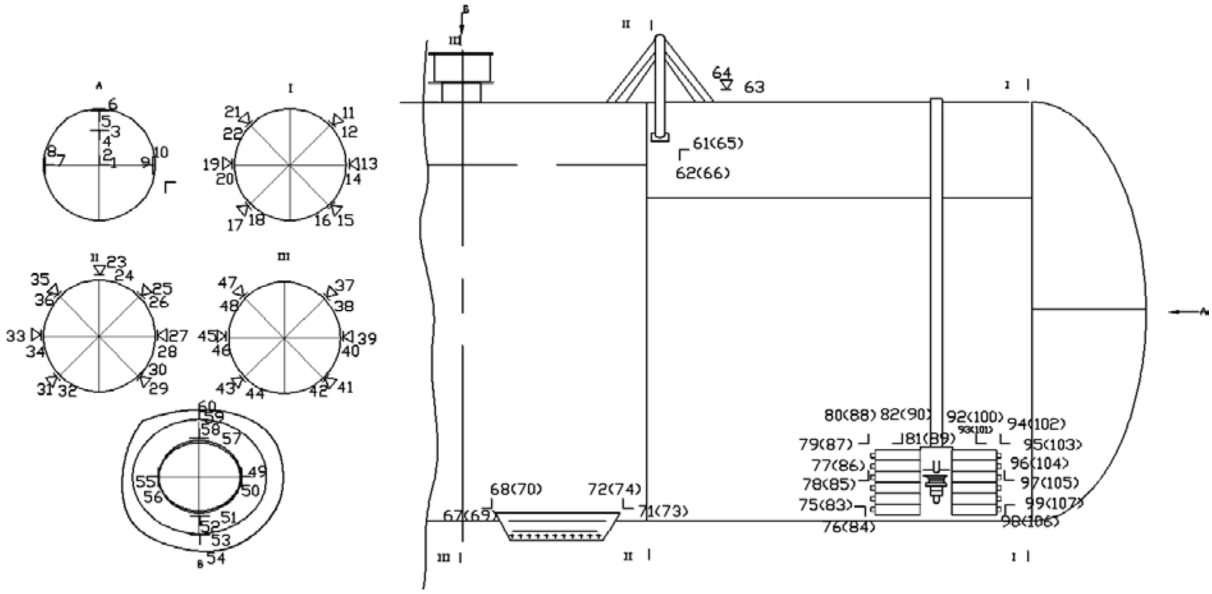
Stresses are determined for each of the control points of a tank-wagon's metal structure. The number of points and their location are determined according to the approved schedule of tests. An example of installation of stress gauges on the boiler of a railway tank-wagon is shown in Fig. 1, in which numbers represent stress gauges, specified for registration of stress. Fig. 1 represents on its right half one symmetrical part of a tank-wagon's boiler and on its left half views A, B, and section drawings I, II, III. Symbol ∇ , or any other that is shown in Fig. 2 indicates places where stress gauges are fixed. Stress gauges are fixed near welds, the boiler foot, holes, paws for mounting of the boiler, elements of fastenings, and at points of elements' connections with rivets, as shown in Fig. 3. The metric system of getting information from stress gauges is explained in [21].

Such deformations are measured using non-destructive methods of control have found their reflection in [22]. Another new treatise confirms the relevance of such non-destructive methods of control [23]. Among treatises that are devoted to problems of developing defect control, the ones by prof. Darryl Almond [24, 25] will be observed.

A tank-wagon, specified for carrying liquid ammonia, of technical model 15-1408-10 was taken as an experimental model. As for scientific works, according to [26], methods for measuring stresses of vehicles (or other metal structures), using strain gauges, have already developed.

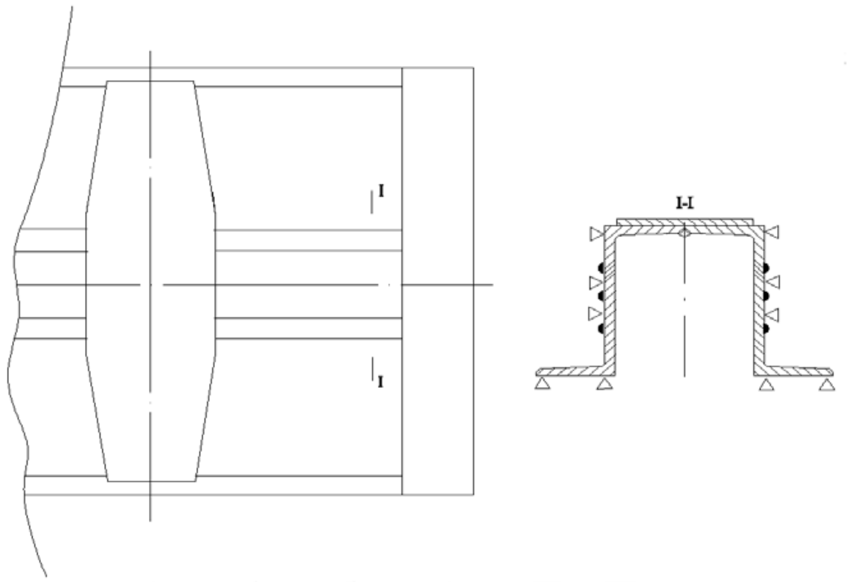
3.1. A working-out of reliability valuation procedures

