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

Zere Kanatovna Ospanova[1], Dinara Tanashbekovna Aldekeyeva[2], Ivan Sergeyevich Bondar[3], Alexey Gennadievich Belov[4], Tatyana Sergeevna Baratova[5], Salman Daoud Salman Al-Dulaimi[6]

[1]Kazakh Head Academy of Architecture and Civil Engineering, Almaty, Republic of Kazakhstan
[2]ALT University named after Mukhamedjan Tynyshpayev, Almaty, Republic of Kazakhstan
[3, 4, 5]Kazakh Automobile and Road Institute named after L. B. Goncharov, Almaty, Republic of Kazakhstan
[6]Ministry of Higher Education and Scientific Research, Baghdad, Iraq
[3]Corresponding author
E-mail: [1]*zere_kanatovna@mail.ru*, [2]*aldekeeva69@mail.ru*, [3]*ivan_sergeevich_08@mail.ru*, [4]*below_aleksei@mail.ru*, [5]*baratovatatyana1@mail.ru*, [6]*salmoon-1985@mail.ru*

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Abstract. This research investigates the dynamic stress–strain behavior of a railway bridge beam superstructure subjected to moving train loads using advanced computational modeling. The study employs MIDAS Civil software to develop a comprehensive three-dimensional finite element model of a typical railway bridge superstructure, incorporating realistic boundary conditions, material properties, and geometric configurations. The analysis examines the temporal variation of stresses, displacements, and internal forces as multiple train axles traverse the bridge at various operational speeds. The investigation reveals critical zones experiencing maximum dynamic amplification factors, which significantly exceed those predicted by static analysis methodologies. Dynamic load allowance coefficients are calculated for different train speeds, demonstrating a nonlinear relationship between velocity and structural response amplification. The model accounts for complex phenomena including moving load effects, inertial forces, and structural damping characteristics. Results indicate that dynamic effects become particularly pronounced at specific resonance frequencies, where vertical deflections and bending moments reach peak magnitudes. The findings provide essential insights for bridge design optimization, maintenance planning, and safety assessment protocols. This comprehensive dynamic analysis framework enables engineers to accurately predict structural behavior under realistic operational conditions, ensuring adequate service life and structural integrity of railway bridge infrastructure systems while maintaining required safety margins for contemporary high-speed rail applications.

Keywords: railway bridge, dynamic analysis, beam superstructure, moving load, MIDAS Civil, finite element method, stress-strain state, dynamic amplification factor, structural response, high-speed rail.

1. Introduction

The infrastructure of railway bridges is a key element of transport networks that ensure the movement of passengers and cargo. With increasing speeds and axle loads, accurate assessment of the dynamic behavior of structures is critically important for the safety and durability of bridges. Traditional static methods do not take into account temporary changes in the reaction of the structure during train movement. Dynamic effects (vibrations, resonance, etc.) lead to stresses and deflections exceeding the calculated static values. The study is devoted to the dynamic analysis of bridge spans by the finite element method using MIDAS Civil software. Tasks: 1) development of a finite element model; 2) assessment of stresses and deformations during train movement;

3) determination of dynamic coefficients and velocity effects; 4) identification of critical stress zones [1].

Dynamic analysis of railway bridges has been actively studied for several decades. Willis and Timoshenko laid the foundations for the dynamic response of beams under moving loads, and Fryba (1999) developed the theoretical foundations for analyzing structural vibrations. Experiments on existing bridges have made it possible to measure dynamic deformations and accelerations, revealing the dependence of the reaction on the characteristics of the train and the structure. Yang et al. (2004) showed that dynamic gain coefficients change with the speed of the train, and critical speeds cause resonance. Modern research (Xia et al., 2018; Zhai et al., 2019) uses 3D models using the finite element method to study the interaction of loads and the path-bridge system. At the same time, a detailed analysis of the stress-strain state of girder superstructures under real train configurations remains an urgent task [2].

2. Materials and methods

The novelty of the research lies in the complex application of the finite element method for the dynamic analysis of railway spans, taking into account real-world operating conditions. Unlike traditional static calculations, the work takes into account temporary changes in the reaction of the structure when trains are moving at high speeds and increased axial loads. The developed finite element model in the MIDAS Civil software makes it possible not only to evaluate stresses and deformations, but also to accurately determine dynamic coefficients and velocity effects. The study identifies areas of critical stress that arise due to vibrations and resonance, which is impossible with a static approach. The results obtained increase the accuracy of forecasting the durability and safety of bridge structures.

Bridge Model Description. The investigation employs a representative railway bridge configuration consisting of a simply-supported steel-concrete composite beam superstructure**.** The bridge span length measures 30.0 meters, reflecting typical dimensions encountered in operational railway infrastructure (Table 1). The superstructure comprises four longitudinal steel I-beams with a concrete deck slab, connected through shear studs to ensure composite action [3, 6, 7].

