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ASSESSING THE FRACTURE HAZARD OF RAILROAD ROLLING STOCK WHEEL FLANGE BASED ON BENDING STRESSES AND CONTACT FATIGUE

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This study investigates the stressed-strained state of a wheel flange in railroad rolling stock under the action of lateral forces of the wheel-rail interaction and the evolution of contact-fatigue damage. The task addressed relates to the lack of a comprehensive assessment of the risk of wheel flange failure, which would simultaneously take into account bending stresses, contact fatigue, and changes in the thickness of the flange due to operational wear.

The wheel flange is proposed as a bending element loaded by the lateral force of the wheel-rail interaction. An analytical dependence has been derived for determining bending stresses depending on the thickness of the flange and the magnitude of the lateral force. A hazard index is proposed, constructed by normalizing equivalent contact stresses relative to the contact endurance limit of the wheel material. Based on the combination of the contact index and the fatigue safety factor, a combined criterion for assessing the risk of flange failure has been devised.

A feature of the results is the established analytical dependence between the thickness of the flange and the fatigue stresses of bending. It was found that reducing the thickness of the flange from 30 to 22 mm leads to an increase in fatigue stresses by almost 1.9 times. A map of the risk of fracture in the coordinates "flange thickness-lateral force" was constructed, which makes it possible to determine the areas of safe and dangerous operation.

The scope of practical implementation of the results is railroad transport.

A condition for applying the findings is to assess the technical condition and predict the resource of rolling stock wheel flanges under the action of lateral loads in the flange contact.

This study could contribute to increasing the efficiency of the maintenance system of wheelsets for railroad transportation

Keywords: railroad transport, bending stresses, contact fatigue, lateral force, flange thickness

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1. Introduction

One of the most loaded areas of the wheel is the flange, which during operation is subjected to significant lateral forces, contact stresses, and cyclic loads.

The most unfavorable operating conditions of the flange occur when rolling along small-radius curves, at flange contact, at two-point contact between the wheel and rail, at intensive slipping and skewing of wheelsets. Under such conditions, significant bending and contact stresses arise in the wheel flange, which could lead to the evolution of contact fatigue damage, crack formation, and subsequent destruction of the flange.

During operation, the flange gradually wears out, which is accompanied by a decrease in its thickness and a change in the geometry of the wheel profile. A decrease in the thickness of the flange leads to a change in the geometric characteristics of dangerous sections, a decrease in the moment of resistance, and an increase in the level of bending stresses. At the same time, the displacement of the flange contact point along the height of the flange causes an increase in the arm of the lateral force application and an increase in the bending moment. The combined effect of bending stresses and contact fatigue creates conditions for the development of dangerous damage to the wheel flange.

The task to ensure the reliability of railroad rolling stock wheels remains one of the most urgent in modern transport mechanics. Of particular danger is the destruction of wheel flanges, which could lead to a violation of conditions of interaction between the wheel and rail, an increase in dynamic loads, and the occurrence of emergencies.

Under modern operating conditions of rolling stock, timely assessment of the risk of wheel flange failure is particularly important. Using only the limiting geometric wear parameters does not allow for full consideration of the impact of changes in the stress state of the flange, the position of the contact point, and the conditions for the evolution of contact fatigue. In this regard, there is a need to devise methods for assessing the risk of flange failure that would take into account the simultaneous impact of flange wear, changes in the geometric characteristics of the cross-section, the position of the point of application of lateral force, bending stresses, and contact fatigue.

The results of research could be used to assess the technical condition of wheelsets, predict the resource of wheel flanges, determine dangerous operating modes, as well as improve rolling stock maintenance systems.

The practical application of research findings could contribute to increasing the durability of wheelsets, reducing costs for repair and maintenance of rolling stock, as well as also improving the efficiency of wheel condition diagnosis systems.

Therefore, it is a relevant task to devise methods for assessing the risk of destruction of railroad rolling stock wheel flanges based on bending stresses and contact fatigue.

2. Literature review and problem statement

The process of railroad wheel failure caused by the formation of a crack in the flange was investigated in work [1]. The authors performed an assessment of the loading conditions that could cause the initiation of a fatigue crack, its further propagation, and the final failure of the wheel. The analysis used numerical modeling of the stress state of the flange, assessment of the failure, and assessment of the influence of overheating of the flange due to the incorrect position of the brake pads. It was established that the failure was caused by cyclic tensile stresses on the inner surface of the flange while overheating contributed to the emergence of additional residual tensile stresses.

However, the work left unresolved the issue of assessing the risk of fracture of the flange depending on its thickness and the magnitude of the lateral forces of the wheel-rail interaction. The authors perform an analysis of an already formed crack and a specific case of failure, but no engineering criterion was proposed that would make it possible to predict the dangerous state of the flange before the crack occurs. In addition, the study did not establish an analytical relationship between the geometric wear of the flange and the level of bending stresses. A likely reason is that the study tackles post fracture and focuses mainly on the reconstruction of the mechanism for the already occurred fracture. Most attention is on the mechanics of fracture, the assessment of crack growth, and the influence of thermomechanical factors, while the issue of changing the bending stiffness of the flange at its operational wear was not considered.

In study [2], current tasks of categorizing wear mechanisms using artificial intelligence methods are considered. The authors analyzed the possibilities of using artificial intelligence-based approaches for automated recognition of wear types based on surface images, damage parameters, and monitoring data. The work shows that the use of machine learning and computer vision methods makes it possible to increase the speed and objectivity of identification of wear mechanisms and creates prerequisites for designing intelligent systems for diagnosing the technical condition of elements in tribological systems. At the same time, the study left unresolved issues of assessing the mechanical causes of damage development and predicting the risk of destruction of structural elements based on the parameters of their stressed state.

In the review paper on rolling fatigue and wear [3], the authors systematized modern approaches to assessing contact fatigue of wheels and rails. The mechanisms of contact damage evolution and the influence of contact stresses on surface degradation are considered. The issue of simultaneously accounting for contact fatigue and flange bending stresses remains unresolved. A likely reason is the concentration of most RCF models on the contact patch and subsurface stresses.