The procedure for obtaining the first main criteria for the determination of residual operation time is shown in Figs. 4 and 5. First, it is necessary to decide in what directions forces from loads during tests will act. It may only be the one in reference axis X, or Y, or both of them simultaneously. Thus, there follow procedures for two occurrences for a reliable valuation of tank-wagons based on the criterion of exceeding stresses in the elements of construction.



┘, ⊥, ▷, ▽, |,- notations for stress gauges.

Fig. 1. Location of stress gauges on the boiler of a tank-wagon



▷- notations for stress gauges.

Fig. 2. Location of stress gauges on the tank-wagon’s frame

According to ***occurrences 1 and 2*** which are shown in Figs. 4 and 5, the procedure for reliability valuation of freight cars consists of five (three) consistent steps. It depends on the direction of forces that influence every under investigation point (see Figs. 2 and 3).

An explanation for ***occurrence 1 and occurrence 2:***

1. stress values:

a) σ_i is basic stresses, which are obtained during the test. These stresses are necessary for further calculations.

Basic stresses are those shown by stress gauges and they depend on applied loads;

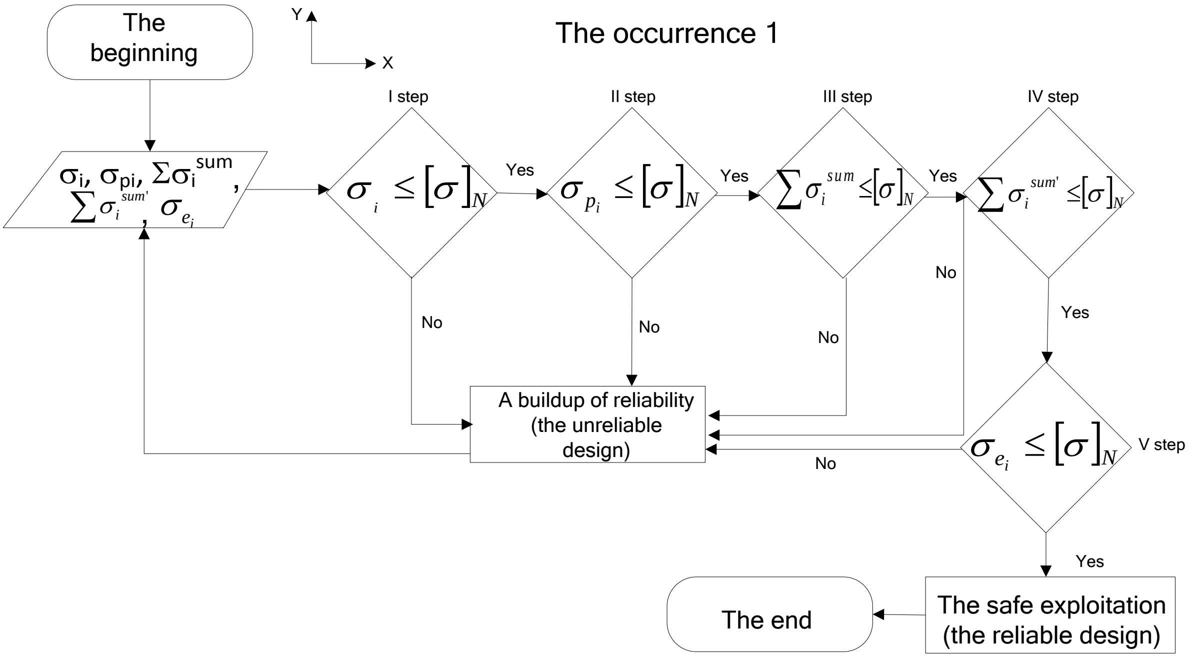


Fig. 3. The procedure of reliability valuation by the criterion of exceeding stresses in the elements of the construction of tank-wagons (the occurrence 1)

