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EXPERIMENTAL IN-SITU TESTING OF AN EXISTING BRIDGE

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Abstract

The assessment of the condition of existing bridges is of great importance, particularly for bridge structures that have been in operation for a long time and for which no adequate technical documentation exists. The behavior and condition of these bridges change over time, making it necessary to perform specific experimental tests and additional analyses to determine their actual load-bearing capacity and usability.

This paper presents the results of experimental in-situ tests conducted on a steel bridge. The experimental activities were divided into two phases. The first phase involved determining the dynamic characteristics of the bridge using the ambient vibration method, while the second phase focused on evaluating the bridge's behavior under static and dynamic loading. The equipment used for determining the dynamic characteristics included accelerometers, a data acquisition system, and a computer. For the static and dynamic loading tests, strain gauges, accelerometers, and linear potentiometers were used.

The results of these tests form the basis for further numerical analyses of the bridge's load-bearing capacity and stability.

In conclusion, following detailed analyses and investigations, conclusions regarding the condition of the bridge structure were drawn.

Keywords: bridge, ambient vibration, static and dynamic loading

1. Introduction

The behavior and condition of existing bridges changes over time. Therefore, to obtain an accurate assessment of their load-bearing capacity and usability, it is necessary to perform specific experimental tests and additional analyses. This paper presents the results of experimental investigations conducted on a steel bridge located in the municipality of Negotino, near the village of Krivolak, Republic of N. Macedonia [1][2][3]. The experimental activities for this structure were divided into two phases. The first phase included tests to determine the dynamic characteristics of the bridge using the ambient vibration method, while the second phase involved tests to evaluate the bridge's behavior under static and dynamic loading. Selected results from these investigations are presented in this paper.

2. Description of the structure

The bridge is a steel structure built in the 1940s, using construction techniques typical of that time (Fig. 1). The structure is straight, with two traffic lanes and steel railings on both sides. It provides a reliable crossing over the Vardar River, connecting the local road from the Krivolak military area to surrounding areas, ensuring the safe passage of motor vehicles.

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Figure 1. View of the bridge

The bridge consists of five spans, each representing a static simply supported beam system. Each span measures 34.0 meters in length. The main load-bearing elements are two longitudinal steel trusses, divided into seven sections, each 4.85 meters long. These trusses are interconnected by transverse girders and braces on the upper side, as well as transverse and longitudinal girders and braces on the lower side.

On the lower longitudinal and transverse girders, a steel sheet is placed, over which a reinforced concrete slab is cast. The total height of the truss is 5.0 meters, and the distance between the two main trusses is also 5.0 meters. All components, including the main trusses, longitudinal and transverse girders on both the upper and lower sides, are made of steel "L," "U," "I," and plate elements. These are connected to form complex cross-sections. The elements of the bridge are interconnected using rivets, providing rigid connections.

The main girders are supported on bearings that are fixed on one side and movable on the other. The usable width of the bridge is 4.0 meters, with an open bridge deck. The deck structure consists of a composite reinforced concrete slab over trapezoidal steel sheeting and a finishing layer of cast asphalt. The thickness of the reinforced concrete slab is 40 cm.

The abutments and central piers are constructed of stone, while the exact foundation type remains unknown.

3. Methodology of testing

The bridge under investigation is a steel structure for which no construction design documentation is available. Consequently, the design loads, characteristics of the structural elements, type of bearings, and calculated deflections and deformations from the design are unknown. Due to these limitations, the testing procedure could not fully comply with the MKS 1019:2018 standard for bridge testing [4]. Instead, the testing was adapted to the on-site conditions and the resources available.

Another significant challenge was the lack of information regarding the bridge's foundation. The condition of the foundation plays a vital role in the overall stability of the structure, particularly under future operational loads.

The tests conducted on the bridge were categorized as control tests, as specified in Section 4.1 of MKS 1019:2018, and performed during its operational phase. Since no documentation was available, an initial visual inspection was carried out. Based on this inspection, a testing program was developed, which included the following tasks described in Section 5.2 of MKS 1019:2018:

- Definition of the size and distribution of loads for each phase;
- Identifying measurement points where maximum deflections and deformations were expected;
- Development of an organizational plan for the application of the loads.

Both static and dynamic load tests were performed in accordance with Section 4.3 of MKS 1019:2018.

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The static load tests provided the following results (as per Section 5.4 of MKS 1019:2018):

– Measurements of vertical deflections at the midspan of the bridge;
– Occurrence of cracks in the structural elements;
– Measurements of deformations at places of expected extreme effects;
– Measurements of residual deflections and deformations after the removal of the loads.

