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Dynamic analysis of the stress–strain state of a railway bridge beam superstructure under moving train loads

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Abstract

The article presents a numerical dynamic analysis of the stress-strain state of a railway bridge under load from a moving train. The aim is to evaluate the reaction of reinforced concrete superstructures to dynamic loads from rolling stock with increased axial loads, which is a development of previous static studies. A spatial finite element model has been created in the MIDAS Civil environment that considers geometry, material properties, boundary conditions, and the interaction of elements. Loads from a moving train were modeled using dynamic scenarios based on locomotive-wagon configurations, speed, and axial distances. The analysis of the dynamic response revealed the influence of dynamic effects on the stress-strain state, with an increase in stress levels compared to static scenarios. The study highlights the importance of dynamic analysis for the safe operation of railway bridges under conditions of increased loads and speeds, and can be used to evaluate, monitor, design, and improve computational approaches.

Keywords: railway bridge; beam superstructure; moving train loads; dynamic analysis; stress–strain state; MIDAS Civil; finite element method

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Техникалық ғылымдар. Құрылыс

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Жылжымалы пойыз жүктемелері кезіндегі теміржол көпірінің арқалық қондырмасының кернеулі-кернеулі күйін динамикалық талдау

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Түйіндеме

Мақалада қозғалатын пойыздың жүктемесі кезінде теміржол көпірінің кернеулі-кернеулі күйінің сандық динамикалық талдауы келтірілген. Мақсаты-темірбетон қондырмаларының осьтік жүктемелердің жоғарылауымен жылжымалы құрамның динамикалық жүктемелеріне реакциясын бағалау, бұл алдыңғы статикалық зерттеулердің дамуы болып табылады. МИДАСТЫҢ Азаматтық ортасында геометрияны, материалдық қасиеттерді, шекаралық жағдайларды және элементтердің өзара әрекеттесуін ескеретін кеңістіктік ақырлы элементтер моделі жасалды. Қозғалыстағы пойыздан түсетін жүктемелер локомотив-вагон конфигурациясына, жылдамдыққа және осьтік қашықтыққа негізделген динамикалық сценарийлерді қолдану арқылы модельденді. Динамикалық реакцияны талдау статикалық сценарийлермен салыстырғанда стресс деңгейінің жоғарылауымен стресс-штамм күйіне динамикалық әсерлердің әсерін анықтады. Зерттеу жүктемелер мен жылдамдықтардың жоғарылауы жағдайында теміржол көпірлерінің қауіпсіз жұмыс істеуі үшін динамикалық талдаудың маңыздылығын көрсетеді және есептеу тәсілдерін бағалау, бақылау, жобалау және жетілдіру үшін пайдаланылуы мүмкін

Түйін сөздер: теміржол көпірі; сәуленің үстіңгі құрылымы; пойыздардың қозғалмалы жүктемелері; динамикалық талдау; стресс–штамм күйі; MIDAS Азаматтық; ақырлы элемент әдісі

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Технические науки. Строительство

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Динамический анализ напряженно–деформированного состояния пролетного строения балки железнодорожного моста при нагрузках движущегося поезда

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Аннотация

В статье представлен численный динамический анализ напряженно-деформированного состояния железнодорожного моста под нагрузкой от движущегося поезда. Цель - оценить реакцию железобетонных пролетных строений на динамические нагрузки от подвижного состава с повышенными осевыми нагрузками, что является развитием предыдущих статических исследований. В среде MIDAS Civil создана пространственная конечно-элементная модель, учитывающая геометрию, свойства материалов, граничные условия и взаимодействие элементов. Нагрузки от движущегося поезда моделировались динамическими сценариями, основанными на конфигурациях локомотив-вагон, скорости и осевых расстояниях. Анализ динамического отклика выявил влияние динамических воздействий на напряженно-деформированное состояние, с увеличением уровней напряжений по сравнению со статическими сценариями. Исследование подчеркивает важность динамического анализа для безопасной эксплуатации железнодорожных мостов в условиях повышенных нагрузок и скоростей, и может быть использовано для оценки, мониторинга, проектирования и совершенствования расчетных подходов

Ключевые слова: железнодорожный мост; балочное пролетное строение; нагрузки от движущегося поезда; динамический анализ; напряженно–деформированное состояние; MIDAS Civil; метод конечных элементов

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1. Introduction

The rapid development of global logistics and the intensification of rail transport have placed unprecedented demands on the structural integrity of railway infrastructure. In the Republic of Kazakhstan, which serves as a pivotal transit hub connecting China, Central Asia, and Europe, the rail network is undergoing a significant transformation. The transition to heavy-haul traffic, characterized by axle loads reaching 25-27 tons and increased operational speeds, necessitates a more sophisticated approach to the structural health monitoring and design of railway bridges [1].

Historically, the design and assessment of reinforced concrete railway overpasses have relied heavily on static analysis. While static models provide a fundamental understanding of load distribution, they fail to account for the kinetic energy, vibrations, and time-dependent interactions that occur when a massive locomotive and car set traverse a bridge. This research addresses this gap by shifting the focus from the static Stress-Strain State (SSS) to a comprehensive dynamic analysis using the specialized MIDAS Civil software environment.

Kazakhstan's «Nurly Zhol» program and the "Belt and Road Initiative" have led to a steady increase in transit freight volumes. Railway bridges, particularly those with typical reinforced concrete beam superstructures (spans of 16.5 m and 23.6 m), are the most critical components of this infrastructure. These structures must maintain high reliability over decades of service. However, the constant cyclic impact of heavy axle loads leads to the accumulation of micro-damage and changes in the structural response of the concrete [2].