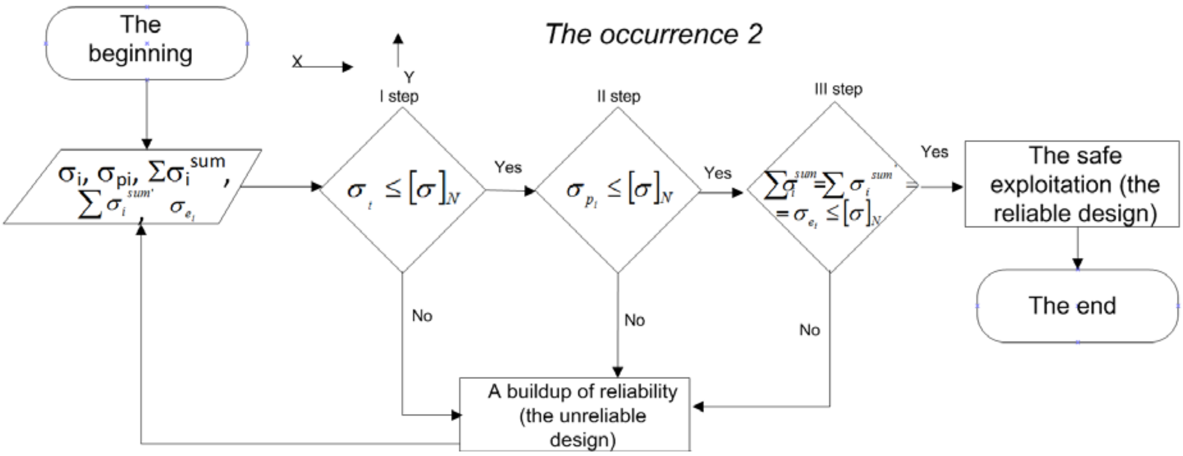


Fig. 4. The procedure of reliability valuation by the criterion of exceeding stresses in the elements of the construction of tank-wagons (the occurrence 2)

b) σ_{Pi} is calculation stress. These stresses include a conversion of basic stress according to an engineering design that simulates the design's active loads;

c) $\sum \sigma_i^{sum}$ is summary stress. It includes all stress that is exerted on tank-wagons from loads in concrete conditions of exploitation;

d) $\sum \sigma_i^{sum'}$ is main total stresses, which consider the influence of different directions of a force;

e) σ_{e_i} is equivalent stress;

f) $[\sigma]_N$ is admissible stress according to [20];

2. a notation of X and Y means that the influence of forces from loads acts in both directions, X and Y ***(occurrence 1)***; the influence of forces from loads acts only along X, or Y, reference axis ***(occurrence 2)***;
3. an execution of every condition from ***step I*** to ***step V (occurrence 1)*** and from ***step I*** to ***step III (occurrence 2)*** gives reason to believe that a design of the tank-wagon is reliable. Thus, non-fulfillment of provisos testifies about unreliable design. You should develop an improvement in the design and then perform all steps ***from I to V (occurrence 1)*** and from ***step I*** to ***step III (occurrence 2)*** from the beginning;
4. ***occurrence 2*** has differences in calculation as against ***occurrence 1*** in that valuation of stress at every investigation point (which is shown in Fig. 3) doesn't need calculations for $\sum \sigma_i^{sum'}$ and σ_{e_i} . This happens because the influence of forces from loads acts only along the X reference axis.

For example, point number 68 (Fig.2) is situated under the influence of forces from loads, which act along X and Y and must be rated for $\sum \sigma_i^{sum'}$ (main total stresses) and σ_{e_i} (equivalent stress).

The determination of these data has different methods of calculation.

Procedure accomplishment steps

Step I for both occurrences supposes a calculation of basic stress σ_i and compares it with admissible stress $[\sigma]_N$.

Step II supposes an evaluation for the calculation of stress σ_{Pi}. As stated earlier these stresses include a conversion of basic stress given the characteristics of the design. For example, calculation of mechanical stress from static vertical Q_{br1} load (simulation of actual cargo) is as follows:

$$\sigma_{br1} = \frac{\sigma_{test}^{Qbr} \cdot (m_c + m_r)}{Q_{test}} \text{ (MPa), - for a boiler of a tank-wagon,} \quad (2)$$

$$\sigma_{br1}^{f} = \frac{\sigma_{test}^{Qbr} \cdot (T - m_b \cdot n + m_r)}{Q_{test}} \text{ (MPa), - for a tank-wagon's frame,} \quad (3)$$

where: σ_i is stress in elements of design of a tank-wagon, which is loaded with a vertical static load (basic stress), MPa is megapascals; T is the tare of the tank-wagon, t; m_c is the mass of the boiler a tank-wagon, t; m_b is the mass of one bogie, t; n is quantity of bogies in a tank-wagon; m_r is rated capacity of a tank-wagon, t; Q_{test} is test of the static vertical load, t.

Step III. For stress evaluation in the design of the tank-wagon, in accordance with the "Norms..."[20], the prototype was subjected to static and dynamic loads, the total stresses were calculated for operational modes I and III, test mode, and for modes that mimic the combination of main loads, such as in the process of operation.

I: designed mode corresponds to starting and upsetting of a heavy freight train and car collision during maneuvering, including humping of cars and extreme braking at slow speed.

II: this is a special mode, set only for certain car types as a combination of loads, typical for these cars. The necessity of such evaluation is determined in requirement specification for design and testing of railway cars. Because the design features of tank-wagons that have passed the procedure of evaluation of residual operating time are not provided based on this regime, the article does not contain such an assessment.

