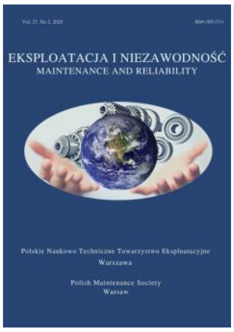

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 27 (2025), Issue 2

journal homepage: http://www.ein.org.pl

Article citation info:
Bulakh M, Estimate and Extend the Time between Overhauls for the Railcar Body, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2025: 27(2) http://doi.org/10.17531/ein/195021

Estimate and Extend the Time between Overhauls for the Railcar Body

Indexed by: Web of Science Group

Maryna Bulakh[a,*]

[a] Faculty of Mechanics and Technology, Rzeszow University of Technology, Poland

Highlights

- The work aimed to estimate and extend the time between overhauls of railcar body.
- A novel approach was proposed, incorporating an operational factor of safety.
- A new equation was introduced to determine the time between overhauls of railcar body.
- The proposed design extends time between overhauls by 1.21 to 2.06 times.

Abstract

This paper addresses the challenge of estimating and extending the time between overhauls of railcar bodies, which are crucial components in rail freight transportation. Railcar bodies endure significant operational loads, leading to damage and the need for frequent repairs. In response to this issue, a novel approach has been proposed: the use of an operational factor of safety that considers both the probability of failure-free operation and the likelihood of load occurrence on the railcar body. A new equation has been introduced to determine the time between overhauls of these bodies. The focus of this paper is on the development of innovative engineering solutions aimed at enhancing the strength and reliability of railcar bodies. Theoretical and experimental studies were conducted to validate the effectiveness of the proposed design. The results demonstrate that the implementation of these solutions can extend the time between overhauls of the railcar body by 1.21 to 2.06 times, depending on operating conditions. This work contributes to the development of efficient and sustainable technologies for railway transport, which is particularly important given the growing demand for freight transportation and the need to reduce environmental impact.

Keywords

railcar body, time between overhauls, railway transport, operational factor of safety; design.

1. Introduction

In today's world, railway transport is crucial for economic stability and development, serving as one of the most efficient methods for transporting large volumes of cargo over long distances. It is a fundamental component of global supply chains. With global trends such as urbanization, globalization, and climate change, enhancing efficient railway transport is vital for the future of sustainable transportation worldwide. Increasing the operational efficiency of railway transport is a priority and a significant challenge for many countries [1]. As the demand for transportation grows, improving the durability, strength, and reliability of rolling stock becomes increasingly important.

Railcars (RCs) play an extremely important role in the railway freight transport system, providing an efficient, economical, and environmentally friendly means of transporting goods. However, RCs operate under specific conditions. The aggressive impact of cargo, damage during loading and unloading operations, significant operational

(*) Corresponding author.
E-mail addresses: M. Bulakh (ORCID: 0000-0003-4264-2303) m.bulakh@prz.edu.pl

loads, worn rolling stock, and poor track conditions lead to damage and necessitate repairs. More than 40% of damages requiring rolling stock repair occur to the RC body (RCB). Meanwhile, damage to critical elements such as the RCB frame accounts for less than 30%,, and to braking equipment, 15%.

The majority of RC malfunctions (over 50%) are technological in nature. This is due to several reasons, with violations of loading and unloading technology being a significant factor. For example, the number of RCs damaged by a grab crane annually fluctuates around 1,000 units.

Among the most common types of RCB malfunctions, a significant portion is due to damage to the material (cladding) in contact with the cargo, caused by the low strength reserve coefficient of the material. Increasing the strength coefficient of RCs is directly related to reducing maintenance and repair costs. A strong and reliable RCB requires less frequent repairs, leading to significant reductions in operational costs [2, 3]. In the context of rising material and maintenance costs, savings on these expenses can significantly increase the profitability of rail transport. Enhancing the durability of RCs also positively impacts the environment. Lower material and energy consumption for producing new cars and repairing old ones contribute to reducing environmental burden, thereby improving the ecological situation and fulfilling international commitments to reduce greenhouse gases. This is particularly important in the context of the need to transition to more sustainable forms of transport. A strong and reliable RC ensures greater transportation efficiency by increasing time between overhauls (TBO) and reducing downtime. This allows for the optimization of logistical processes and increases the throughput capacity of railway lines [4].

In addition to the negative operational and financial consequences, RC malfunctions often cause transportation incidents of varying degrees of severity, making them highly significant in terms of safety. Among the RC elements whose failures cause transportation incidents, braking equipment ranks first, box knots second, and the RCB third [1, 4]. Collectively, the failure of these elements accounts for over 70% of all RC malfunctions [1, 5]. Therefore, increasing the strength of the car body also contributes to improving railway transport safety.

Higher operational efficiency of railway transport can be ensured by implementing new engineering solutions for RC design. These solutions should focus on increasing the strength and reliability of the RCB, improving the anti-corrosion and anti-friction properties of structural materials, extending TBO, and reducing overall production and operational costs [5]. A strong RCB has a lower risk of deformation and accidents, reducing track wear and the risk of incidents. Additionally, a robust RCB enhances the dynamic characteristics of trains, contributing to more stable and predictable movement.

Modern materials and engineering solutions enable the creation of RCs with increased strength and durability coefficients without compromising their weight. The use of high-strength steels, aluminium alloys, and composite materials provides the necessary rigidity and stability while maintaining or even reducing the optimal weight.

2. Literature review.

Maintenance is crucial for ensuring the durability, reliability and safety of rail transport. According to the authors [6], the cost of maintenance over the entire life cycle of rolling stock accounts for 60%-75% of its initial cost. Therefore, maintaining stability and reducing maintenance costs are also important from the perspective of lowering overall operating expenses.

The development of a maintenance strategy in rail transport is a significant concern for scientists, as it involves many factors. These factors include the specifics of maintenance facilities, the purpose of its implementation, budget, considerations, equipment criticality, available resources, technological capabilities, and more. Additionally, railway companies often employ a combination of different strategies, tailored to specific needs and conditions. Hence, in the works [7-9] a significant number of studies have been conducted on mathematical models and decision support models to improve the applications of planning and scheduling of railway track and bridge maintenance. Meanwhile, the authors in [10, 11] introduced intelligent Petri net models that effectively address the maintenance and operation of railway sections and systems. Specifically, the model [10] combines Petri net with reinforcement learning to create a model capable of simultaneous simulation and learning. In addition to the track strategy, the authors also developed innovative methods for reliability testing [12].

Regarding the main goals of developing maintenance strategies, most authors emphasize reliability and the maximization of TBO. For example, in [13], a model is proposed that generates a joint schedule for train operation and opportunistic predictive maintenance activities to maximize the TBO. The application of this model to the high-speed train fleet in Spain shows a significant improvement in component resource utilization. The effect of maintenance on equipment age can be estimated using the Weibull risk function, while the effect on condition can be assessed using the Cox risk function [14].