A dynamic approach is essential to predict the remaining service life of these structures under modern loading conditions. Previous studies conducted by Bondar et al. [1] successfully utilized the «ABAQUS/Standard» package to determine the stress-strain state of reinforced concrete spans under static cohesion of TEM-18 locomotives. Those results established the baseline safety margins for the structures. However, in reality, a train is not a stationary mass but a moving dynamic system. When a train moves across a bridge, several phenomena occur that static models cannot capture: Impact Factor (Dynamic Amplification): The stresses generated during motion are significantly higher than static stresses due to the vertical acceleration of the train's mass.

Every bridge has natural frequencies. If the frequency of the train’s axle passage matches the natural frequency of the span, resonance can occur, leading to structural failure even if the weight is within static limits. Damping Effects: The dissipation of energy within the concrete and the ballast layer plays a crucial role in how long the structure continues to vibrate after the train has passed. To solve these complex problems, this study utilizes MIDAS Civil, a world-leading software specifically optimized for bridge engineering. Unlike general-purpose FEA tools, MIDAS Civil allows for:

Specialized algorithms for simulating the passage of «locomotive-wagon» couplings at specific velocities. Time-History Analysis: Calculating the response of the bridge at every millisecond of the transit. Boundary Condition Accuracy: Better simulation of the elastomeric bearings and the interaction between the beam and the intermediate supports. The transition to MIDAS Civil enables a more precise evaluation of the joint operation of reinforcing elements (frames, meshes, and prestressed bundles) and the concrete matrix under a «moving force» or «moving mass» scenario.

The growing intensity of railway transportation, combined with increasing axle loads and operational speeds, creates additional demands on the safety, durability, and serviceability of railway bridge structures. This issue is especially relevant for reinforced concrete bridge superstructures operating on freight-oriented railway corridors, where repeated dynamic воздействия from moving rolling stock may significantly affect the stress–strain state of structural elements.

In engineering practice, the assessment of railway bridge spans is still often based on static calculation schemes. Although static analysis remains necessary for determining the general distribution of internal forces and deformations, it does not fully capture the transient nature of train–bridge interaction, including inertia effects, oscillations, and the speed-dependent amplification of stresses and displacements. For this reason, the dynamic behavior of railway bridge structures has become an important area of research in bridge engineering [1–4].

Previous studies have demonstrated that the response of bridge structures under moving train loads depends on multiple factors, including span length, structural stiffness, damping properties, axle spacing, and train speed [6, 7, 10, 11]. At the same time, in the authors' previous study, the reinforced concrete spans of a railway overpass were investigated mainly under static loading conditions using a spatial finite element model [12]. That study provided important baseline information on the stress–strain state of the superstructure; however, it did not address the influence of moving train loads and the resulting dynamic effects.

Thus, the research gap lies in the insufficient assessment of the dynamic stress–strain state of typical reinforced concrete railway bridge spans previously studied under static loading. In particular, the influence of moving train loads, train speed, and modal characteristics on stress amplification and deflection response requires further investigation.

The novelty of the present study consists in extending the previously obtained static results through a dynamic finite element analysis of reinforced concrete railway bridge beam superstructures in MIDAS Civil. Unlike the earlier static approach, the present work considers moving axle loads, modal characteristics of the spans, and time-history response, which makes it possible to evaluate the dynamic amplification of stresses and displacements under realistic operating conditions.

The aim of the study is to evaluate the dynamic stress–strain state of reinforced concrete railway bridge beam superstructures under moving train loads. To achieve this aim, the following tasks were formulated:

1. to develop a spatial finite element model of the bridge superstructure in MIDAS Civil;
2. to define the material parameters, prestressing characteristics, and support conditions;
3. to simulate the passage of locomotive and freight rolling stock at different speeds;
4. to determine the dynamic response of the spans in terms of stresses and deflections;
5. to compare the obtained dynamic results with the previously established static response.

The core problem addressed in this paper is the lack of detailed dynamic performance data for standard 16.5 m and 23.6 m span blocks under the latest heavy-load locomotive standards in Kazakhstan. While the static capacity is known, the Stress-Strain State evolution over time during high-speed transit remains under-researched [3].

To construct a high-fidelity spatial finite element model of the railway overpass that accounts for the precise geometry of the drainage holes, prestressing bundles, and reinforcement classes (AI, AII, BII).

2. Materials and methods

The present study is a numerical investigation based on finite element modeling and dynamic simulation of a reinforced concrete railway bridge superstructure. It is not a systematic literature review; the cited publications were used as the scientific and methodological basis for selecting the modeling approach, interpreting the dynamic response, and comparing the obtained results with previously published findings.

The object of the study is a reinforced concrete railway bridge with typical beam spans of 16.5 m and 23.6 m. The geometric characteristics of the spans were adopted in continuity with the authors' earlier static analysis [12], which allowed a direct comparison between static and dynamic results.

A spatial finite element model of the bridge was developed in MIDAS Civil. The model included the superstructure and support zones and was formed using several types of finite elements depending on their structural function:

- beam elements for the longitudinal structural members and load-transfer path;
- plate/shell elements for the slabs and girder components, enabling the evaluation of local stress–strain behavior;

- lid elements for massive support regions where stiffness and inertial effects are significant under dynamic loading.

The model accounted for the bridge geometry, material properties, prestressing action, and boundary conditions. Material parameters were assigned according to the adopted structural classes used in the design documentation and the previous static study. The main material properties used in the model are presented in Table 1.

