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Field Static and Dynamic Load Testing for Operational Safety Assessment of a Reinforced Concrete Overpass

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ABSTRACT

This study presents a field-based assessment of the operational safety of a reinforced concrete overpass in Astana, Kazakhstan, using combined static and dynamic load testing. The structure is a three-span overpass with 41.0 m reinforced concrete main spans formed by prefabricated UBS 187.14 blocks with variable cross-sections. Static tests were conducted using six ballast-loaded trucks with an average weight of 21.0 t, while dynamic tests were performed under moving vehicle loads at speeds ranging from 3.5 to 70 km/h. The measured maximum static deflection at midspan was 23.5 mm, which is substantially lower than the regulatory limit of 102.5 mm for the 41 m span. Dynamic measurements showed stable structural behavior, with principal frequencies of 3.37–3.39 Hz in the main vibration modes and damping ratios of 3.5%–3.8%, exceeding the minimum reference value of 1.5% for reinforced concrete structures. The recorded vibration periods were outside the code-defined critical ranges, indicating no resonance-related operational concern. The elevated damping capacity is attributed to the variable cross-section of the girders, which increases bending stiffness and internal energy dissipation near the supports. Overall, the combined test results indicate that the overpass remains in satisfactory technical condition and can continue safe operation, although periodic monitoring is recommended in view of increasing traffic intensity and vehicle loads.

1. INTRODUCTION

Bridge structures are in more difficult conditions compared to buildings of any purpose. Wear can be caused by human action or natural phenomena that cause changes in the geometric, physical, and mechanical properties of bridges [1-3]. The severity of the consequences of failures in bridge collapses is very significant. Collapses of bridge structures lead to the deaths of people, failure of vehicles [4], long-term interruptions in traffic, large economic losses, and environmental pollution [5]. Dangerous meteorological phenomena and processes, such as temperature and wind influences, lightning strikes, affect the reliability and durability of bridges. Natural processes in materials, such as saturation of materials with moisture, and chemical effects of the environment, can be the causes of premature wear of the structure [6]. The following causes of hazards are relevant for bridge structures: concrete leaching and carbonation, metal corrosion, loss of prestress, and exposure to variable loads [7].

Monitoring, continuous maintenance, and extending the service life of existing bridges are essential to ensure the long-term service of bridges. The purpose of studying the risks of bridge structures is to increase the efficiency of managing their technical condition to ensure the safety and health of people, prevent economic and other losses. Bridges with reinforced concrete beams featuring a variable cross-section of the lower chord are commonly used in major cities of Kazakhstan, particularly in Astana and Almaty, as well as in other countries. Ensuring the safety, durability, and functionality of bridges, especially as they age within critical transportation networks, is a critical aspect of infrastructure management aimed at improving their overall resilience to various stressors. Determining and maintaining structural stability is now becoming the dominant agenda in safety research. In studies on the sustainability of infrastructure networks, sustainability is defined as the ability of a system to restore its previous state after a violation.

Methods of bridge structures risk research and assessment are diverse, and in recent decades, the development of digital technologies, sensor systems, and probabilistic methods has given rise to a new interdisciplinary approach, risk-based bridge reliability management. It is based on three interrelated blocks: Risk assessment, Dynamic reliability, and Structural Health Monitoring (SHM). The international standards ISO 2394, ISO 13822, and EN 1990 (Annex C) provide a normative and methodological framework for reliability and risk-based analysis [8-10]. ISO 2394:2015 defines the fundamental structure of a probabilistic approach to the safety of structures. The standard offers the Reliability-Based Design and Assessment methodology, a unified approach to design, operation and evaluation based on probabilistic modeling and the selection of target values of β depending on the class of consequences (CC1–CC3). In ISO 13822, studies related to bridge structures are based on a transition from simple defect identification to a risk-oriented approach. According to the standard, the determination of initial hazards requires a preliminary investigation aimed at identifying and performing a preliminary risk assessment. ISO 13822 provides for detailed inspection, parameter refinement, and the conduct of field tests and monitoring, which is the subject of this study. Data obtained during the tests, including actual deflections and frequencies, are used for updating probabilistic models (Bayesian updating). This approach, prescribed by ISO 13822, helps reduce uncertainty in the reliability assessment of existing structures.

A distinctive feature of EN 1990 (Annex C) is that it establishes rules for ensuring the required reliability, taking into account random actions and uncertainties in the properties of construction materials.

Structural Health Monitoring (SHM) plays a key role in achieving this by constantly assessing the integrity and performance of the structure, allowing early detection of problems such as cracks, corrosion, and unusual vibrations that can lead to catastrophic failures [11, 12].

There are many examples of instrumental monitoring of the condition and operation of bridge structures during operation: Akashi Kaikyo, Japan [13], Commodore John Barry, USA [14], in China [15], and in the UK [16].

A visual inspection of the existing infrastructure is a critical asset management step, as damage detection and quantification should be useful in determining maintenance priorities. In the works of Saleem et al. [17], a methodology for assessing the condition of existing road bridges based on system reliability is proposed. The initial optimal repair strategy is updated using both two-year visual inspections and special non-destructive testing methods. In the works of Frangopol and Estes [18], a general methodology is proposed for determining the optimal planning of bridge inspection and repair programs for the entire service life, based on minimizing expected costs while maintaining an acceptable level of reliability. The results are important for the development of future reliability-based maintenance guidelines and criteria for bridge inspection and repair. Bertola and Brühwiler [19] use an example of a strategic road with sixty bridges to assess the condition of the bridge using a risk assessment methodology based on recent visual inspections. The study shows that the inclusion of the consequences of component failure in the assessment of the condition of bridges contributes to a more accurate assessment of the impact of damage on global structural safety, which leads to more objective asset management decisions. Different on-site conditions and individual experience contribute to the subjective nature of bridge inspection processes, which involve uncertain human factors. The results show that aggregating 96 people's inspection records based on their reliability indexes effectively filters out false alarms, while maintaining reliable defect records [20].

