**O. V. Fomin**[*1],
orcid.org/0000-0003-2387-9946,
**I. V. Shcherbyna**[1],
orcid.org/0000-0002-9574-2757,
**Ie. P. Medvediev**[2],
orcid.org/0000-0001-8566-9624,
**T. V. Emelyanova**[3],
orcid.org/0000-0001-7451-8193,
**O. O. Ostrohliad**[4],
orcid.org/0000-0002-8496-3271

https://doi.org/10.33271/nvngu/2025-5/061

1 – National Transport University, Kyiv, Ukraine
2 – Gdansk University of Technology, Gdansk, Republic of Poland
3 – Kharkiv National Automobile and Highway University, Kharkiv, Ukraine
4 – Zaporizhzhia Polytechnic National University, Zaporizhzhia, Ukraine
* Corresponding author e-mail: fomin1985@ukr.net

# ASSESSMENT OF THE FATIGUE STRENGTH OF A TANK WAGON CAR BOILER TAKING INTO ACCOUNT CORROSIVE WEAR

**Purpose.** The goal of the article is to present the results of research on determining the stress-strain state of a tank car boiler's shell and assessing its fatigue strength using computer modeling. This was done while accounting for various levels of corrosion wear.

**Methodology.** A specific methodology based on general calculation principles for railway vehicle components was used to assess the tank car boiler's resistance to failure from repeated loads. Various scenarios simulating metal corrosion damage were examined: complete absence of corrosion; corrosion with a depth of up to one millimeter; corrosion with a depth of up to two millimeters; corrosion damage with a depth of up to three millimeters.

**Findings.** Based on the analysis, the depth and location of corrosion significantly impact the strength of a tank car boiler. These factors are critical when evaluating the reliability of the structural elements. Therefore, the degree and location of metal corrosion wear must be taken into account when determining the strength of the boiler.

**Originality.** The research revealed a direct relationship between changes in fatigue safety factors in the most stressed areas of a tank car boiler and the appearance and development of corrosion defects. The findings demonstrate the critical importance of the metal shell's thickness for ensuring the structural reliability of the tank, particularly for wagons nearing the end of their service life. The proposed methodology allows for the evaluation of extending the service life of such tank cars by taking into account the level of corrosion damage.

**Practical value.** The study found that areas around the bottoms and manholes of the tank car boiler are critical zones for corrosion damage with a depth of three millimeters or more. This level of damage makes further operation of the boiler impossible. However, if corrosion is less deep (up to two millimeters), the boiler's service life can be extended to thirty years. If there are no signs of corrosion, the service life can be extended by twelve years beyond the standard term, for a total possible service life of thirty-six years. Implementing these results will allow for more informed decisions regarding the extension of tank car service life and help prevent accidents related to worn-out rolling stock.

**Keywords:** *transport mechanics, rolling stock, wagons, computer modeling, metal corrosion*

**Introduction.** In the current context, the importance of uninterrupted rail transport of liquid cargo is beyond doubt. At the same time, the fleet of tank wagons includes many units with an expired service life. Extending their operational period and conducting various types of repairs necessitate scientific studies into the impact of corrosive cargoes on the strength characteristics of structural elements.

However, the existing calculation methods for tank components are based on simplified models that do not account for operational specifics or interaction with aggressive environments. As a result, reduced shell thickness due to corrosion leads to significant weakening of the structure.

Inspections of tank wagons used for chemical cargo with extended operational periods have revealed considerable corrosion damage to the load-bearing structure and body. These defects pose a direct threat to rolling stock safety and require detailed analysis. Special attention must be paid to evaluating how reduced metal thickness affects structural strength. A comprehensive study of critical areas is necessary to determine the residual service life. Corrosion of major components can reduce load-carrying capacity and increase operational risks. Forecasting the remaining service life of individual elements will support well-grounded decisions about further use of these wagons.

Measures must be developed to improve safety, including regular structural condition monitoring. Considering the level of corrosion wear will help prevent emergency situations. Additional material testing will enable more accurate strength assessments. A comprehensive diagnostic approach will allow continued operation with minimal risk.

Given the above, it is clear that assessing the fatigue strength of tank wagon boilers, taking into account the effect of corrosion, is a matter of high importance and relevance.

**Literature review.** In [1], the authors present scientific developments related to the creation and use of a model for studying the perception and redistribution of loads by wagons using Y-25 bogies. The focus was mainly on the connecting elements.

Article [2] is devoted to the study of the dynamics of a freight wagon model with viscous damping, which is important for understanding its behavior during motion. The authors evaluated dynamic characteristics, taking into account the effects of viscous resistance. The results can be used to optimize wagon design and improve operational safety. This research makes a valuable contribution to railway transport, providing quantitative data for engineering decisions.

In [3], the dynamics of a rail vehicle are assessed in terms of running performance on a realistic track model. The authors analyze various parameters that affect movement stability and smoothness. The results improve understanding of vehicle-track interaction and are important for the safety and comfort of passenger and freight transport.

Study [4] focuses on the analysis of lateral forces acting on a specialized train transporting long rails, to assess the risk of derailment. The authors investigate the factors that could lead to dangerous lateral loads. These data are critical for developing preventive safety measures. The research emphasizes the need to analyze the dynamics of specialized rolling stock to ensure railway transport safety.

In [5], new approaches to improving freight wagon components are proposed, including mathematical descriptions and computer simulations.

Article [6] examines the evaluation and reduction of energy consumption in railway trains moving along straight track sections, using lighter freight wagons. The author analyzes how reducing wagon mass affects overall train energy consumption. The findings support the development of energy-efficiency strategies for rail transport. This study is relevant to sustainable development and reducing environmental impact.

Scientific work [7] considers damage to wagons during the final stages of their life cycle (corrosion, accidents, impacts). The authors highlight the importance of launching R&D projects aimed at reducing and correcting operational deformations.