According to the authors [15], the future maintenance work will be based on the creation of systems focused on reliability. To ensure the high reliability of rolling stock, it is crucial to implement reliability analysis methods and utilize new management indicators that account for the impact of faults on both transport and economic characteristics. Supporting this view, the authors have developed strategies for reliability-oriented maintenance [15, 16]. It is important to note that in developing such strategies, evaluation methods [17, 18], analysis techniques [19], reliability modeling [20, 21] and the prediction of failure frequency [22] and reliability indicators are vital, both for the entire system [23] and for its individual elements [24-26].

Many authors consider reliability in relation to durability. When designing new systems and components, it is crucial to accurately determine their ability to withstand stress and load. The article [27] explores the possibility of modeling this ability. The authors applied the interference theory of reliability, which is based on the analysis of the patterns and properties of two random variables that characterizing reliability.

In [28], a discrete PH distribution method for determining the TBO of a component under shock is presented. The relationship between various system reliability indicators and different parameters is established, and a new approach to system reliability research, based on a discrete and shock distribution, is introduced. Additionally, in [29], reliability analysis using adaptive training neural networks based on importance sampling is proposed.

Research on increasing the durability of RCs is an important element of the modernization of rail transport. Therefore, the first direction in which a number of studies can be combined is the optimization of RC design.

New and modernized RCs, in which critical elements have been improved, are presented in [30-32]. It should be noted, however, that these studies concern RCs intended for the transport of bulk materials, focusing mainly on improving the body structure to shorten loading and unloading times. For the same purpose, the authors of [33] modernized a RC for the transport of other types of cargo.

Research on methods for reinforcing RC components to reduce wear and extend TBO is presented in[36]. However, none of these studies address the RCB.

The design of the car body to increase the load-bearing capacity of railway RCs is discussed in [37]. The modernization proposed by the authors involves the fabrication of double walls filled with aluminium foam. Research results indicate that this engineering solution can enhance the operational efficiency of rail transport by increasing load-bearing capacity and reducing dynamic loads. However, it should be noted that the introduction of new materials, such as aluminium foam, and double walls may increase the production cost of the RCs. Additionally, the lack of detailed studies on the optimal pore size of aluminium foam and the technology for filling aluminium foam into tubes may pose challenges in the practical implementation of this solution.

The work [38] demonstrates the effect of aluminum alloy processing on the fatigue properties of this alloy during operation, aiming to achieve maximum reliability and safety in railway transport.

The next area of research is the application of modern materials and coatings in the construction of RCs. According to the prevailing opinion of most authors, the use of lightweight yet strong composite materials [40], aluminium alloys, and advanced steel alloys [41, 42] can significantly reduce the RCs own weight, allowing them to carry larger loads. However, the extension of TBO has not been established in these studies. Furthermore, composite structures for testing have been produced in limited quantities or as single instances. The methods used to manufacture these components are expensive for mass production.

Various approaches are used to predict the reliability and TBO of composite materials, including the Similarity Learning Hidden Semi Markov Model [43], the Navier grillage method (Monte Carlo) [44], the Arrhenius model, time-temperature superposition (TTSP), the Williams-Landel-Ferry (WLF) model, and five isoconversional approaches: Friedman's, Ozawa-Flynn-Wall (OFW), the OFW method corrected by N. Sbirrazzuoli et al., the Kissinger-Akahira-Sunose (KAS) algorithm, and the advanced isoconversional method by S. Vyazovkin [45], assumptions of the Haigh diagram, artificial neural networks, using the probabilistic Stüssi fatigue S-N fields [46], software calculation methods adapted for estimating/predicting the fatigue life of engineering structures and materials [47].

RCB malfunctions during the inter-repair operation period are detected through visual inspections. The parameters monitored include the condition of the RCB as a whole and its main load-bearing structure (LBS), such as mechanical and corrosion damage, deflections and deformations of beams, side and end walls, hatch covers, deformations of side and end walls from thrust loads, cracks in sheets, beams, and welded joints, etc. Timely detection of such damage requires the implementation of innovative maintenance methods, including predictive maintenance based on sensor data and wagon condition monitoring [48-50], as well as the development of methods for ongoing monitoring of critical wagon components and predicting their wear [51-53]. Additionally, the creation of autonomous power supply systems for these monitoring systems is necessary [54-56].

Research into the properties of railway vehicle components during the design stage is crucial for modernizing rolling stock. Contemporary approaches to designing railway cars, including optimal shapes and structures, are discussed in [57, 58]. The design solution proposed in [57] focuses on enhancing the LBS of the car platform to improve fatigue strength during operation. A distinctive feature of this solution is the use of U-profiles covered with horizontal plates for the main longitudinal beams in the frame. Flexible elements are placed between the horizontal parts of the profiles and the plates. This technical solution reduces dynamic loads on the LBS of the car platform during operation.

Prototypes of railway cars developed in [58] are adapted to various loading conditions. The research includes modelling and simulating the dynamic behaviour of these cars under different loads using CAD tools and finite element methods. The article explores various materials, including aluminium alloys, which offer higher strength at a lower weight. This results in reduced fuel consumption and increased speed.

The article [59] analyses dynamic parameters that impact the design and upgrading of freight rail equipment. It presents theoretical studies on the dynamic characteristics of various types of cars, including open wagons, flatcars, and self-discharging wagons. The article discusses how different loading conditions affect dynamic loads and their interaction with the tracks, considering the speed of movement on curves with short and medium radii. The author emphasizes that reducing the weight of wagons is crucial for increasing payload capacity and lowering operational costs by reducing metal and energy consumption.

The main directions for improving the design of RCs, as outlined in [60], include: the use of high-strength steels and innovative components and materials; reinforcing existing cars and developing entirely new types of LBSs for RCs; maximizing space utilization; creating multifunctional car designs capable of transporting a wide range of cargo, which to reduce the number of empty trips and enhances transport efficiency; increasing the structural strength of cars; applying modern assembly and welding technologies; and designing new types of cars.

These improvement directions aim to modernize freight rail equipment to enhance its efficiency, safety, and durability, which is crucial for the development of railway transport in the face of contemporary challenges. However, literature analysis indicates that none of the proposed methods for increasing the operational efficiency of rail transport are cheaper than existing methods, and most require additional operational measures.

Parallel to the development of modernization approaches for wagons, methods for researching their characteristics are also evolving. For example, [61] presents a test stand that achieves reduced testing time, decreased energy consumption, and increased measurement accuracy.

The studies reviewed place great emphasis on the development of predictive maintenance models and strategies, but they have several potential limitations, including a high dependence on the quality and quantity of available data and high investment costs in technology and expertise. These factors may not be feasible for all railway companies, particularly those in developing regions.

Another issue is the limited focus on the practical implementation of the proposed innovations. While advanced materials and coatings are suggested to reduce weight and increase load-bearing capacity, their feasibility in mass production and consistency in real-world conditions remain under-researched. Additionally, the proposed designs and materials are often tested in isolated or prototype conditions, raising concerns about their scalability and reliability in large-scale operations.

It is impossible to dismiss the importance of any of these research directions, but each requires testing new designs and materials on wagon prototypes to verify their performance under real operational conditions. Literature analysis also indicates that reducing the weight of RCs is achievable through design optimization.

The assessment and increase in the TBO of RCs is carried out based on experimental assumptions and without theoretical justification. In this regard, an urgent problem is to evaluate and increase the TBO of RCs, since the amount of goods transported on railways is constantly growing.