Tests of multi-span bridge systems conducted via the Internet show that a collaborative testing network with powerful capabilities provides a well-coordinated testing platform for complex models or real-world projects and enables the remote use of test equipment. Monitoring the condition of the structure and measuring the dynamic characteristics of a balanced cantilever bridge based on a digital twin [21] has shown that the proactive SHM approach promotes timely maintenance and repair, reducing the risks associated with accidents, downtime, and high costs. The detection and prevention of anomalies using an autoencoder-based method was proposed by Tian [22].

Static and dynamic tests are key methods for verifying the actual bearing capacity of bridges. Static tests make it possible to compare calculated deflections and deformations, revealing underestimated structural weaknesses. Hidden defects and degrades, such as cracks in concrete, corrosion of steel elements, insufficient strength of supports, and weakening of reinforcement, are revealed during static tests before an accident occurs. During the tests, the load is applied in a controlled manner, and the monitoring system records nonlinear deformations, residual deflections, and deviations in stress distribution, which allows timely detection of defects. In the study, static load tests of bridges were carried out, and the actual structural rigidity was assessed [23]. Static tests were carried out on a bridge reinforced with prestressed wire in polyurethane cement in the work of the authors [24]. Identification of the bridge structure through combined static and dynamic tests and verification of the FEM model [25].

Dynamic tests of bridge structures, along with static ones, are currently the main evaluation factors of the bearing capacity of bridge spans. The study of the dynamic reliability of bridges within the framework of the time-dependent reliability concept takes into account the change in system parameters over time. The main factors are fatigue accumulation of damage, corrosion degradation, and changes in dynamic properties in case of bridge damage. Dynamic bridge tests are closely related to the assessment of safety risk through the prism of reliability and structural monitoring [26, 27]. Dynamic testing of bridges reflects the condition of the structure, and its change may be a sign of loss of rigidity or damage.

If necessary, static and dynamic tests are performed at the same time. In the study, the analysis of the operation of the YangHwa bridge superstructure (Seoul, Korea) using the short-term SHM system under static (heavy truck stationary) and dynamic (truck moving) loads was carried out, and the safety of the bridge was determined with various indicators [28].

In the study, the results of load tests reveal the advantage of a detailed analysis of the behavior of the structure under the influence of critical loads [29]. Such experiments make it possible to refine the calculated models and determine the actual limits of the bearing capacity of bridges. The article emphasizes the need for standardization of trial load testing, especially important for aging bridges, in order to avoid conservative solutions for their reinforcement or replacement

[30].

Modern methods of research and assessment of the risk of bridge structures combine qualitative and quantitative methods. Qualitative methods involve the use of risk matrices as a tool for classifying bridges by levels of probability and severity of consequences, Condition Rating Systems, and building a decision tree. Methods for quantifying the stress state of reinforced concrete, including the use of experimental data and numerical models, emphasize the importance of taking into account temporary changes in the characteristics of materials and structures for a reliable assessment of structural strength [31]. These works form the basis for the development of methods for extending the service life of structures.

The article investigates the need to take into account the influence of variable transport loads and operating conditions on the durability of bridges and shows that dynamic and temperature effects can significantly distort the results of monitoring the condition of structures [32], which requires the introduction of more accurate analytical approaches. Methods of compensation of the so-called "mass load effect" caused by heavy truck traffic are described.

The use of stainless steel materials and high-strength strands to increase the reliability of reinforced concrete structures in aggressive environments demonstrates a significant increase in durability and a reduction in bridge maintenance costs. The influence of variable transport loads and temperature on the dynamic behavior of bridges has been described [33-35]. These studies provide empirical data for diagnosing the condition of bridges and analyzing their stability under various dynamic influences. Structural fragility assessment models [36-38] emphasize the importance of taking into account operational loads and time factors to ensure the long-term safety of bridges. Fragility models provide an accurate assessment of the vulnerability of bridges and can be used for priority repairs. And dynamic loads need to be taken into account when monitoring the condition of bridges to avoid errors in data interpretation.

2. MATERIALS AND METHODS

The purpose of the study is to assess the technical condition of a bridge structure with reinforced concrete blocks UBS 187.14 with a variable section of the lower belt to determine its safety for the public and ensure uninterrupted and trouble-free operation of the transport structure. The object of the study is a road overpass in the city of Astana (Kazakhstan).

Static and dynamic tests of the overpass have been carried out. Trucks of the 'SAMS' brand were adopted as the test load in the static tests.

2.1 Description of the object

Figure 1 shows a general view of the bridge. The road overpass is a three-span, reinforced concrete frame with a hinged support of the outermost superstructures on the abutments. The total length of the highway overpass is 82.4 m.