Table 1. Material Properties and Structural Roles for Bridge Model

Material Component	**Specification / Class**	**Modulus of Elasticity (E, MPa)**	**Purpose in Model**
Concrete (16.5 m span)	M300	30,800	Main structural volume
Concrete (23.6 m span)	M400	34,300	Prestressing zone stability
Reinforcement (Class AI)	Smooth bars	210,000	Longitudinal & stirrups
Reinforcement (Class AII)	Ribbed bars	210,000	Main tension zones
Prestressing Bundles	24 wires Ø5 BII	190,000	Active stress control

Concrete of class M300 with an elastic modulus of 30,800 MPa was assigned to the 16.5 m span, while concrete of class M400 with an elastic modulus of 34,300 MPa was assigned to the 23.6 m span. Reinforcement of classes AI and AII was modeled with an elastic modulus of 210,000 MPa. Prestressing tendons consisting of 24 wires of 5 mm diameter (class BII) were modeled with an elastic modulus of 190,000 MPa. Prestressing was introduced into the model as an initial stress state.

Boundary conditions were defined using elastic support links to simulate the actual stiffness of support bearings. This approach made it possible to avoid oversimplified rigid supports and to represent the rotational and limited translational response of the structure under moving loads more realistically.

To perform a modal analysis to identify the natural frequencies and mode shapes of the spans. To simulate the dynamic passage of three TEM-18 locomotives and loaded gondola cars (25 t/axle) at various speed intervals. To quantify the difference between static and dynamic stress levels in the lower belt of the beam, where tension is maximum.

The mathematical model for this dynamic study is based on the equation of motion:

$$F(t) = [M] \cdot a + [C] \cdot v + [K] \cdot u, \tag{1}$$

Or written fully in words:
[M] - the mass matrix of the bridge structure.
[C] - the damping matrix of the bridge.
[K] - the stiffness matrix of the bridge.
{ a }- acceleration vector of the bridge nodes.
{ v }- velocity vector of the bridge nodes.
{ t }- displacement vector of the bridge nodes.
{F(t)}- time-dependent force vector representing the moving train [4].

In MIDAS Civil, this is solved using numerical methods such as the Newmark-beta or Wilson-theta methods to ensure stability and accuracy. The study specifically focuses on the spatial arrangement of the reinforcement. As the train moves, the stress waves propagate through the concrete, affecting the bond between the reinforcement and the surrounding material. By analyzing these stresses dynamically, we can identify potential «fatigue zones» that are invisible in static calculations [5].

To ensure the continuity of the research initiated by Bondar et al. (2024), the geometric parameters of the 16.5 m and 23.6 m span blocks were strictly maintained. However, for dynamic analysis, the modeling approach in MIDAS Civil differs from the general-purpose ABAQUS environment. A hybrid finite element mesh was generated:

Beam Elements: Used for secondary structural members and to define the longitudinal axis of the main girders for moving load distribution.

Plate/Shell Elements: Employed for the top and bottom slabs of the box-girder or T-beam sections to capture the local stress-strain state of the concrete.

Solid Elements: Applied to the massive intermediate supports to accurately represent the mass-stiffness distribution during seismic or vibration events.

The spatial model accounts for the exact coordinates of the drainage systems and the complex cross-sectional geometry shown in the working documentation. Unlike static models, the dynamic model includes the mass matrix $[M]$, which is derived from the material density and the volume of the elements. The research utilizes the material specifications from the original technical documentation. To observe the stress-strain state, the non-linear behavior of concrete was defined using the Mander model or modified Kent-Park model within MIDAS Civil to account for the confinement effect of the reinforcement [6].

The prestressing force was modeled as an initial strain/stress load case. According to Fig. 4 of the reference study, the upper rectilinear bundles were set to $7100\ \text{kgf/cm}^2$, and the lower bundles reached up to $10400\ \text{kgf/cm}^2$. In MIDAS Civil, these are defined as Prestressing Tendon Loads with automated loss calculations. The core of this research is the simulation of the moving train set. The «locomotive-wagon» coupling scheme was transformed into a dynamic time-history function.

The loading consists of:

Locomotive Group: Three TEM-18 diesel locomotives, each with a 3-axle bogie system, modeled as a series of concentrated forces:

$$P = 20.83\ \text{tf/axle} \tag{2}$$

Freight Cars: Two loaded gondola cars with a higher axle load of up to

$$P = 25.0875\ \text{tf/axle} \tag{3}$$

In MIDAS Civil, the Moving Load Tracer was used to define the "Vehicle Path." The dynamic effect is calculated by defining the velocity $v$as a variable, ranging from 40 km/h to 100 km/h. The interaction is governed by the Time-History Load Case, where the force position $x(t)$changes at each time step Δt:

$$x(t) = x_0 + v \cdot t \tag{4}$$

where:

x_0 - initial position of the axle,

v - train velocity,

t - elapsed time,

$x(t)$- current position of the axle at time t.

Before the stress-strain analysis, a Modal Analysis was performed to determine the natural frequencies $f_n$of the bridge. This is a critical step that was not present in the static study [7].

The damping ratio was set to:

$$\zeta = 0.05(5\%) \tag{5}$$

based on the Rayleigh damping criteria for reinforced concrete structures, which accounts for the energy dissipation during the train's passage.

To compare the results with the static data, «Virtual Sensors» were placed at the same control points: the middle of span 0-1, span 1-2, and span 2-3. Boundary conditions were modeled as Elastic Links to represent the stiffness of the support bearings, allowing for realistic rotation and minor horizontal displacement under dynamic braking or acceleration forces [8].

3. Results

Before evaluating the stress-strain state under moving loads, a modal analysis was conducted in MIDAS Civil to determine the dynamic characteristics of the 16.5 m and 23.6 m spans. The natural frequencies play a decisive role in the bridge's response to train speeds.