In [8], the authors created an adequate computer model of the load-bearing system of a specialized wagon. However, applying this model to other types of wagons requires further adaptation and tuning.

In [9], results of computer simulations assessing the strength of interacting rolling stock components are presented. However, a comprehensive study of the stress-strain state of the load-bearing structure was not carried out.

Study [10] provides experimental results on metro rolling stock, focusing on energy efficiency. However, fatigue accumulation in structural modules was not examined.

In [11], the authors present research aimed at improving traction processes in rolling stock. Load interaction was considered at fixed values, without analyzing the structural behavior in response to loads.

Paper [12] provides practical and scientific results for improving the performance of metal structures. However, there was limited attention to in-depth analysis of the stress-strain state.

Study [13] proposes a new approach to improving energy transfer processes among vehicle components. However, stress redistribution was not sufficiently addressed.

In [14], scientific results are presented on optimizing processes in the power module of a transport vehicle, with the main focus on increasing energy efficiency.

In [15], the authors scientifically justify promising directions for freight transport development. They emphasize the need to improve structural systems, particularly by enhancing strength.

Study [16] seeks scientific and practical solutions for improving transport processes. One key aspect highlighted is the need to renew rolling stock fleets with next-generation models, requiring appropriate scientific and practical tools.

Article [17] presents the application results of an algorithm developed by the authors, aimed at improving load perception based on materials science achievements.

In [18], improvements to structural elements of flying vehicles made of composites are proposed, including a new structural-material composite. However, applying these findings to other transport modes requires additional in-depth research.

Study [19] outlines perspectives for the development of freight transport structures, highlighting the importance of using advanced materials science achievements.

Article [20] presents applied scientific solutions for improving the interaction of different transport types. However, stress redistribution by individual structural elements was not considered.

In publication [21], the authors offer a method for solving an urgent transport problem. However, the method focuses on improving power equipment characteristics and does not account for the frame module.

Article [22] is devoted to determining the optimal loading of an improved tank container for rail transport. The authors analyze factors affecting the efficiency and safety of cargo transport in such containers. The results can inform operational guidelines. This research is vital for optimizing logistics processes in rail transport.

In [23], the authors assess the strength of an improved tank container design under operating conditions. They analyze stresses and deformations during transportation. The results confirm the reliability of the new design and support its further implementation. This work contributes significantly to the safe transport of hazardous cargo by rail.

Article [24] discusses improvements to the power loss model in pulsed-current traction motors of electric locomotives. The authors review existing models and propose a more accurate one, considering harmonic effects. The findings can optimize traction motor control systems and improve locomotive energy efficiency.

In [25], a spectral analysis method for AC electric locomotive traction current is presented. The approach helps identify and analyze harmonic components, assess power quality, and detect potential issues. The results support diagnostics and efficiency improvements.

In [26], an improved model of an asynchronous traction motor is presented. The authors analyze electromagnetic processes and develop a more accurate mathematical model that includes nonlinear effects and magnetic core saturation. The model enables better prediction of motor behavior in various operating modes. These findings aid in developing more reliable traction drive control systems.

**Unsolved aspects of the problem.** Excessive wear of the boiler is a key obstacle to extending the service life of tank wagons designed for transporting chemical substances. The primary cause of this phenomenon is the corrosive effect of aggressive chemical cargoes on the internal walls of the tank. Researchers and engineers must study how corrosion affects structural strength, particularly by analyzing changes in the boiler's geometry. A crucial task is to identify zones where critical stress values arise, exceeding allowable limits. Such studies will allow for the evaluation of material fatigue under various degrees of corrosion damage. To achieve this, modern computer modeling methods can be applied.

The data obtained will make it possible to predict the remaining structural life. As a result, accidents can be prevented, and the period of safe operation optimized. Corrosion leads to localized weakening of the metal, which may cause structural failure. Therefore, it is necessary to accurately determine the areas with the greatest wear. Computer models can simulate boiler behavior under different levels of damage. This enables an assessment of corrosion's impact on the load-bearing capacity of the structure. Stress analysis helps identify potentially dangerous zones. Such calculations serve as the basis for deciding on boiler repair or replacement.

Ultimately, this contributes to improving the reliability and durability of tank wagons.

**Purpose.** The purpose of this article is to present the results of the research aimed at determining the stress-strain state of the tank wagon boiler shell and assessing its fatigue strength under different levels of corrosion wear, using computer modeling tools.

To achieve this goal, the following scientific and practical objectives were set and addressed:

- to analyze existing developments on the subject matter;
- to develop a methodology for carrying out the calculations;
- to create an adequate finite element calculation model of the tank wagon boiler;
- to perform calculations using computer modeling tools;
- to analyze the obtained results.

The fatigue strength calculation methodology for the tank wagon boiler is based on generalized approaches used for the components of wagons operating under constant dynamic loads. The main evaluation criterion for cyclic strength is the ***fatigue safety factor***. The accumulation of fatigue damage is calculated according to ***the linear damage summation hypothesis***. It is assumed that corrosion wear of the boiler metal is uniformly distributed over its surface. Fatigue failure is considered to occur within the elastic deformation range.

Four calculation scenarios are considered in the analysis:

Option 1 – Ideal condition with no corrosion damage.

Option 2 – Corrosion depth up to 1 mm.

Option 3 – Corrosion wear depth up to 2 mm.

Option 4 – Significant corrosion damage up to 3 mm.

This research enables evaluation of how corrosion depth affects the fatigue strength of the structure. The linear damage summation hypothesis allows for predicting the boiler's service life under various wear conditions. Assuming uniform corrosion simplifies calculations, although in real conditions wear may be non-uniform. The elastic deformation analysis identifies critical stress zones without considering plastic deformations. Comparative analysis of the scenarios makes it possible to establish a relationship between corrosion depth and fatigue strength reduction.