The main supporting structure of the overpass, which covers the space between its supports and accepts all types of loads, is its superstructures. The 41 m-long overpass spans are made of reinforced concrete and consist of prefabricated reinforced concrete blocks UBS 187.14 with a length of 18.7 m each, joined together in the middle of the span by a sealing seam. In the transverse cross-section, the blocks have an I-beam shape, while closer to the midspan, they exhibit a T-shaped cross-section.

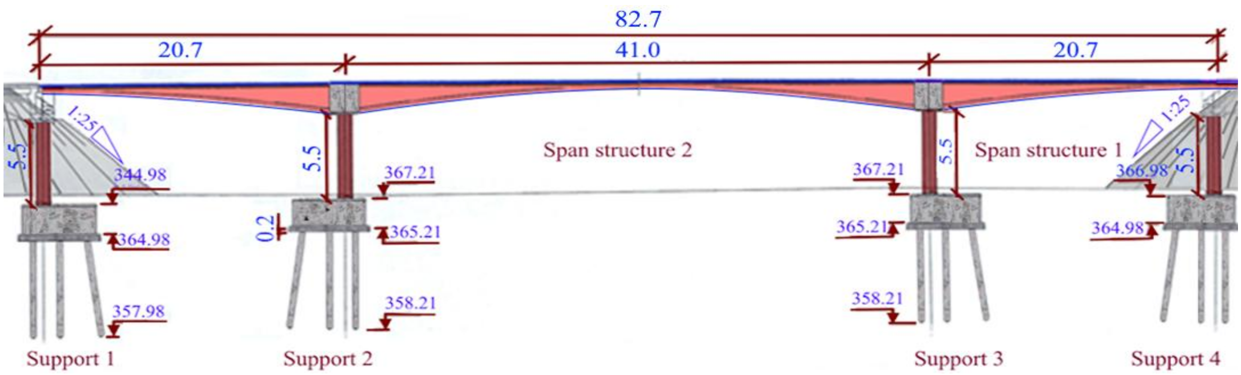


Figure 1. General layout of the bridge, (dimensions in m)

The successful use of hybrid materials, monitoring systems, and composite materials [39-43] increases the durability and stability of bridges. It is shown that innovative solutions open up new opportunities to increase the stability of bridges.

Modern methods for evaluating and strengthening bridges [44-48] include the use of high-strength materials and numerical models to optimize modernization procedures.

Effective methods of evaluating and strengthening bridges ensure their durability and the safety of operation.

Along the axis of the overpass above the intermediate supports, in the support area, the blocks have a 2 m wide alignment seam, and in the middle of the middle span, its value is 1.6 m. Abutments and intermediate supports are reinforced concrete, rack-type. Pile foundations are arranged at the base of the supports. The piles are prismatic, with a cross-section of 35 × 35 cm and a length of 7 m. There are three rows of piles in the grillage; the outermost row has an 8:1 slope.

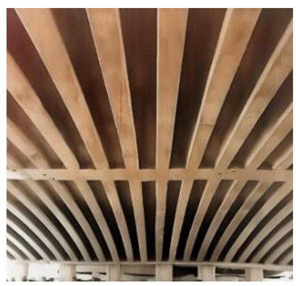


Figure 2. Consolidation of reinforced concrete blocks of UBS 187.14 in the middle of the middle span of the overpass

Visual inspection of the supports and superstructures of the overpass showed that there were no defects reducing the operational reliability of the structure. Figure 2 shows the transverse seam of the homologation of the UBS 187.14 blocks in the middle of the middle span. Inspection of this joint showed that its concrete is of a dense structure, without defects.

2.2 Static and dynamic tests of the overpass

2.2.1 Methodology and results of static tests of the overpass for structural safety

The purpose of conducting static tests of the highway overpass through Abylai Khan Avenue in Astana was to establish the conformity of the actual strength and deformation properties of the structures with the design data. Static Load Testing is one of the key methods for verifying the actual load-bearing capacity of bridge structures. Their purpose is to confirm that the bridge meets the reliability and safety requirements laid down in regulatory documents (ISO 13822, ISO 2394, EN 1990 Annex C, as well as national building codes).

Each bridge is designed for certain loads, but as a result of operation, fatigue damage, changes in the geometry of elements, and force redistribution may occur. Static tests record nonlinear deformations, residual deflections, and deviations in stress distribution. In the assessment of man-made risks (ISO 31000, PIARC, ASCE), static tests make it possible to identify the probability of failure of structural elements and determine the risk levels for girders, supports, and nodes, on the basis of which it becomes possible to build a risk matrix during bridge operation. During static tests, the load is applied in a controlled manner, which makes it possible to detect defects before an accident occurs [49]. SHM systems help calibrate finite element models (FEM) based on real load data and bridge responses. Without them, it is impossible to guarantee the safe and long-term operation of bridge structures. Studies show that, based on monitoring and analysis, it is possible to determine the operating time of a bridge structure in advance [50].

Static tests of the structure were carried out by loading the 41 m long middle span with SAMS trucks with ballast. The average weight of one truck was assumed to be 21.0 tons. According to the test program, a phased loading (6 stages) of the span structure with a test load was carried out, followed by its unloading (6 stages). Static tests of the structure were carried out in two stages.

At the test stage, six trucks were installed in the middle of the middle span, with the longitudinal axis of the outermost vehicle 1.5 m away from the edge of the safety lane. The distance between the cars was 3 m.

Deflection meters and laser rangefinders were used to detect deflections of the UBS 187.14 blocks at two test stages. During static tests, deflections in the UBS 187.14 blocks in the middle of the middle span structure No. 2 were determined.