Unfortunately, due to limited access, it was not possible to measure displacements at the bridge bearings.

The dynamic load tests provided the following results:

– Measurements of vertical deflections at the midspan during the passage of a moving load;
– Measurements of the speed at which the load traveled across the bridge.

Additional measurements during the dynamic tests included:

– Deformations at critical locations under extreme effects;
– Transverse and longitudinal displacements at the midspan of selected spans;
– Remaining dynamic characteristics of the bridge structure.

The experimental setup included PCB Piezotronics 393B12 accelerometers, Kyowa KC-70-A1-11 strain gauges, and Micro-Epsilon WDS-1000-P60-SR-U linear potentiometers to measure accelerations, strains, and displacements, respectively. Data acquisition was performed using National Instruments cDAQ 9188 and National Instruments cDAQ 9178 systems, connected to a portable laptop for real-time monitoring and recording.

Some of the results are presented in this paper.

4. Determination of the bridge's dynamic characteristics using the ambient vibration method

4.1. Testing procedure and Instrument layout

The testing procedure consisted of recording real-time accelerations and processing the data in both the time and frequency domains. Accelerometers were placed at predefined points on the bridge structure. The arrangement of these measurement points was designed to maximize the number of necessary records to accurately determine the required dynamic characteristics [5][6][7].

At each point, three accelerometers were installed to measure accelerations in the transverse, longitudinal, and vertical directions. One point (Point 13, Fig. 2) was selected as a reference point, where the accelerometers remained in a fixed position throughout all measurements. The other 12 accelerometers were moved across the remaining predefined points. In total, 42 measurement points were defined for the bridge. Fig. 2 illustrates the placement of the accelerometers at these measurement points.

To record the acceleration time histories at all predefined points, 11 measurements were conducted. Each dataset consisted of acceleration time histories with a duration of 300 seconds and a sampling frequency of 2048 Hz (2048 samples per second). During the field measurements, the bridge and surrounding structures were in a state of rest. A bandpass filter ranging from 0.5 Hz to 35 Hz was applied to remove low-frequency drift and high-frequency noise, ensuring accurate measurement of the structural response.

This methodology ensured that the collected data could be used to accurately determine the dynamic characteristics of the bridge.

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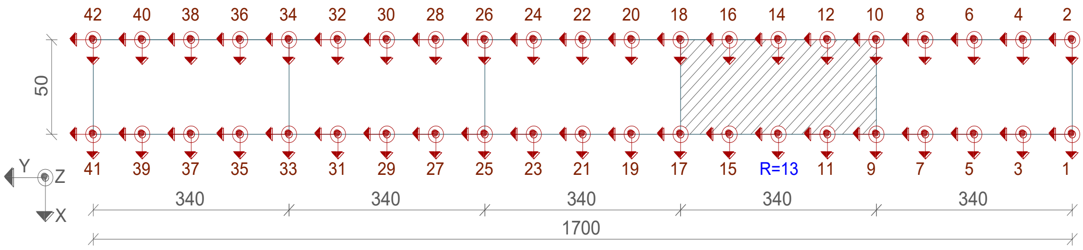

Figure 2. Position of accelerometers at measuring points

4.2. Results and Discussion

The recorded ambient vibration data were analyzed and processed using the ARTeMIS Modal software (version 7.1), developed by Structural Vibration Solutions A/S [8]. The dynamic characteristics of the bridge—natural frequencies, mode shapes in different directions, and damping coefficients—were determined using the Peak Picking (PP) technique, an identification method applied in the frequency domain to the recorded data. Table 1 presents the identified dominant frequencies of the bridge and their corresponding mode shapes.

Table 1. Dominant frequencies of the structure – model of the integral bridge

Frequency [Hz]	Mode
5.4	First mode – vertical direction
6.9	First mode – transverse direction
9.1	First mode - torsion
11.0	Second mode – vertical direction

By analyzing the determined dynamic characteristics of the bridge, it can be concluded that the fundamental natural frequencies are relatively clearly defined, and the mode shapes exhibit a continuous deformation pattern. This suggests a uniform distribution of stiffness across the structure. The modes of vibrations are given in Fig. 3, Fig. 4, and Fig. 5.

