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Research Article

Load testing of new Bridges with wireless system equipment

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Abstract:

Bridges are construction objects that are an integral part of almost every road. Their damage often results in the collapse of the transport system and particularly affects traffic safety. To avoid such a thing, it is necessary to carry out certain checks before putting the bridges into traffic, which will provide information in advance about whether there is a possibility of future damage. One of them is the so-called test load for new bridge before it is taken into service. Therefore, bridge testing is the last external monitoring action to be performed when a new bridge is built. The objective of these tests is to verify that the mechanical behavior of the loaded structure conforms to its design model. The system evaluated as part of this study was the Bridge Diagnostics, Inc. (BDI) Wireless Structural Testing System (STS-Wi-Fi). All results are compared with theoretic values based on the FE-model of the bridge and are calculated using software SOFISTIK AG. Both the experimental results as well as the and analytical results are presented in this paper and compared. The comparison of the analytical results showed good agreement with the experimental results.

1. Introduction

In order to provide an assessment regarding the use of new bridges, it is necessary to compare the results of the actual behavior of the bridge structure with test loads corresponding to the respective static design calculation. In general, it will be verified that the finished construction of the structure is technically correct, the behavior of the structure under test load is in accordance with the static calculation of the project, and that there are no functional deficiencies during use. On the other hand, the main objectives of the load testing is to better understand the response of the bridge to static and dynamic loads and conclude if the bridge can be used in the future.
Within the framework of the standard for bridge testing, HRN U.M1.046, the following are defined: types of loads for testing, testing procedures and evaluation of test results.[1] Verifications are made for the relevant situations for reinforced concrete bridges, pre-stressed concrete bridges, steel bridges and composite structures.[2], [3] According to the procedures defined by this standard, the response of the bridge structure under the action of static and dynamic loads is determined. It is estimated, however, that the construction work has fulfilled quality control/assurance requirement according to the standard and project specifications for the design life of service.
Environmental factors such as temperature, humidity, and wind can affect structural response and should be properly accounted for during the load test preparation, the testing, and also the post-test analysis [4].Temperature changes can affect the results of a load test by:

a) causing an unexpected response of the sensor or measuring technique, and
b) inducing thermal stresses and strains to the structure.
The next sections compile information from load tests on concrete bridges reported in the

literature, and the measuring techniques or sensors used during these tests[4][5].

During the testing of the bridge in our case, the atmospheric conditions were suitable for the testing equipment, so they were within the criteria required by these equipment's.

The approach of increasing refinement of the assessment is in line with the Levels of Approximation, first introduced in the fib Model Code 2010 (fib, Citation2012). Figure 1 illustrates the concept of the Levels of Approximation. For assessment, this approach is called Levels of Assessment [6] Many of the techniques mentioned, such as the use of nondestructive testing, structural monitoring [7], and assessment using nonlinear finite element analysis currently do not form part of the structural or bridge engineering curriculum, but these techniques are becoming increasingly important tools for bridge engineers.

A load testing has been carried out on the fully completed bridge in Arllat, Km 7+817.86, Road M9. Before conducting the test, the project documentation was reviewed and the elements of the structure were checked.

The purpose of this research is based on the comparison of the results of the deflections, the results of the strains, the angle of rotation in the supports as well as the determination of the dynamic response through the acceleration and frequency from the mathematical model determined by the software with the results obtained from the test load carried out through the loaded with assigned loads.

The program and testing were performed under the leadership of the IPE-PROING team using the System Test Framework - Wireless (STS-Wi-Fi) from Bridge Diagnostics, Inc. (BDI).[8]

2. Materials and methods

2.1 Loading tests on bridges

Testing of the finished bridge under a specific load is necessary after the work is completed. This procedure, based on which it will be established whether there are conditions to conclude that the constructed bridge is technically correct, that the behavior of the structure under load is in accordance with the static calculation provided by the project, and that there are no functional defects during loading.[9] Both static and dynamic test loads are mandatory for road bridges with a span of 15 meters or more, railway bridges with a span of 10 meters or more, and bridges with exceptional test loads regardless of the span.[10]

During static load testing it is mandatory to measure the vertical displacement between each span of the bridge, measure the displacements of the supports, evaluate the appearance of cracks, measure the deformations at the positions of the maximum expected impacts, measure the permanent deformations and deformations after unloading.

