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# Analysis of Limit Loads and 3D Modeling of Removable Equipment for Rail Transporters

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**Abstract.** The paper analyzes critical issues related to the reliability of transporting long rail strings exceeding 800 m in length along curved sections of the railway network of the Republic of Kazakhstan using specialized rail-transport wagons. An original methodological approach is presented for the analytical determination of limit force effects arising in the detachable equipment of flat wagons when negotiating track sections with circular geometry. A detailed three-dimensional representation of the structure was created within the ANSYS computational framework to enable numerical simulation and analysis. The developed digital model was verified through a comparative analysis of theoretical and experimental data, demonstrating a high degree of accuracy (with an error margin not exceeding 5%). The results obtained allow for a more precise assessment of the structure's safety under complex geometric conditions, which is particularly relevant in the context of modernizing the country's transportation infrastructure.

**Keywords:** railway transport, rail carrier, rail platforms, long welded rails, limit loads, oversized cargo transportation

**Introduction.**

In his address to the citizens of the Republic of Kazakhstan on September 1, 2023, President Kassym-Jomart Tokayev emphasized the need to prioritize the development of the national transport and logistics system, highlighting the importance of implementing large-scale railway infrastructure projects. Among the key initiatives identified were the construction of the "Bakhty–Ayagoz" and "Darbaza–Maktaaral" railway lines, as well as the development of a railway bypass route in the Almaty region, underscoring the high relevance of the project under consideration [1].

At present, the railway sector is increasingly focused on the widespread adoption of high-speed continuous welded rail technologies, which involve the use of long rail strings. This approach significantly reduces the number of rail joints and improves the operational performance of the track structure [2–4]. Eliminating joints decreases dynamic impacts on the track, significantly reducing wheel wear on rolling stock and train resistance, which in turn lowers fuel and electricity consumption for traction [2-4].

An analysis of practices applied in northern countries demonstrates successful experience in transporting long rail strings exceeding 800 m in length using specialized rail-carrying platforms of the RS-800/3 type (Figure 1) [5, 6]. At the same time, the specific natural and geographical conditions of the Republic of Kazakhstan impose increased requirements on the reliability and safety of such transportation, particularly when rolling stock operates on track sections with curved alignment [7].

An extensive survey and critical assessment of the available scholarly literature and normative calculation procedures [7–10] has shown that, at present, no generalized analytical dependencies or validated mathematical formulations exist that can reliably characterize the force interactions between rolling stock components during the movement of continuous rail strings exceeding 800 m in length along curved track sections. Among the methods currently reported, the approach most closely aligned with the technical concept proposed in this work is the calculation scheme developed by specialists of the China Academy of Railway Sciences for the Ministry of Railways of the People's Republic of China (Beijing) [9].

In that research, a dynamic simulation model was formulated to estimate the loads generated during the transportation of rail strings with lengths of up to 100 m on curved track segments with radii not exceeding 300 m. The results of experimental validation demonstrated that the calculated dynamic responses satisfy the prescribed safety requirements for transportation. Nevertheless, the scope of applicability of this approach is confined to relatively short rail strings (up to 100 m), which makes it unsuitable for assessing the behavior and loading conditions of ultra-long rail elements during transportation.