**Presentation of the main material and description of the software and mathematical tools.** ***Development of the calculation model of the tank wagon boiler*****.** The development of the calculation model of the tank wagon boiler was carried out using a modern engineering software suite. The model was based on design and technological documentation for a standard reference structure.

The calculation model includes the geometric parameters of the investigated object. It accounts for the mass-inertia characteristics of the boiler when fully loaded, in accordance with the design documentation standards. The physical and mechanical properties of the boiler material were also integrated into the computational scheme. The thickness of individual structural elements was specified based on the degree of their corrosion wear. The model makes it possible to assess how corrosion affects the load-bearing capacity of the boiler walls. Accounting for variable metal thickness improves the accuracy of strength predictions. The calculated parameters correspond to the operating conditions of the tank wagon. The stress-strain analysis considers the actual technical condition of the boiler. Modeling also accounts for the interaction between individual structural elements under load. The obtained results allow for the estimation of the boiler's residual service life, taking material degradation into account.

The boiler model is implemented using three-dimensional solid finite elements of the tetrahedral type. Each node in the model has six degrees of freedom, which allows for all possible displacements and deformations to be considered. The boundary surfaces of the elements are described using parabolic functions to increase modeling accuracy. The geometry of joints between shell plates and the end caps is detailed. Shaped brackets and saddle supports are modeled as simplified elements that constrain the boiler's position. These elements restrict the boiler's movement in the longitudinal, transverse, and vertical directions.

The computational mesh contains 540,440 finite elements and 1,015,310 nodes. The maximum element size is 48 mm, ensuring efficient computation. The minimum element size is 8 mm, allowing precise representation of critical zones. The mesh gradient has a refinement factor of 1.4, ensuring smooth transitions between zones of varying detail. The use of tetrahedral elements makes it possible to effectively model the complex geometry of the boiler. Parabolic surface approximation

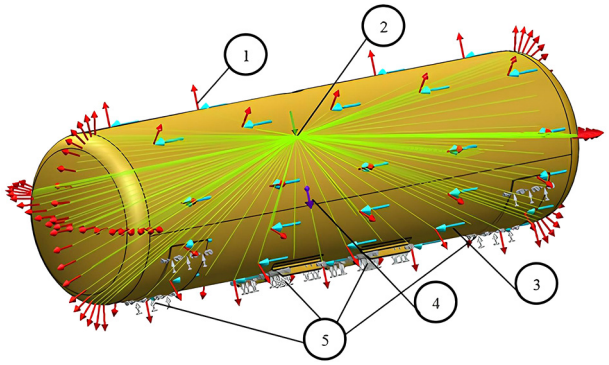


*Fig. 1. Calculation scheme of the tank wagon for analyzing the stress-strain state under longitudinal impact force:*

*1 – Internal pressure in the boiler; 2 – Cargo weight; 3 – Longitudinal impact load; 4 – Gravitational acceleration; 5 – Boiler fixation on supporting elements*

improves the accuracy of stress-strain state calculations. Detailed modeling of plate joints provides more accurate estimates of local stresses in these zones. The simplified representation of attachments maintains model adequacy while reducing computational load.

The mesh density is optimized to balance result accuracy with computational efficiency.

The calculation scheme of the tank boiler under the action of longitudinal impact force is shown in Fig. 1.

***Calculations performed.*** According to the existing methodology [8–10], the calculated strength limits were determined for the control zones of the boiler. Manhole area: 48.2 MPa. Shaped brackets: 41.72 MPa. Saddle supports: 123.92 MPa. End caps: 92.92 MPa.

The formula for determining the stress amplitude under vertical dynamic forces is

$$\sigma^I_{a,i} = \sigma_{st} \cdot k_d, \qquad (1)$$

where $\sigma^I_{a,i}$ is stress amplitude (dynamic level); $\sigma_{st}$ is static stress calculated from permanent loads (e.g., cargo weight, internal pressure); $k_d$ is the dynamic coefficient depending on the load type and natural frequencies of the structure.

The dynamic coefficient in the $i^{th}$ velocity range is defined as

$$k_d = \frac{\bar{k}_d}{\beta}\sqrt{\frac{4}{\pi}\ln\frac{1}{1-P(k_d)}}, \qquad (2)$$

where $\bar{k}_d$ is average probable value of the vertical dynamic coefficient; β is a distribution parameter (dimensionless), β = 1.13; $P(k_d)$ is random function with a probabilistic distribution, $P(k_d) = 0.97$.

General notes include:

1) the dynamic coefficient accounts for:

2) resonance (if the load frequency is close to the natural frequency of the boiler);

3) impulse shape (impact, vibration, pressure pulsation, etc.);

4) static stress is calculated using classical strength of materials formulas:

- for internal pressure: $\sigma_{st} = \frac{p \cdot D}{2t}$ (for thin-walled cylinders);

- for cargo weight: $\sigma_{st} = \frac{m \cdot g}{A}$ ($A$ is the area).

Additional factors are as follows:

- for greater accuracy, material damping and nonlinear deformation can be included;

- in case of impact loads (e.g., longitudinal forces during coupling), impact theory or simulation is used.

The authors performed a series of studies to determine the amplitude levels of stress in the $i^{th}$ interval of Mode I for options 1–4 using formula (1). As an example, the results for Option 3 (2 mm corrosion) are shown below.