Mode III presumes a combination of loads, typical for the normal operation of a tank-wagon: the movement of the carriage in a train along straight and curved sections of the road at the correct speed, the design speed of controlled braking during periodic service, and the normal operation of units and mechanisms.

Testing mode covers the railway tank-wagons carrying pressurized cargo and presumes testing at the test pressure. We can also find criteria for questions and answers devoted to loss in mechanical strength of materials used in metal constructions, which work under pressure, in [27].

Shock test modes are required to assess the durability of the structure and its elements under critical impacts.

Thus, $\sum \sigma_i^{sum}$ involves calculation using four modes: $\sum \sigma_{Ii}^{sum}$, $\sum \sigma_{IIIi}^{sum}$, $\sum \sigma_{\text{test}}^{sum}$, and $\sum \sigma_{ud}^{sum}$.

Summary stresses, according to mode I are as follows [20]:

$$\sum \sigma_{Ii}^{sum} = \sigma_{br1i} + \sigma_{PIi} + \sigma_{Ni=^{-2,5}_{+2,0}} + \sigma_{eks_i} + \sigma_{pop_i} \le [\sigma]_{NI}, \text{(MPa)} \quad (4)$$

where i is a point under investigation; σ_{br1} is mechanical stresses from static vertical Q_{br1} load (simulation of actual cargo); σ_{PI} is stresses from calculated internal pressure for mode I, P_I; $\sigma_{Ni=^{-2,5}_{+2,0}}$ is stresses from tensile and compressive forces, which equals 2,5, 2,0 meganewtons (MN); σ_{eks_i} is stresses from the voltage arising because of the difference in the height of automatic coupling axes (± 100 mm); σ_{pop_i} is the stresses arising from the action of lateral forces when passing the curved sections of the track; $[\sigma]_{NI}$ is allowed stresses for mode I.

$\sigma_{Ni=^{-2,5}_{+2,0}}$, σ_{eks_i}, σ_{pop_i} are determined only for a car frame, not for a boiler of a tank-wagon.

According to mode III summary stress are as follows [20]:

$$\sum \sigma_{IIIi}^{sum} = \sigma_{br1i} + \sigma_{PIIIi} + \sigma_{Ni=\pm 0,1} + \sigma_{din_i} + \sigma_{bok_i} \le [\sigma]_{NIII}, \text{(MPa)} \quad (5)$$

where: σ_{PIII} is stresses from internal pressure for mode III, MPa; σ_{din} is voltage and dynamic additives that are obtained by multiplying the stresses from the static load $Q_{бpI}$ on the coefficient of vertical dynamics $\sigma_{din}=\sigma_{br1}\cdot K_d$, MPa; σ_{bok} is stress from side load, which is 10% of the static load Q_{br1}; $\sigma_{bok}=0,1\sigma_{br1}$, MPa; $\sigma_{Ni=\pm 0,1}$ is stresses from tensile and compressive forces which equal 2,5, 2,0 MN; $[\sigma]_{III}$ is the permissible loads for mode III, Mpa; $\sigma_{Ni=\pm 0,1}$ is is determined only for a car frame, not for a boiler of a tank-wagon.

The IIId mode provides the effect of horizontal longitudinal and transverse forces resulting from stretching or compression of the tank-wagon in operation. However, as a rule, the serviceable life is extended for the boiler as the most expensive element of the supporting structure and the frame must be replaced at overhaul to a new, commercially available one. The above-mentioned forces act on the frame of the tank-wagon; therefore, tensile test-compression for the boiler does not hold.

Testing mode [20]:

$$\sum \sigma_{test_i}^{sum} = \sigma_{br2_i} + \sigma_{Ptest_i} \le [\sigma]_{N_{test}}, \quad (6)$$

where σ_{br2} is is stress from vertical static load Q_{br2}, MPa; σ_{Ptest_i} is stress from test pressure inside the boiler P_p, MPa; $[\sigma]_{Ntest}$ is permissible stress for the test mode, MPa.

Summary stresses during the shock tests will be as follows [20]:

$$\sum \sigma_{ud_i}^{sum} = \sigma_{br1i} + \sigma_{Pr_i} + \sigma_{Ni=3,5} \le [\sigma]_{Nud}, \text{(MPa)} \quad (7)$$

where σ_{Pr_i} is stress, gained from internal operation pressure, MPa; $\sigma_{Ni=3,5}$ is stresses when an automatic coupling device collides with a force of 3.5MN; $[\sigma]_{Nud}$ is permissible stresses for the mode of the shock tests, MPa.