The aim of this study is to increase the TBO of the RCB.

To achieve this goal, theoretical and experimental studies were conducted on the TBO of RCB. The methods, materials, and results of these studies on the TBO of RCB are presented below.

3. Material and Methods.

3.1. Load model of a RCB.

Figure 1 illustrates the loading model of a RCB. For clarity, the load is depicted specifically for the fourth section of the body. In this model, the same load is applied uniformly across the entire floor of the RCB

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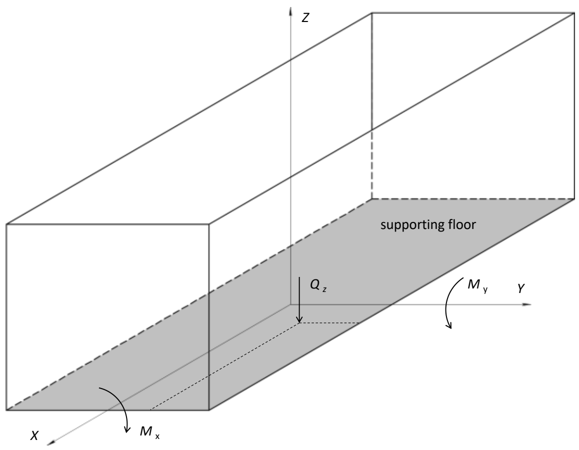


Figure 1. RCB load model.

The equation (1) can be used to calculate based on the strength condition to calculate the maximum stresses in the floor of the RCB:

$$\sigma_{max} = \frac{Q_z}{A} + \frac{M_x}{S_x} + \frac{M_y}{S_y} \leq [\sigma], \quad (1)$$

where Q_z is the vertical force acting (axe OZ) on the floor of the RCB;

A is the floor area cross-sectional value;

M_x, M_y are the OX and OY axes moments, respectively;

S_x, S_y are the axial moments of resistance, OX-axis and OY-axis, respectively;

$[\sigma]$ is the allowable stress for the material floor of the RCB. Usually the value of the yield strength of the material σ_y is taken.

Q_z, M_x, M_y represent the mechanical parameters of the load with distribution density $f(s)$.

A, S_x, S_y represent the characteristics of the strength parameters of the material floor of the RCB with distribution density $f(S)$.

Based on statistical observations of the operation of RCs, it can be argued that the distribution densities $f(S)$ and $f(s)$ are characterized by three distribution laws: normal, exponential and Weibull. Let's consider possible variations in the distribution densities $f(S)$ and $f(s)$.

Distribution density $f(S)$ of the strength parameter characteristics of the RCB floor for [24]:

- Normal distribution:

$$f(S) = \frac{1}{\sigma_S\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{S-\mu_S}{\sigma_S}\right)^2\right]; \quad (2)$$

- Exponential distribution:

$$f(S) = \lambda_S\, exp[-\lambda_S S]; \quad (3)$$

- Weibull distributions:

$$f(S) = \frac{\beta}{(\theta-S_0)^\beta}(S-S_0)^{\beta-1} exp\left[-\left(\frac{S-S_0}{\theta-S_0}\right)^\beta\right]. \quad (4)$$

Distribution density $f(s)$ of the mechanical parameters of the load for:

- Normal distribution:

$$f(s) = \frac{1}{\sigma_s\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{s-\mu_s}{\sigma_s}\right)^2\right]; \quad (5)$$

- Exponential distribution:

$$f(s) = \lambda_s\, exp[-\lambda_s s]; \quad (6)$$

- Weibull distributions:

$$f(s) = \frac{\beta_s}{\theta_s}\left(\frac{s-s_0}{\theta_s}\right)^{\beta_s-1} exp\left[-\left(\frac{s-s_0}{\theta_s}\right)^{\beta_s}\right]. \quad (7)$$

To calculate the factor of safety, the following equation is usually used [9]:

$$n = \frac{\sigma_y}{\sigma_{max}}. \quad (8)$$

However, equation (8) is applicable at the structural design stage.

During the operation of RCs, the factor of safety changes. It is known that the material of a RCB is susceptible to aging and degradation. The σ_y value decreases after 8-10 years. In this work, it is necessary to find out and theoretically justify the change in the factor of safety of the RCB over 2 years or 200,000 km. At this moment, repairs are being made. In this regard, the value of σ_y can be taken as constant.

The values of the mechanical parameters of the load Q_z, M_x, M_y, change during the operation of the RC. A RC mileage can be empty or loaded. This means that the σ_{max} value changes. This change can be taken into account using the probability of loading the body of RC $P(s)$.

Characteristics of the strength parameters of the material floor of the RCB A, S_x, S_y, during operation, also affect the value of σ_{max}. In order to take into account the influence of these characteristics, we use the probability of failure-free operation (PFO) $P(S)$.

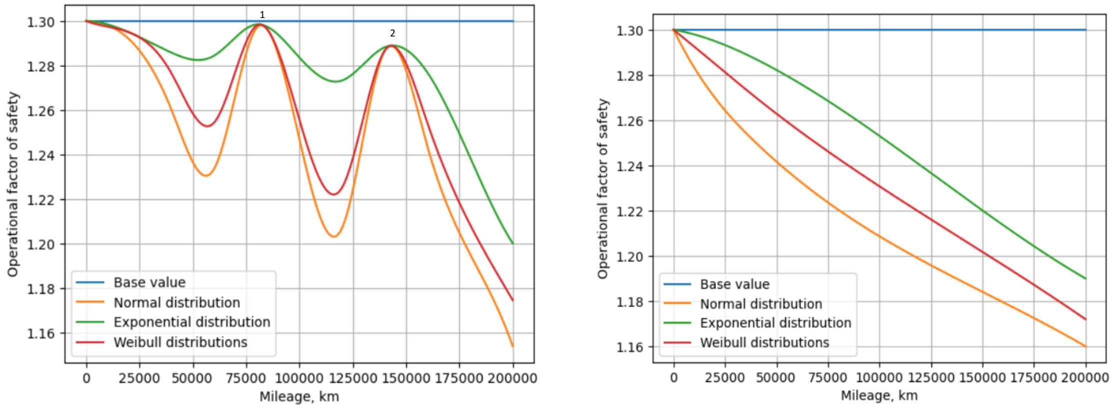
The probability $P(S)$ over the distance $[S_1, S_2]$ is calculated using the formula:

$$P(S) = \int_{S_1}^{S_2} f(S)dS. \quad (9)$$

As a result, taking into account the above, Equation (8) will have the form and be called the operational factor of safety:

$$n_o = \frac{\sigma_y}{\sigma_{max}\cdot\frac{P(S)}{P(s)}}. \quad (10)$$

Considering the available statistics on the wear and failure of RCB elements, Figure 2 presents the characteristic dependencies for the operational factor of safety (Equation (10)).



a b

Figure 2. Characteristic dependencies for the operational factor of safety of the RCB: (a) with restoration of operability (PFO); (b) without carrying out remedial repair work.

Points 1 and 2 in Figure 2(a) illustrate the restoration of operability (PFO) achieved through routine repairs to the RCB.