Table 1. Bridge geometric parameters and material properties [4, 5]

Component	Parameter	Value	Material	Property	Value
Bridge	Span length	30.0 m	Steel	Modulus of elasticity (E_s)	210 GPa
–	Support type	Simply-supported	–	Density (ρ_s)	7,850 kg/m^3
Steel I-Beam	Web depth	800 mm	–	Yield Strength	355 MPa
–	Flange width	300 mm	Concrete	Modulus of Elasticity (E_c)	35 GPa
–	Number of Beams	4	–	Density (ρ_c)	2,500 kg/m^3
Concrete Deck	Thickness	250 mm	–	Compressive Strength	40 MPa
–	Width	12.0 m	–	–	–

2.1. Finite element modeling in MIDAS Civil

The calculation model was created in the MIDAS Civil 2023 software using the finite element method. Steel I-beams are modeled by 3D elements with 6 degrees of freedom per node; the length of the elements is 0.50 m (60 elements per beam). The concrete floor slab is divided into 1,440 plate elements (0.50×0.50 m cells). The interaction of beams and flooring is determined by rigid connections. Modal analysis determines the frequencies and waveforms through iterations in the subspace. Damping is according to Rayleigh (2.0 % of the critical value). Train load: locomotive (4 axles, 250 kN/axle) and 5 freight wagons (8 axles each, 225 kN/axle). There are 24 axes in total with a total weight of over 5,000 kN [8, 9].

Dynamic analysis uses the Newmark-beta implicit integration method ($\beta = 0.25, \gamma = 0.50$) in 0.005 s increments, which is enough to capture peak responses. The analysis is performed for train speeds from 40 to 160 km/h (in increments of 20 km/h) [10]. The range covers the speeds at which

the excitation frequencies are close to the fundamental frequency, hence the peaks of dynamic amplification [11].

Table 2. Train load configuration [10]

Component	Axle load (kN)	Number of axles	Total load (kN)
Locomotive	250	4	1,000
Freight car (each)	225	4	900
Total freight cars	225	20	4,500
Complete train	–	24	5,500

3. Results and discussion

The results of the modal analysis showed the dynamic characteristics of the bridge superstructure. The first natural frequency (symmetrical vertical bend) is 4.28 Hz, the second (antisymmetric bend) is 11.64 Hz, and the third (second symmetrical bend) is 17.32 Hz (Table 3). The main mode of transport provides about 78 % of the total structural response under vertical loads from the train [12].

Table 3. Natural frequencies and modal characteristics [12]

Mode	Frequency (Hz)	Period (s)	Description
1	4.28	0.234	Symmetric vertical bending
2	11.64	0.086	Antisymmetric vertical bending
3	17.32	0.058	Second symmetric bending
4	23.57	0.042	Torsional mode
5	29.84	0.034	Third symmetric bending

3.1. Static analysis results

Static analysis provides basic response values at maximum train loads. The maximum vertical displacement is 18.7 mm (L/1604) in the middle of the span. The stress in the lower flange is 142.6 MPa, the bending moment is 8460 kN·m, and the shear force is 1892 kN at the supports (see Table 4) [13].

Table 4. Static analysis results summary [13]

Response parameter	Maximum value	Location
Vertical displacement	18.7 mm	Mid-span
Longitudinal stress (steel)	142.6 MPa	Bottom flange, mid-span
Longitudinal stress (concrete)	8.4 MPa	Top deck, mid-span
Bending moment	8,460 kN·m	Mid-span
Shear force	1,892 kN	3.0 m from support

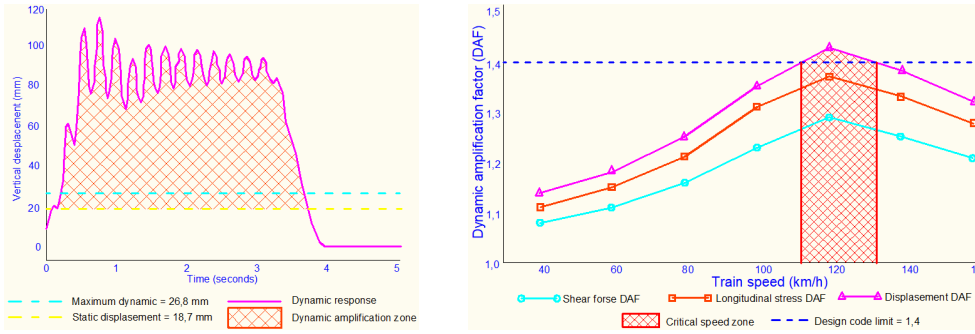
3.2. Dynamic analysis results

The results of the dynamic analysis revealed an increase in the reactions of the structure relative to static forecasts. At a speed of 120 km/h: displacement – 26.8 mm (DAF = 1.43), voltage – 194.7 MPa (DAF = 1.37). The maximum responses are observed at intermediate speeds (about 120 km/h) – close to the resonant conditions (Fig. 1). DAFS vary: for displacements – 1.14-1.43, stresses – 1.11-1.37, shear forces – 1.08-1.29. Fluctuations in the displacement of the average span occur under successive loads (Table 5) [13].

