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EXPERIMENTAL VERIFICATION OF REAL BEHAVIOR OF BRIDGE STRUCTURES USING PROOF-LOAD TESTS

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Abstract: The aim of the paper is to point out the inevitability of the proof-load tests for the real and correct behavior of bridge structures in ultimate limit state and maximum allowable deformations in serviceability limit states. It is needed to point to the most consequences of resistance, reliability, durability and lifetime of the bridge structures. Using the proof-load tests for new bridges is prescribed by the Slovak standard STN 73 6209.

Keywords: Bridge, Proof-load test, Real behavior, Truck, Deflection, Verification

1. Introduction

Bridges are inseparable and significant elements of the communication systems and thus of the entire traffic infrastructure. In the past, they have been and still are considered to be the most important and significant construction works in the hierarchy of engineering structures [1]. By building up and putting the bridge into operation, the care about the bridge object does not end. Bridge administrator should perform the maintenance of the structure and, in addition, the supervision program. This means that he should perform regular inspections, detect possible defects and analyze their influence on reliability.

In general, the deficiencies of the bridge structure, from its creation (start of design and construction) to the end of the lifetime, are divided into two basic groups [2]:

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- defects of the bridge object or its part before putting into operation - production defects;
- defects of the bridge object or its part after putting into operation - failures.

The production defects characterize the difference between the properties required for the new structure and the actual structure properties just after the completion. The defect does not always mean reducing the resistance, durability or usability of the structure or its element. Essentially, they are hidden design defects that are caused by inappropriate design or realization, so that they arise in the design and during construction of the bridge [3]-[4]. They should be revealed using reception of main inspections and control proof-load tests. If they are found, they are the so-called 'visible' defects, which should be removed before starting of operation. If they do not influence the load-carrying capacity and the reliability [5], they can be removed gradually even during operation. However, there can be the so-called 'hidden' defects that were not found out for any reason. These are very dangerous because they can be the source of later faults.

Defects may occur:

- during the design phase, because of
  - incorrect conception [6];
  - incorrect construction solution;
  - incorrectly designed details; and
  - bad designer information about the real properties of the materials [7];
- during the construction, because of
  - concrete quality (concrete composition - recipe, transport - transport concrete, fresh concrete working-up, concreting and compaction, treatment);
  - reinforcement (lower quality, depositing reinforcement, concrete cover layer);
  - geometric dimensions (element dimensions, flatness, inclination, dimensioning or prefabrication position);
  - surface protection of concrete (painting, coats, coatings, insulation);
- during the operation due to
  - aging of materials and structures [8]-[9];
  - extraordinary loads [10]-[13];
  - aggressiveness of the environment[14]-[15];
  - inadequate or inappropriate maintenance.

As it has been mentioned above, proof-load tests have to be carried out to detect defects prior to putting the bridge into operation [16]-[19]. Basically, it is an experimental verification of the real behavior of a bridge structure in order to detect the visible and hidden defects that could limit or disable the operation of the bridge. The proof-load tests must be carried out according to Slovak standard STN 73 6209 [20].

2. Proof-load test of bridges

Standard STN 73 6209 [20] determines the design, safety and processing of the load test in Slovakia, which is necessary for putting the bridge structure into operation. During the loading, a set of measurements is performed. Depending on the character of the test load, the proof-load tests are divided into static and dynamic. The static load tests are divided into basic, stricter and extraordinary. The static test load has negligible dynamic effects on the structure. It must accurately represent the real load of the bridge and move easily to allow a rapid change of load to complete unloading. Measuring devices are installed on the bridge, and sensors and long-term-monitoring devices are also used (if installed). Usually, the following measurements are normally performed:

– deformations/deflections of the superstructure;
– settlement and tilting of the abutments and piers;
– shifts and slew of the superstructure and substructure;
– width of the cracks.

Efficiency of the test load η is determined from the values of the vertical deformations in the mid-span, as well as from the bending moment values at those same points according to STN 73 6209 [20]. The numerical values of those test load efficiencies, for the most stressed sections in the mid-span of each field, should fulfil the following conditions:

$$\eta = \frac{f_{test}}{f_{cal}}\,, \tag{1}$$

$$\eta_M = \frac{M_{test}}{M_{cal}}\,, \tag{2}$$

$$0.5 < \eta \leq 1.0\,, \tag{3}$$

$$0.8 < \eta_M < 1.0\,, \tag{4}$$

where f_{test} is the vertical deformation in the mid-span measured during proof-load test; f_{cal} is the vertical deformation in the mid-span calculated from the theoretical model; M_{test} is the bending moment in the mid-span measured during proof-load test; M_{cal} is the bending moment in the mid-span calculated from the theoretical model.

In construction design theory, the design is reliable if its design resistance (R) and design load effect (E) fulfil the inequality

$$R > E\,. \tag{5}$$

3. Verifying real behavior of bridge structures using proof-load tests

In this paper two new bridge objects are presented, where the proof-load tests were performed, therefore, their real behavior was verified before putting them into operation.