Under real operating conditions, the RCB cannot be repaired. Therefore, the distribution shown in Figure 2(b) accurately represents the actual operation of the RCB.

In general, the operational factor of safety of the RCB varies with mileage. Unlike the basic safety factor value of 1.3, which is calculated using equation (8), the values of the operational safety factor for the RCB, calculated using equation (10), change depending on the RC's mileage. This reflects the actual operation of the RCB, providing a more accurate assessment of its reliability.

3.2. Determination of the TBO of the RCB.

To determine the TBO of the RCB, we will apply the following reasoning. The TBO, with the basic factor of safety, can be determined using the following function:

$$SL = \frac{1}{\delta} exp\left(-\frac{Q}{n}\frac{P(s)}{P(S)}\right), \qquad (11)$$

where Q represents the body loading as a percentage of load capacity;

δ is the coefficient of wear intensity of the RCB, given in relative units per 200,000 km of RC mileage.

Theoretical dependence of the TBO of the RCB on body loading and at δ = 1.1 is shown in Figure 3.

The TBO of the RCB (Figure 3) at 100% load and using the basic value of factor of safety (Equation (8)) corresponds to 210,622.5 km. The TBO of the RCB values using the equation for the operational factor of safety (10) are lower by: 9.3%; 6.2% and 7.9% compared to the base value of 210,622.5 km.

The standard TBO of a RC before repair is 200 thousand kilometers or 2 years of operation. However, the actual TBO of a RC before repair is 5-7% lower than the standard value. To increase the TBO, it is proposed to increase the value of the factor of safety. Then we can expect an increase in the TBO of the RCB. Therefore, a new design of the RCB is proposed in order to increase its TBO.

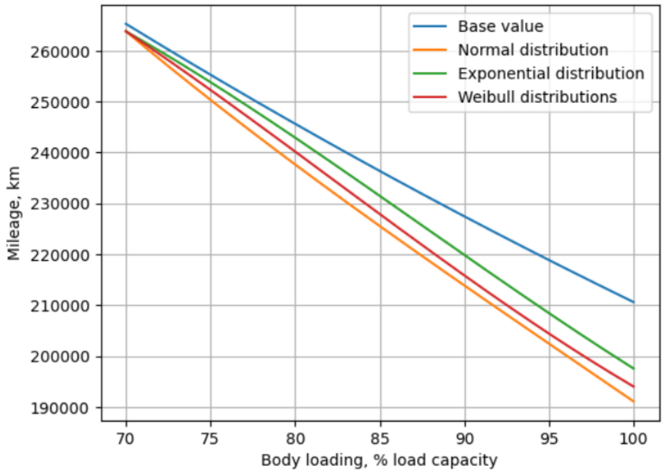


Figure 3. Theoretical dependence of the TBO of the RCB on body loading (δ = 1.1 relative units per 200,000 km of RC mileage).

3.3. The proposed design of the RCB.

Since the highest equivalent loads occur precisely in the unsecured areas of the RCB floor, it is proposed to modify the design of the floor itself. The proposed design of the RCB is shown in Figure 4.

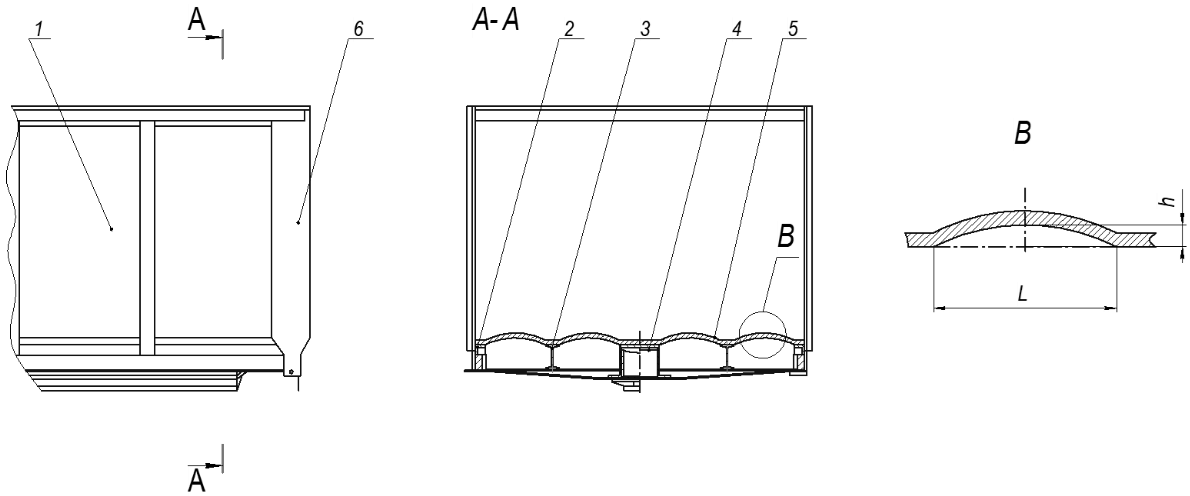


Figure 4. Proposed design of the RCB: 1 – side wall; 2 – extreme supporting beam; 3 – intermediate supporting beam; 4 – spinal beam; 5 – floor; 6 – end wall.

Figure 4 (View B) shows the floor dimensions L, h, on which the initial physical and mechanical properties depend: area, volume, mass, axial moments of resistance.

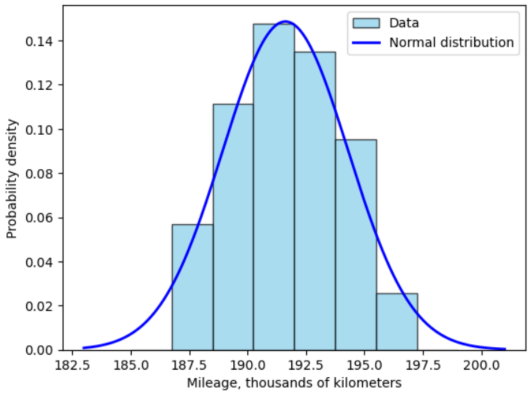
Based on logical considerations, the *L/h* ratio can be taken in the range of 7.5-30.0. This value of L/h will not lead to an intensive increase in the weight of the floor and a decrease in the volume of the RCB. The axial moments of resistance S_x, S_y will increase. The floor area of the RCB will also increase.

Due to an increase in the values of A, S_x, S_y (Eq. (1)) provided that the values of force Q_z and moments M_x, M_y are constant, the maximum stresses σ_{max} in the floor of the RCB (1) will decrease.

4. Results and discussion.

4.1. Results of statistical studies of the TBO of the RCB.

To substantiate the theoretical premises for the application of Equations (10) and (11), statistical experimental studies on the TBO of the RCB were conducted. Three groups of RCs were examined: the first group included 967 RCs, the second group included 903 RCs, and the third group included 602 RCs. The results are shown in Figure 5.