3.3. Stress-strain state analysis

Studying the stress distribution provides insight into the behavior of the structure. At 120 km/h in the average span: longitudinal stresses range from +194.7 MPa (lower steel flange) to –11.8 MPa (upper concrete fiber). The distribution is almost linear (according to Euler-Bernoulli

theory). The Von Mises stresses are up to 162.4 MPa (Table 6), and the elastic behavior is below the yield point (Fig. 2) [14].

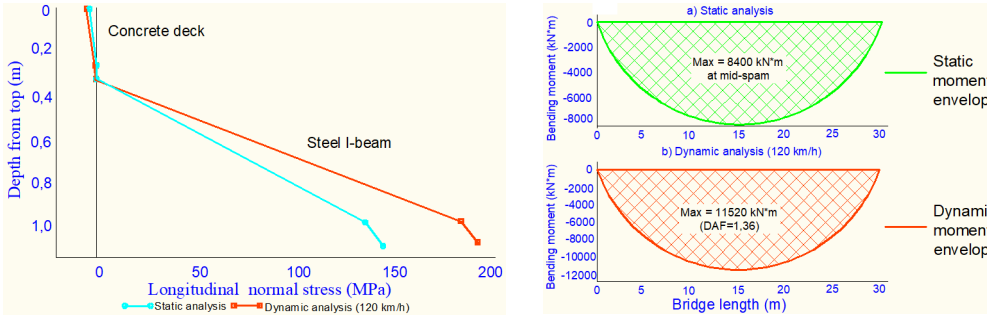


a) Mid-span displacement time history at 120 km/h b) Dynamic amplification factors versus train speed

Fig. 1. The dynamics of movement depending on the speed of the train

Table 5. Dynamic analysis results at various speeds [13]

Speed (km/h)	Max Disp. (mm)	DAF Disp.	Max Stress (MPa)	DAF Stress	Max Accel. (m/s^2)
40	21.4	1.14	158.3	1.11	0.68
60	22.1	1.18	164.0	1.15	0.85
80	23.4	1.25	172.5	1.21	1.02
100	25.2	1.35	186.8	1.31	1.21
120	26.8	1.43	194.7	1.37	1.38
140	25.8	1.38	189.7	1.33	1.29
160	24.7	1.32	182.5	1.28	1.18



a) Longitudinal stress distribution through depth b) Bending moment envelopes

Fig. 2. Longitudinal stresses and bending moment

Table 6. Stress components at mid-span (120 km/h) [15]

Location	σ_x (MPa)	τ_{xy} (MPa)	σ_{vm} (MPa)
Concrete top	–11.8	0.5	11.9
Concrete bottom	–1.1	1.2	2.1
Steel top flange	–0.7	2.8	4.2
Steel web center	96.5	18.4	103.2
Steel bottom flange	194.7	3.2	162.4
Note: σ_x – longitudinal normal stress, τ_{xy} – shear stress, σ_{vm} – von Mises equivalent stress			

3.4. Acceleration response analysis

Time diagrams of acceleration show an increase in frequency with increasing train speed. The maximum is 1.38 m/s^2 at 120 km/h, which is higher than the forecasts of quasi-static methods. Accelerations affect the path, the interaction of the wheel with the rail, and passenger comfort.

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The reaction peaks correspond to the passage of the axis groups and the natural frequencies of the structure (Fig. 3) [15].

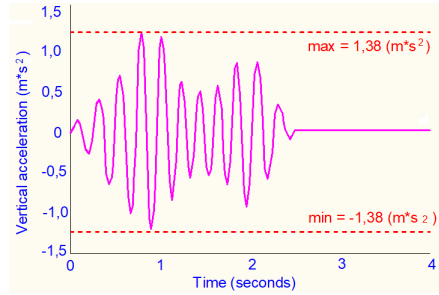


Fig. 3. Vertical acceleration time history at mid-span

4. Conclusions

The study carried out a dynamic analysis of the railway bridge superstructure (finite element method, MIDAS Civil). The effects of dynamic amplification and the relationship between the speed of the train and the behavior of the structure are revealed. Key findings: DAF: 1.14–1.43 (displacements), 1.11-1.37 (stresses) – effects exceed static forecasts; maximum gain – at ~120 km/h (resonance); 3D modeling reflects stress and strain distributions; The coefficients are consistent with the design code. Critical speeds require special attention. Stress data helps to estimate fatigue life and plan maintenance [16-20]. The prospects: analysis of multi-span structures, consideration of the interaction of track and bridge, validation by field measurements.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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