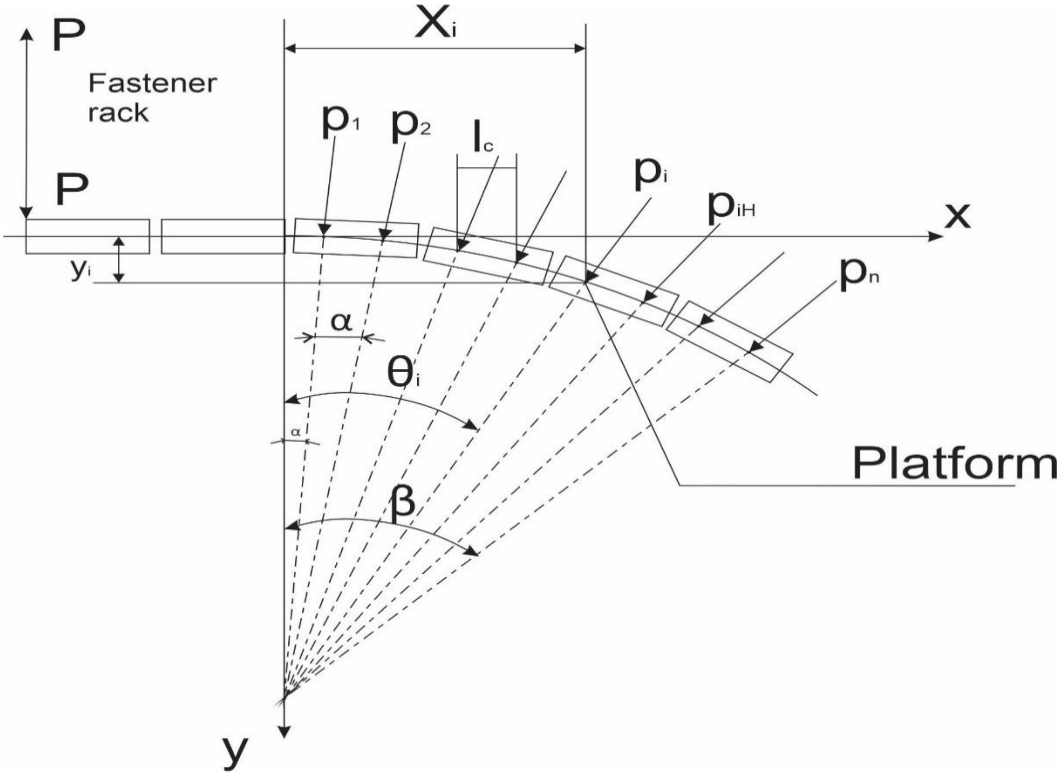
a) b)

**Fig. 1. –** Transportation (a) and Laying (b) of Long Welded Rails

As a result, the development of a reliable calculation methodology, along with the verification of a numerical model realized within the ANSYS simulation platform, continues to be an open issue of substantial practical importance. This makes it necessary to employ a methodology capable of accurately determining the load effects imposed on the removable structural elements of rail-transporting flatcars as continuous welded rails longer than 800 m are conveyed along curved portions of the railway alignment.

**1 Materials and Methods**

Figure 2 illustrates the suggested computational method for assessing the maximum loads on the detachable components of rail transport platforms arranged in a connected formation while conveying welded rails exceeding 800 m along curved track sections.




$P_i$ – loads (support reactions) resulting from the imposed deformation of the continuous welded rail at the i-th support; $l_e$ – distance between the supports of the fastening platform; R – curve radius; $y_i$ – bending deformation of the long welded rails at the i-th support; α – rotation angle between adjacent supports of the fastening platform; β – total curve rotation angle; $x_i$ – distance from the bending angle to the i-th support of the fastening platform in the curve; θ – cross-section rotation angle of the long welded rails at the i-th support.

**Fig. 2. –** Methodology for Evaluating Maximum Loads on Detachable Components of Coupled Rail Transport Platforms During the Conveyance of Continuous Welded Rails Exceeding 800 m Along Curved Track Sections

Obvious geometric relationships derived from the calculation scheme (Figures 2 and 3) have been observed.

$$x_i = \sum_{j=1}^{i} l_e$$
$$\theta_i = \sum_{j=1}^{i} \alpha$$

$$\mathbf{\Delta} = l_e \cdot tg\alpha \tag{1}$$

$$\alpha = arctg\frac{l_e}{2R}$$

where **Δ** – bending or distortion of an individual segment spanning between two support points.