In [4], a thorough analysis of modern approaches to understanding and modeling creep forces in the wheel-rail system was performed. The authors considered the tribological aspects of the wheel-rail interaction, the influence of contact conditions, surface layers, roughness, plastic deformation, and friction coefficients on the formation of creep forces. The work shows that creep forces play a key role in the processes of adhesion, braking, wear, rolling fatigue, stability, and interaction of a vehicle with a track. The complex multifactorial nature of wheel-rail contact and the need to take into account non-stationary contact conditions are also emphasized. The authors analyze in detail the mechanisms of formation of creep forces and contact stresses but do not consider the wheel flange as a separate bending element prone to fatigue failure at operational wear.

In [5, 6], the influence of curved sections of the track on the reduction of wheel flange thickness was investigated. The authors performed an analysis of the wear processes of flanges using dynamic modeling of the wheel-rail interaction and established that the radius of the curve, the magnitude of the lateral forces, and the driving modes significantly affect the intensity of flange wear. It was shown that in small-radius curves there is a significant increase in contact loads and an accelerated decrease in the thickness of the flange, which can worsen conditions for the interaction of the wheel-rail system. At the same time, the work left unresolved the issues of assessing the change in the stress state of the flange due to a decrease in its thickness and determining the level of bending fatigue stresses under the action of lateral forces.

In work [7], a multi-criteria optimization of the wheel profile was proposed to reduce flange wear. The authors took into account the interaction of the wheel with the worn rail and the dynamic characteristics of the carriage. However, no dependence was established between the geometry of the flange and bending stresses. This is explained by the fact that most attention is paid to profile optimization, and not to the assessment of the risk of destruction.

The authors of [8] considered the task of optimizing the profile of the rolling stock wheel in order to reduce the intensity of flange wear when moving on worn rails. The authors used methods of numerical modeling of the interaction of the wheel and the rail and multi-criteria optimization of the geometry of the wheel profile. The work shows that changing the profile parameters makes it possible to reduce contact stresses, the intensity of flange wear, and improve the conditions for passing curved sections of the track. At the same time, the work left unresolved the issues of evaluating the flange bending stresses and their changes when the flange thickness decreases due to operational wear.

In [9, 10], the optimization of the wheel profile was performed taking into account damage to the railroad wheel and dynamic characteristics. The authors showed that the geometry of the profile significantly affects the conditions of the wheel and rail interaction. At the same time, critical values of the flange thickness under the action of lateral forces were not determined. This is explained by the lack of a model of flange bending as a separate structural element.

The authors of work [11] performed a comprehensive analysis of dynamic loads in the wheel-rail system, determined the features of the change in contact forces and stresses under different operating conditions. They established the relationship between damage to the wheel surface, wheel and rail forces, and axle bending stresses. The work shows that real operational loads are significantly variable and can significantly affect the evolution of fatigue damage to the elements of the wheelset. However, the work left unresolved the issues of assessing local bending stresses in the wheel flange and determining the impact of reducing the thickness of the flange on the risk of its destruction.

In [12] it is shown that the lateral forces of the wheel-rail interaction are one of the determining factors of the occurrence of derailment, especially when passing through curved sections of the track, switches, and irregularities of the rail track. The importance of accurate modeling of the wheel-rail contact for assessing traffic safety is also emphasized. The authors analyze in detail the conditions for the occurrence of wheel slippage and loss of stability of the rolling stock but do not consider the change in the stressed-strained state of the flange at its operational wear. The study also lacks a criterion for assessing the risk of flange failure under the conditions of the combined action of contact fatigue and bending loads.

The study of the influence of temperature loads on the processes involved in wheel-rail interaction is reported in [13]; it proves the need for joint consideration of mechanical and thermal loads when assessing damage to wheels and rails. Most attention is paid to thermomechanical processes in the contact zone of the rolling surface while the wheel flange is not considered as a separate structural element prone to fatigue bending under the action of lateral forces.

Study [14] is essentially thermomechanical and tribological and is aimed at analyzing the transitional behavior between rolling fatigue and thermal fatigue in the wheel-rail contact zone. The work focuses on the processes of heat release, contact stress development, and fatigue crack formation on the wheel rolling surface, while the local flexural strength of the flange and the influence of its geometric wear remain outside the scope of the study.

In [15], a system was designed to monitor the wear of wheel flanges of rolling stock under operational conditions. The authors proposed a system for measuring the wear of the wheel flange using sensor technologies and data processing algorithms, which allows for continuous monitoring of changes in the geometric parameters of the flange without dismantling the wheelset. The work shows that the operational determination of the thickness of the flange makes it possible to timely detect dangerous wear and increase the efficiency of rolling stock maintenance. However, the work left unresolved issues of assessing the stressed-strained state of the flange and determining the risk of its destruction based on the results of thickness measurements.

Numerical modeling of the interaction of the wheel with the rail, taking into account different degrees of flange wear, was carried out in [16]. It is proven that a decrease in the thickness of the flange significantly affects the nature of contact between the wheel and rail, the magnitude of lateral forces, dynamic loads, as well as the conditions for passing switches. However, the work does not consider the flange as a separate structural element subject to fatigue bending. The main objective of work [17] is to analyze the fatigue life and model the problems of wheel-rail contact for a repeated wheel loading cycle, taking into account the influence of normal and tangential contact forces under different vehicle loading conditions. The work investigates the influence of tangential contact forces on the durability of the contacting surfaces. The results of the finite element analysis showed that contact damage and structural integrity of the wheel-rail contact surface strongly depend on the type of contact force and may depend on the track geometry parameters. However, the work left unresolved the issues of the influence of flange thickness and its geometry on the fatigue durability.

Study [18] proved the influence of wheel flange wear on railroad rolling stock traffic safety indicators. Two traffic safety criteria were considered – the risk of wheel derailment and the criterion of unstable traffic. The result of the work was the justification of the use of wheel profile control systems for the timely detection of dangerous geometric parameters. It was confirmed that geometric parameters significantly affect traffic safety and the conditions of wheel-rail interaction. However, the issue of assessing the risk of flange failure based on bending stresses and contact fatigue is absent, although it would be appropriate.