If additional measurements are required by the test program, then the following must be evaluated: rotation angle, horizontal displacements, displacements of supports and foundations.

During dynamic load testing, it is mandatory to measure the velocity of the moving load passing on the bridge as well as the vertical displacement between certain locations during the 3 passage of the vehicle. [11][12] If additional measurements are required by the test program, then these additional measurements must also be evaluated: measurement of transverse and longitudinal displacements between the selected locations and measurement of the dynamic characteristics of the structure (vibration frequencies, mode shapes and damping value). [10]

In order to be able to start applying the test load, it is necessary to do the following: review the project documentation, compile a test program that includes the size and distribution of the load by stages, the calculation of the expected deformations and deflections, the layout of the measuring points and the test scheme. Furthermore, it is necessary to look at the documentation on the quality of the materials and finally to carry out a macroscopic inspection of the bridge.

The bridge will be considered a correct construction if:

- Measured deflections and displacements are less than or equal to the theoretical ones.
- Measured permanent deflections after unloading less than 15% max. of measured deflections at the same place for steel and coupled bridges, 20% of measured

deflections for prestressed concrete bridges and 25% max. of measured deflections for reinforced concrete bridges.

- Width of measured cracks in reinforced concrete bridges smaller than allowed, in accordance with technical regulations.
- Sizes of measured deflections such that they do not affect the functionality or aesthetic appearance of the structure.

2.1.1 Description of the bridge

E Based on the data of the main project, the Bridge structure - Overpass in Arllat, Km 7+817.86, Road M9, consists of a prestressed concrete bridge, which is designed and built as a bridge with a continuous static beam system with five spans measuring 5x18 .0m (Figure 1). For the structure of the bridge, grade C 30/37 concrete was used in the foundations, C 35/45 in the piers and C 40/50 in the beam-slab. [13], [14], [15].

For the materials used, relevant certificates have been provided from which it can be concluded that the elements of the structure are made of materials with physical-mechanical characteristics that meet project requirements.

Base Station, STS-Wi-Fi Node and corresponding sensors. Each component of the system is involved in the data collection process. (Figure 2)

When BDI system is used, it is organized into an infrastructure. This means that the Mobile Base Station is used to run the system. The Mobile Base Station serves two purposes: first, it extends the range of the system using antennas, and second, it increases the efficiency of the system by acting as a relay between the PC and the STS-Wi-Fi nodal point. The diagram below shows the infrastructure's shape (Figure 2)

Figure 2. *The wireless Structural Testing System (STS-WiFi) by Bridge Diagnostics, Inc. The BDI test equipment system.*