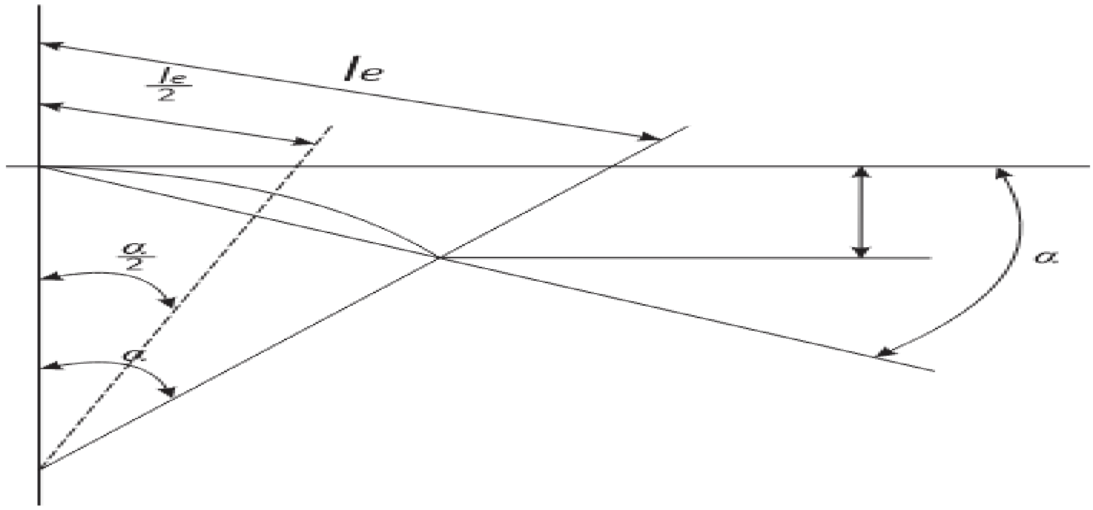



**Fig. 3.** – Procedure for Assessing the Bending of Continuous Welded Rails

Subsequently, the general expression for the elastic curve, formulated using the initial parameters, can be written as follows:

$$y = y_0 + \theta_Q x + \frac{M_0 x^2}{2EY} + \frac{Q_0 x^3}{6EY} + f(x), \tag{2}$$

where $y_0$, $\theta$, $Q_0$, and $M_0$represent the initial values of deflection, rotation angle, transverse load, and bending moment at the reference point, respectively.

To enhance the accuracy of predicting the maximum forces acting on the removable coupling elements of flatcars during the transport of rail strings exceeding 800 m along curved track segments—and to validate the proposed computational model—comprehensive numerical analyses were conducted within the ANSYS simulation environment.

In the course of developing and executing the numerical simulations, the following methodological and investigative steps were completed:

– assessment of the principal geometric and structural characteristics of the studied components;

– evaluation of real-world operating conditions and service scenarios of the rolling stock;

– formulation of a procedure for carrying out the computational experiment;

– execution of preliminary trial calculations to verify the fidelity of the 3D simulation model by comparing numerical predictions with experimental data [11–12].

The numerical study was conducted step by step in the following sequence:

– creation of a 3D representation of the removable components of flat rail transport wagons using AutoCAD (Figure 4);

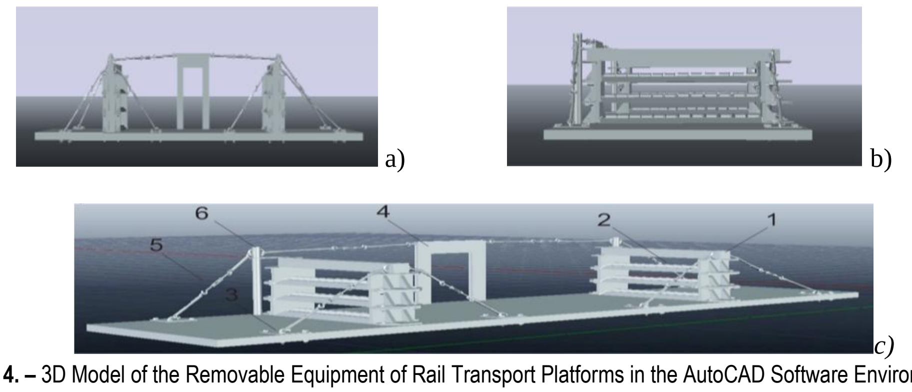



**Fig. 4. –** 3D Model of the Removable Equipment of Rail Transport Platforms in the AutoCAD Software Environment: 1) Support post; 2) Roller supports; 3) Platform attachment; 4) Side support; 5)Turnbuckle; 6) Tension post.