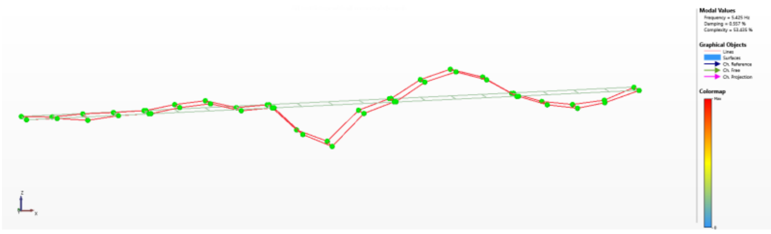

Figure 3. First mode – vertical direction [5.4Hz]

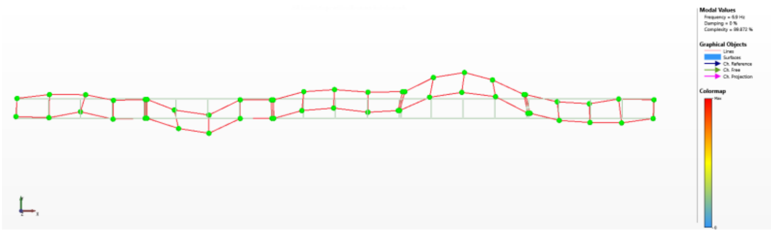

Figure 4. First mode – transverse direction [6.9Hz]

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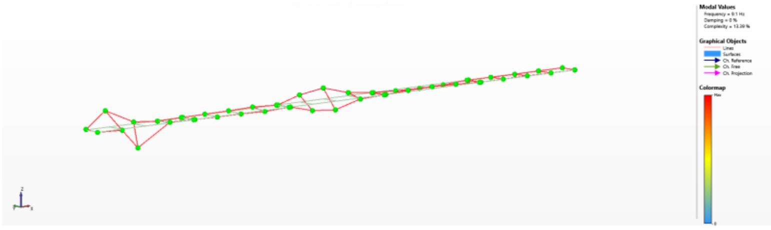

Figure 5. First mode - torsion [9.1Hz]

5. Static and Dynamic loading

To determine the control parameters during serviceability of the bridge, appropriate instrumentation was installed, as shown in Fig. 6. A total of 29 instruments were placed, including 10 strain gauges (SG) positioned at key locations to measure strains, 15 accelerometers (ACC) placed at five points to measure acceleration in the three directions (x, y, and z), and 4 linear potentiometers (LP) for measuring deflections (vertical deformations).

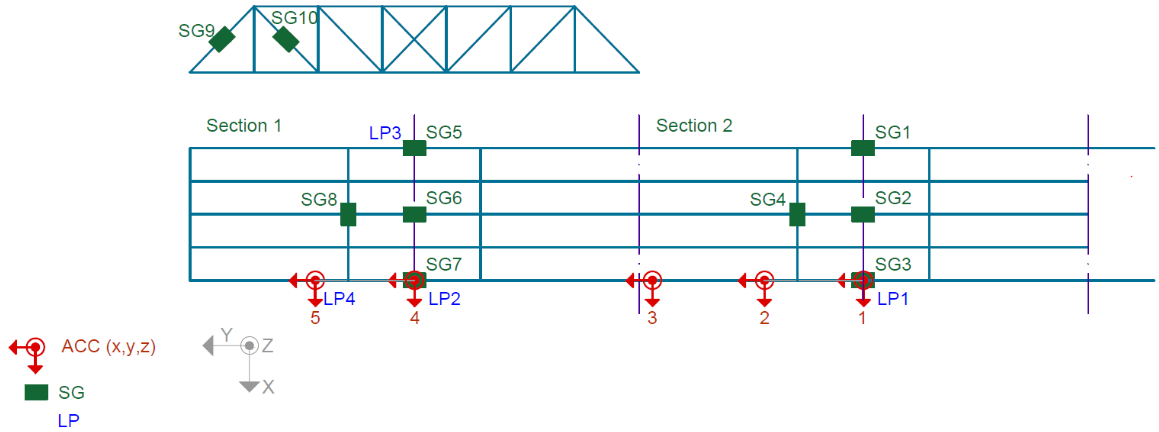

Figure 6. Scheme of instruments on the steel bridge

For the static and dynamic loading tests, two types of trucks were used, with a total of four trucks. The characteristics of the trucks used, Truck A and Truck B, are provided in Fig. 7 and Table 2, along with a more detailed presentation of the distribution of forces on the wheels during the static loading test.