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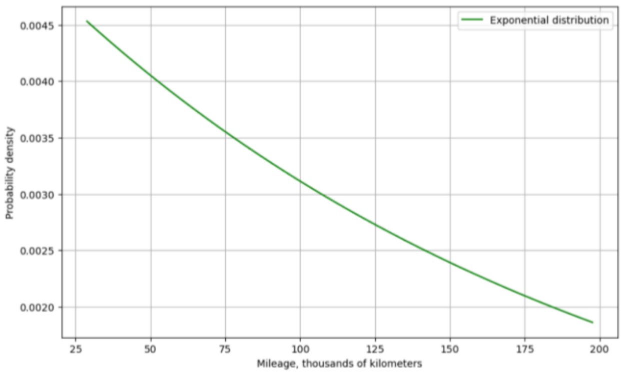

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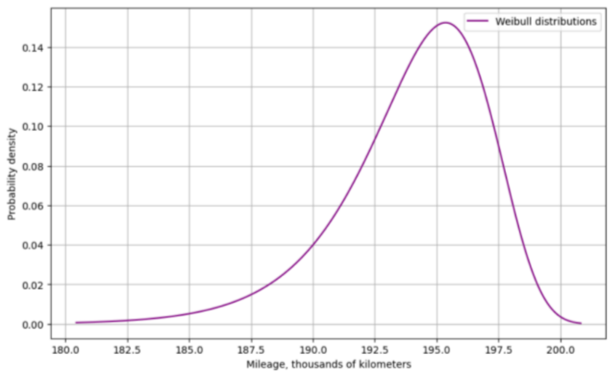


c)

Figure 5. Results of statistical studies of the TBO of the RCB: (a) data and normal distribution for the first group; (b) exponential distribution for the third group; (c) Weibull distribution for the second group.

The results of statistical studies (Figure 5) show that the average values of the TBO of the RCB for the normal distribution are 191,622±2,685 km of mileage, for the Weibull distribution – 194,858 km of mileage. For exponential distribution, the TBO of the RCB is 195,943 km of mileage.

A comparison of the results of theoretical studies on the TBO of the RCB (Figure 3) at 100% body load with the results of experimental studies (Figure 5) shows good agreement. The deviations between the theoretical and experimental results are:

- for the normal distribution: 0.27-1.67%;
- for the exponential distribution: 0.83%;
- for the Weibull distribution: 0.43%.

The deviation between the theoretical and experimental results may indicate the adequacy of the proposed equation (11) for determining the TBO of the RCB.

When compared to the TBO of the RCB under 100% load and using the base factor of safety value (210,622.5 km), the deviations from the statistical results, assuming a normal distribution, range from 8.4% to 11.5%.

4.2. Assessing the adequacy of theoretical and experimental results.

To assess the adequacy of the obtained data, the Pearson criterion was used. To do this, it is necessary to compare the observed values (the results of statistical studies) with the theoretically expected values (calculated theoretical values) for each distribution. Let us calculate the value of the Pearson χ^2 test statistic for each case and compare it with the critical value.

Formula for calculating the Pearson χ^2 test statistics:

$$\chi^2 = \sum \frac{(Q_i - E_i)^2}{E_i}; \qquad (12)$$

where Q_i is the observed value;

E_i is expected (theoretical) value.

Results of calculations of the Pearson χ^2 test for each distribution:

- Normal distribution: χ^2 =1.40;
- Exponential distribution: χ^2 =13.53;
- Weibull distribution: χ^2 =3.52.

The critical value for a significance level of 0.05 and one degree of freedom is χ^2 =3.84.

For a normal distribution:

$\chi^2 = 1.40 < \chi^2_{crit} = 3.84$.

This means that there are no statistically significant differences between the theoretical and observed values, and the model is adequate.

For exponential distribution:

$\chi^2 = 13.53 > \chi^2_{crit} = 3.84$.

This indicates a significant discrepancy between the theoretical and observed value, and the model may be inadequate.

For the Weibull distribution:

$\chi^2 = 3.52 < \chi^2_{crit} = 3.84$.

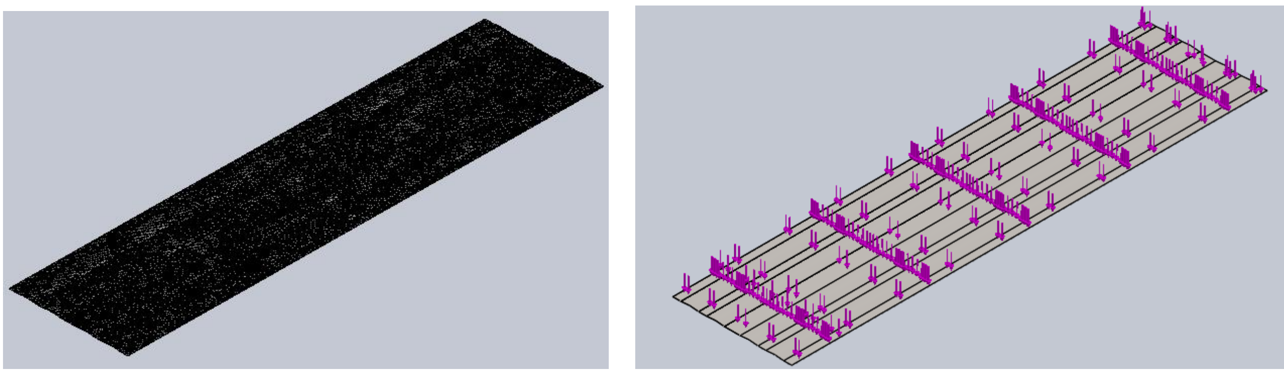
Here the discrepancy is not statistically significant, and the model is also considered adequate.

We have finally accepted that the model with the exponential distribution is inadequate and will be omitted from further calculations.