– transfer of the three-dimensional geometry to the ANSYS computational environment for further analysis (Figure 5);

– identification of the structural components selected for simulation and loading during virtual testing (Figure 6a);

– the physical and mechanical properties of the materials in the computational model were defined, and a structural steel material from the built-in ANSYS library with typical mechanical properties was used (Figure 6b).;

– generation of the finite element mesh and computation of the stress–strain state taking into account all adopted assumptions and boundary conditions (Figure 6c, d);

– interpretation and systematization of the numerical analysis results (Figure 7).

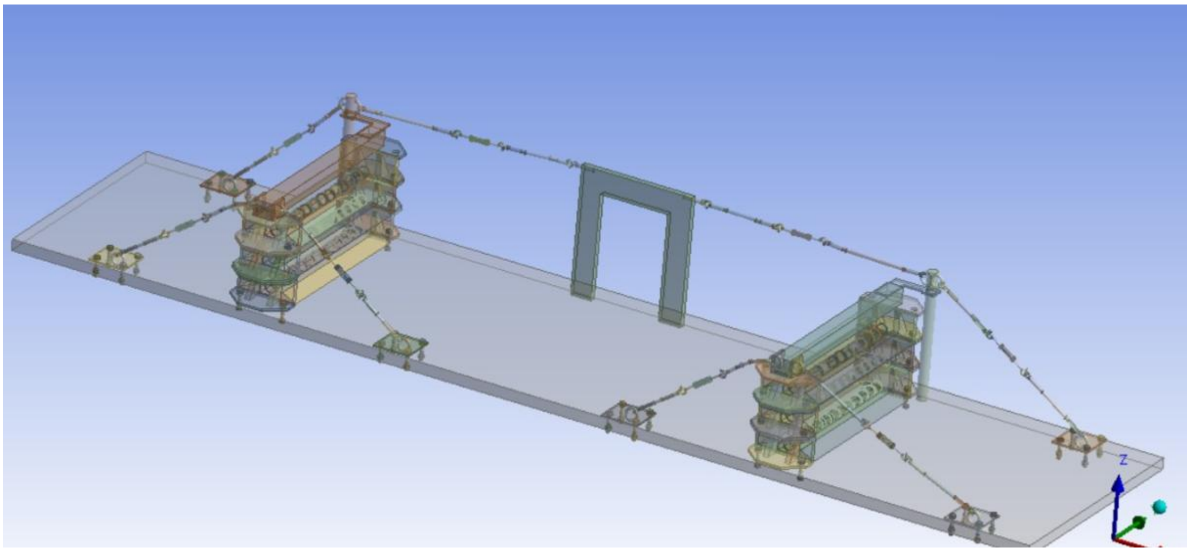
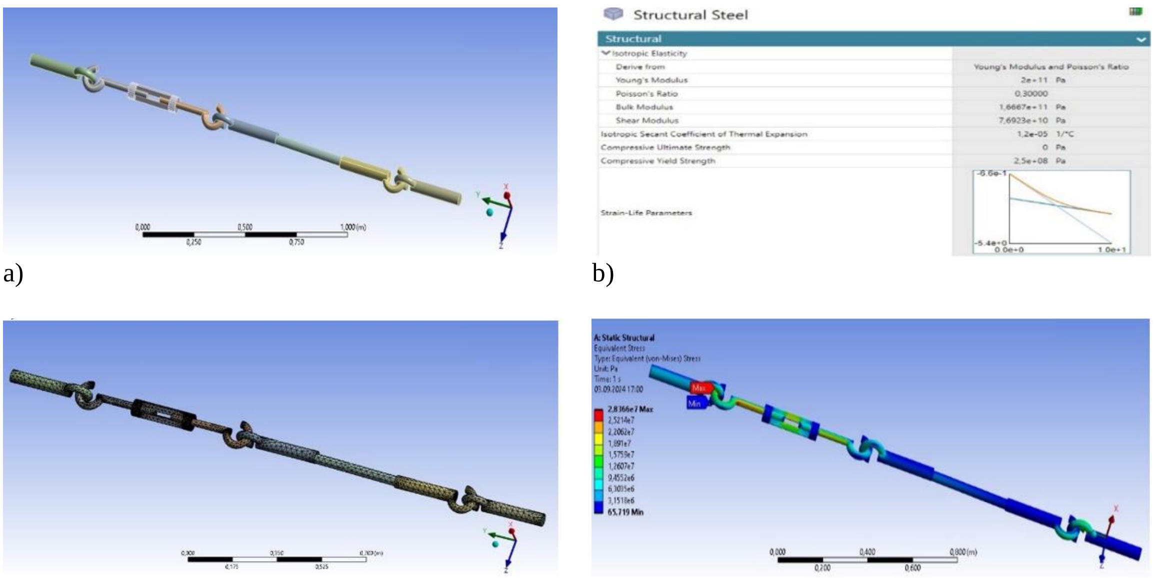