According to the study, the elastic deflection of the spans of urban highway bridges from the action of the temporary vertical load of motor vehicles [51], with a load reliability coefficient at f = 1, and a dynamic coefficient, should not exceed

$$f_{cont} = \frac{\ell}{400} \quad (1)$$

where, ℓ is the design length of the middle span structure, equal to 41 m.

The layout of trucks during testing is shown in Figure 3.

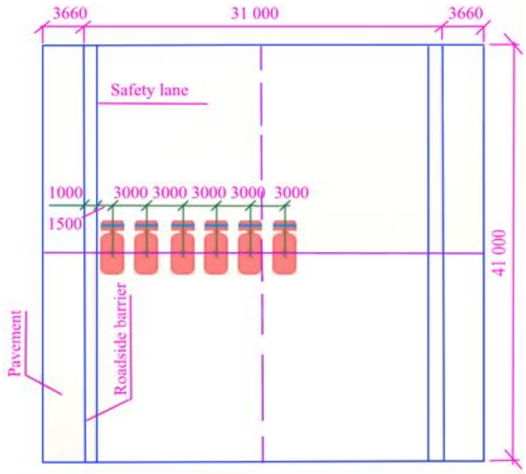


Figure 3. The distance of trucks on the roadway for testing, (dimensions in mm)

According to the accepted methodology for conducting static tests, deflections were recorded during tests in the UBS 187.14 blocks at each stage of loading and unloading of the superstructure.

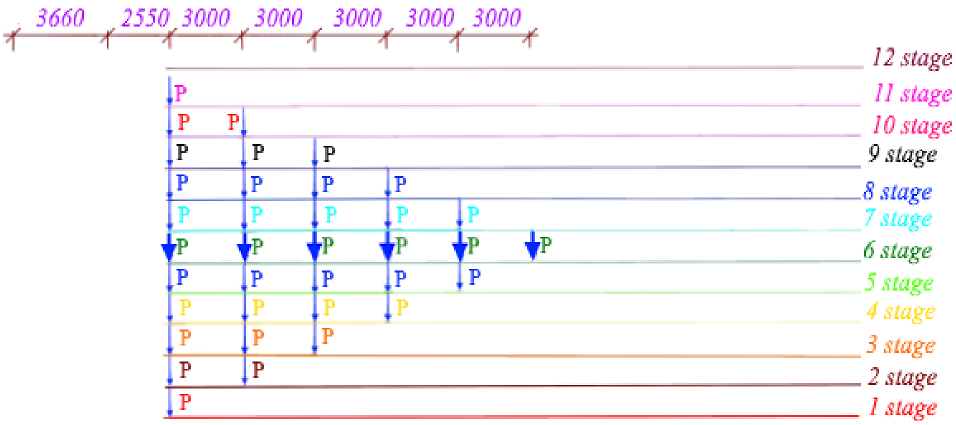
Examination of the shape of the deflections during loading of the 41 m long average superstructure by six SAMS trucks showed that during the tests, the maximum deflection value was recorded in block No. 9 of UBS 187.14, which was fe = 23.5 mm.

The analysis of the increments in deflection values of the UBS 187.14 blocks during loading and unloading tests indicated an elastic nature of deformation of the middle span structure (Figure 4).

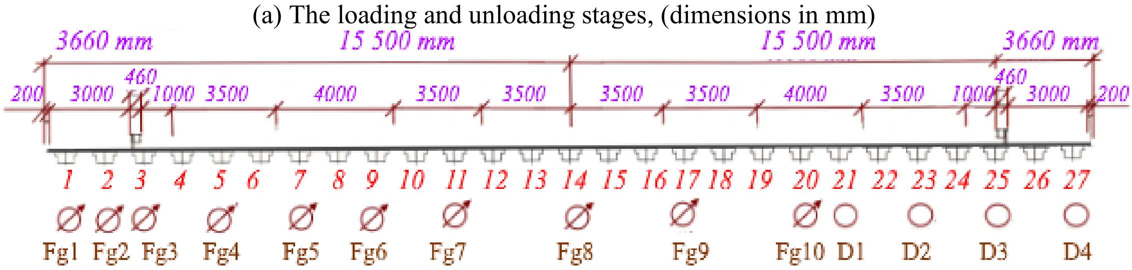
The methodology of load testing and the analysis of the deflections of the superstructure are confirmed in studies [52], which describe the results of laboratory and field tests of bridges for strength. These tests help to understand the limits of constructive possibilities and identify the risks of destruction.

2.2.2 Methodology and results of dynamic tests of the overpass for structural safety

Dynamic bridge testing is closely related to safety risk assessment through the lens of reliability and structural monitoring. The purpose of dynamic testing of the highway overpass was to determine the main dynamic characteristics of the superstructures - periods of natural oscillations, attenuation parameters. The dynamic characteristics of the bridge (frequencies, attenuation, modal shapes) are sensitive to damage, stiffness reduction, cracks, and fatigue. By changing these characteristics, structural defects can be identified before they lead to critical failures. The authors constructed reliability models (probabilistic models) that take into account statistical uncertainty in loads, material properties, and measurements [53]. The risk-assessed models obtained allow us to calculate the reliability index, the probability of failure, and the remaining service life of the bridge. The dynamic impact on the structure was created when a truck was passing through the carriageway of the overpass. The races were carried out at different speeds of the truck.