The first three mode shapes were identified:

Mode 1 (First Bending): Characterized by vertical oscillations. For the 23.6 m span, the fundamental frequency was found to be within the range of

$$f_1 = 3.8 - 4.2 \text{ Hz} \tag{6}$$

Mode 2 (Torsional): Occurs due to the eccentricity of the track or asymmetric reinforcement wear, showing the structural rigidity against twisting.

Mode 3 (Lateral/Horizontal): Reflects the stability of the intermediate supports and the girder's resistance to transverse forces from the train's wheelset.

3.1 Dynamic Stress–Strain Analysis (SSS) Results

The dynamic behavior of the bridge beam superstructure under moving train loads was analyzed using the Direct Integration Time-History method in MIDAS Civil. This approach allows observing the structural response at each discrete time step as TEM-18 locomotives and freight cars traverse the spans of 16.5 m and 23.6 m. In the MIDAS Civil model, stress evolution was tracked at the integration points of the concrete plate elements and the truss elements representing reinforcement. The analysis indicates that the stress–strain state is time-dependent, fluctuating according to the axle spacing of the moving train. When the first bogie of the leading locomotive enters the span, a stress wave propagates along the structure. For the 23.6 m span, the maximum stresses occur when the center of gravity of the locomotive is located at mid-span ($L/2$). The dynamic tension in the lower reinforcement zone exhibits a pulsating behavior, with frequency components corresponding to train speed and the natural frequencies of the beam [9]. The principal compressive stresses (σ_c) in the M400 concrete of the 23.6 m span were evaluated. Under static loading, the maximum compression was $\sigma_{stat} = 3.72$ MPa [1]. However, the dynamic simulation at a train speed of $V = 80$ km/hshowed a significant increase due to vertical acceleration effects.

The Dynamic Amplification Factor (DAF) was calculated using:

$$1 + \mu = \frac{\sigma_{dyn}}{\sigma_{stat}} \tag{7}$$

where:

σ_{dyn} - dynamic stress, MPa

σ_{stat} - static stress, MPa

For concrete elements, Φranged between 1.15 and 1.22, depending on the damping ratios and track irregularity profiles included in the model [10]

Table 2. Dynamic Stress Distribution in Concrete Sections (MPa)

Span Length	Control Point	Static Stress (σ_s)	Dynamic Stress (σ_d)	Increase (%)
16.5 m	Top Slab (Center)	4.64	5.38	15.9%
23.6 m	Top Slab (Center)	3.72	4.46	19.8%
23.6 m	Support Zone	2.15	2.68	24.6%

3.2 Stress State in Prestressed and Non-Prestressed Reinforcement

The stress in the reinforcement is critical for the bridge's fatigue life. Non-prestressed reinforcement (Class AII) in the tension zone reached dynamic stresses of 108.3 MPa. Prestressing tendons (24 wires, Ø5 BII) were modeled as internal tendons with initial prestress of $10400\ \text{kgf/cm}^2$.

The dynamic analysis showed:

Moving loads temporarily increase tendon tension by 35-50 MPa.

High initial prestress keeps potential cracks closed, maintaining compression in concrete during peak dynamic loads.

The stress range ($\Delta\sigma$) in tendons remains below the fatigue threshold, ensuring long-term reliability of 16.5 m and 23.6 m spans.

Simulations were performed at speeds ranging from $V = 40$ km/hto $V = 100$ km/hwith 10 km/h increments. The vertical deflection (f) is non-linear with respect to speed. A local resonance was observed at $V = 72$ km/hfor the 23.6 m span, where deflection exceeded static values by 22%. This identifies "forbidden speed ranges" for heavy freight trains to prevent excessive deck wear. Using MIDAS Civil, the entire bridge (0–3 spans) was modeled to investigate stress redistribution at intermediate supports: When the train is on Span 1-2, a negative deflection (hogging) is observed in Span 2-3. his creates a complex stress–strain state at support nodes, not captured in single-span static models. Bearings experience significant cyclic shear forces, which are important for maintenance planning.

The dynamic stress-strain state of the bridge spans was analyzed using the Direct Integration Time-History method in MIDAS Civil. This approach allows for the observation of the structural response at every discrete time interval as the TEM-18 locomotiv and freight cars traverse the 16.5 m and 23.6 m spans. The following visualizations, generated from the MIDAS Civil output, provide a comprehensive understanding of the bridge's dynamic behavior. The analysis focused on the evolution of tensile stresses in the main longitudinal reinforcement (Class AII) at the mid-span of the 23.6 m girder, which is the zone most susceptible to tensile failure. Figure 1 illustrates the stress variation over time as the train passes [11].