**Fig. 5.** – 3D Model of the Removable Equipment of Rail Transport Platforms in the ANSYS Software Environment




a) b)

c) d)

**Fig. 6.** – Preparation of a 3D Model Element of the Removable Equipment of Rail Transport Platforms in a Coupled Configuration for Simulation Testing in the ANSYS Software Environment

## 2. Results and discussion

Within the numerical investigation, four calculation scenarios were implemented, differing in the combinations of external loads applied to the analyzed element of the spatial model of the detachable coupling units of flat wagons (rail carriers). Upon completion of each scenario, distributions of the stress–strain state were obtained in the form of graphical stress fields, and the corresponding output parameters of the model were calculated (Figure 7a–c).

To clarify the differences between the implemented calculation scenarios, Table 1 summarizes the loading conditions in terms of the ratio of the applied tensile force to the cross-sectional area (F/S), along with the corresponding maximum equivalent stresses.

**Table 1**. Parameters of calculation scenarios and simulation results

| Scenario | Fi/S (MPa) | Max stress $\sigma_e$ (MPa) | Description |
|---|---|---|---|
| Test I | Low | 28.4 | Initial loading condition |
| Test II | Medium | 85.1 | Increased tensile load |
| Test III | High | 141.8 | Near allowable stress |
| Test IV | Critical | 198.6 | Exceeds allowable limit |

As shown in Table 1, an increase in the applied load leads to a nonlinear growth in equivalent stresses. It should be noted that in Test IV the stress level exceeds the allowable limit of 160 MPa, indicating a potentially unsafe operating condition

Based on the calculations performed using the ANSYS software package, an experimental–computational relationship was established (Figure 5d) that describes the variation of equivalent mechanical stresses $\sigma_{ei}$ (MPa) in the structural material as a function of the intensity of the applied external force, characterized by the ratio Fi/S (MPa), at a maximum allowable stress level of 160 MPa.

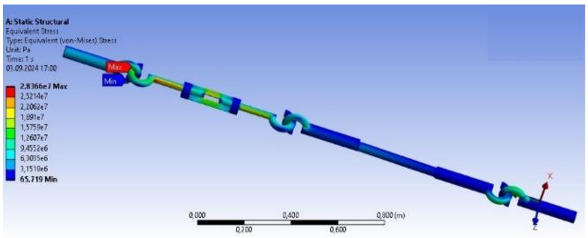
To identify the functional relationship between the model input parameters (Fi/S) and the corresponding structural responses ($\sigma_{ei}$), an approximating empirical equation was derived:

$$y_{Ti} = a \cdot e^{bx_i} = 26{,}188 \cdot e^{0{,}311x_i} \,. \quad (3)$$

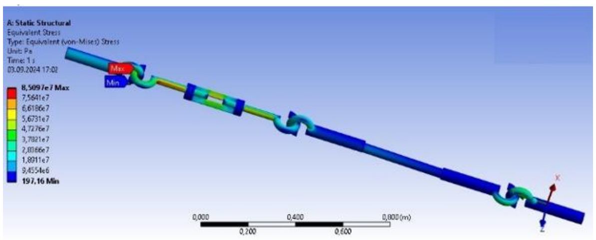
where $x_i$ – influencing factors, $F_i$/S, MPa;

$y_{ti}$ – output parameters, $\sigma_{ti}$, MPa.