4.3. Simulation results the proposed design of the RCB.

4.3.1. Results of the calculations von Mises stress.

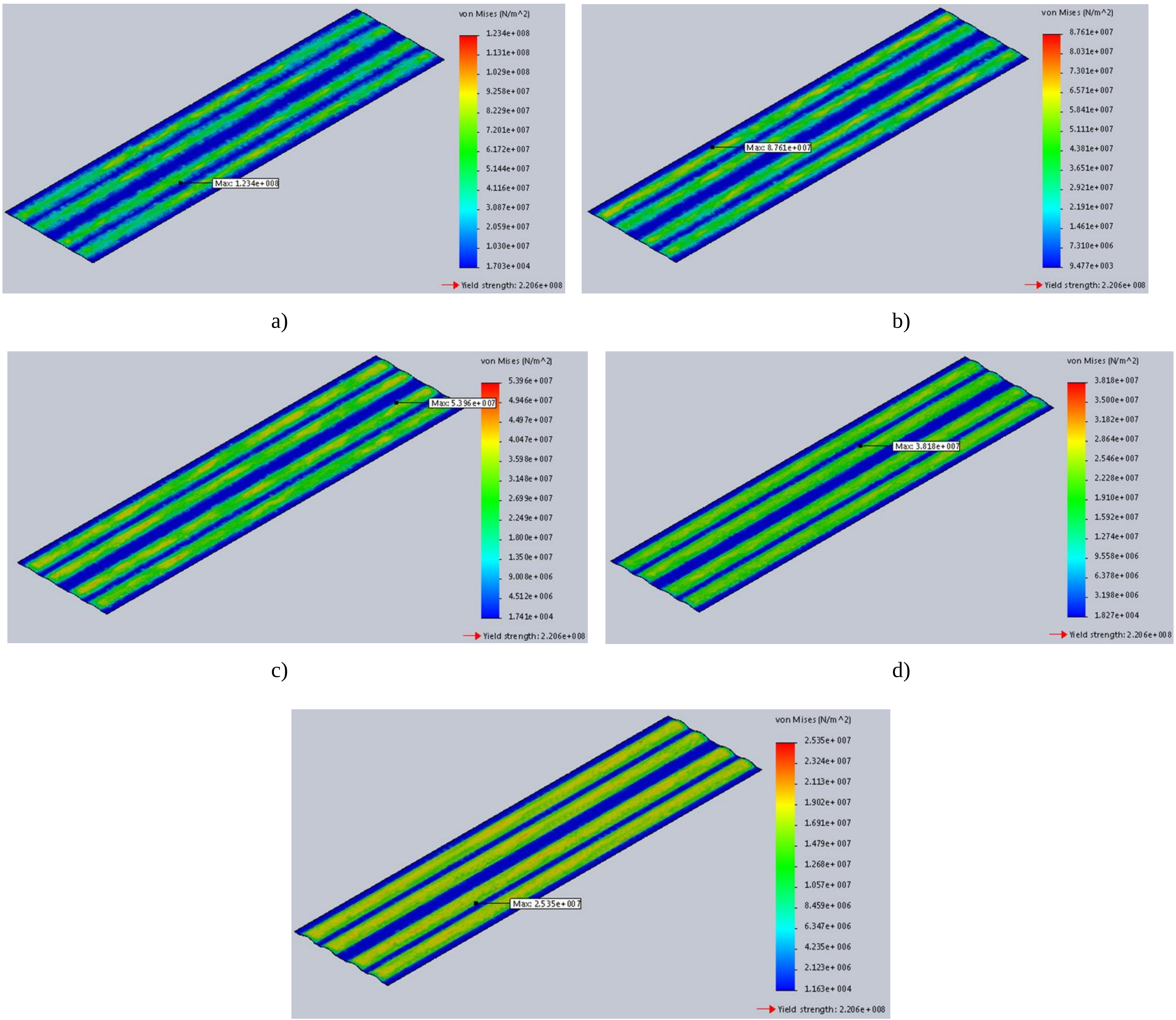
The calculations von Mises stress were carried out for the developed CAD model of the RCB floor. The 'SOLIDWORKS 2017' complex was used to test the strength of the RCB floor. Spatial tetrahedrons served as the finite elements for modelling the RCB floor. The optimal number of elements was determined using the graphoanalytic method. The model comprised a total of 327,912 nodes and 648,608 elements. The elements ranged in size, with a maximum of 40 mm and a minimum of 8 mm. Notably, 84.7% of the elements had an aspect ratio of less than three, while none exceeded an aspect ratio of ten, and no distorted elements were detected (Jacobian = 0.0). The model ensured a minimum of 10 elements within any given circle, with a size magnification ratio of 1.6. The material is plain carbon steel with yield strength of 220.6 MPa. The finite element model the RCB floor is shown in Figure 6, a. The floor of the RCB was loaded with a constant force of 250 kN per square meter. Estimation scheme of the RCB floor is shown in Figure 6, b.



a b

Figure 6. The finite element model the RCB floor (a); Estimation scheme of the RCB floor (b).

Result of the calculations von Mises stress for the proposed RCB floor design are shown in Figure 7.



e)

Figure 7. Result of the calculations von Mises stress for the proposed RCB floor design (thickness 6 mm): (a) L/h=30.0; (b) L/h=22.5; (c) L/h=15.0; (d) L/h=10.0; (e) L/h=7.5.

Figure 7 presents the von Mises stress results for the proposed RCB floor design with a thickness of 6 mm across different L/h ratios. The von Mises stress is a crucial parameter in assessing material yield under complex loading conditions.

Maximum von Mises stress for the proposed RCB floor design with a thickness of 6 mm are:

- 123.4 MPa at L/h=30.0, which is 44.1% less than the yield strength;

- 87.6 MPa at L/h=22.5, which is 63.0% less than the yield strength;

- 54.0 MPa at L/h=15.0, which is 75.5% less than the yield strength;

- 38.2 MPa at L/h=10.0, which is 82.7% less than the yield strength;

- 25.4 MPa at L/h=7.5, which is 88.5% less than the yield strength.

As indicated in the theoretical part, a reduction in maximum stresses is possible by modifying the floor of the RCB. This is confirmed by the calculation results presented in Figure 7. The following are the results of calculating the floor of the RCB displacements.

4.3.2. Displacement calculation results.

The calculations of displacement were carried out for the developed CAD model of the RCB floor. The "SOLIDWORKS 2017" complex was used to carry out displacement studies of the RCB floor. The calculation results are shown in Figure 8.