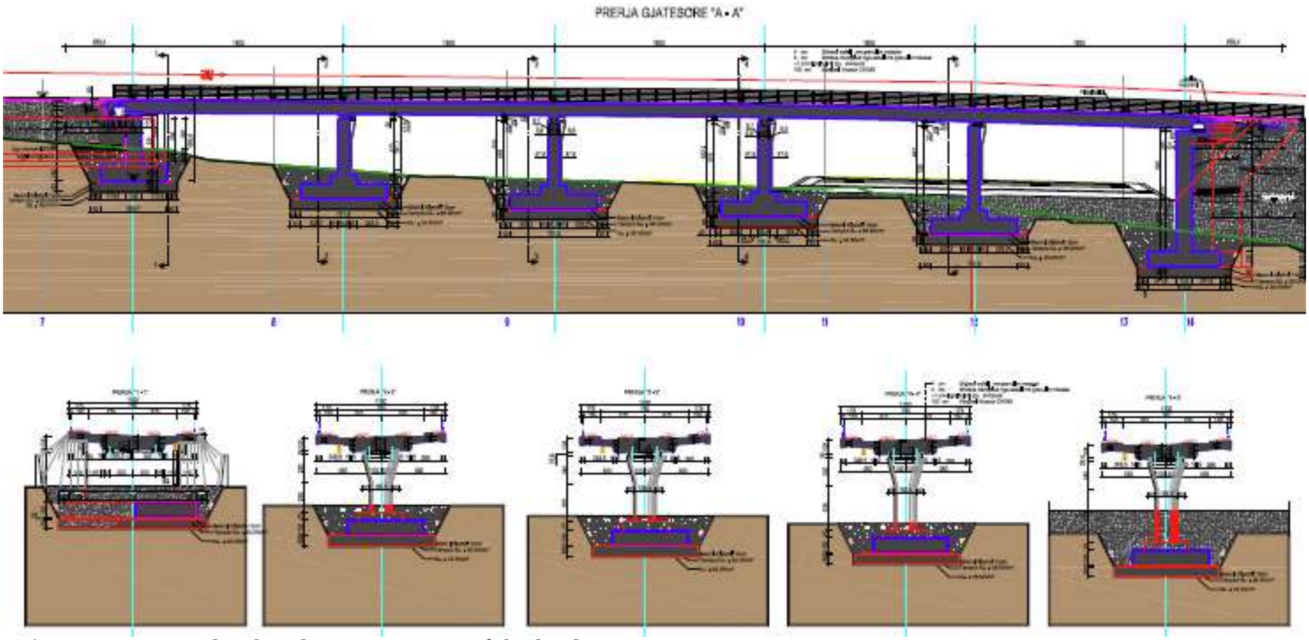

Figure 1. *Longitudinal and cross sections of the bridge*

The Structural Testing System - Wireless (STS-Wi-Fi) from Bridge Diagnostics, Inc.[16] (BDI) was used to perform load testing of the bridge. The BDI test equipment system consists of the STS-Wi-Fi

As seen in this figure, everything is controlled on the PC. The PC sends commands to the base station; from there, the commands are distributed to all system nodes. Each node is responsible for collecting data from four sensors and converting this data into a digital format.[8] Thus, the data is transferred back to the base station and then to the PC in real time. Consequently, by installing sensors in the primary elements of the structure and using the data 5 recorded from each node, a clear picture of how the applied actions distribute those effects is presented.

The BDI Software Packet is the analytical modeling part of the testing system and consists of three main components: WinGRF – data presentation, WinGEN - model generator, and WinSAC - structural analysis and correlation. All elements serve different purposes, but each is essential to the overall process. Each component has been developed to move data from one application to another seamlessly. WinGRF is used for graphical data presentation and is the first step in modeling, while WinGEN is a finite element model generator.[8], [17], [15]

Instrumentation of the bridge in this case study consisted of: 10- LVDT (Linear Variable Differential Transducer), 10-Accelerometers, 4 Tiltmeters and located as shown in (Figure 3).[18]

For static load, 4 trucks were used with the following loads:

Tr. 1 = 40520 kg, Tr. 2 = 39380 kg, Tr. 3 = 39380 kg and Tr. 4=39660 kg.