Using the known values for the total number of dynamic stress cycles from vertical dynamic forces, the component values of dynamic stress amplitudes in a conventional symmetric cycle during impact interaction of the tank wagon are determined using the following formula

$$\sigma^I_{a,e} = \sqrt[m]{\frac{N^I_c}{N_0}\sum_{i=1}^{n}(\sigma^I_{a,i})^m \cdot p^I_i}, \qquad (3)$$

where $N^I_c$ is the total number of cycles of longitudinal forces transmitted through the coupler over the calculated service period; $N_0$ is an amplitude stress level in the $i^{th}$ interval; $m$ is exponent in the fatigue curve equation; $p_i$ is probability of occurrence of amplitude in the $i^{th}$ interval.

As an example, Table 2 provides the results for Option 3 (corrosion depth of 2 mm)

The amplitude levels of stress due to the impact interaction of the tank wagon with adjacent wagons in the $i^{th}$ interval are interrelated with equivalent stresses in the examined areas. These are defined by the computational scheme (Fig. 1) and are illustrated in Figs. 2–4 as examples for Option 3 (corrosion depth = 2 mm).

Maximum equivalent stresses in the most loaded boiler areas. The maximum values of equivalent stresses in the most stressed regions of the tank wagon boiler are listed below: Variant 1 (no corrosion): Manhole area: 121 MPa. Bracket area: 86 MPa. Saddle area: 123 MPa.

*Table 1*

Calculated stress amplitude levels for Option 3

| Speed Interval, m/s | Vertical Dynamic Coefficient $k_d$ | The level of stress amplitudes in the $i^{th}$ interval for the $i^{th}$ mode, MPa | | | |
|---|---|---|---|---|---|
| | | $\sigma^I_{a,i1}$ | $\sigma^I_{a,i2}$ | $\sigma^I_{a,i3}$ | $\sigma^I_{a,i4}$ |
| | | Manhole | Brackets | Saddle | End Caps |
| 0–12.5 | 0.039 | 1.28 | 1.01 | 4.17 | 3.63 |
| 12.5–15.0 | 0.086 | 2.82 | 2.23 | 9.17 | 7.98 |
| 15.0–17.5 | 0.110 | 3.63 | 2.87 | 11.80 | 10.28 |
| 17.5–20.0 | 0.144 | 4.73 | 3.75 | 15.41 | 13.41 |
| 20.0–22.5 | 0.178 | 5.84 | 4.63 | 19.01 | 16.55 |
| 22.5–25.0 | 0.211 | 6.95 | 5.51 | 22.61 | 19.69 |
| 25.0–27.5 | 0.245 | 8.05 | 6.39 | 26.22 | 22.83 |
| 275–30.0 | 0.279 | 9.16 | 7.27 | 29.82 | 25.96 |
| 30.0–32.5 | 0.312 | 10.2 | 8.15 | 33.42 | 29.10 |
| 32.5–35.0 | 0.346 | 11.3 | 9.02 | 37.02 | 32.24 |

*Table 2*

Calculated amplitude components of dynamic stress for a conventional symmetric cycle during impact interaction (Option 3)

| Interval No. | The level of stress amplitudes in the $i^{th}$ interval for the $i^{th}$ mode, MPa | | | |
|---|---|---|---|---|
| | $(\sigma^I_{a,i1})^m \cdot p^I_i$ | $(\sigma^I_{a,i2})^m \cdot p^I_i$ | $(\sigma^I_{a,i3})^m \cdot p^I_i$ | $(\sigma^I_{a,i4})^m \cdot p^I_i$ |
| | Manhole Area | Bracket Area | Saddle Area | End Cap Area |
| 1 | 0.216 | 0.085 | 24.187 | 13.901 |
| 2 | 10.746 | 4.256 | 1,204.005 | 692.002 |
| 3 | 38.184 | 15.124 | 427.429 | 2,459.029 |
| 4 | 151.056 | 59.830 | 16,925.355 | 9,727.854 |
| 5 | 210.000 | 83.176 | 23,529.926 | 13,523.833 |
| 6 | 116.771 | 46.250 | 13,083.906 | 7,519.979 |
| 7 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 |
| $\sum_{i=1}^{n}(\sigma^I_{a,i})^m \cdot p^I_i$ | 526.973 | 208.721 | 59,045.807 | 33,936.599 |

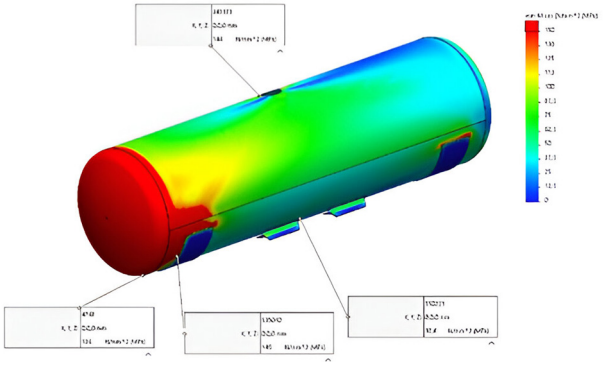

*Fig. 2. Stress field distribution in the tank boiler under a longitudinal impact force of 3.8 MN with 2 mm corrosion depth*

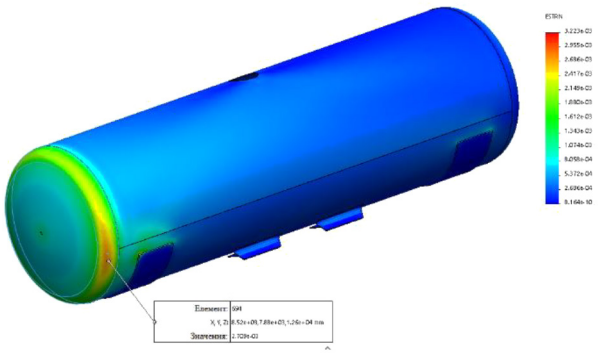

*Fig. 4. Strain distribution of the tank shell under 3.8 MN longitudinal dynamic load with 2 mm wall thickness reduction*