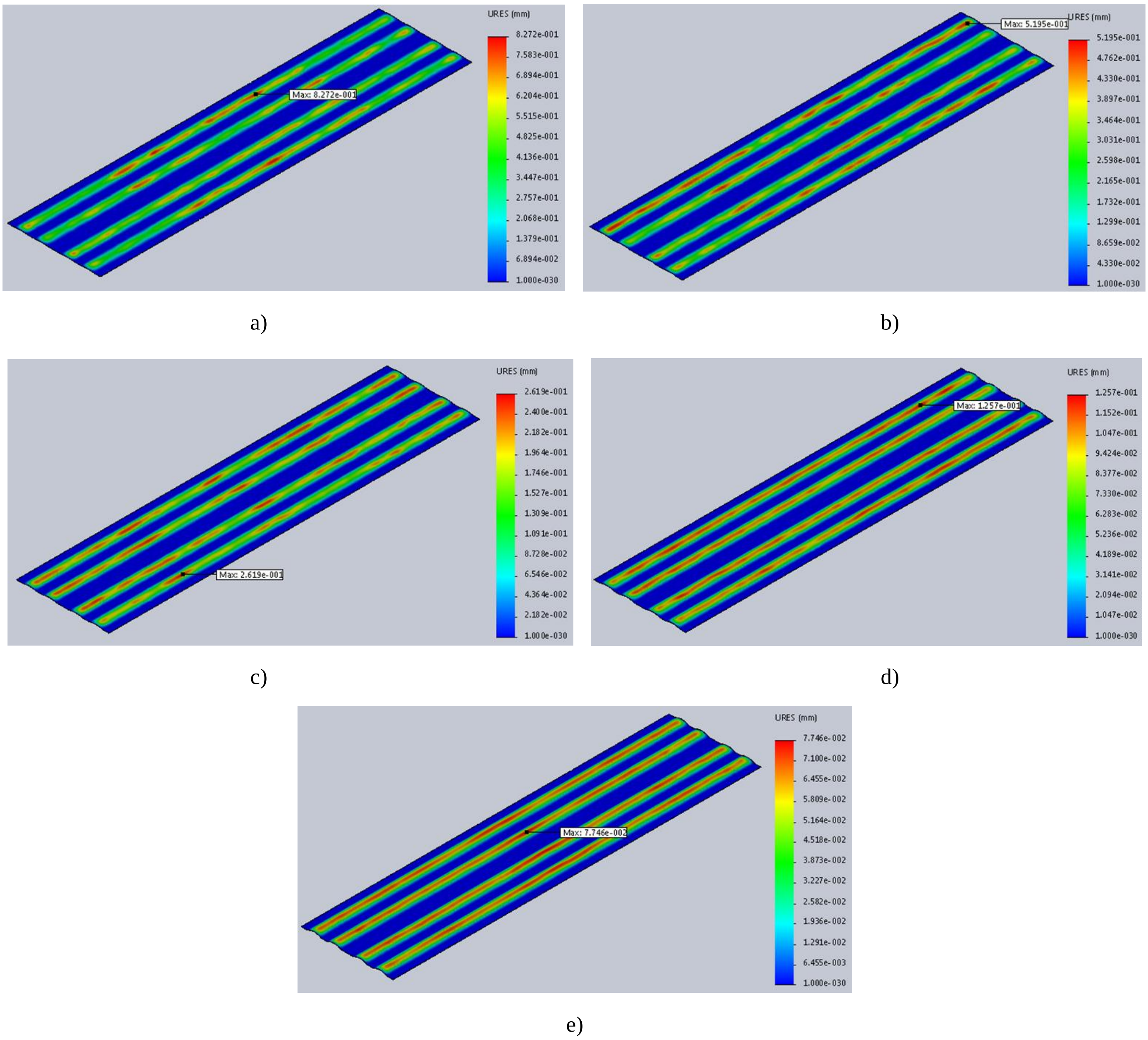


Figure 8. Result of the calculations of displacement for the proposed RCB floor design (thickness 6 mm): (a) L/h=30.0; (b) L/h=22.5; (c) L/h=15.0; (d) L/h=10.0; (e) L/h=7.5.

The results shown in Figure 8 indicate a decrease in movements in the floor of the RCB. The maximum displacement values of the floor of the RCB under load are:

- 0.83 mm at L/h=30.0, which is 59.6% more compared to the base option;
- 0.52 mm at L/h=22.5, which is the same value as for the base option;
- 0.26 mm at L/h=15.0, which is 50.0% less compared to the base option;
- 0.13 mm at L/h=10.0, which is 75.0% less in comparison with the base option;
- 0.08 mm at L/h=7.5, which is 84.6% less in comparison with the base option.

However, all values of the maximum displacements of the floor of the RCB are within the limits of the permissible displacement values. This means that according to the criterion of maximum displacements, the proposed floor of the body can be used in RC.

4.3.3. Results of equivalent deformation calculations.

The calculations of equivalent deformation were carried out for the developed CAD model of the RCB floor. The 'SOLIDWORKS 2017' complex was used to test the equivalent deformation of the RCB floor. The calculation results are shown in Figure 9.

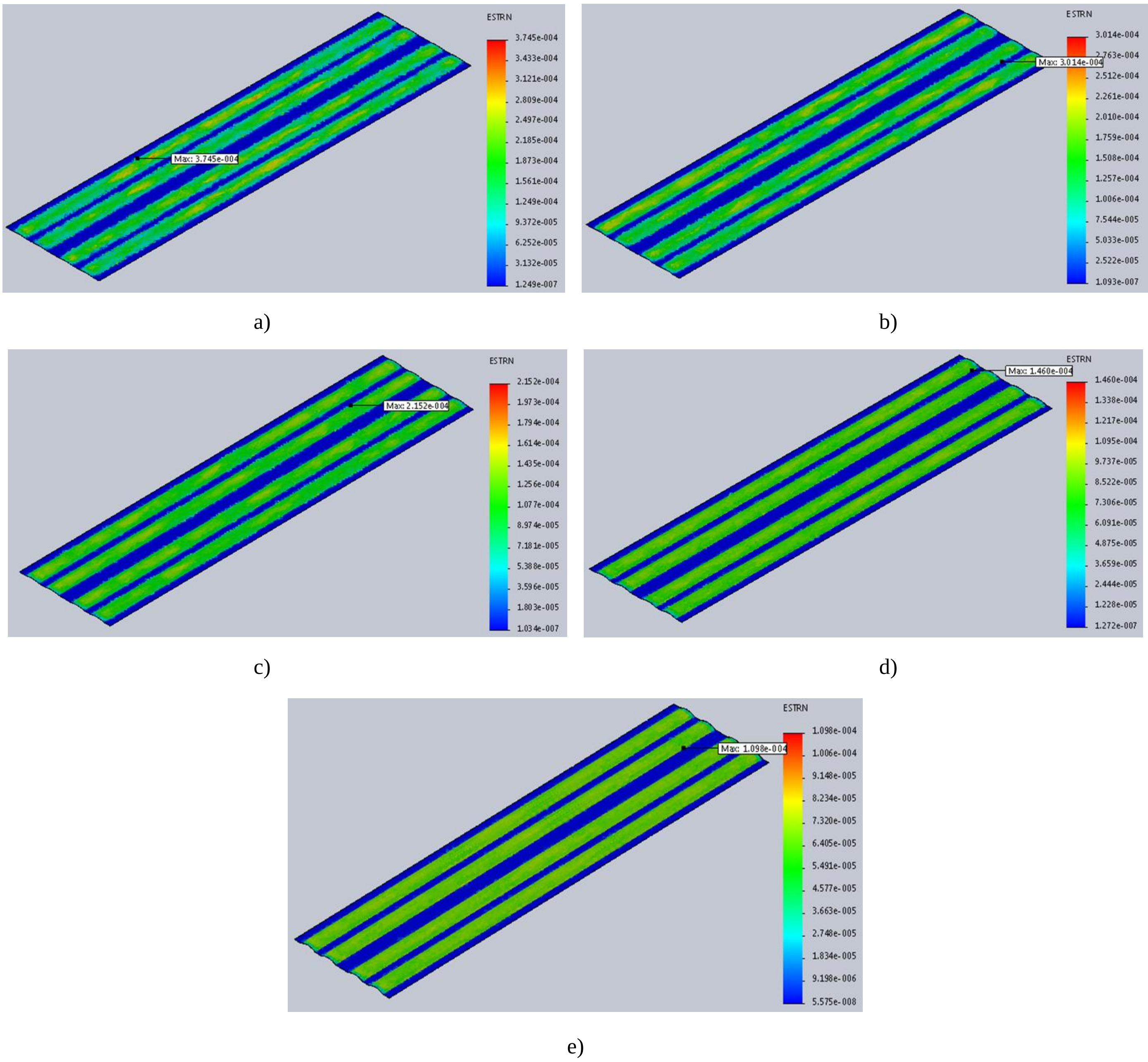


Figure 9. Result of equivalent deformation calculations for the proposed RCB floor design (thickness 6 mm): (a) L/h=30.0; (b) L/h=22.5; (c) L/h=15.0; (d) L/h=10.0; (e) L/h=7.5.

The results of calculations of the maximum equivalent deformation of the proposed RCB floor design are within the permissible limit for railway rolling stock. The values of the maximum equivalent deformation of the floor of the RCB are as follows:

- $3.75 \cdot 10^{-4}$ at L/h=30.0, which is 33.9% less compared to the base option;
- $3.02 \cdot 10^{-4}$ at L/h=22.5, which is 46.7% less compared to the base option;
- $2.15 \cdot 10^{-4}$ at L/h=15.0, which is 62.1% less compared to the base option;
- $1.46 \cdot 10^{-4}$ at L/h=10.0, which is 74.3% less compared to the base option;
- $1.10 \cdot 10^{-4}$ at L/h=7.5, which is 80.6% less compared to the base option.