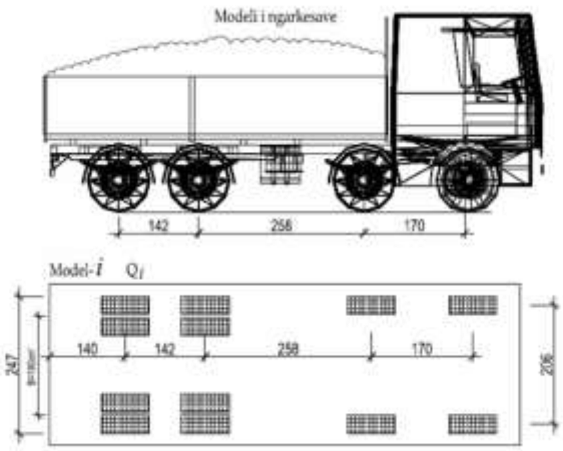

Figure 4. *Loaded trucks, axle dimensions and loads*

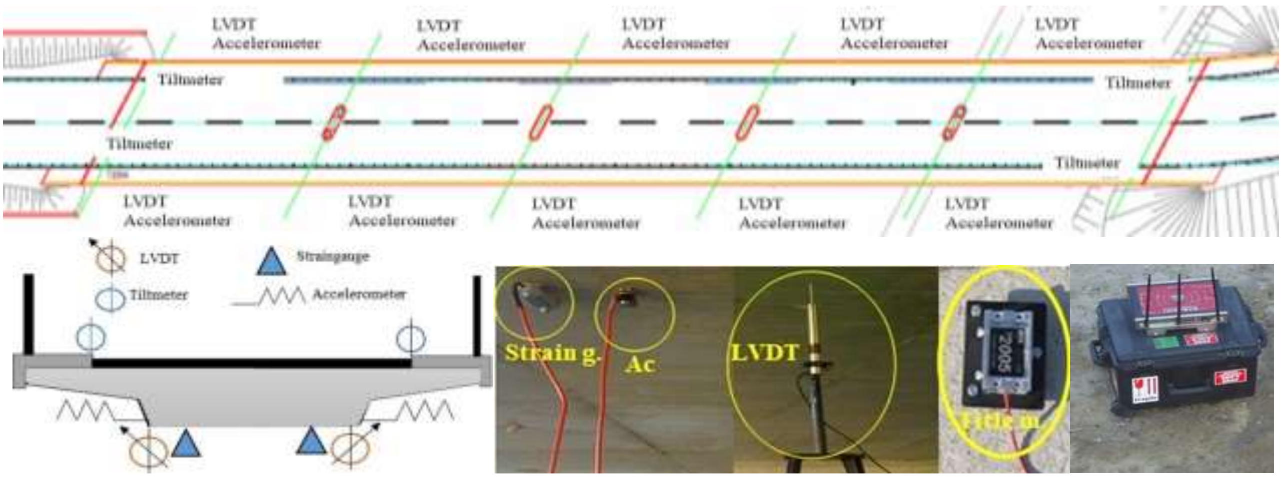

Figure 3. *Instrument positioning in the Bridge and basse station*

2.1.2 Testing Loads

Static loading is usually conducted with trucks filled with sand or gravel that have been weighed, and the load is distributed along the axles (Figure 4).[10][19] The bridge was loaded in accordance with the phases and the load scheme that were drawn up before the start of the measurement. [20]

For static load, 4 trucks were used, which were directed and positioned in the most unfavorable positions on the bridge (Figure 5,and Figure 6). During the loading-unloading 6 process of the bridge, the following measurements were taken: delflection, acceleration and rotation angle at the characteristic points of the bridge.[21], [22], [23], 24]

Dynamic loads were selected from the ranks of static loads used. For dynamic load, 2 trucks = ~ 800kN were used (the number of vehicles is equal to the number of lanes). These vehicles moved uniformly from the beginning to the end of the bridge, with velocity of ~5 and 20 km/h. In the case of the action of moving loads, the deflection, rotation angle vibration acceleration and dynamic characteristics of the bridge were measured at the characteristic points of the bridge.[11]

Figure 5. *Loaded trucks-Static load position*

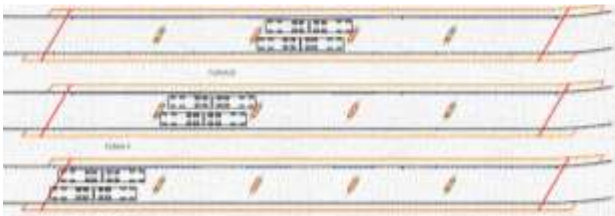

Figure 6. *Static load position – first Span loading*

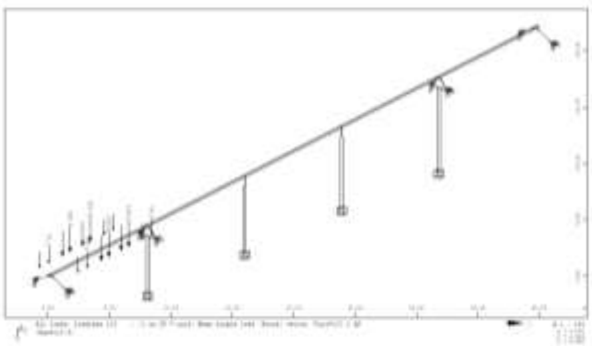

Figure 7. *Load position on Sofistic – firs Span loading*

3. Results and discussion

In principle, during load testing, subject of measurement in the relevant elements of the bridge are displacements, deformations, rotation angle, oscillation phenomena, etc.