Our review of the literature [1–18] proves that in most studies the wheel flange is considered mainly as an element of contact interaction or a geometric parameter of the wheel profile. The issues of assessing flange bending stresses, changes in its bending stiffness during wear, as well as the evolution of fatigue damage under the action of lateral forces, remain insufficiently studied. The aforementioned studies lack a comprehensive approach that would simultaneously take into account contact fatigue, bending stresses, changes in the thickness of the flange, and the influence of lateral forces of the wheel-rail interaction. Therefore, there is a need for research into this area.

3. The aim and objectives of the study

The purpose of our study is to assess the risk of fracture of railroad rolling stock wheel flanges based on bending stresses and contact fatigue, which can be used to build intelligent systems for monitoring the technical condition of wheelsets in railroad rolling stock.

To achieve this aim, the following objectives were accomplished:

– to determine the geometric characteristics of dangerous cross-sections of a wheel flange for the DSTU GOST 11018 profile for different values of flange thickness;

– to investigate the influence of the position of the point of application of lateral force on the change in bending stresses in the wheel flange;

– to assess the influence of operational wear of the flange on the fatigue strength reserve factor and the risk of fracture development;

– to devise a combined criterion for assessing the risk of fracture of the flange taking into account bending stresses and contact fatigue.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the stressed-strained state of railroad rolling stock wheel flanges under the action of lateral forces of the wheel-rail interaction and the evolution of contact-fatigue damage.

The principal hypothesis assumes that a decrease in the flange thickness and a shift of the flange contact point to the upper part of the flange lead to a nonlinear increase in bending stresses and an increase in the risk of contact-fatigue damage.

The adopted assumptions had a minor impact on the results of our study. The wheel material was assumed to be homogeneous and isotropic. The loads on the wheel flange were cyclic in nature. The destruction of the flange was determined by the combined action of bending and contact-fatigue stresses. The geometric characteristics of the cross-section changed depending on the degree of wear of the flange. The position of the flange contact point changed the magnitude of the bending moment.

To simplify the calculations: the spatial contact of the wheel and the rail was replaced by an equivalent lateral force; temperature effects and residual technological stresses were not taken into account; the influence of dynamic vibrations of the carriage was taken into account in a generalized manner through the magnitude of the lateral force.

The accepted assumptions allow for a parametric analysis of the influence of flange wear and the position of the contact point on the risk of wheel flange failure.

The work considered the locomotive wheel profile according to the DSTU GOST 11018 drawing, which is used at the Ukrainian railroads with a gauge of 1520 mm in accordance with the Instructions for the formation, repair, and maintenance of wheelsets of traction rolling stock of the Ukrainian railroads with a gauge of 1520 mm. VND 32.0.07.001.2001. The instructions have an analog of EN15313: Railroad applications. In-service wheelset operation requirements. Service and off-vehicle wheelset maintenance. The geometric parameters of the wheels were taken in accordance with the requirements by DSTU 9289:2024 Wheels for railroad rolling stock. The standard has an analog of EN 13262:2020. Railroad applications – Wheelsets and bogies – Wheels – Product requirements.

In the work, the thickness of the flange h_f was considered as the main parameter of operational wear. Analysis was performed for three characteristic values: $h_f = 30, 25, 22$ mm.

In this case, $h_f = 30$ mm corresponds to the new profile, $h_f = 25$ mm is the minimum permissible thickness of flange in operation, $h_f = 22$ mm is a critical design value that is not allowed for operation and is used to assess the risk of fracture evolution.

To assess the influence of the position of a flange contact point on the stressed state of the flange, six characteristic positions of application of lateral force Y were considered, which corresponded to cross-sections 1-1, 2-2, 3-3, 4-4, 5-5, and 6-6. The cross sections corresponded to different coordinates of the contact point along the height of the flange and different values of the arm of application of lateral force.

This approach makes it possible to take into account a change in the position of the contact point when passing curved sections of the track, two-point contact, change in the position of the wheelset in the rail track, and operational wear of the wheel profile.

4. 2. Wheel material and mechanical characteristics

The mechanical characteristics of wheel steel, typical for locomotive wheels and railroad rolling stock, were used for calculations.

The following material parameters were assumed in the model: the elastic modulus of the wheel material, $E = 2.1 \cdot 10^5$ MPa, Poisson's ratio $\nu = 0.30$, the yield strength of the material $\sigma_{0.2} = 550$ MPa, the temporary resistance of the material $\sigma_B = 950$ MPa, the endurance limit under a symmetric load cycle $\sigma_{-1} = 380$ MPa, the contact endurance limit of wheel material $\sigma_H = 1200$ MPa.

To take into account the local concentration of stresses, the concentration coefficient $K_f = 2.0$ was used.

To estimate the safety margin of the flange, the fatigue strength margin was used

$$K = \frac{\sigma_{-1}}{\sigma_b}, \tag{1}$$

where σ_{-1} is the material endurance limit; σ_b is the calculated bending stresses.

4. 3. Method for determining the geometric characteristics of dangerous cross sections

To assess the stressed state of a wheel flange, a calculation scheme was used (Fig. 1), in which the flange is represented as a cantilever bending element loaded by the lateral force of the wheel-rail interaction.

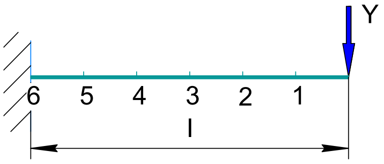


Fig. 1. Calculation diagram of wheel flange

The calculation scheme was built on the basis of a real new wheel profile, DSTU GOST 11018, and took into account the geometry of the flange, the change in the thickness of the flange at wear, the position of the point of application of the lateral force, as well as a change in the geometric characteristics of dangerous cross sections.