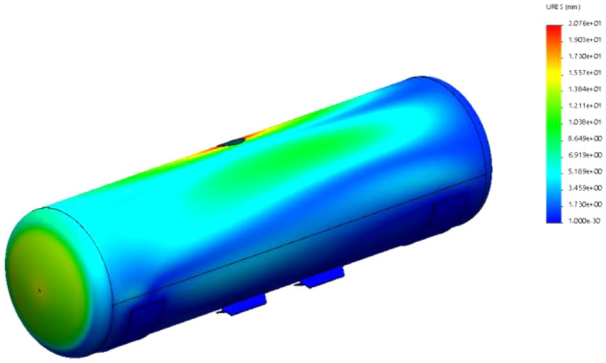

*Fig. 3. Displacement distribution of the tank boiler walls under 3.8 MN longitudinal dynamic load with 2 mm corrosion loss*

End cap area: 152 MPa. Variant 2 (corrosion depth up to 1 mm): Manhole area: 126 MPa. Bracket area: 93 MPa. Saddle area: 135 MPa. End cap area: 170 MPa. Variant 3 (corrosion depth up to 2 mm): Manhole area: 144 MPa. Bracket area: 98 MPa. Saddle area: 149 MPa. End cap area: 186 MPa. Variant 4 (corrosion depth up to 3 mm): Manhole area: 156 MPa. Bracket area: 119 MPa. Saddle area: 167 MPa. End cap area: 210 MPa. Formula for the total number of longitudinal load cycles on the coupler over the service life. The total number of longitudinal force cycles acting on the automatic coupler over the calculated service life is determined using the formula

$$N_c^{II} = N_p \cdot T_K, \tag{4}$$

where $N_p$ is the annual number of impact loads on the coupler, according to references [8–10], $N_p = 20.197$; $T_K$ is duration of the considered service period in years

Table 3 presents the annual distribution of longitudinal impact forces depending on cycle amplitude and frequency.

Table 4 presents calculated amplitude stress levels in Mode II for Variant 3 (corrosion depth 2 mm).

Table 5 shows the dependency of the total number of longitudinal load cycles on the extended service life of the tank wagon, including up to 1.5 times the normative period (24–36 years).

The calculated values of the fatigue safety factor for the tank wagon boiler were determined under opera-

tional conditions involving variable wall thickness. The research covers an extended service period, up to 1.5 times the normative service life (24–36 years) for all analyzed Variants 1–4, reflecting different levels of material degradation.

The modeling took into account the probabilistic nature of loads depending on the train's speed. The obtained data were systematized to evaluate the long-term effect of operation on the boiler's load-bearing capacity.

*Table 3*

Distribution of longitudinal impact forces

| Distribution of longitudinal impact forces, MN | Cycle amplitude, MN | Frequency of amplitudes | Number of cycles per year |
|---|---|---|---|
| | $F_{ai}^{y}$ | $p_i^{II}$ | $N_p$ |
| 0.1–0.4 | 0.25 | 0.1258 | 2,539 |
| 0.4–0.8 | 0.6 | 0.2852 | 5,761 |
| 0.8–1.2 | 1 | 0.2802 | 5,661 |
| 1.2–1.6 | 1.4 | 0.1832 | 3,699 |
| 1.6–2.0 | 1.8 | 0.0772 | 1,554 |
| 2.0–2.4 | 2.2 | 0.0359 | 725 |
| 2.4–2.8 | 2.6 | 0.0098 | 202 |
| 2.8–3.2 | 3 | 0.0023 | 48 |
| 3.2–3.6 | 3.4 | 0.0003 | 6 |
| 3.6–4.0 | 3.8 | 0.0001 | 2 |
| Total: | 1 | 20,197 | |

*Table 4*

Calculated Amplitude Stress Levels for Mode II (Variant 3)

| Interval No. | Manhole area, MPa | Bracket area, MPa | Saddle area, MPa | End cap area, MPa |
|---|---|---|---|---|
| | $\sigma_{a,i1}^{II}$ | $\sigma_{a,i2}^{II}$ | $\sigma_{a,i3}^{II}$ | $\sigma_{a,i4}^{II}$ |
| 1 | 9.474 | 6.421 | 9.803 | 12.237 |
| 2 | 22.737 | 15.411 | 23.526 | 29.368 |
| 3 | 37.895 | 25.684 | 39.211 | 48.947 |
| 4 | 53.053 | 35.958 | 54.895 | 68.526 |
| 5 | 68.211 | 46.232 | 70.579 | 88.105 |
| 6 | 83.368 | 56.505 | 86.263 | 107.684 |
| 7 | 98.526 | 66.779 | 101.947 | 127.263 |
| 8 | 113.684 | 77.053 | 117.632 | 146.842 |
| 9 | 128.842 | 87.326 | 133.316 | 166.421 |
| 10 | 144.0 | 97.60 | 149.0 | 186.0 |

*Table 5*

Dependence of total number of longitudinal load cycles on extended service life

| $N_c^{II}$, Total number of cycles | 484,728 | 525,122 | 565,516 | 605,910 | 646,304 | 686,698 | 727,092 |
|---|---|---|---|---|---|---|---|
| $T_K$, Service life (years) | 24 | 26 | 28 | 30 | 32 | 34 | 36 |

To illustrate the research results, graphical dependencies are presented below for Variant 3.

These figures reflect the influence of operating speed and time on the decline of fatigue strength, even in the absence of corrosion. In subsequent scenarios (Variant 3), the influence of corrosion is overlaid onto these baseline curves.

**Discussion of the obtained results.** The analysis of the fatigue strength results for the tank wagon boiler allowed the following conclusions to be drawn:

*Variant 1 (No Corrosion):*

At speeds of 90, 100, and 120 km/h, the fatigue safety factors remain within acceptable limits over the full 24–36 year service range. The boiler structure demonstrates stability under dynamic loads in all control areas.