After the measurement, the data is processed and displayed as presented: Figures 8-13 present the results of deflections from the action of the static load as well as from the action of the dynamic load during the movement of trucks at a speed of 20 km/h for spans I, II and III, while in figures 9, 11, 13, they are presented the results of the magnitudes, the angle of rotation in the first span, while the results of the accelerations in spanss II and III from the action of the dynamic load (load movement speed 20km/h). Figure 14 shows the results of the deflections in the first area calculated in the mathematical model with the Sofistic software. In the end, the obtained results are compared with the calculations by measurement phases. As a final step in the load testing of bridges , is the compilation of a report issued by the entity that conducts the test.

Modeling and analysis of the structure was performed using "SOFISTIK" software.[25] The load is modeled same as in the test phase and traffic loads. Based on the results obtained from the experimental measurements and the theoretical values from the analysis, the maximum displacement values from the respective analysis are presented below. The maximum values of span displacements in the static system of the bridge as a function of static loads for 4-vehicles and from dynamic loads for 2-parallel vehicles are given in table 1.

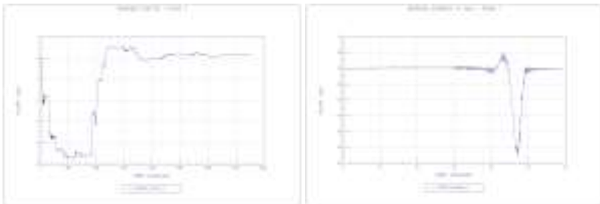

Figure 8. *Deflections in the first span-static and dynamic load (20km/h)*

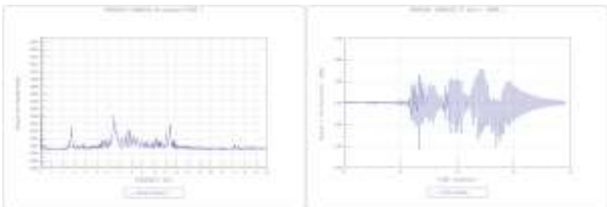

Figure 9. *Magnitude and angle of rotation first span-dynamic load (20km/h)*

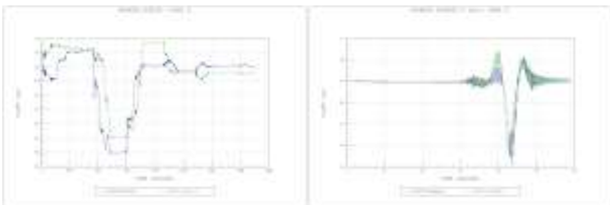

Figure 10. *Deflections in the 2 span-static and dynamic load (20km/h)*

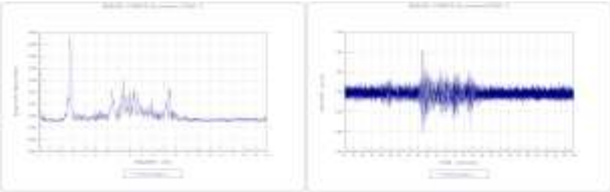

Figure 11. *Magnitude and acceleration 2 span-dynamic load (20km/h)*

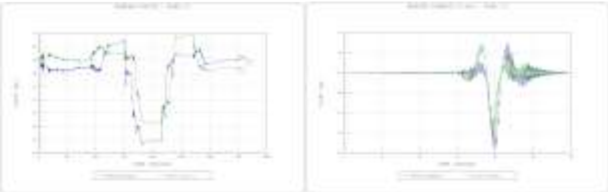

Figure 12. *Deflections in the 3 span-static and dynamic load (20km/h)*

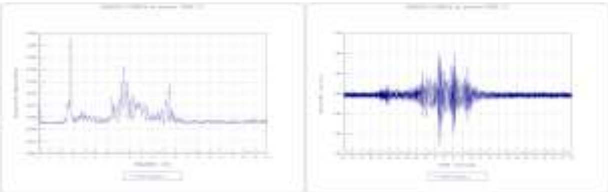

Figure 13. *Magnitude and acceleration 3 span-dynamic load (20km/h)*

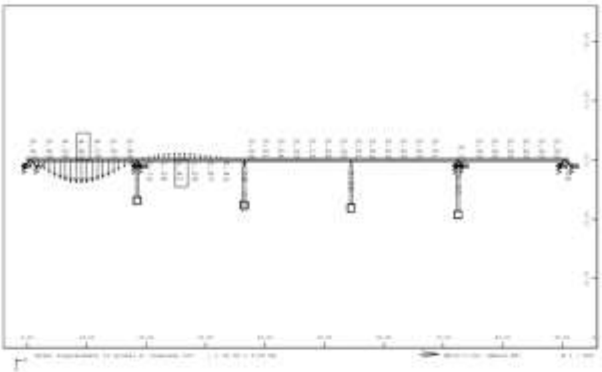

Figure 14. *Displacements in the first span-analytical*

Based on the results from the load testing of the bridge structure and the analytical results of the model with a load equivalent to that of the test, as well as the results obtained from the design loads, basic information on the general response of the structure under the respective loads has been extracted. From what was presented above, it can be concluded that:

- During the process of load testing of the bridge, it was estimated that the bridge structure reacted as an elastic structure with limited deformations and no cracks.

Table 1. *The maximum values of displacements in the spans of the static system of the bridge and dynamic characteristics of the bridge*

Span 1				
Loads			Static 4 Trucks	Dynamics 2 Trucks
Displ. [mm], Testing Displ. [mm], Calculated			4.6 4.8	2.8 3.0
Span 2				
Loads			Static 4 Trucks	Dynamics 2 Trucks
Displ. [mm], Testing Displ. [mm], Calculated			3.0 3.4	1.9 2.1
Span 3				
Loads			Static 4 Trucks	Dynamics 2 Trucks
Displ. [mm], Testing Displ. [mm], Calculated			3.2 3.4	1.8 1.9