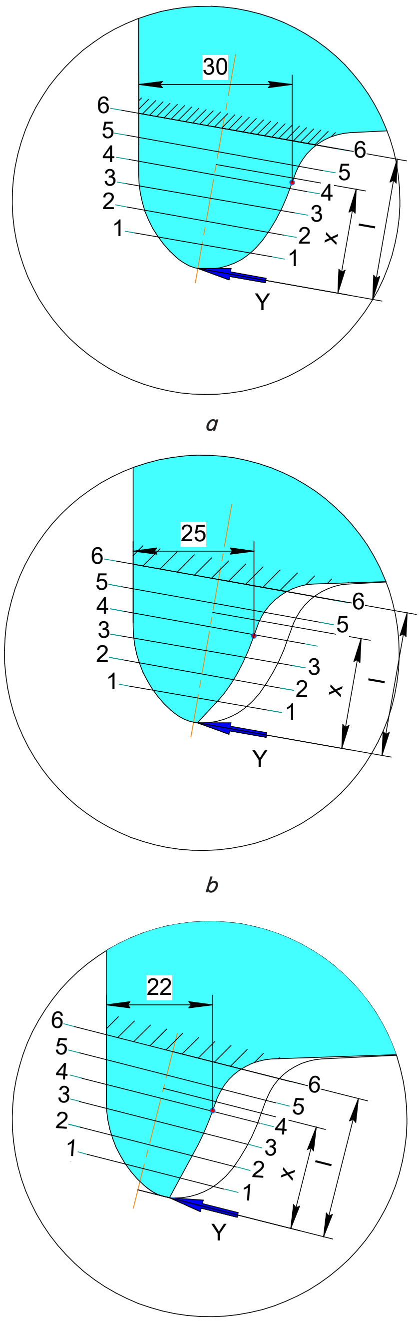
Within the framework of the adopted scheme, the lateral force Y was applied to different points on flange surface, corresponding to cross sections 1-1, 2-2, 3-3, 4-4, 5-5, and 6-6. This representation allowed us to take into account a change in the position of flange contact along the height of the flange under different conditions of wheel and rail interaction (Fig. 2).

For each position of the force application point, the arm l was determined, which characterized the distance from a dangerous cross section to the point of application of the lateral force and was characterized by the x coordinate.

To assess the influence of the position of a contact point on a change in the stress state of the flange, the arm of the lateral force application $5 \leq l \leq 30$ mm was used. For cross sections 1-1, 2-2, 3-3, 4-4, 5-5, and 6-6, the following were determined: cross-sectional area – S; coordinates of the center of gravity – x; moment of inertia of the section – J; moment of resistance of the cross section – W.

Unlike simplified models, in which the flange is represented as a cross section of constant shape, the geometric characteristics of the real profile of the flange were used in our work (Fig. 3). That made it possible to take into account the influence of changes in the shape and dimensions of the cross section on the stressed state of the flange.

For each dangerous cross section, the following parameters were additionally determined: half-width of the cross section – a; half-height of the cross section – b.



a

b

c

Fig. 2. Schematic showing the application of lateral force Y at different values of flange thickness: $a - h_f = 30$ mm; $b - h_f = 25$ mm; $c - h_f = 22$ mm

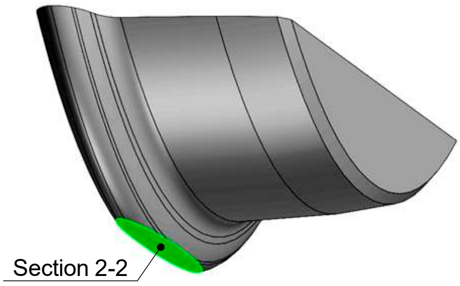


Fig. 3. Example of constructing a 2-2 cross section to determine the geometric parameters of a flange

Parameters a and b were used to describe the geometry of dangerous cross sections of the flange and determine their geometric characteristics. The values of parameters were determined for each position of the point of application of the lateral force and for each value of flange thickness.

4. 4. Method for determining bending stresses

To determine stresses in the flange, provisions from the classical theory of bending of beams and resistance of materials were used [19–21].

Bending stresses were determined using the following dependence

$$\sigma_b = \frac{M}{W}, \tag{2}$$

where M is the bending moment;

W is the moment of resistance of the dangerous cross section

$$W = \frac{J}{b}. \tag{3}$$

The bending moment was defined as

$$M = Y \cdot l, \tag{4}$$

where Y is the lateral force of the wheel-rail interaction;

l is the lateral force application arm.

To assess the influence of lateral load on the stressed state of the flange, the generalized lateral force $Y = 200$ kN was used.

For each position of the contact point and for each value of flange thickness, the following were determined: bending stresses; fatigue safety factor; failure hazard parameters.

The amplitude of fatigue stresses was determined using the following dependence

$$\sigma_f = \frac{K_t \sigma_b}{2}, \tag{5}$$

where σ_f is the amplitude of fatigue stresses;

K_t is the stress concentration coefficient.

To assess the stressed state of the flange, an analytical method based on provisions from the resistance of materials and the classical theory of bending was chosen. The use of this approach is due to the possibility of studying the influence of the geometric parameters of the flange, the position of the point of application of the lateral force, and a change in the moment of resistance of the cross section on the level of bending stresses.

4. 5. Method for assessing the risk of flange fracture

To assess the contact component of the risk of fracture, the following index was used

$$R = \frac{\sigma_{eq}}{\sigma_H}, \tag{6}$$

where σ_{eq} is the equivalent contact stress;

σ_H is the contact endurance limit of the material.

The fatigue safety factor was determined as

$$n_f = \frac{\sigma_{-1}}{\sigma_f}, \tag{7}$$

where n_f – fatigue safety factor;

σ_{-1} – material endurance limit;

σ_f – fatigue stress amplitude.

For a comprehensive assessment of the risk of flange failure, a combined criterion is proposed

$$C = R \cdot \frac{1}{n_f}, \tag{8}$$

where R is the contact hazard index.

Our study is computational and analytical in nature and is based on determining the geometric characteristics of the real flange profile and subsequent parametric analysis of the stressed state at different values of flange thickness and positions of the lateral force application point. We used SolidWorks Simulation software (France) and the Mathcad 15 computer algebra and computer-aided design system (USA).

The calculation of bending stresses was performed on the basis of classical provisions from material resistance and the theory of beam bending [20]. Fatigue strength assessment was based on fatigue fracture mechanics approaches [19, 20]. To assess the contact component, provisions from contact mechanics and contact fatigue of the wheel-rail system were used [1, 20].