Low values of maximum equivalent deformations are achieved due to the use of the floor of the RCB. These research results confirm the feasibility of using the proposed RCB design.

4.3.4. Results of the factor of safety calculations.

The factor of safety calculations were performed using Equation (8) for the basic value and Equation (10) for the normal distribution and Weibull distribution. These calculations were applied to the developed CAD model of the RCB floor, with the results presented in Figure 10.

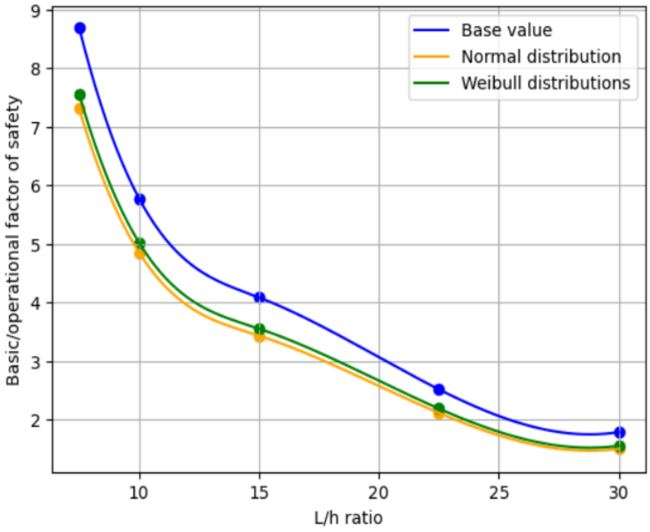


Figure 10. Result of the basic/operational factor of safety calculations for the proposed RCB floor design.

According to Equation (8), the minimum value of the factor of safety was found to be 1.4 to 6.7 times higher compared to the basic option of the RCB. Based on Equation (10), the minimum value of the operational factor of safety is 1.5 to 4.8 for a normal distribution, and 1.6 to 5.0 for a Weibull distribution. The latter values align more closely with the actual operational factor of safety for the RCB. Consequently, this result suggests that the operational factor of safety has increased, implying that the TBO of the RCB has been extended several times.

4.4. Results of extending the TBO of the RCB.

Based on the results shown in Figure 10, we calculate the TBO of the RCB using equation (11). To estimate the TBO, a floor wear intensity coefficient of 1.15 relative units per 200,000 km of RCB mileage was used. The results showing the extended TBO of the proposed RCB design are presented in Table 1.

Table 1. Results of extending the TBO of the proposed RCB design, %.

L/h ratio	Normal distribution	Weibull distributions
30	22.3	23.2
22.5	48.3	48.4
15	77.8	76.8
10	93.6	91.9
7.5	107.4	105.3

Table 1 shows that the TBO of the RCB can be increased by 1.21 to 2.06 times for a normal distribution and by 1.22 to 2.04 times for a Weibull distribution, depending on the L/h ratio, compared to the basic RCB model. However, this increase will also depend on other operational factors affecting the RCB's performance.

5. Conclusions.

The work focused on estimating and extending the TBO of the RCB. During the operation of freight cars, the physical and mechanical properties of the body materials change, which in turn alters the loads on the RCB. In this context, a novel approach was proposed: the use of an operational factor of safety that accounts for both the PFO and the probability of loading of the RC (as described in equation (10)). Additionally, a new equation (11) was introduced for determining the TBO of the RCB.

The calculations revealed that the proposed operational factor of safety varies depending on the mileage of the RCB. These values differ from the base factor of safety by 7.7-11.5%.

At 100% load and using the base factor of safety, the TBO of the RCB (Figure 3) is estimated at 210,622.5 km. This value is overestimated by a factor of 1.1. When applying the equation for the operational factor of safety (10), the TBO values of the RCB are 9.3%, 6.2%, and 7.9% lower compared to the base value of 210,622.5 km.

Statistical analysis showed that the average TBO of the RCB, assuming a normal distribution, is 191,622±2,685 km. For
a Weibull distribution, the average is 194,858 km, while for an exponential distribution, it is 195,943 km.

A comparison of theoretical and experimental results confirms the adequacy of the proposed equation (11) for determining the TBO of the RCB, as the deviations are less than 2%. However, the Pearson χ^2 test indicated that while the normal and Weibull distribution models are adequate, the exponential model is not. Consequently, the model with exponential distribution was excluded from further studies.

To extend the TBO of the RCB, a new design has been proposed that reduces the maximum stresses in the body floor, thereby increasing the safety factor. By modifying the floor design and optimizing the L/h ratio, the maximum von Mises stress experienced by the RCB floor can be significantly reduced. At an L/h ratio of 7.5, the stress is 88.5% less than the material's yield strength, indicating a much lower risk of material failure under load. The proposed RCB design also reduces the maximum displacements experienced by the floor. For lower L/h ratios, such as 7.5, displacement is reduced by 84.6% compared to the base design, suggesting improved structural stability. Calculations show that the equivalent deformation of the RCB floor design is significantly lower. For an L/h ratio of 7.5, deformation is 80.6% less than the base option, contributing to the structural integrity of the RCB under operational loads. The redesigned RCB floor eliminates the need for supporting transverse beams, ensuring that the load capacity of the RCB remains unchanged. The proposed RCB design allows for more efficient use of materials and space, achieving higher safety factors and reduced stress, displacement, and deformation levels without additional support structures.

The design modifications significantly enhance the safety factor. The minimum safety factor is 1.4-6.7 times higher than that of the basic design, indicating a substantial increase in safety and reliability. The minimum operational safety factor for a normal distribution is 1.5-4.8, and for a Weibull distribution, it is 1.6-5.0. These values are more consistent with the actual operational safety factor of the RCB, suggesting that the TBO of the RCB has increased several times.

The proposed design modifications substantially extend the TBO of the RCB. Depending on the L/h ratio, the estimated TBO for the proposed RCB design ranges from 233,806.4 to 396,436.6 km for a normal distribution and from 239,089.9 to 398,263.5 km for a Weibull distribution. While this extension depends on operational conditions, it promises much longer durability.

The prospects for the development of this study will include:

- Conducting experimental studies of the proposed RCB design modifications.

- Material degradation studies. Understanding how materials degrade over time and under various operational stresses will allow for more accurate predictions of TBO and necessary maintenance intervals.

- Refinement of the models for determining the TBO of the RCB and operational factor of safety. The development of more sophisticated models that take into account a wider range of operational variables (e.g., varying load conditions, environmental factors) will improve the accuracy of TBO predictions and operational factor of safety.

- Integration of predictive maintenance technologies.

- Lifecycle cost analysis. Conducting comprehensive cost-benefit analyses of the proposed design modifications and maintenance strategies will be essential to justify investments.

Acknowledgments: I would like to express my gratitude to Professor Denys Baranovskyi for his support and guidance in implementing the research.

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