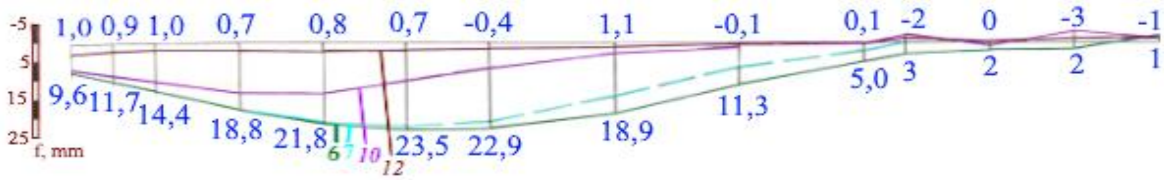


(a) The loading and unloading stages, (dimensions in mm)



(b) The cross section of the superstructure with deflectors P1-P10, (dimensions in mm)

(c) the outline of the deflections of the beams in the middle of the span structure at the loading and unloading



(d) stages during testing (P is the mass of one car, 1,3,6 are loading stages, 7,10,12 are unloading stages)

Figure 4. Loading scheme and deflections of the span structure

To record the vibrations of the superstructure on the carriageway of the overpass, six precision accelerometers were installed in the middle of the middle and extreme spans, three in each span. Accelerometers No. 14, No. 12, and No. 1 are installed in the first span, and accelerometers No. 13, No. 15, and No. 2 are installed in the second span. The sensors were located in groups at observation points (Figure 5). The first and second observation points included sensors that recorded fluctuations in the horizontal direction in the longitudinal and transverse directions of the overpass and vertical fluctuations in the intermediate structures (Table 1). At the third observation point, vibrations of the intermediate bridge supports were recorded.

At the third observation point, vibrations of the intermediate bridge supports were recorded.

To record horizontal (longitudinal and transverse) vibrations of the intermediate support during dynamic tests, two accelerometers, No. 18 and No. 4 were installed at the top of the rack (Figure 6). Monitoring point 3 (MP 3) consisted of sensors:

• No. 18 - for recording horizontal vibrations of the top of pillar No. 1 of intermediate support No. 2 in the transverse direction of the overpass (direction Y);

• No. 4 is used to register horizontal vibrations of the top of pillar No. 1 of intermediate support No. 2 in the longitudinal direction of the overpass (X direction).

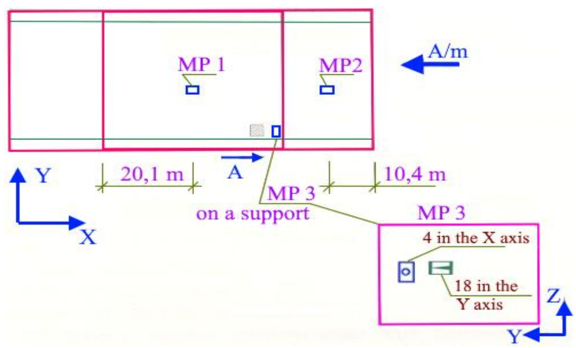


Figure 5. The layout of the observation points

Signal registration was carried out using the ERA-PRIS hardware-software system, employing accelerometers and displacement sensors. The raw data were recorded in the time domain, in terms of displacements (mm) and accelerations (m/s^2).

Table 1. Location of observation points during dynamic tests of the superstructure

Monitoring Point (MP)	The Type of Fluctuations Under Study	Span Length (m)	Direction of the Oscillation Axis	Sensor Number
MP1	horizontal in the longitudinal direction	41	X	No.14
	horizontal in the transverse direction	41	Y	No.12
	vertical	41	Z	No.1
MP2	horizontal in the longitudinal direction	20.7	X	No.15
	horizontal in the transverse direction	20.7	Y	№13
	vertical	20.7	Z	No.2

The initial speeds of the cars were 3.5 km/h and gradually increased. The last measurements were carried out at a speed of 70 km/h. The selection of vehicle speeds was determined by the need to simulate different loading regimes, ranging from a quasi-static regime (3.5–10 km/h) to a dynamic regime (30–70 km/h). The speed of 70 km/h corresponds to the maximum allowable limit for this section of the urban road network.

The adopted sensor layouts made it possible to determine the accelerations and deformations of superstructures: horizontal in the longitudinal direction, horizontal in the transverse direction and vertical.

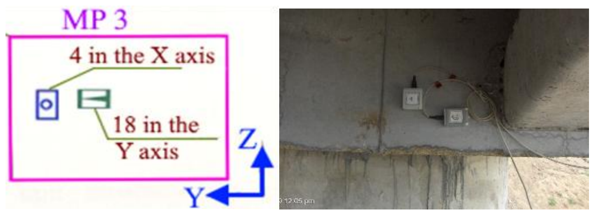


Figure 6. Accelerometers located at observation point 3

3. RESULTS AND DISCUSSION

The received data were processed using programs included in the ERA-PRIS complex. They make it possible to fully automate in-house recording, processing and theoretical analysis of test results (construction of deformation patterns of an experimental object, determination of basic oscillation parameters, calculation of spectral characteristics). To identify the natural frequencies of vibration, a Fast Fourier Transform (FFT) was applied. Analysis of the power spectral densities allowed the identification of dominant peaks corresponding to the primary modes of vertical vibrations of the span structure. Based on these data, a check was performed to ensure that the frequencies remained outside the "forbidden" range (0.45–0.60 s), established to maintain ride comfort and prevent resonance. For each loading regime (from 10 to 70 km/h), a comparison of the extreme values (amplitudes) in real time was conducted, which enabled the recording of beating effects - resulting from the superposition of vibrations as a vehicle traversed adjacent spans, indicating the dynamic connectivity of the system.