5. Results of parametric study on the risk of wheel flange fracture

5. 1. Determinong the geometric characteristics of dangerous wheel flange cross sections

To assess the impact of operational wear on the stressed state of the flange, the geometric characteristics of wheel profile cross sections, DSTU GOST 11018, were determined for three values of flange thickness h_f = 30, 25, 22 mm.

The calculation of geometric characteristics was performed for cross sections 1-1, 2-2, 3-3, 4-4, 5-5, and 6-6, which corresponded to different positions of the point of application of lateral force along the flange height. For each cross section, the following were determined: cross-sectional area – S; parameters a and b; moment of inertia J; moment of resistance W; bending stresses σ_b; fatigue safety factor k (Tables 1–3).

The bending moment W was determined using dependence (4). The results of the bending moment calculations are given in Table 4.

Fig. 4 show a change in the moment of resistance W of cross sections depending on the position of the cross section and the thickness of the flange, which was determined from formula (3), and its change – according to Tables 1–3.

Table 1

Geometric characteristics of flange cross sections at $h_f = 30$ mm

Cross section	S, mm^2	a, mm	b, mm	J, mm^4	W, mm^3	σ_b, MPa	k
1-1	2306	75.0	9.8	55413	5 654	177	2.5
2-2	4476	105.0	13.2	189575	14 362	139	3.2
3-3	6418	129.0	15.2	352125	23 243	129	3.5
4-4	8114	149.0	16.2	497280	30 696	130	3.5
5-5	9651	166.0	17.2	657310	38 327	130	3.4
6-6	11 279	181.0	19.5	1053543	54 028	111	4.1

Table 2

Geometric characteristics of flange cross sections at $h_f = 25$ mm

Cross section	S, mm ^{2}	a, mm	b, mm	J, mm^4	W, mm^3	σ_b, MPa	k
1-1	1529	75.0	6.5	15 798	2 449	408	1.1
2-2	3213	105.0	10.0	82 425	8 243	243	1.9
3-3	4794	129.0	11.8	166 382	14 100	213	2.1
4-4	6182	149.0	13.2	269 016	20 380	196	2.3
5-5	7480	166.0	14.3	381 053	26 647	188	2.4
6-6	9005	181.0	15.9	571 136	35 921	167	2.7

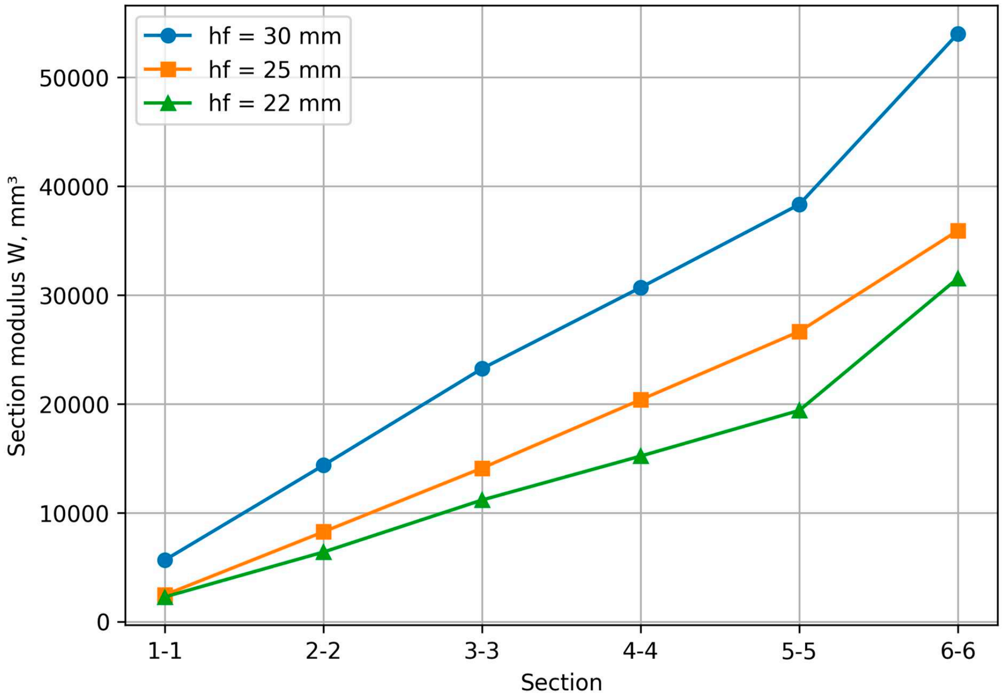


Fig. 4. Dependence of the moment of resistance W on the position of cross section

The results of our calculations showed that with an increase in the height of the cross section, the value of the moment of resistance W increases for all studied values o flange thickness. The maximum values of W are observed in the 6-6 cross section, which is explained by the increase in the cross-sectional area and its geometric dimensions.

The results demonstrated that the most intensive decrease in geometric characteristics is observed in the lower part of the flange where the values of parameters b, J, and W take minimal values.

A decrease in parameters a and b at operational wear of the flange leads to a decrease in the stiffness of dangerous cross sections and an increase in the sensitivity of the flange to the action of lateral loads.