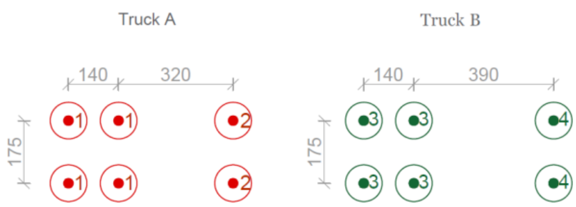

Figure 7. Axial distance of wheels of trucks A and B

Table 2. Axial distribution of forces in the wheels of trucks A and B

Truck A ≈ 24.8t		**Truck B ≈ 24.5t**	
Point	Force [kN]	Point	Force [kN]
1	46.5	3	46
2	31.5	4	31.9

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Initially, the section marked as 2 was loaded, starting with one truck positioned at the center, as shown in Fig. 8, with a load of 24.0 tons, for a duration of three minutes. Consequently, the load was increased by adding two, and then four trucks, resulting in a total load of 48.0 tons and 96.0 tons, respectively (Fig. 8). Between all the tests, unloading was performed, and a baseline (empty) measurement was taken without any load, lasting three minutes.

It is important to note that due to a lack of space to place the four trucks as a concentrated load in the midspan of section, they were arranged in a line along the entire length of the field. Fig. 9 shows a photo of the sixth static loading test of section 2.

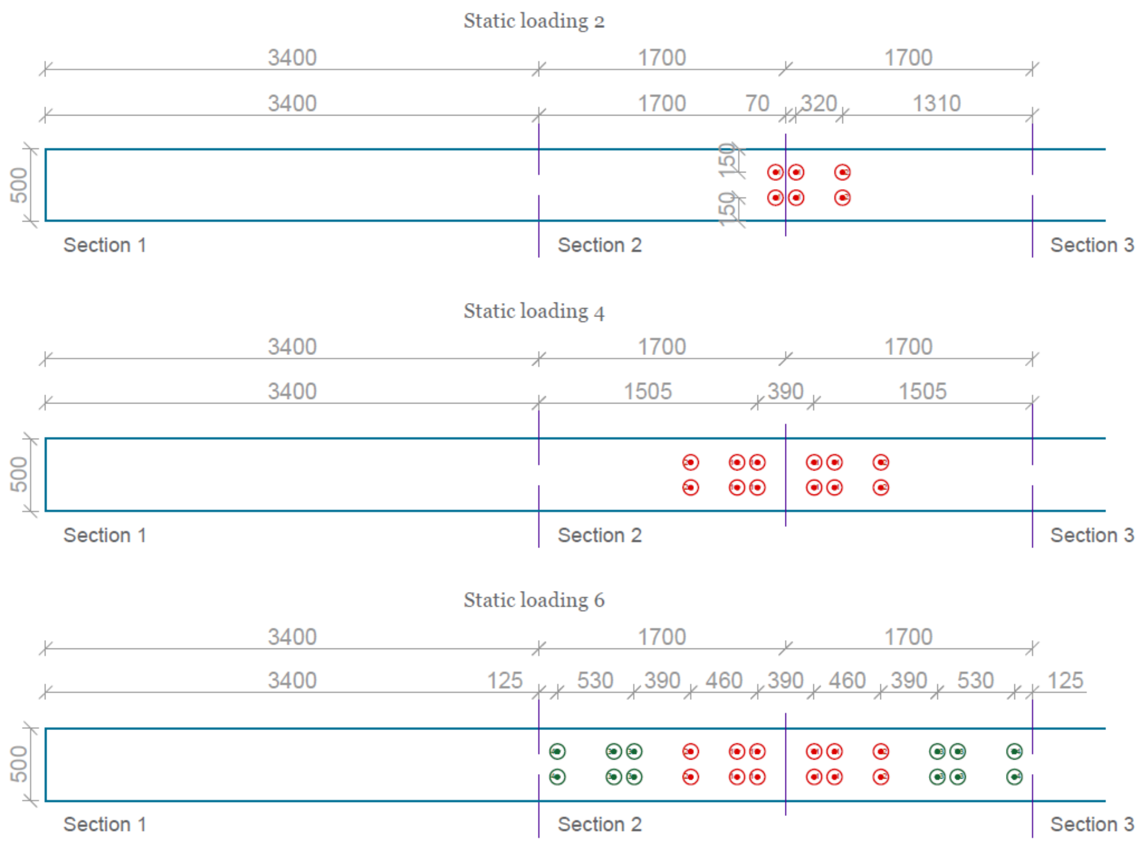

Figure 8. Position of trucks during static tests in section 2

Figure 9. Photo of static loading of section 2

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Table 3 presents the maximum values of strains and deflections under characteristic loadings for section 2. From the results of the vertical displacements, it can be concluded that the measured vertical deformations are smaller than the allowable limit of L/750. Fig. 10 shows the strains measured by the strain gauges.