Before and after exposure, “background” areas were recorded, during which the superstructure fluctuated under the influence of natural causes: wind, microseismic fluctuations, the work of people, or equipment.

From the general review of the records, it follows that

- As the car's speed increases, the amplitudes of vibrations (accelerations) tend to increase;
- As the speed of the car increases, the impacts become more and more close to impulsive;
- On most recordings, during the time intervals when the car passed the next overpass span, “beats” are visible, which indicates the presence of vibrations with similar frequencies; this is the result of adding vibrations of the middle span with vibrations of the adjacent overpass span.

The most suitable recording areas were selected to determine the attenuation (damping) parameters.

Table 2. Data on the movements of span structures No. 2 and No. 1 under dynamic load action

No.	Code of Record (Name of File)	Description	Speed, km/h	Duration of Records, sec	Maximum Movement of Span Structure in Vertical Direction, mm Sensor No. 1 at MP1	
					Curve	Deflection
1	Rec 01	The dynamic impact on the superstructures was created by a moving car	3-5	85.33	0.77	0.62
2	Rec 02		10	77.82	0.72	0.72
3	Rec 03		20	60.76	1.02	1.36
4	Rec 04		30	59.39	1.53	1.69
5	Rec 05		40	57.34	1.22	1.35
6	Rec 06		50	61.44	0.98	0.85
7	Rec 07		60	53.25	1.03	1.21
8	Rec 08		70	68.27	1.61	1.57
9	Rec 09		70	67.58	2.02	2.17

Dynamic effects were created by moving a truck along the carriageway of the overpass. Dynamic impacts on the structure were created at different vehicle speeds (Table 2). The dependencies of the superstructure’s displacement on changes in vehicle speeds are shown in Figure 7.

The difference in values (1.57 mm and 2.17 mm) at a speed of 70 km/h can be attributed to the vehicle’s trajectory. In the first case (1.57 mm), the truck moved along the central axis of the carriageway, whereas in the second case (2.17 mm), it was displaced toward the lane located closer to the sensor installation line.

The developed monitoring approaches, such as using public transport vehicles as dynamic sensors, have proven effective in detecting damage, particularly on short- and medium-span bridges. This reduces costs and increases the efficiency of diagnostics [26, 54-56]. At the same time, in order to improve the accuracy of forecasting and reliability of assessing the condition of bridges, it is important to take into account factors of prolonged wear, such as fatigue of materials, concrete degradation, and joint failure. These aspects are especially relevant for post-stressed reinforced concrete structures.

Figure 8 shows accelerograms, with vertical lines (highlighted in bold) marking the outer limits of the range prohibited for fluctuations in this direction.

An analysis of the recorded accelerograms in the vertical, longitudinal, and transverse directions shows that the movement of a car weighing 21 tons causes vibrations characteristic of the elastic operation of the girder superstructure. The recordings show a pronounced impulse effect, especially with increasing vehicle speed, which is consistent with the dynamics of a mobile concentrated load. It is noted that the amplitudes of accelerations and displacements increase with increasing driving speed. At speeds of 3-10 km/h, the oscillatory process is predominantly quasi-static, whereas at speeds of 30-70 km/h it becomes more dynamically pronounced.

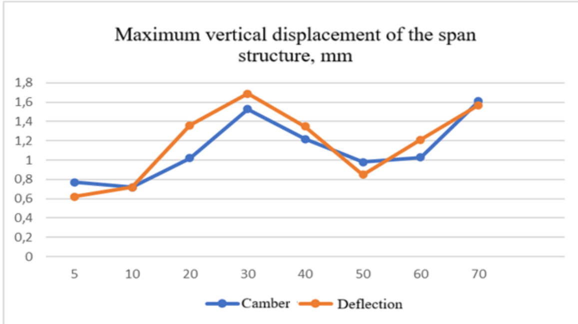
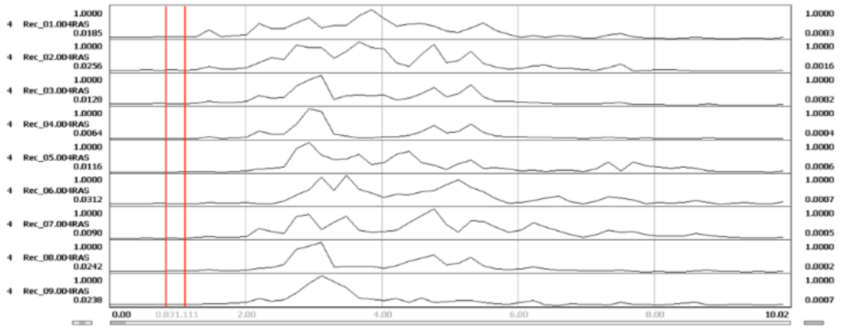
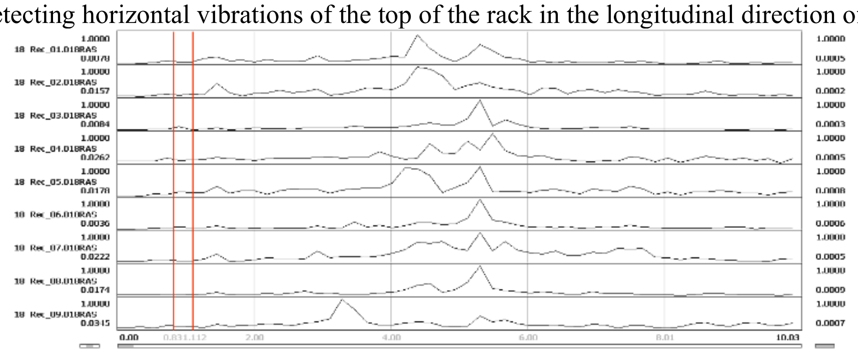