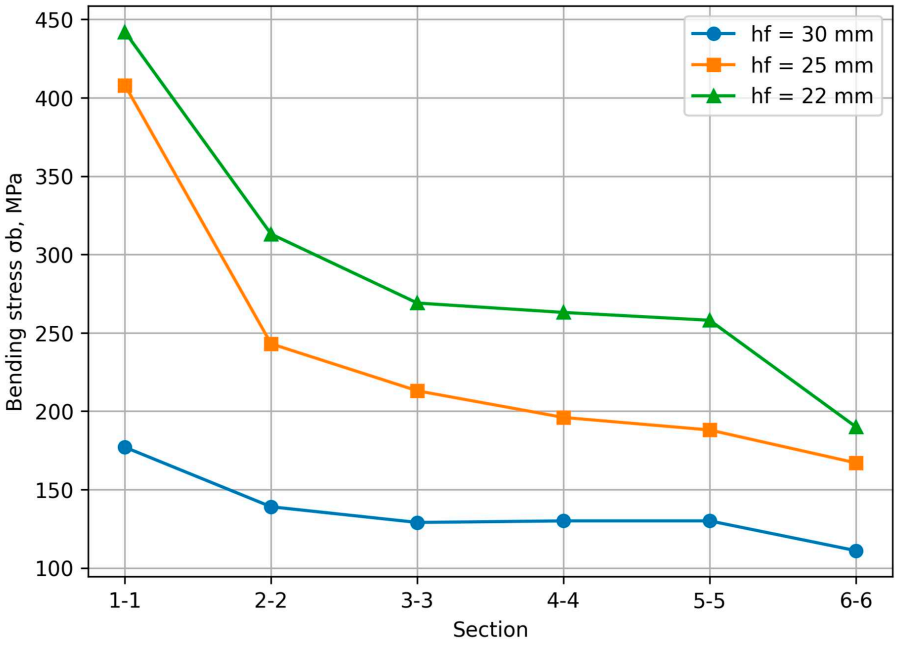


Fig. 5. Dependence of bending stresses σ_b on the position of cross section

Table 3

Geometric characteristics of flange cross sections at $h_f = 22$ mm

Cross section	S, mm ^{2}	a, mm	b, mm	J, mm^4	W, mm^3	σ_b, MPa	k
1-1	1465	75.0	6.2	14 032	2 263	442	1.0
2-2	2937	105.0	8.8	56 170	6 383	313	1.4
3-3	4344	129.0	10.5	117 227	11 164	269	1.7
4-4	5595	149.0	11.4	173 289	15 201	263	1.7
5-5	6791	166.0	12.2	236 623	19 395	258	1.7
6-6	8516	181.0	14.9	470 010	31 544	190	2.4

Table 4

Change in bending moment depending on the position of the point of application of lateral force

Cross section	l, mm	M, kN·m
1-1	5	1
2-2	10	2
3-3	15	3
4-4	20	4
5-5	25	5
6-6	30	6

5. 2. Investigating the influence of the position of the point of application of lateral force on the change in bending stresses

To assess the influence of the position of flange contact on the stressed state of the flange, the calculation of bending stresses was performed according to formula (2) and Tables 1–3 for six positions of the point of application of lateral force Y (Fig. 5), which corresponded to cross sections 1-1, 2-2, 3-3, 4-4, 5-5, and 6-6.

The calculations used a generalized lateral force $Y = 200$ kN, which corresponds to unfavorable conditions of flange contact and was used for parametric assessment of the influence of operational wear on the stressed state of the flange.

The arm of application of the lateral force varied within $5 \leq l \leq 30$ mm.

The results of our calculations showed that changing the position of the point of application of lateral force significantly affects the level of bending stresses in the wheel flange.

For the new profile $h_f = 30$ mm, the values of bending stresses varied within the range of $111 \leq \sigma_b \leq 177$ MPa.

For the thickness of the flange $h_f = 25$ mm, the values of stresses were within the range of $167 \leq \sigma_b \leq 408$ MPa.

For the critical state $h_f = 22$ mm, the bending stresses reached the limits of $190 \leq \sigma_b \leq 442$ MPa.

The results showed that with a decrease in the thickness of the flange, the level of bending stresses increases significantly. The highest stress values are observed in the lower part of the flange, where the values of the moment of resistance have minimal values.

The results of the calculations also showed that with an increase in the height of the contact point, the increase in bending moment is partially compensated for by an increase in the moment of resistance of the cross section. Consequently, a decrease in the level of bending stresses is observed in the upper part of the flange compared to the lower cross sections.

Our dependences confirm the significant influence of operational wear and the position of the point of application of lateral force on a change in the stressed state of a wheel flange.

5. 3. Assessing the impact of operational wear on the fatigue strength safety factor

To assess the risk of developing fatigue damage to the flange, the fatigue strength safety factor was determined, which was calculated using dependence (1). The amplitude of fatigue stresses was determined using dependence (5). The results of the fatigue safety factor calculations are given in Tables 1–3, Fig. 6.

For the new profile $h_f = 30$ mm, the values of fatigue safety factor are within $2.5 \leq k \leq 4.1$, which corresponds to the safe level of operation.

For thickness $h_f = 25$ mm, the values of fatigue safety factor are reduced to $1.1 \leq k \leq 2.7$, which indicates an increased risk of fatigue damage.

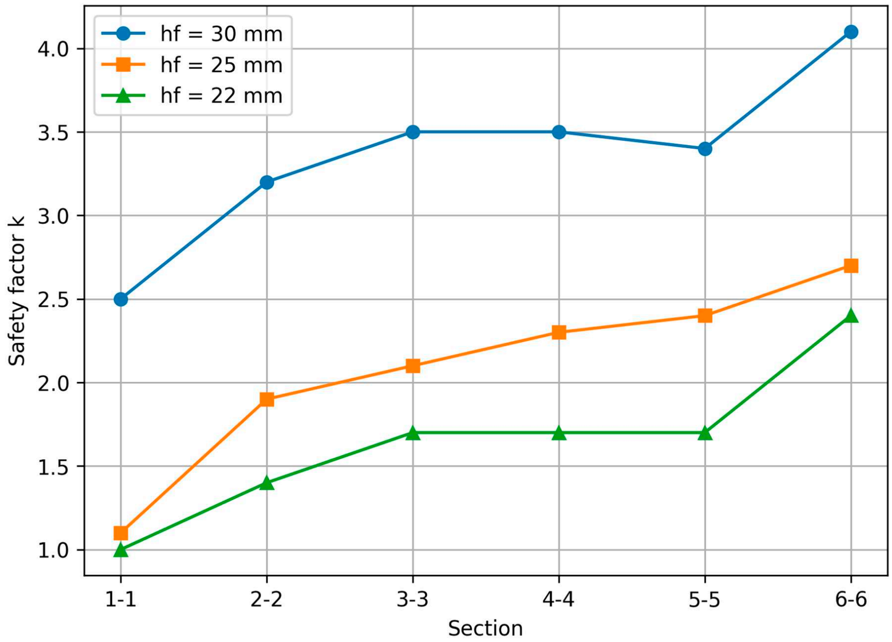


Fig. 6. Dependence of the safety factor *k* on the position of a cross section

For the critical state h_f = 22 mm in the lower part of the flange, the values of fatigue safety factor are reduced to $k \approx 1$, which corresponds to the limit state for fatigue strength.