Span 4				
Loads			Static 4 Trucks	Dynamics 2 Trucks
Displ. [mm], Testing Displ. [mm], Calculated			2.6 3.4	1.8 1.9
Span 5				
Loads			Static 4 Trucks	Dynamics 2 Trucks
Displ. [mm], Testing Displ. [mm], Calculated			2.5 4.9	1.8 3.02
Frec [Hz]	1	2	3	4
Testing	2.7	6.4	7.4	11.4
Calculated	2.57	5.95	7.67	10.45

- Thus, after unloading the bridge structure from the test loads, all the deflections deformations in the structural elements were reversible. Consequently, irreversible deflections-deformations (residual) have been negligible.
- By comparing the obtained results corresponding to the deformations, a relatively good correlation between the measured and the calculated values is obtained. Referring to the calculated values, it is found that they are higher than the measured values. From this, it follows that the quality of the elements of the structure is higher than the calculated values and it is estimated that the structure provides the capacity of the intended bearing capacity.
- From the calculated stress values, the bridge in service behaves as a linear elastic structure.
- Through comparison of frequency values from experimental measurements with dynamic loads and those calculated from free oscillations of the structure, it is clear that these values agree very

well. This shows that the dynamic behavior of the bridge is satisfactory and that the numerical model used in the analysis of the existing structure is realistic.

- It is also estimated that the bridge was built in accordance with the quality of the works according to the requirements of the project and the design lifetime of service.
- It is generally verified that the finished construction of the structure is technically correct, the behavior of the structure under test load is in accordance with the static calculation of the project and that there are no functional deficiencies during use.

3. Conclusion

Before commencement of testing the bridge, the project documentation must be verified. Determination of intensity and classification of loads by phases, classification of measurement sites, test scheme, and calculation of expected deformations. In the same way, documentation of the quality of the materials should be checked, as well as a complete overview of the bridge.

The nature and geometry of the bridge, and in particular, the characteristics of the superstructure and the nature of the supports, influence on the choice and positioning of the measuring equipment.

Through comparison of frequency values from experimental measurements with dynamic loads and those calculated from free oscillations of the structure, it is shown that the dynamic behavior of the bridge is satisfactory and the numerical model used in the analysis of the existing structure is real.

In general, load testing of road bridges will prove that the finished construction of the structure is technically correct, the behavior of the structure under test load is in accordance with the static calculation of the project and that there are no functional deficiencies during service.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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