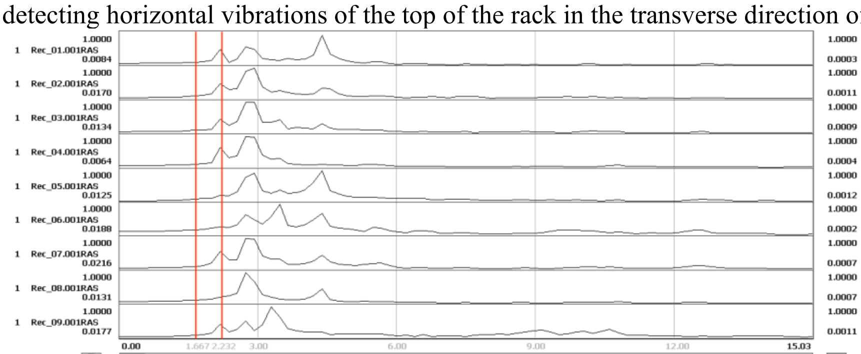
Figure 7. The layout of the observation points



(a) Sensor No. 4 – for detecting horizontal vibrations of the top of the rack in the longitudinal direction of the bridge (X direction)



(b) Sensor No. 18 – for detecting horizontal vibrations of the top of the rack in the transverse direction of the bridge (Y direction)



(c) Sensor No. 1 – for recording vertical vibrations of the bridge (Z direction)

Figure 8. The layout of the observation points

According to the data in Table 2, the deflections for sensor No. 1 were recorded within the range of 0.62 to 2.17 mm. The maximum vertical deflections recorded by sensor No. 1 ranged from 1.57 to 2.17 mm, which represents a small fraction of the expected deflections for a 41 m span, confirming the adequate stiffness of the span structure. Most of the recordings show beats caused by the superposition of natural vibrations of adjacent span structures. The observed “beating” in the recordings (periodic amplitude variations) occurs when the test load leaves the span under investigation (Span No. 1) and moves onto the adjacent span (Span No. 2). From a structural dynamics perspective, this can be explained by the following factors:

- The spans have identical geometric and stiffness characteristics, resulting in closely spaced natural frequencies. As the load moves over the adjacent span, forced vibrations are induced, which are transmitted to the monitored span via common supports or expansion joints:

- The presence of beating confirms that the expansion joints and support nodes provide a certain degree of dynamic continuity in the system, despite the segmented design of the spans. This indicates the cooperative behavior of the bridge components as a single structural unit:

- As the truck speed increases to 70 km/h, the nature of the load changes from quasi-static to impulsive. Even under impulsive loading, the resulting damped vibrations do not trigger resonance phenomena, as the spectral peaks of the primary frequencies lie outside the critical excitation range. This confirms the high dynamic stability of the system.

In accordance with the requirements of clause 1.48* in the spans of urban highway bridges, the estimated periods of natural oscillations in the two lower forms should not be from 0.45 to 0.60 seconds in the vertical and from 0.9 to 1.2 seconds in the horizontal planes.

A comparative analysis of the experimental and calculated values showed that the experimental periods of natural vibrations of the superstructures of the highway overpass do not fall into the "forbidden" ranges specified in paragraph 1.48* of the bridge standards SNiP 2.05.03-84* "Bridges and pipes". Records of the natural vertical vibrations of the bridge structure are shown in Figures 9-11.

Modern methodology [57], such as weighing systems on a moving bridge, can be used to monitor the effects of loads and identify damage to bridges, which is necessary to maintain safe operation.

Dynamic effects on bridge structures emphasize the importance of taking the dynamic boost factor into account when designing. This shows that structures often require a comprehensive analysis of dynamic behavior to ensure safety and durability.

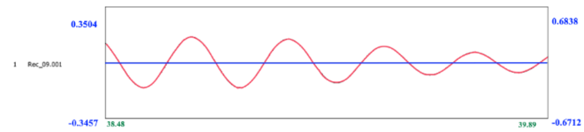


Figure 9. Proper vertical vibrations of span structures No. 2 according to sensor No. 1 (Z direction)

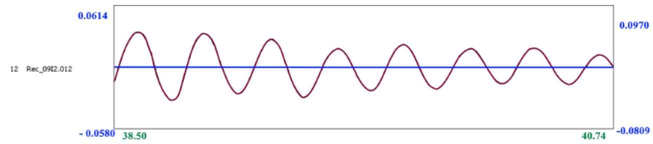


Figure 10. Proper vertical vibrations of span structures No. 2 according to sensor No. 12 (Y direction)

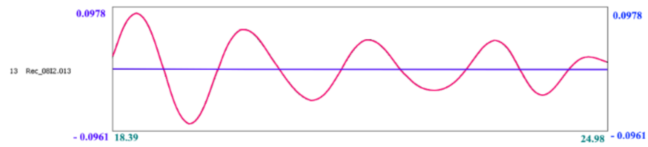


Figure 11. Proper vertical vibrations of superstructure No. 1 according to sensor No. 13 (Y direction)

The results of calculations of the logarithmic decrement of oscillations and damping coefficients (attenuation) are summarized in Table 3.