5. 4. Construction of a combined criterion for assessing the risk of flange fracture

For a comprehensive assessment of the risk of wheel flange fracture, a combined criterion has been proposed that corresponds to dependence (8). The contact hazard index can be determined using dependence (6). But in our work, the index *R* was used as a generalized parameter of contact hazard, characterizing the degree of approach of contact stresses to the contact endurance limit of the wheel material. Due to the fact that the purpose of the work was to assess the influence of operational wear on the risk of flange fracture, contact fatigue was taken into account using the dimensionless contact hazard index *R*.

For a parametric assessment of change in the risk of flange fracture at different degrees of wear, characteristic values of the contact hazard index were adopted:

– R = 0.40 – moderate level of contact interaction;

– R = 0.60 – increased level of contact interaction;

– R = 0.80 – dangerous level of contact interaction.

The results of our calculations of the combined criterion for the danger of destruction at $R = 0.80$ are given in Table 5.

To assess the level of danger of flange collapse, the following areas were identified: $C < 0.30$ – safe condition; $0.30 \leq C < 0.60$ – high-risk zone; $C \geq 0.60$ – dangerous condition (Fig. 7).

Our results showed that the most dangerous are the lower cross sections of the flange, which are characterized by minimum values of the moment of resistance; maximum bending stresses; minimum values of the safety factor; maximum values of the combined hazard criterion.

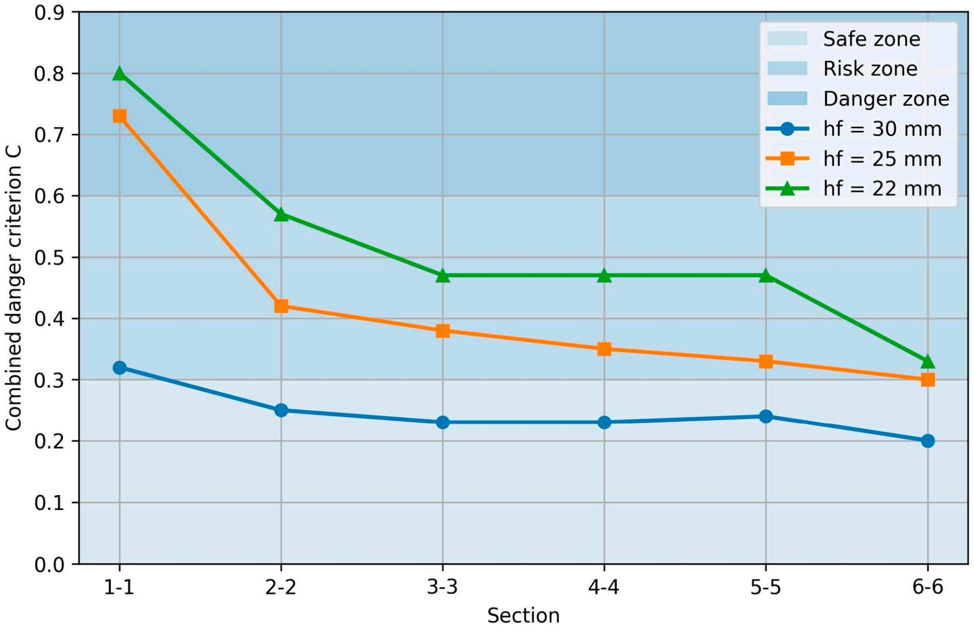


Fig. 7. Dependence of the combined failure hazard criterion *C* on the position of a cross section

Table 5

Value of the combined failure hazard criterion *C* at $R = 0.80$

Cross section	k at $h_f = 30$ mm	C	k at $h_f = 25$ mm	C	k at $h_f = 22$ mm	C
1-1	2.5	0.32	1.1	0.73	1.0	0.80
2-2	3.2	0.25	1.9	0.42	1.4	0.57
3-3	3.5	0.23	2.1	0.38	1.7	0.47
4-4	3.5	0.23	2.3	0.35	1.7	0.47
5-5	3.4	0.24	2.4	0.33	1.7	0.47
6-6	4.1	0.20	2.7	0.30	2.4	0.33

6. Discussion of results based on the parametric study of the risk of wheel flange destruction

Our studies could be used as a basis for designing digital intelligent systems for monitoring the technical condition of railroad rolling stock wheelsets and the risk of their destruction.

The derived dependences (Fig. 4, Tables 1–3) showed that when the flange thickness is reduced from h_f = 30 mm to h_f = 22 mm, the moment of resistance of the cross sections decreases by 1.7–2.5 times. The most intensive decrease in geometric characteristics is observed in the lower part of the flange where the values of parameter b take minimal values.

In [5, 6, 16] it is shown that the reduction in flange thickness significantly affects contact conditions, the magnitude of lateral forces, and the dynamics of interaction in the "wheel-rail" system. At the same time, those studies did not evaluate the change in the bending stiffness of a flange at its operational wear.

In [7–10], most attention was paid to the optimization of the wheel profile and the reduction of wear intensity. The authors showed an important influence of the profile geometry on the contact conditions and dynamic characteristics of rolling stock. However, the local bending strength of the flange and a change in the moment of resistance of dangerous cross sections at operational wear were not considered.

Our dependences (Fig. 5, Table 4) showed that the position of the point of application of the lateral force significantly affects the level of bending stresses in the wheel flange.

When the thickness of the flange is reduced to h_f = 22 mm, the bending stresses in the lower part of the flange reach σ_b = 442 MPa, which is approximately 2.5 times higher than the stress level for the new profile.