Step IV. For evaluation of equivalent stress σ_{e_i} it is required to reduce the overall stress to main overall stress. It is necessary use following formulas for the calculation of main overall stress at one point under investigation [20]:

$$\sum \sigma_i^{sum'(x)} = \frac{E}{1-\mu^2}(\varepsilon_{x_i} + \mu\varepsilon_{y_i}),$$
$$\sum \sigma_i^{sum'(y)} = \frac{E}{1-\mu^2}(\varepsilon_{y_i} + \mu\varepsilon_{x_i}); \quad \text{(MPa)} \qquad (8)$$

After the conversion:

$$\sum \sigma_i^{sum'(x)} = \frac{1}{1-\mu^2} E\varepsilon_{x_i} + \frac{1}{1-\mu^2}\mu E\varepsilon_{y_i},$$
$$\sum \sigma_i^{sum'(y)} = \frac{1}{1-\mu^2} E\varepsilon_{y_i} + \frac{1}{1-\mu^2}\mu E\varepsilon_{x_i};$$

Taking into account that: μ= 0,3, E = 2,1 10^5, $E\varepsilon_{y_i} = \sigma_{Y_i}, E\varepsilon_{x_i} = \sigma_{X_i}$, then:

$$\sum \sigma_i^{sum'(x)} = \frac{1}{1-0{,}3^2}\sigma_{X_i} + \frac{1*0{,}3}{1-0{,}3^2}\sigma_{Y_i},$$
$$\sum \sigma_i^{sum'(y)} = \frac{1}{1-0{,}3^2}\sigma_{Y_i} + \frac{1*0{,}3}{1-0{,}3^2}\sigma_{X_i};$$

After that we obtain:

$$\sum \sigma_i^{sum'(x)} = 1{,}1 \cdot \sigma_{X_i} + 0{,}33 \cdot \sigma_{Y_i}; \; \textit{at that} \; \sum \sigma_i^{sum'(x)} \le [\sigma]_N,$$
$$\sum \sigma_i^{sum'(y)} = 1{,}1 \cdot \sigma_{Y_i} + 0{,}33 \cdot \sigma_{X_i}; \; \textit{at that} \; \sum \sigma_i^{sum'(y)} \le [\sigma]_N;$$

where E is the modulus of elasticity of the first type for steel (the material from which the boiler is manufactured), MPa; μ is the Poisson ratio; ε_{x_i} is a deformation with respect to the X axis, mm/metre; ε_{y_i} is a deformation with respect to the Y axis, mm/meter; σ_{X_i}, σ_{Y_i} is summary stresses along X and Y axes (for example, which have been obtained using formulas 3–6); $[\sigma]_N$ is admissible stresses according to [20].

Calculations using formula 7 must be done for all modes (I, III, testing mode, shock test mode). Thus, for every point where the forces from loads act on the X and Y axes simultaneously there will be 4 parameters for the X direction and 4 parameters for Y.

Step V supposes determination of equivalent stress. Equivalent stresses are determined according to this formula [20]:

$$\sigma_{e_i} = \sqrt{\sigma_{X_i}^2 + \sigma_{Y_i}^2 \cdot \sigma_{X_i} \cdot \sigma_{Y_i}}; \text{ at that } \sigma_{e_i} \le [\sigma]_N, \text{(MPa)} \qquad (9)$$

4. ESTABLISHING RELIABLE SERVICEABLE LIFE WITH THE ACCUMULATION OF DAMAGE ACCORDING TO THE CRITERION OF FATIGUE FAILURE

The evaluation of the residual operation time of a railway tank-wagon according to the criterion of accumulation of damages at the number of load cycles from 1,000 to 500,000 (fatigue failure) should be performed according to the main formula as follows [19, 20]:

$$n = \frac{\sigma_{a,N}}{\sigma_{a,e}} \ge [n], \qquad (10)$$

where $\sigma_{a,N}$ is the limit of endurance of the structure's element, which is obtained experimentally, by carrying out forced tests, MPa; $\sigma_{a,e}$ is the value of equivalent reduced amplitude of dynamic stress, determined by computation, MPa; $[n]$ is the permissible coefficient of reserve in resistance to fatigue.

The permissible coefficient of reserve in resistance to fatigue is connected with the process of origin and development of fatigue cracks, leading to the destruction of the part. This is a measure of the ability of the design to withstand the accompanying loads above the estimated value.

The proposed design-experimental method comprises the formula for evaluation of the amplitude of dynamic stress (MPa), obtained for the first time, that takes into account peculiarities of the design of the tank-wagon, for transportation of liquid gas. This formula allows us to determine the overall equivalent stress, arising at a maximum possible unfavourable combination of simultaneous loads at exploitation and takes into account the pressure change [20] as well as alternations in internal pressure during discharge and loading operations:

$$\sigma_{a,e} = \sqrt[m]{(\sigma_{a,e}{}^{v})^2 + (\sigma_{a,e}{}^{pr})^2 + (\sigma_{a,e}{}^{d})^2}, \text{ (MPa)} \quad (11)$$

where ($\sigma_{a,e}{}^{v}$) is the value of the equivalent stress that takes into account the dynamic action of vertical forces when the train is moving, MPa; ($\sigma_{a,e}{}^{pr}$) is the value of the equivalent stress that takes into account the action of longitudinal forces in case of a shock in the automatic coupler device, MPa; ($\sigma_{a,e}{}^{d}$) is the value of equivalent stress, taking into account the action of alternations in internal pressure during discharge and loading operations, MPa; m is the degree of the amplitude of dynamic stress in the equation of fatigue curve.