*Variant 2 (Corrosion up to 1 mm):*

Compared to Variant 1, a decrease in the fatigue safety factor by 8–11 % is observed across all speed ranges (90–120 km/h). These values still do not reach critical thresholds even with 1.5 times the normative service life. The structure remains safe, although corrosion effects are already noticeable.

*Variant 3 (Corrosion up to 2 mm):*

After 34 years of operation at 90–100 km/h, the fatigue safety factor in the manhole area approaches the allowable limit. At 30 years and 120 km/h, critical values are reached in the manhole and end cap areas. The brackets and saddle supports remain within safe operating limits. There is a risk of failure in the most heavily loaded zones.

*Variant 4 (Corrosion up to 3 mm):*

Manhole area: Reaches critical condition after only 26 years at 90 km/h.

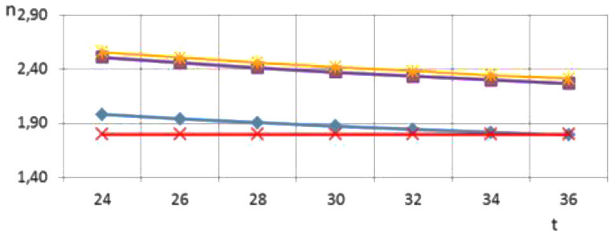


*Fig. 5. Graph of fatigue safety factor vs. service life for the boiler (Speed = 90 km/h, no corrosion, Variant 3)*

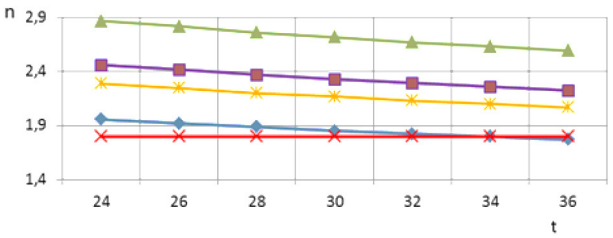


*Fig. 6. Graph of fatigue safety factor vs. service life for the boiler (Speed = 100 km/h, no corrosion, Variant 3*

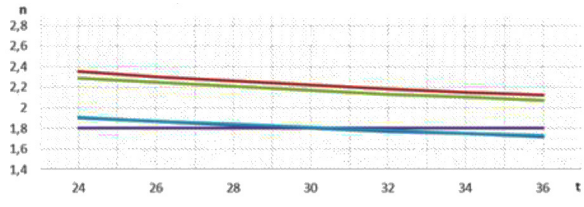


*Fig. 7. Graph of fatigue safety factor vs. service life for the boiler (Speed = 120 km/h, no corrosion, Variant 3)*

End caps: Structural strength falls below safe levels after 30 years at 100 km/h.

Brackets: Exceed safe limits after 34 years at 120 km/h.

The structure loses integrity across all main elements, requiring immediate repair or replacement.

***Key conclusions.*** Corrosion significantly reduces the structural lifespan of the boiler, especially in the manhole and end cap areas.

When corrosion exceeds 2 mm, critical conditions may arise before the normative service life ends.

Increased operating speeds accelerate fatigue failure.

Brackets and saddle supports exhibit greater strength reserves than the boiler's main elements.

To extend service life, anti-corrosion measures and regular condition monitoring are essential.

The findings support the need for preventive maintenance and speed restrictions on tanks with significant corrosion wear.

**General conclusions.** The diagnostics revealed significant corrosion of the load-bearing system in chemical tank wagons that have exceeded their normative service life. This necessitates: Evaluation of residual structural strength; Calculation of ultimate service life; Development of technical solutions for extending safe operation.

Both directions emphasize: The seriousness of corrosion-related defects; The direct threat to operational safety; The need for urgent engineering actions.

This paper presents the results of a stress-strain state analysis of the tank boiler using SolidWorks. The theoretical analysis confirmed that the depth and location of corrosion significantly influence structural strength. The most dangerous zones under corrosion damage exceeding 3 mm were identified as the end caps and manholes. Corrosion of 3 mm or more renders further operation of the boiler unsafe.

With corrosion up to 2 mm, the maximum service life is approximately 30 years. If no corrosion is present, service life may be extended by an additional 12 years, resulting in a total of 36 years. The SolidWorks simulation system effectively identified critical stress zones. The results highlight the necessity of regular metal condition monitoring, with particular attention to end caps and manholes.

The study revealed a clear relationship between reduced wall thickness due to corrosion and the decrease in the fatigue safety factor. Corrosion has the most critical impact on highly stressed zones of the tank boiler. Metal thickness is a key parameter when assessing the structure's remaining life. The proposed methodology allows for accurate prediction of safe operating limits. For tank wagons beyond their nominal service life, corrosion monitoring is especially critical. Chemical cargoes accelerate the corrosion process.

The established patterns provide a basis for justified service life extension. A systematic approach to condition assessment helps prevent accidents. The methodology accounts for the individual wear characteristics of each tank. The findings can serve as a basis for updating safety regulations.

The proposed method enables residual life assessment of tank wagon boilers after the normative period ends. By factoring in corrosion wear and stress concentration, the method forecasts safe continued use. Analysis of the most loaded structural areas is crucial for determining fitness for further use.

The approach combines computer simulations and real-world tests, providing an objective evaluation of the structural condition. The results support reasoned decisions on the permissible duration of extended operation.

The method is especially effective for tanks transporting aggressive substances. The evaluation criteria account for both general wear and localized defects. Applying this method can prevent premature decommissioning of structurally sound wagons and inform the development of new safety standards.