Our results are consistent with the conclusions drawn in [1, 11, 12, 17, 18], which show a significant influence of lateral forces and contact loads on the evolution of wheel damage. However, no dependence between the reduction in flange thickness and the increase in local bending stresses was determined in those studies. In [4], the important role of creep forces in the formation of contact loads and wear processes in the wheel-rail system is shown. The results in our study confirm that creep forces and lateral interaction forces not only affect the contact processes but also determine the level of local bending stresses in a wheel flange.

The derived dependences (Fig. 6) showed that the thickness of the flange and the position of the point of application of force Y of the flange significantly affect the fatigue safety factor.

For the new profile h_f = 30 mm, the values of safety factor correspond to the safe level of operation. However, when the thickness of the flange is reduced to h_f = 22 mm in the lower cross sections of the flange, the safety factor decreases to $k \approx 1$, which corresponds to the limit state for fatigue strength.

Our results confirm the conclusions drawn in [3, 13, 14, 17], which show the important role of contact fatigue, cyclic loads, and thermomechanical processes in the evolution of wheel damage. At the same time, the cited papers focused on the contact patch, subsurface stresses, and thermomechanical processes, while local bending stresses of the flange were not considered.

In work [1], the important influence of cyclic tensile stresses and residual thermal stresses on the development of flange cracks is shown. The results in our study confirm that even in the absence of thermal factors, a critical decrease in the thickness of the flange could lead to the transition of the flange to a state close to fatigue failure.

One of the principal findings in our study is the devised combined criterion for assessing the risk of flange failure (Fig. 7, Table 5). The calculation results showed that for h_f = 22 mm the value of hazard criterion in the lower part of the flange reaches 0.80, which corresponds to a dangerous operational state.

The reviewed literature [1–18] lacks a comprehensive criterion that would simultaneously take into account contact fatigue, bending stresses, and changes in the thickness of the flange. In [2, 15], the prospects of using intelligent monitoring systems and automated control of wear parameters of flanges are shown. At the same time, there is no mechanical criterion in the cited studies that would make it possible to assess the risk of destruction based on the results of measuring the geometric parameters of the flange.

A particular danger is the destruction of wheel flanges, which could lead to a violation of conditions for interaction between the wheel and rail, an increase in dynamic loads, and the occurrence of emergencies.

Assessment of the risk of destruction of the wheel flange in railroad rolling stock by bending stresses and contact fatigue makes it possible to take into account the change in the bending stiffness of the flange at operational wear. This allows us to assess the influence of the position of the point of application of lateral force in the contact of the wheel flange and the rail on the level of bending stresses, as well as on the dependence of fatigue safety factor on the thickness of the flange. The devised criterion makes it possible to assess the risk of flange failure during operation.

A basic condition for using the research results is their application to the wheels in railroad rolling stock when assessing their technical condition.

The limitation of this study is that the generalized lateral force and parametric index of contact hazard were used without full three-dimensional modeling of the contact interaction of the wheel and rail. In addition, temperature effects and residual technological stresses were not taken into account.

The disadvantage of our study is that the parametric assessment of contact hazard may change under actual modes of movement of the carriage, rail profile, as well as operating conditions. This disadvantage is a prospect for subsequent studies. In the future, these issues will be resolved.

7. Conclusions

1. As a result of our parametric study, the geometric characteristics of the dangerous cross sections of wheel flange, DSTU GOST 11018 profile, were determined for flange thickness h_f = 30, 25, 22 mm. It was found that when the flange thickness is reduced from 30 to 22 mm, the moment of resistance of the dangerous cross sections decreases by 1.7–2.5 times. A feature of our result is the consideration of the real geometry of the flange and changes in the geometric characteristics of dangerous cross sections at operational wear. Unlike other studies, in which the flange is considered mainly as an element of contact interaction, the flange is considered in this work as a separate bending element. The results are explained by a significant decrease in parameters b, the moment of inertia j, and the moment of resistance W in the lower part of the flange at operational wear.

2. The influence of the position of the point of application of lateral force on the change in bending stresses in

the wheel flange was investigated. It was found that when the flange thickness is reduced to $h_f = 22$ mm, the bending stresses in the lower part of the flange reach $\sigma_b = 442$ MPa, which is approximately 2.5 times higher than the stress level for the new profile. In contrast to known approaches, our work establishes an analytical relationship between the reduction in flange thickness, the change in the moment of resistance, and the increase in local bending stresses. The results are explained by the nonlinear increase in stresses with a decrease in the bending stiffness of dangerous flange cross sections.

3. The influence of operational wear on the fatigue strength reserve factor of a wheel flange was assessed. It was established that at the critical value of flange thickness $h_f = 22$ mm in the lower cross sections of the flange, the fatigue safety factor decreases to $k \approx 1$, which corresponds to the limit state for fatigue strength. A feature of our result is the consideration of the combined influence of bending stresses and operational wear of the flange on the change in fatigue strength. In contrast to existing studies on contact fatigue, our work shows that the risk of damage evolution is determined not only by contact stresses but also by a decrease in the bending stiffness of the flange at its wear.

4. A combined criterion for assessing the risk of flange failure has been devised, which makes it possible to simultaneously take into account contact risk; level of fatigue strength; change in geometric characteristics of the flange; influence of lateral forces; as well as a degree of operational wear. It has been established that for a flange thickness $h_f = 22$ mm, the value of hazard criterion in the lower part of the flange reaches $C = 0.80$, which corresponds to a dangerous operational state. Unlike existing approaches, the proposed criterion allows for a comprehensive assessment of the risk of flange failure, taking into account the simultaneous influence of contact fatigue, bending stresses, and geometric wear. Our results could be used to improve systems for monitoring the technical condition of wheelsets and predicting dangerous wear of wheel flanges.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under full human control.

Artificial intelligence was not used to generate, process, or interpret scientific data, draw conclusions or other elements of the scientific results. Tool used: ChatGPT (OpenAI GPT-5, version 2025). The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

Authors' contributions

Svitlana Sapronova: Conceptualization, Validation, Writing – review & editing; **Oleksandr Vorobiov:** Methodology, Investigation, Writing – review & editing; **Andriy Klimash**: Investigation, Validation.

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