4.1. Results of the calculation of coefficients of reserve of fatigue resistance

The values of coefficients of reserve of fatigue resistance were obtained as a result of tests on an experimental specimen (see Fig. 6).

Diagrams show areas of investigation with the highest stresses observed in investigation points. All units for numbers which are shown in Fig. 6 represent numbers of points corresponding with Fig. 2 in the body of the tank-wagon. For example, in the area where the paws for mounting of the boiler are situated, stresses were obtained by following characteristic signs: dropping from wedges, level of endurance achieved by the structure, and reduced equivalent amplitude (markers are shown in Fig. 2). Subsequently, the coefficient of reserve of fatigue resistance is obtained (the formula 9).

Let's choose any investigation point. The point 7 level of endurance reached by the structure was 21 MPa. Dropping from wedges tank-wagon was conducted by pushing it on wedges and from wedges with the help of a locomotive. Effective frequency dynamic stress needed for the calculation of ($\sigma_{a,e}{}^{v}$) (the formula 10) has been determined. Stress based on this parameter was equal to 13,5 MPa. The reduced equivalent amplitude which was calculated by the formula 10 was equal to 7 MPa. The coefficient of reserve of fatigue resistance for this point was equal to 2,87. This is a good result, as this coefficient should be increased toward 1.5 and not less [20].

The smallest values of the coefficient of reserve of fatigue resistance, following the results of our experiments, were obtained in the area of the paws for mounting of the boiler in point 79, level of endurance achieved by the structure.

If the obtained value of the coefficient of reserve of fatigue resistance is $n \geq [n]$, then the tank-wagon has a reserve of residual operation time during the lifespan for the whole expected term of exploitation, where n is the coefficient of reserve of fatigue resistance, determined using tests.

In case $n < [n]$, in one or several control points of a tank-wagon, the tank-wagon will not have a lifespan resource for the expected exploitation period.