Table 3. Maximum values from instruments under static trial loading of section 2

	SG1 [mstr]	SG2 [mstr]	SG3 [mstr]	SG4 [mstr]	LP1 [mm]
Static loading 2	44.72	134.99	45.32	81.50	2.5
Static loading 4	65.31	34.82	70.04	93.97	3.62
Static loading 6	73.08	38.43	89.54	93.11	4.12

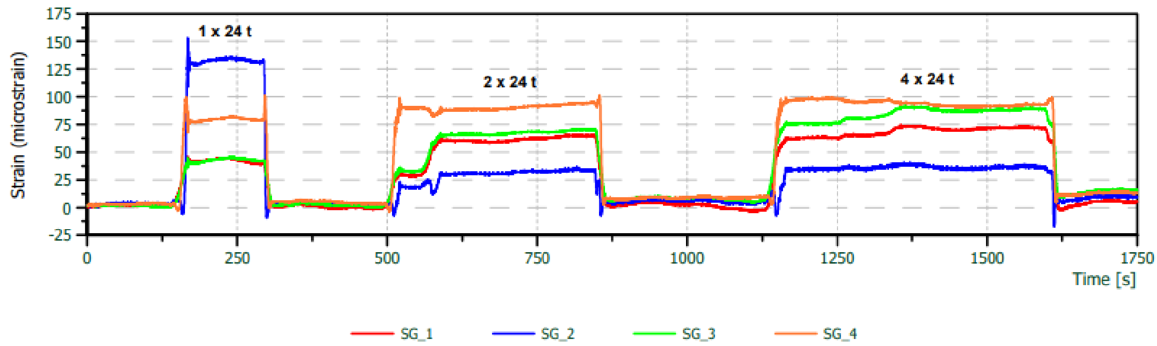

Figure 10. Time histories from strains measured by strain gauges during static loading of section 2

Residual deformations were analyzed to assess their significance. The results indicate that the maximum residual deformation does not exceed 10%, corresponding to approximately 10-15 microstrains. This is a small value and within acceptable limits, meaning it does not pose any structural concerns. The minor residual strain is likely due to measurement sensitivity or localized material behavior, and it does not affect the overall stability of the bridge.

The dynamic loading was carried out through three different tests, simultaneously on section 1 and section 2. The trucks passed over the bridge at various characteristic speeds (5 km/h – 20 km/h). A metal plate obstacle was placed at the third points of the bridge, in section 1 and 2, to simulate an impulsive dynamic excitation. Table 4 presents the maximum deflections (vertical deformations).

Table 4. Tabular presentation of deflections during the dynamic tests

Instrument	Vertical deformation due to static load [mm]	Vertical deformation due to dynamic load – 5km/h [mm]	Vertical deformation due to dynamic load – 10km/h [mm]	Vertical deformation due to dynamic load – 20km/h [mm]
LP1	4.12	1.27	2.11	2.73
LP2	4.73	1.8	2.32	285
LP1	4.12	1.27	2.11	2.73

6. Conclusions

Based on the conducted experimental investigations, the following conclusions can be drawn:

- Dynamic characteristics: The dynamic properties of the bridge, such as natural frequencies and mode shapes, were clearly defined. The bridge shows a consistent deformation pattern, indicating a uniform distribution of stiffness across its structure.

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- Deflections and deformations: Both static and dynamic deflections and deformations were within acceptable limits set by the standards. The vertical deflections after unloading were well below the allowed limits for steel and composite bridges.
- Impact on functionality: The deflections and vibrations do not affect the bridge's use, safety, or appearance. Vibrations did not cause discomfort for users, showing that the bridge works well under the applied loads.
- Conformance to standards: Although the tests could not fully follow the MKS 1019:2018 standard due to missing design data, the methods were adjusted to fit the available conditions on-site, ensuring reliable results.
- Further investigations: More studies are needed to check the condition of the foundation, as the lack of detailed information about it could affect the bridge's overall stability and long-term performance.

Based on all the results obtained, it was determined that the bridge is in good condition and performs well under the loads applied during the tests.

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