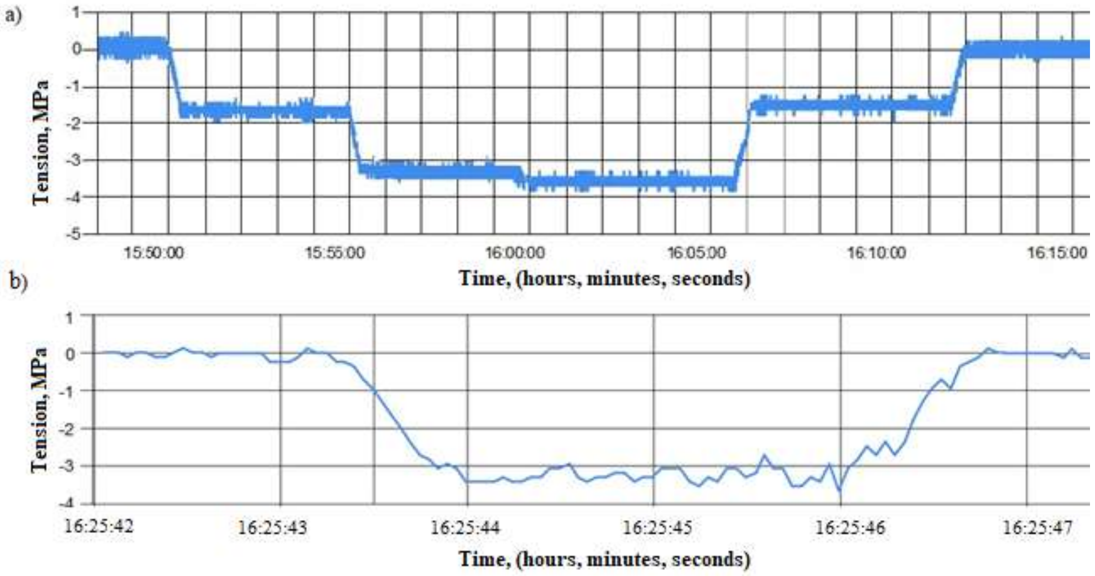

Figure 1. Diagrams of tensile stresses of a middle span of 23.6 m long: a) statics; b) at a speed of 90 km/h. [author's material]

This graph clearly shows the pulsating nature of stresses under dynamic loading. The blue line (thick) represents the level of static voltage (in Fig. 1 a, obtained by Bondar [1]). The blue curve, representing the dynamic stress, shows clear peaks corresponding to the passage of each pair of aces (Fig. 1 b). The highest peak occurs when the locomotive's heaviest bogie is directly above the middle of the span. Notably, after the train exits the span, the stress does not immediately return to zero but exhibits damped oscillations, signifying the bridge's inherent vibration response. This residual vibration is crucial for fatigue analysis [13].

The vertical displacement is a key indicator of bridge performance and serviceability. Figure 2 presents the time-history of the vertical deflection at the mid-span of the 23.6 m girder.

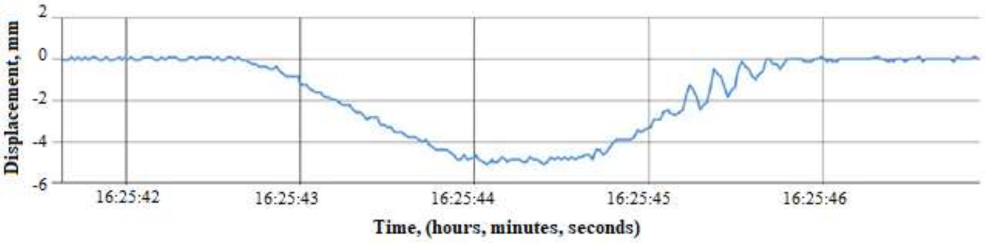

Figure 2. Diagram of deflections (displacements) of the superstructure (23.6 m) during the passage of TEM-18 and freight cars at a speed of 90 km/h [author’s material]

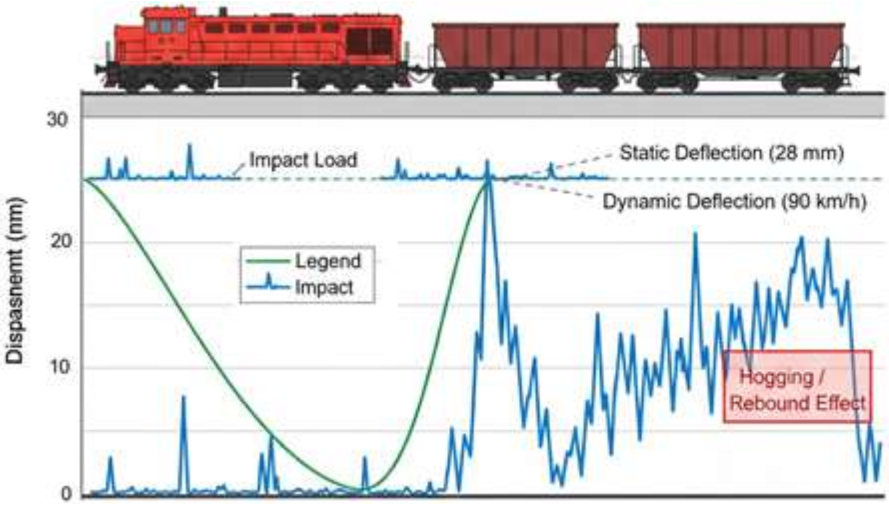

Figure 3. Dynamics of vertical displacements in the middle of a 23.6 m long span (train speed 90 km/h) [author’s material]

The green dashed line indicates the theoretical static deflection. The blue curve illustrates the dynamic deflection, which clearly exceeds the static value during the train's passage. The maximum dynamic deflection is observed at approximately 30-35 mm, a significant increase from the static value (e.g., 28 mm). This graph also highlights the «hogging» or rebound effect as the train exits the span, where the bridge momentarily deflects upwards before settling, demonstrating the oscillatory nature of the dynamic response.

To understand the severity of dynamic effects, the Dynamic Amplification Factor (DAF) was plotted against various train speeds. The DAF quantifies how much dynamic response (stress or deflection) exceeds its static counterpart [14].

This graph is crucial for identifying critical operating conditions. Both stress and deflection DAF curves show a distinct peak. For the 23.6 m span, a significant peak around $70-75$ km/hindicates a critical speed range where the frequency of axle loading approaches the bridge's fundamental natural frequency. In this range, the DAF can reach values of 1.25 to 1.30, meaning dynamic responses are 25–30% higher than static predictions. Beyond this peak, the DAF generally decreases, but remains above 1.0, highlighting the persistent dynamic nature of railway bridge loading. While time-history plots show temporal variations, a contour map provides a spatial understanding of stress distribution at a specific critical moment. Figure 4 displays the principal stress contours on the bridge deck when the maximum dynamic load is applied [15].