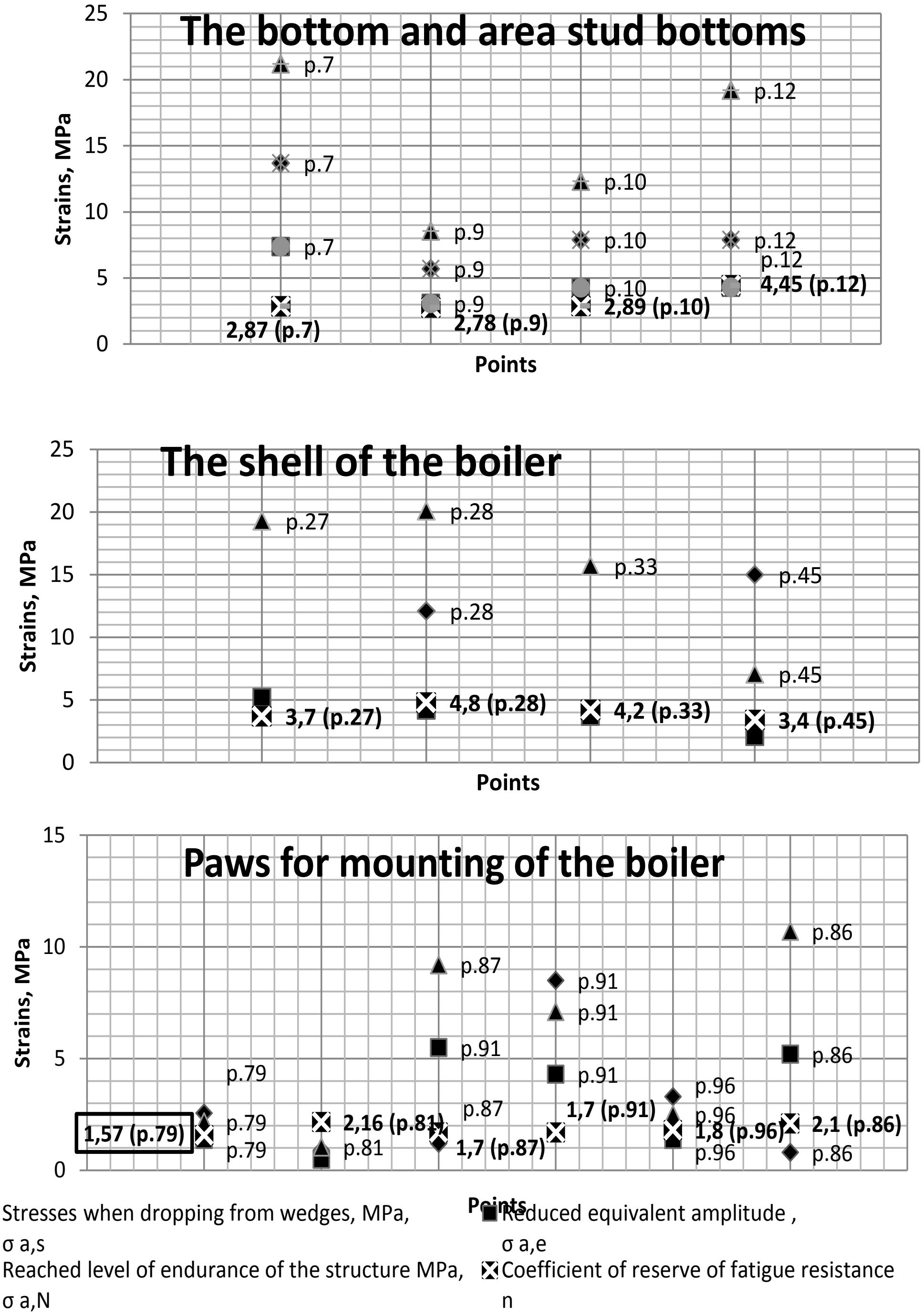


Fig. 5. Design-experimental coefficients of reserve in fatigue resistance.

4.2. The formula, based on received coefficients of reserve in fatigue resistance for the determination of reliability exploitation

Evaluation of the coefficient of reserve of fatigue resistance presumes determination of the number of cycles of dynamic and static loads, acting upon a tank-wagon. Having the determined data, regarding the number of such cycles per specified exploitation term of the tank-wagon, and having the data, regarding the number of cycles at the conducted tests, it is possible to determine the term of exploitation of the tank-wagon which was tested, in accordance with the following formula [19]:

$$T_c^n = \left(\frac{n}{[n]}\right)^m \cdot \overline{T}, \text{ (years)} \tag{12}$$

where T_c^n is the serviceable life obtained by using the calculation–experimental method, in years; $\overline{T}$ is design serviceable life, in years.

5. CARRYING OUT TESTS

Preliminary testing of a prototype tank-wagon intended for the carriage of liquid ammonia, technical models 15-1408-10 (tank-wagon after a capital repairs with extension of useful life), has been carried out using receiving data for calculations of residual operation time.

Given the design of the tank-wagon, in the testing were included the following:

- static: vertical load and the loading from working and test pressure;
- shock tests;
- tests when dropping from wedges;
- endurance testing for a limited resource: re-static (load with a small number of cycles) loading of the boiler with internal extreme pressure and test pressure.

The static tests and repeated static testing (load with a small number of cycles) was carried out based on determination of strain from loading in the control points section of the tank-wagon. The location of these points is shown in Figs. 2 and 3. Also, the parameters of acoustic emission signals and loading the wagon to an unacceptable level have been determined.

Before static and dynamic strength tests the body structure of the prototype is glued over the stress gauges. Also, wiring and testing of cables for measuring schematics, connector equipment, calibration division of a torque coupler, and test operation of instruments with a record of results in a test log are carried out.

Stress gauges should be placed at a distance of 25–30 mm from the weld and 15–20 mm from the selvage of the mating parts.

Normative longitudinal quasi-static stresses are assumed to be as follows: 2500 kilonewtons and 2000 kilonewtons (mode I) and ±1000 kilonewtons at mode III. The loading frame is carried out stepwise with a step of 500 kilonewtons and an interim analysis of data. Static load from the weight of the load is simulated by filling the tank with water. Measurement of voltages is carried out with an empty boiler, and also when the loading was 25, 50, 75, and 100% of the volume. The safety valve is dismantled before the loading of the tank-wagon's boiler with the inner process pressure and the flange that connects the stand for hydraulic tests. Loading of the tank-wagon's boiler, completely filled with water, running the inner process pressure is created in steps of 0.05 MPa from zero to 0.50 MPa. Reducing the pressure to zero is as per the same steps. At each stage of loading stresses at the investigated point of the structure are sequentially recorded. Then, you drain the water from the boiler with the measurement of stresses in the empty boiler followed by re-filling with voltage measurement at zero pressure and subsequent loading with the inner process pressure as per the same step as the first loading. During the test, usually, three cycles of loading and unloading are performed, for the tank pressure, the longitudinal efforts of the tension–compression, and weight of the cargo.

About 40 loadings by internal extreme pressure (2,0 MPa) and 1 loading by test pressure (3,0 MPa) are carried out during static load.

Tensile compression is performed in the stand for tensile and compression (Fig. 7).