**References.**


**1.** Coto, B. V., Luque Rodríguez, P., Álvarez Mántaras, D., & Perez, J. A. (2025). Influence analysis of secondary suspension preload on the dynamic response of Y-25 bogie based on multibody simulations. *Vehicle System Dynamics*, 1-23. https://doi.org/10.1080/00423114.2025.2460494

**2.** Melnik, R., Koziak, S., Seńko, J., Dižo, J., & Caban, J. (2024). Evaluation of Dynamics of a Freight Wagon Model with Viscous Damping. *Applied Sciences, 14*(22), 10624. https://doi.org/10.3390/app142210624

**3.** Dižo, J., Blatnický, M., Harušinec, J., & Suchánek, A. (2022). Assessment of Dynamics of a Rail Vehicle in Terms of Running Properties While Moving on a Real Track Model. *Symmetry, 14*(3), 536. https://doi.org/10.3390/sym14030536

**4.** Stoilov, V., Sinapov, P., Slavchev, S., Maznichki, V., & Purgic, S. (2024). Analysis of Lateral Forces for Assessment of Safety against Derailment of the Specialized Train Composition for the Transportation of Long Rails. *Applied Sciences, 14*(2), 860. https://doi.org/10.3390/app14020860

**5.** Shvets, A. (2021). Analysis of the dynamics of freight cars with lateral displacement of the front bogie. *Advanced Mathematical Models and Applications, 6*(1), 45-58. Retrieved from https://crust.ust.edu.ua/server/api/core/bitstreams/500db76a-d3a8-4b5f-bcc2-2f385e-ab0952/content

**6.** Bulakh, M. (2025). Evaluation and Reduction of Energy Consumption of Railway Train Movement on a Straight Track Section with Reduced Freight Wagon Mass. *Energies, 18*(2), 280. https://doi.org/10.3390/en18020280

**7.** Shvets, A., Bolotov, O., Percevoj, A., Ghlukhov, V., Bolotov, O., & Saparova, L. (2020). Research of dynamic indicators and influence of different types of rolling stock on railway track. *IOP Conference Series: Materials Science and Engineering, 985*(1), 012010. https://doi.org/10.1088/1757-899X/985/1/012010

**8.** Koshel, O., Sapronova, S., & Kara, S. (2023). Revealing patterns in the stressed-strained state of load-bearing structures in special rolling stock to further improve them. *Eastern-European Journal of Enterprise Technologies, 4*(7(124)), 30-42. https://doi.org/10.15587/1729-4061.2023.285894

**9.** Sapronova, S., Tkachenko, V., Fomin, O., Hatchenko, V., & Maliuk, S. (2017). Research on the safety factor against derailment of railway vehicles. *Eastern-European journal of enterprise technologies*, *6*(7(90)), 19-25. https://doi.org/10.15587/1729-4061.2017.116194

**10.** Fomin, O., Sulym, A., Kulbovskyi, I., Khozia, P., & Ishchenko, V. (2018). Determining rational parameters of the capacitive energy storage system for the underground railway rolling stock. *Eastern-European Journal of Enterprise Technologies, 2*(1(92), 63-71. https://doi.org/10.15587/1729-4061.2018.126080

**11.** Sulym, A. O., Fomin, O. V., Khozia, P. O., & Mastepan, A. G. (2018). Theoretical and practical determination of parameters of onboard capacitive energy storage of the rolling stock. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 79-87. https://doi.org/10.29202/nvngu/2018-5/8

**12.** Sokolov, V. (2021). Hydrodynamics of Flow in a Flat Slot with Boundary Change of Viscosity. In *Proceedings of the 6th International Conference on Industrial Engineering (ICIE 2020). Lecture Notes in Mechanical Engineering, 2*, 1172-1181. Springer, Cham. https://doi.org/10.1007/978-3-030-54817-9_136

**13.** Sokolov, V. (2020). Increased Measurement Accuracy of Average Velocity for Turbulent Flows in Channels of Ventilation Systems. *Proceedings of the 6th International Conference on Industrial Engineering (ICIE 2020). Lecture Notes in Mechanical Engineering, 2*, 1182-1190. Springer, Cham. https://doi.org/10.1007/978-3-030-54817-9_137

**14.** Sagin, S., Kuropyatnyk, O., Sagin, A., Tkachenko, I., Píštěk, V., & Kučera, P. (2022). Ensuring the Environmental Friendliness of Drillships during Their Operation in Special Ecological Regions of North-