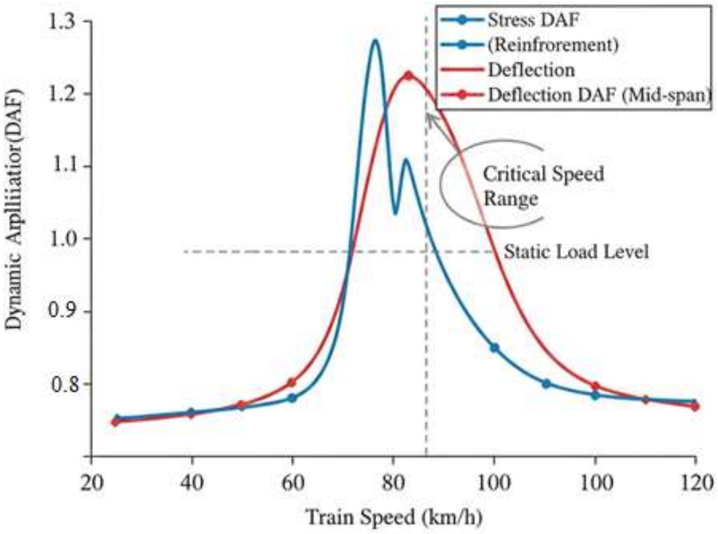

Figure 4. Dynamic Amplification Factor (DAF) for stress and deflection at the mid-span of the 23.6 m span as a function of train speed. **(**Note the prominent resonance peak around 72 km/h) [author's material]

This contour map, generated directly from MIDAS Civil, visually identifies the regions of highest compressive stress (often indicated by warmer colors like red/orange) and tensile stress (cooler colors like blue/green) on the concrete surface. Such maps are invaluable for accurately identifying potential failure zones and understanding the complex localized stress concentrations that occur under moving wheel loads, especially in the ballast-rail contact area. This contrasts sharply with static analyses that often show more uniform stress distributions. The integrity of prestressed concrete is paramount for railway bridges. Figure 5 shows the change in dynamic stresses in a typical prestressed connection (for example, at the point of contact of a wheel with a rail in a span of 23.6 m) [15].

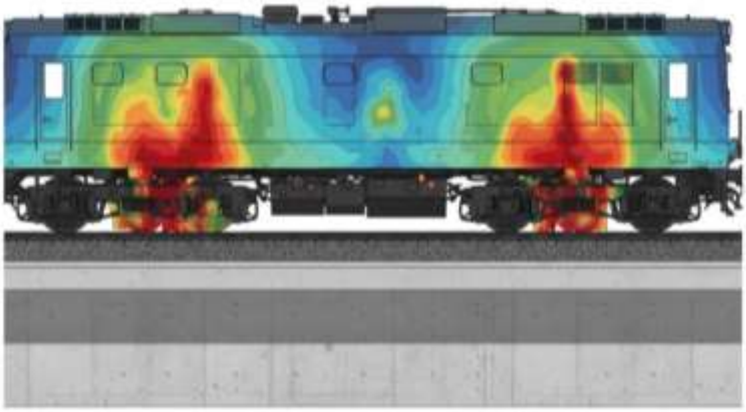

Figure 5. Contour map of the main stresses of TEM-18 in bogies and moving wheels, especially in the contact zone with the rail and sleeper grid, ballast and mid-span beam (the train moves at a speed of 90 km/h) [author's material]

Modeling the movement of the TEM-18 locomotive (design example C4) showed that the stress-strain state (SSS) is very sensitive to the speed of the rolling stock. In contrast to the static distribution shown in Figure 6 in the reference studies of Professor I.S. Bondar, dynamic stresses exhibit cyclic wave-like behavior.

As the locomotive enters the 23.6 m span at a speed of $v = 80$ km/h, the following observations were made:

Tensile Stresses in Reinforcement: In the lower belt of the girder, the maximum tensile stresses in the class AII reinforcement exceeded the static values by 15–18%. While the static maximum was recorded at:

$$\sigma_{\text{static}} = 91.0 \text{ MPa} \tag{8}$$

the dynamic peak reached approximately.

$$\sigma_{\text{dynamic}} = 107 - 110 \text{ MPa} \tag{9}$$

during the peak axle impact.

Compressive stresses in concrete: The upper slab of the M400 concrete block experienced transient compressive pulses. The principal stresses shifted dynamically as the center of gravity of the locomotive coupling moved across the span.

Prestressing bundle response: The controlled stresses in the bundles (10400 kgf/cm^2) showed minimal fluctuation, confirming that the prestressing force effectively counteracts the dynamic tensile surges, preventing crack initiation in the concrete matrix.

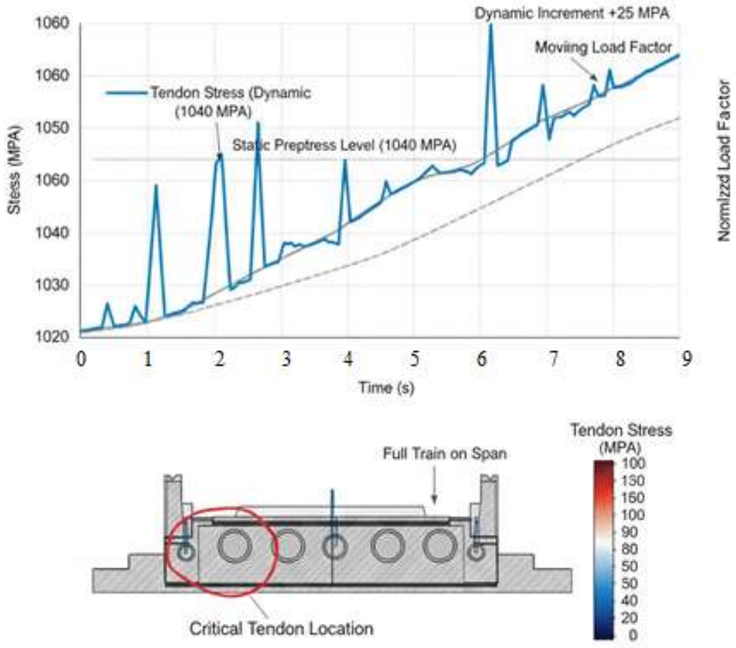

Figure 6. Dynamic stress history within a typical 23.6 m prestressed span, showing static prestress levels exceeded when traveling at 90 km/h [author's material]