At the next stage of experimental research shock tests of the tank-wagon are carried out. Shock loads are simulated during shock tests. Shock loads occur during shunting operations. Shock tests are carried out during daylight hours on a straight track using a locomotive. A series of shocks are produced and the special freight car is loaded in a tank-wagon, standing in the backwater in a clutch with other cars. The magnitude of the impact force is determined by reading of showings of the automatic coupling device as dynamometric while passage of the front wheel pair of freight car of two pickets, are located at a distance of 1 meter from each other. The chart of the arrangement of tank-wagons during the shock tests is shown in Fig. 8.

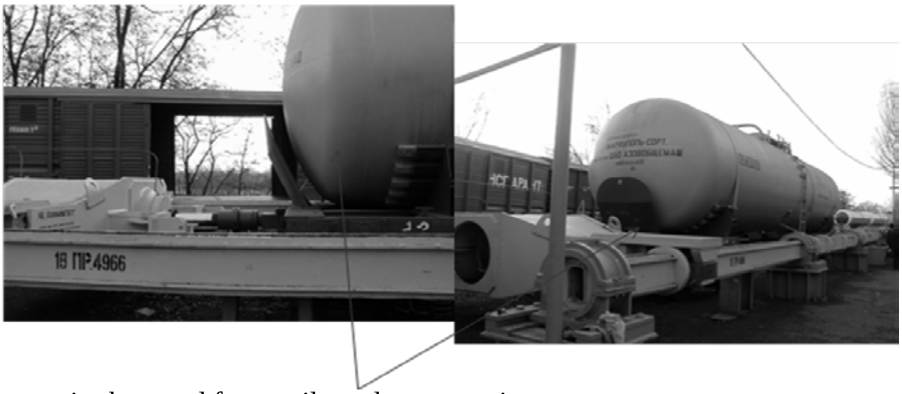


Fig. 6. A device for obtaining stresses from compressive and tensile forces

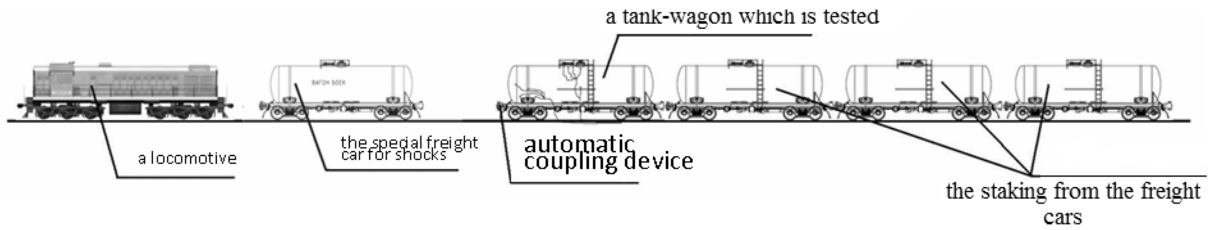


Fig. 7. The chart of shock tests being carried out

To carry out the test when dropping from wedges, the tank-wagon was rolled on wedges of size 400x70x28 mm with the help of a locomotive.

Static and shock tests of the tank-wagon can confirm whether the design will comply (or not comply) with the current regulatory requirements after carrying out the required volume of repair.

6. CONCLUSIONS

1. According to the developed methodology, there are two occurrences of reliability evaluation and tank-wagons' residual operation time evaluation, the procedure for which depends on the direction of the applied forces.

1.1. As a result of the use of this methodology the tank-wagon's elements can be classified in two groups. Those items, whose reliability will be evaluated according to occurrence 1 (first group) – the bottom and the shell of the boiler – that is, the carrier portion of the design, which is subject to bi-directional synchronous active forces, such as longitudinal (transverse) force and pressure force. In addition to the evaluation of the prototype reliability and similar models of tank-wagons, this occurrence of the developed procedure can be applied to evaluate any other vessels working under pressure and subject to dynamic (static) load.

1.2. The elements of the tank-wagon, whose reliability must be estimated in occurrence 2 (second group) are the elements of a frame that receives the action of either the longitudinal or transverse loads. The assessment of such a procedure's reliability, in addition to the railway cars, can be used for any metal beams used in the context of static and dynamic loads.

2. Evaluation of the reliability of railway cars in the proposed methodology is more accurate compared to the standard method of reliability assessment such as, for example, the estimated probability of failure-free operation, the calculation of the availability factor, the calculation of the

failure rate, and other indicators, because the basis of this method is the calculation of these indicators according to statistical data of the retrospective period of tank-wagons' operation. In that time, as the assessment of the reliability by the developed methodology enables accurate calculation of dynamic load cycles for failure (cracks in the structural element, fracture, or any other violation of the structure integrity) and, therefore, gives an accurate prediction for the specific design of the tank-wagon.

3. A high importance of the proposed methodology is in substantiation of the min exploitation parameters for railway tank-wagons, carrying liquid gas. In accordance with test loads, it allows application of these data in further exploitation of railway tank-wagons, similar in design.

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