ern Europe. *Journal of Marine Science and Engineering*, *10*, 1331. https://doi.org/10.3390/jmse10091331
**15.** Sagin, S. V., Sagin, S. S., Gaichenia, O., Zablotskyi, Y., Píštěk, V., & Kučera, P. (2024). Use of biofuels in marine diesel engines for sustainable and safe maritime transport. *Renewable Energy, 224*, 120221. https://doi: 10.1016/j.renene.2024.120221
**16.** Krol, O. (2021). Modeling of Worm Gear Design with Non-clearance Engagement. *Proceedings of the 6th International Conference on Industrial Engineering (ICIE 2020). ICIE 2020. Lecture Notes in Mechanical Engineering, 1*, 36-46. Springer, Cham. https://doi.org/10.1007/978-3-030-54814-8_5
**17.** Kondratiev, A., Píštěk, V., Smovziuk, L., Shevtsova, M., Fomina, A., Kučera, P., & Prokop, A. (2021). Effects of the temperature–time regime of curing of composite patch on repair process efficiency. *Polymers, 13*(24), 4342. https://doi.org/10.3390/polym13244342
**18.** Kondratiev, A. V., & Kovalenko, V. O. (2019). Optimization of design parameters of the main composite fairing of the launch vehicle under simultaneous force and thermal loading. *Space science and technology, 25*(4(119)), 3-21. https://doi.org/10.15407/knit2019.04.003
**19.** Melnyk, O., Onishchenko, O., Mykhailova, I., Zaiets, A., & Kotenko, O. (2024). Safety management in maritime transport within the framework of current challenges, trends, risks and settlement strategies. *Studies in Systems, Decision and Control*, *561*, 459-475. https://doi.org/10.1007/978-3-031-68372-5_25
**20.** Onishchenko, O., Bulgakov, M., Melnyk, O., Volianska, Y., Storchak, O., & Kovalchuk, M. (2024). Environmental sustainability in maritime transportation through the development of strategies to reduce emissions from marine internal combustion engines. *Studies in Systems, Decision and Control, 561*, 509-534. https://doi.org/10.1007/978-3-031-68372-5_28
**21.** Kurdiuk, S., Dremliuk, V., Melnyk, O., Onishchenko, O., Píšťek, V., & Kučera, P. (2025). Development of a High-Reliability Hybrid Data Transmission System for Unmanned Surface Vehicles Under Interference Conditions. *Drones, 9*, 174. https://doi.org/10.3390/drones9030174
**22.** Lovska, A., Muradian, A., Barsukova, H., Yurchenko, O., & Demydiukov, O. (2025). Determining the loading of an improved tank container for railroad transportation. *Eastern-European Journal of Enterprise Technologies, 1*(7(133)), 90-98. https://doi.org/10.15587/1729-4061.2025.321858
**23.** Panchenko, S., Gerlici, J., Vatulia, G., Lovska, A., Rybin, A., & Kravchenko, O. (2023). Strength Assessment of an Improved Design of a Tank Container under Operating Conditions. *Communications – Scientific Letters of the University of Zilina, 25*(3), B186-B193. https://doi.org/10.26552/com.c.2023.047
**24.** Goolak, S., Sapronova, S., Tkachenko, V., Riabov, Ie., & Batrak, Ye. (2020). Improvement of the Model of Power Losses in the Pulsed Current Traction Motor in an Electric Locomotive. *Eastern-European Journal of Enterprise Technologies, 6*(5(108)), 38-46. https://doi.org/10.15587/1729-4061.2020.218542
**25.** Goolak, S., Tkachenko, V., Bureika, G., & Vaičiūnas, G. (2020). Method of spectral analysis of traction current of AC electric locomotives. *Transport, 35*(6), 658-668. https://doi.org/10.3846/transport.2020.14242
**26.** Goolak, S., Liubarskyi, B., Sapronova, S., Tkachenko, V., & Riabov, Ie. (2021) Refined Model of Asynchronous Traction Electric Motor of Electric Locomotive. *Transport Means – Proceedings of the International Conference*, 2021-October, (pp. 455-460).

## Оцінка втомної міцності котла вагона-цистерни з урахуванням корозійних зносів

*О. В. Фомін*[*1], *Ю. В. Щербина*[1], *Є. П. Медведев*[2], *Т. В. Ємельянова*[3], *О. О. Остроглядо*[4]

1 – Національний транспортний університет, м. Київ, Україна
2 – Гданський технологічний університет, м. Гданськ, Республіка Польща
3 – Харківський національний автомобільно-дорожній університет, м. Харків, Україна
4 – Національний університет «Запорізька політехніка», м. Запоріжжя, Україна
[*] Автор-кореспондент e-mail: fomin1985@ukr.net

**Мета.** Визначення напружено-деформованого стану оболонки котла вагона-цистерни та оцінки її втомної міцності при виникненні різного рівня корозійного зносу засобами комп'ютерного моделювання.

**Методика.** Для оцінки стійкості до руйнування від багаторазових навантажень котла вагона-цистерни застосовувалася спеціальна методика. Вона базується на загальних принципах розрахунку, що використовуються для вузлів і деталей залізничних вагонів. Розглядалися різні сценарії, що імітують корозійні пошкодження металу: повна відсутність корозії, наявність корозії глибиною до одного міліметра, корозія глибиною до двох міліметрів і корозійне пошкодження глибиною до трьох міліметрів.

**Результати.** Результати проведеного аналізу вказують на значний вплив глибини корозійного ураження та його розташування на міцність котла вагона-цистерни. Ці фактори є критично важливими при оцінюванні надійності елементів конструкції. Отже, при визначенні міцності необхідно обов'язково враховувати ступінь і місце корозійного зносу металу.

**Наукова новизна.** Проведене дослідження виявило наукові залежності зміни коефіцієнтів запасу міцності щодо втоми в найбільш навантажених зонах котла вагона-цистерни. Ці зміни безпосередньо пов'язані з появою й розвитком корозійних дефектів. Отримані закономірності чітко демонструють важливість товщини металевої оболонки для забезпечення надійності конструкції. Особливо це актуально для вагонів, термін експлуатації яких добігає кінця. Запропонована методика дозволяє оцінити можливість подальшого використання таких цистерн зі збільшеним терміном служби, ураховуючи рівень корозійних пошкоджень.

**Практична значимість.** Дослідження виявили, що критичними зонами при корозійному руйнуванні глибиною від трьох міліметрів є ділянки днищ і люка котла вагона-цистерни. Пошкодження такого рівня роблять подальшу експлуатацію котла неможливою. Водночас, при виникненні корозії з меншою глибиною, до двох міліметрів, граничний термін служби котла може сягати тридцяти років. За умови відсутності будь-яких ознак корозії, термін експлуатації може бути значно подовжений. Зокрема, його можна збільшити на дванадцять років понад встановлений термін. Таким чином, загальний можливий термін служби становитиме тридцять шість років. Упровадження цих результатів дозволить більш обґрунтовано приймати рішення щодо продовження терміну служби вагонів-цистерн і допоможе запобігти виникненню аварійних ситуацій, пов'язаних зі зношеністю рухомого складу.

**Ключові слова:** *транспортна механіка, рухомий склад, вагони, комп'ютерне моделювання, корозія металу*

*The manuscript was submitted 18.03.25.*