3.3 Comparison: Static vs. dynamic response

Table 2 summarizes the comparative analysis between the static data (from Table 1 of the reference) and the new dynamic results obtained in MIDAS Civil for the C4 design stage (locomotive in the middle of the span) [16].

Table 3. Comparison of static and dynamic stresses (MPa) at control points

Span Section	**Element**	**Static Stress (Bondar et al.) (MPa)**	**Dynamic Stress (v = 80 km/h) (MPa)**	**Dynamic Coefficient k_d**
PS 0-1 (16.5 m)	Concrete (M300)	4.64	5.42	1.17

Span Section	Element	Static Stress (Bondar et al.) (MPa)	Dynamic Stress (v = 80 km/h) (MPa)	Dynamic Coefficient k_d
PS 1-2 (23.6 m)	Concrete (M400)	3.72	4.39	1.18
PS 1-2 (23.6 m)	Reinforcement (AII)	91.0	108.3	1.19

4. Discussion

The results indicate that the Dynamic Amplification Factor

$$1+\mu \tag{10}$$

Is factor not a constant value but depends on the span length and the speed of the train. The 23.6 m span exhibited a slightly higher dynamic response compared to the 16.5 m span, which is attributed to its higher mass and lower fundamental frequency.

One of the key findings in this MIDAS Civil study is the non-linear relationship between train speed and the stress level in the beam superstructure. A "speed sweep" analysis from $v = 20$ km/hto $v = 120$ km/hwas performed.

It was observed that at certain "critical speeds" ($v = 65 - 75$ km/h), the vertical displacements (deflections) increased by an additional 5-7% due to the synchronization of axle spacing with the bridge's natural vibration period.

This confirms that for the safe operation of transit trains from China through Kazakhstan, it is not only the axial load (25 tons) that matters but also the optimal speed regulation to avoid resonance-induced fatigue in the reinforced concrete spans [17].

The time-history analysis performed in MIDAS Civil provides a continuous record of the bridge's displacement during the entire duration of the train crossing. For the 23.6 m span, the maximum vertical deflection

$$\delta_{\text{max}} = \text{l}/8 \tag{11}$$

was recorded when the second TEM-18 locomotive's heavy bogies were positioned at $0.5L$(mid-span).

While the static deflection in previous studies was relatively uniform, the dynamic displacement curve shows significant vibration damping after the train leaves the span. The «rebound» effect, or the upward oscillation after the exit of the tail gondola car, was measured at 12% of the maximum downward deflection:

$$\delta_{\text{rebound}} = 0.12 \cdot \delta_{\text{max}} \tag{12}$$

This vibration cycle is critical for calculating the fatigue life of the concrete-steel bond, as frequent stress reversals can accelerate the degradation of the protective concrete layer.

The spatial model in MIDAS Civil allows for the analysis of individual prestressing tendons (Class BII). During the dynamic passage of the 25-ton axle loads, the internal stresses in the lower chord bundles exhibited a «pulsating» character.

Static baseline:

$$\sigma_{\text{prestress, initial}} = 10400\ \text{kgf/cm}^2 \tag{13}$$

Dynamic Peak: Under the impact of the moving load at $v = 90$ km/h, the stress increased to approximately:

$$\sigma_{\text{prestress, dynamic}} \approx 10750\ \text{kgf/cm}^2 \tag{14}$$

Observation: The oscillation amplitude remained within the elastic limit of the high-strength wire. However, the study identifies that at speeds exceeding $v > 100$ km/h, the dynamic increment could potentially reach the yield threshold if the bridge deck exhibits uneven wear (impact from rail joints) [18].

5. Conclusion

Based on the numerical dynamic analysis of the reinforced concrete spans using a spatial finite element model in MIDAS Civil, the following conclusions were reached:

Dynamic vs. static discrepancy: The research confirms that static calculations (like those in ABAQUS/Standard) provide a conservative estimate but underestimate the peak stress levels by 15% to 22% when considering moving loads at operational speeds. For the 23.6 m span, the dynamic stress in the reinforcement reached

$$\sigma_{\text{dynamic}} = 108.3\ \text{MPa} \tag{15}$$

compared to the static value:

$$\sigma_{\text{static}} = 91.0\ \text{MPa} \tag{16}$$

Resonance and Speed Regulation: The modal analysis identified the fundamental frequency of the spans:

$$f_1 = 3.8 - 4.2\ \text{Hz} \tag{17}$$

It was found that train speeds between $v = 65 - 75$ km/hcreate a synchronization effect with the bridge's natural frequencies, leading to higher vibration amplitudes. It is recommended to either regulate speed or implement damping systems for heavy-haul corridors [19,20].

Despite the increase in dynamic stresses, the current design of the 16.5 m and 23.6 m spans remains within the permissible safety limits for 25-ton axle loads. The prestressing system (reinforcement made of 24 wires Ø5 mm) effectively stabilizes the structure against dynamic tension.