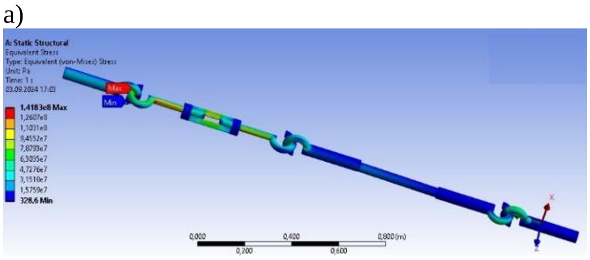
Figure 7(d) presents a comparison between the outcomes of the numerical simulations and the analytical calculations. The evaluation indicates that the results derived from Equation (3) deviate only within the acceptable ranges defined by relevant standards, thereby validating the reliability of the employed computational methodology..



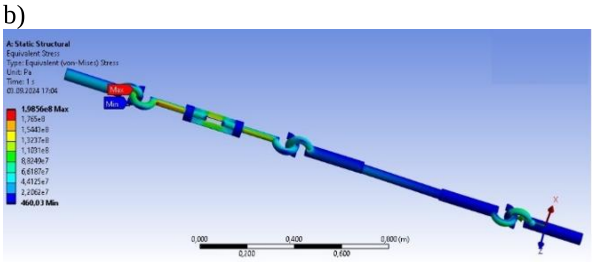
a)



b)



c)



d)

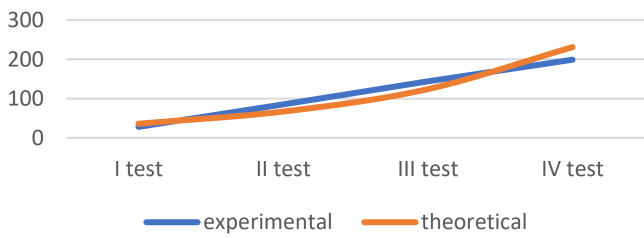



**Fig. 7.** – Simulation Test Results of a 3D Model Element of the Removable Equipment of Rail Transport Platforms (Rail Carriers) in the ANSYS Software Environment

The application of numerical modeling using the ANSYS software package enabled the evaluation of the maximum permissible force effects arising during the transportation of long rail strings exceeding 800 m in length along curved sections of railway track. Within a series of four computational scenarios, distributions of the stress–strain state were obtained, indicating that when the equivalent stress level does not exceed 160 MPa, the strength characteristics of the structure satisfy the established requirements.

A generalized analysis of the numerical experiment results demonstrated a high degree of agreement between the computational and analytical data, with discrepancies not exceeding 5%, which confirms the correctness and robustness of the proposed calculation model. At the same time, to further improve the accuracy of predicting limit loads, it is advisable to conduct extended simulation studies followed by the development of a specialized computational approach for determining allowable loads in the elements of detachable equipment of flat wagons (rail carriers). Implementation of this approach will enhance the reliability of safety assessments for the transportation of long rail strings (over 800 m) when negotiating circular curves on the railway network of the Republic of Kazakhstan.

## Conclusions

The conducted study confirmed the feasibility of using the improved computational model and digital simulation in ANSYS to determine the maximum loads in the detachable equipment of rail transporters during the transportation of long welded rails along curved tracks. The simulation tests demonstrated a strong correlation between experimental data and theoretical calculations, which validates the reliability of the developed model. This provides a solid basis for considering the proposed methodology as an effective tool for assessing the strength and safety of structures under challenging operational conditions. The findings of this study may be utilized in engineering applications to refine design solutions, enhance the safe transport of extended welded rails, and contribute to the advancement of regulatory guidelines and technical norms within Kazakhstan's railway sector.

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