Table 3. Results of calculations of the logarithmic decrement of oscillations and damping coefficients (attenuation)

Direction/ Sensor	Frequency, Hz	Period, sec	Logarithm Decrement	Ratio of Damping	
				As Fractions of a Critical	As a Percentage of Critical
Z/001	3.37	0.297	0.239	0.038	3.8
Y/012	3.39	0.295	0.223	0.035	3.5
Y/013	0.628	1.592	0.224	0.036	3.6

The three frequencies shown in Table 3 characterise the dynamic behaviour of the various components and directions of movement of the overpass:

- Frequency 3.37 Hz (sensor Z/001): Corresponds to the principal vertical natural vibrations (Z-direction) of the main 41.0 m-long span. This parameter determines the bending stiffness of the span in the vertical plane;

- Frequency 3.39 Hz (sensor Y/012): Characterises the horizontal transverse vibrations (Y-direction) of the same main span structure (41.0 m). The proximity of this frequency to the vertical frequency indicates comparable bending stiffness of the structure in both directions for this span;

Frequency 0.628 Hz (sensor Y/013): Reflects the horizontal transverse vibrations (Y-direction) of the 20.7 m-long span. The physical significance of this frequency lies in the assessment of the dynamic behaviour of the shorter span in conjunction with the support, which provides information on the lateral stability and flexibility of the entire system in this zone. The low frequency (0.628 Hz) for sensor Y/013 in the transverse direction (Y) is explained by the fact that this sensor records the natural vibrations of the 'span structure – intermediate support' system. In other words, sensor Y/013 records a vibration mode characteristic of a more flexible or differently fixed section of the structure.

In accordance with the requirements of clause 1.48* [51] in the superstructures of urban highway bridges, the estimated periods of natural oscillations in the two lower forms should not be from 0.45 to 0.60 seconds in the vertical and from 0.9 to 1.2 seconds in the horizontal planes.

A comparative analysis of the experimental and calculated values showed that the experimental periods of natural vibrations of the superstructures of the highway overpass do not fall within the "forbidden" ranges specified in paragraph 1.48* of the bridge regulations.

In the standards [58], the lower limit of the damping coefficient ζ is given as 1.5% for steel–concrete and reinforced concrete, and 0.5% for steel and composite materials.

On this bridge, reinforced concrete beams with variable cross-sections in the bottom flange are used. Increasing the cross-sectional height near the supports shifts the center of mass and increases the bending stiffness in zones of maximum negative moments (for continuous-span systems). This results in higher natural vibration frequencies compared to beams with a constant cross-section. Additionally, the larger contact area between concrete and reinforcement in the support zones with maximum cross-section enhances internal friction, leading to a higher damping coefficient, $\zeta = 3.5…3.8\%$.

An analysis of the temporal realizations of accelerations, spectra, and waveforms showed that:

• There are no low-frequency parasitic modes characteristic of defects in the supporting parts or beams;

• The recorded frequencies are stable and correspond to the calculated ones.

This indicates the normal technical condition of the bridge, the absence of loose connections or damage to the bearing elements. However, it should be noted that due to the increased traffic intensity and higher vehicle loads, monitoring of these bridges is required in accordance with the applicable regulatory standards.

4. CONCLUSIONS

The results of static and dynamic tests have confirmed that the integration of static and dynamic methods can significantly reduce the uncertainty in assessing the structural condition and provide a more accurate calculation of reliability indicators, including the safety index and the probability of failure. This directly increases the accuracy of the safety risk assessment associated with the operation of bridges under conditions of intense traffic impact and aging of structures. The combined analysis of test data and computational models expands the possibilities for timely forecasting of the remaining resource, identifying critical elements, and forming optimal solutions for maintenance.

1. An inspection of the load-bearing structures of reinforced concrete span structures 41.0 m and 20.7 m long made of UBS 187.14 blocks, overpass supports, and carriageway elements showed that the geometric dimensions correspond to the working design. No defects or malfunctions affecting the operational reliability of the facility have been identified. The technical condition of the overpass should be considered satisfactory.

2 The results of static tests showed that the maximum deflection in the middle of the middle span was 23.5 mm. The analysis of the increments of deflections of the UBS 187.14 blocks during the step-by-step loading and unloading of the test testified to the elastic nature of their deformation.

3. Dynamic tests of a reinforced concrete girder bridge with a span of 41 m under the influence of a moving load weighing 21 tons have shown that the structure works stably, with limited amplitudes of movements and accelerations, and its natural frequencies lie outside the forbidden ranges established by regulations.

4. The increasing traffic intensity and higher vehicle loads necessitate monitoring of these bridges at intervals specified by the applicable regulatory standards.

Thus, the complex of static and dynamic tests should be considered as an integral part of the modern safety management system for bridge structures. It provides a reliable basis for engineering decisions aimed at reducing operational risks, extending service life and maintaining the required level of structural reliability in accordance with international standards (ISO 13822, ISO 2394, EN 1990). The introduction of such approaches is especially important for bridges with a high degree of congestion, as well as for structures that have been in operation for a long time and are exposed to climatic and man-made factors.

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