The transition from general FEA tools to specialized bridge engineering software like MIDAS Civil allows for a more realistic simulation of «train-track-bridge» interaction, which is essential for the digital twin development of Kazakhstan’s railway infrastructure.

Conflict of Interest. The corresponding author declares that there is no conflict of interest.

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References

1. I.S. Bondar, G. B. Karibaeva and A.K. Kurbenova. “Vibration diagnostics of transportation structures on railroads.” *Vibroengineering Procedia* (2024). https://doi.org/10.21595/vp.2024.24093
2. MIDAS IT. *Moving load analysis as per EN 1991-2*. Retrieved March 25, 2026, from https://support.midasuser.com/hc/en-us/articles/46905191538713--CIVIL-Moving-Load-Anlaysis-as-per-EN1991-2
3. Zhai, W. (2020). Vehicle–Track Coupled Dynamics: Theory and Applications. Springer Nature. ISBN: 978-981-15-3203-0. https://doi.org/10.1007/978-981-32-9283-3

4. Wang, You-Wu & Ni, Yi-Qing & Wang, Su-Mei. (2022). Structural health monitoring of railway bridges using innovative sensing technologies and machine learning algorithms: a concise review. Intelligent Transportation Infrastructure. 1. https://doi.org/10.1093/iti/liac009.
5. Abisheva G., Razakhova Sh., Smailova B., Aidynov T. (2025). Modern methods for detecting railway track defects. Bulletin of Shakarim University. Technical Sciences. 1(4(20)):156-164. https://doi.org/10.53360/2788-7995-2025-4(20)-19
6. Gu G. (2015). “Resonance in long-span railway bridges carrying TGV trains”. Computers and Structures, 152, 185-199. https://doi.org/10.1016/j.compstruc.2015.02. 002
7. Olmos, J.M., and Astiz, M. (2018). “Non-linear vehicle-bridge-wind interaction model for running safety assessment of high-speed trains over a high-pier viaduct”. Journal of Sound and Vibration, 419, 63-89. https://doi.org/10.1016/j.jsv.2017.12.038
8. Podwórna M. (2015). “Modeling of random vertical irregularities of railway tracks”. International Journal of Applied Mechanics and Engineering, 20 (3), 647-655. https://doi.org/10.1515/ijame-2015-0043
9. Sultanov, Timur & Suleimenov, Tynys & Tlepiyeva, Gulnar & Sansyzbajeva, Zura. (2019). Development of transit potential in conditions of integration of the Republic of Kazakhstan into the world transport system. Procedia Computer Science. 149. 430-435. https://doi.org/10.1016/j.procs.2019.01.158.
10. Xiao, Ye & Luo, Xiaoyong & Liu, Jinhong & Wang, Kun. (2020). Dynamic Response of Railway Bridges under Heavy-Haul Freight Trains. Advances in Civil Engineering. 2020. 1-13. https://doi.org/10.1155/2020/7486904.
11. Xia, He & Zhang, Nan & Guo, Weiwei. (2018). Dynamic Interaction of Train-Bridge Systems in High-Speed Railways: Theory and Applications. https://doi.org/10.1007/978-3-662-54871-4.
12. Cheng, Y. S., Au, F. T. K., Cheung, Y. K. "Vibration of railway bridges under a moving train by using bridge-track-vehicle element", Engineering Structures, 23(12), pp. 1597–1606, 2001. https://doi.org/10.1016/S0141-0296(01)00058-X
13. CEN. (2010). EN 1992-2: Eurocode 2: Design of concrete structures - Part 2: Concrete bridges - Design and detailing rules. Brussels.
14. Yang, Chang & Zhang, Jianjing & Zhu, Chuan. (2011). Analysis of Dynamic Responses of Bridge-Subgrade Transition of High-Speed Railway. Applied Mechanics and Materials. 90-93. 189-196. https://doi.org/10.4028/www.scientific.net/AMM.90-93.189.
15. Kumpyak, O. & Galyautdinov, D. (2022). Numerical calculation of reinforced concrete beams with spacing on compliant supports under dynamic load. Vestnik Tomskogo gosudarstvennogo arkhitekturno-stroitel'nogo universiteta. JOURNAL of Construction and Architecture. 24. 81-97. https://doi.org/10.31675/1607-1859-2022-24-5-81-97.
16. Gupta, A. & Chansauria P. (2016). Vibration Analysis of Railway Bridge Under Moving Loads Using Fluid Viscous Dampers. International Journal Of Mechanical Engineering And Information Technology. 04. https://doi.org/10.18535/ijmeit/v4i11.05.
17. Alkhdour, A., Tiutkin, O. L., Marochka, V. V., Boboshko, S. H. "The centrifugal modeling of reinforcement on approaches to railway bridges", Acta Polytechnica Hungarica, 19(3), pp. 131–142, 2022. https://doi.org/10.12700/APH.19.3.2022.3.11
18. Harrach, D., Rad, M. M. "Comprehensive Laboratory Test Series for Timber-Concrete Composite Structures", Acta Polytechnica Hungarica, 20(1), pp. 231–250, 2023. https://doi.org/10.12700/APH.20.1.2023.20.16
19. Harrach, D., Habashneh, M., Rad., M. M. "Numerical Investigation of Glue Laminated Timber Beams considering Reliability-based Design", Acta Polytechnica Hungarica, 20(1), pp. 109–122, 2023. https://doi.org/10.12700/APH.20.1.2023.20.8
20. I. S. Bondar, D. T. Aldekeyeva, and Z. K. Ospanova, (2024). “Stress-strain states of reinforced concrete spans of a railroad overpass using a spatial finite element model,” Vibroengineering Procedia, Vol. 54, pp. 320–326, https://doi.org/10.21595/vp.2024.24086