3.1. Object No. 1 - bridge over Old Creek on road I/59 near Dolný Kubín

The first bridge structure by-passes the natural valleys with a creek named Old Creek and afforested with mixed vegetation. The bridge conducts the road I/59 in km 1.821 with a three-lane pavement arrangement of category C 11.5/70 with width of 14.75 m between barrier railings on the left-hand side of the bridge with the slow-speed lane. The communication on bridge is along a curve with radius 190 m with a consequential transition curve. The vertical declination is 6%. The pavement has a one-sided transverse declination also of 6%. The superstructure, consisting of three beams of 2.4 m in height and 217.5 m in length, was made of the pre-stressed concrete and has 6 spans. The theoretical spans of continuous girders are 28.0 m + 4 x 40.0 m + 28.0 m in the communication axis (see *Fig. 1*). The beams of constant height of 2.4 m have a width at the bottom edge of 1.0 m and 1.2 m at the upper edge. The total width of the bridge deck is 17.25 m. The base thickness of the slab (bridge deck) is 250 mm and it is increased to 400 mm when connected to the beams - using haunches. At the end of the cantilever, the slab was of a size 200 mm. The bridge was made of concrete C35/45 - XC4, XD3, XF4, XA3 (SK) - Cl 0.1 - S3 and cast in-situ on a truss formwork. The cables from 19 strands ϕ Ls 15.7/1860 MN/m^2 in tubes ϕ 95 mm pre-stressed at 1440 MN/m^2 in sequential stages were used for pre-stressing. The superstructure was supported on elastomeric bearings.

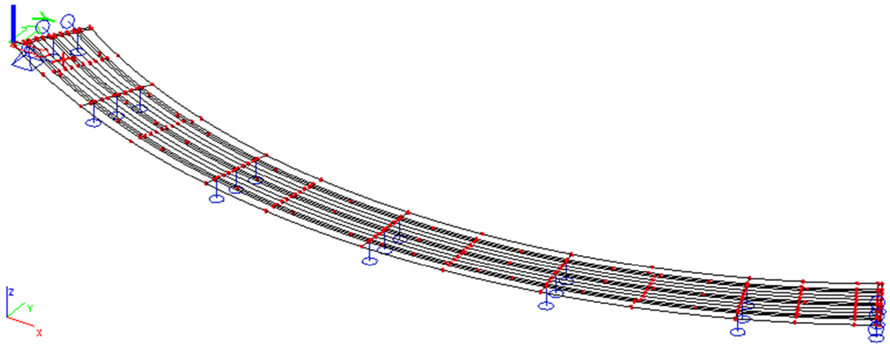

Fig. 1. Slab-girder model of bridge structure No. 1

First numerical model

A slab-girder model developed in SCIA Engineer was used for a model of the bridge structure. The slab of bridge deck was modeled as slab elements. The three longitudinal main beams and cross beams were modeled as 2.4 m high ribs of slab with inclined haunches in the transverse direction, the effective width of the beams/ribs was specified as unsymmetrical. Due to verification, it was not needed to model the pre-stressed cables due to low influence on a vertical deflection.

Second numerical model - simplified model for comparison

For verification and comparison of numerical results and results from measurements, there was developed second model. For simplifying, the simple girder bridge model was used as second model. The model was loaded by stand-alone forces on eccentricity. Position and effectiveness of variable load (LM1) was verified on slabs-girder model. The proof-load test TATRA 815 was modeled in the same position as in real structure. The vertical displacement in middle span were observed, which was compared with a vertical deflection from slabs-girder model and the proof-load test. Subsequently, individual deformations were compared.

Variable load according to standard

The load model LM1 according to code STN EN 1991-2 [21] was applied for each field in that bridge structure. A maximum Uniformly Distributed Load (UDL) of $\alpha_{q1} \cdot q_{1k} = 8.10$ kN/m^2 and a Tandem System (TS) was located in the edge lane in the case of the second span, in the case of first and third span, the maximum UDL and TS (axle forces) were located in the pavement axis. The TS was arranged for the maximum bending moment and maximum deflections in the center of each span. Three loading states were performed in the first three spans.

Test load for proof-load test

TATRA 815 trucks were used for test load. The front axle transmits a force of 64.4 kN and a back axles transmit forces 2 x 107.8 kN. The load was modeled as a uniformly distributed load over the area 0.4 x 0.4 m under each wheel according to STN EN 1991-2 [21].

Organization and processing of the proof-load test

The static test was performed in that manner to achieve the greatest effect in the middle of each span of the continuous superstructure. The vertical deflections of the beams in the middle of each span, as well as decreases of the lower edges of the beams at the positions of bearing over the supports, were measured. A settlement of all supports (abutments and piers) was measured geodetically. The vehicles were arranged at the specified places. Once the measured deflections have stabilized, the final deformations have been recorded, after that the test load has left the bridge structure and deformations have been red again. The procedure was used also for testing of other two bridge spans.

Results of measurement

During the test, the bridge structure, bearings and bridge supports were monitored. No anomalies were found in the behavior of the bridge structure under test load. During the test, cracks or opening of the working or dilatation joints were not found. The results of proof-load test of bridge No. 1 are shown in *Table I.*

Table I

Comparison of theoretical and measured values - bridge No. 1

Span	Beam	Deflection due to the test load (slab-girder model) $f_{calc,1}$ [mm]	Deflection due to the test load (simple girder model) $f_{calc,2}$ [mm]	Measured values of deflection [mm] f_{test}	Efficiency of the test load $\eta=f_{test}/f_{calc,1}$ [-]	Efficiency of the test load $\eta=f_{test}/f_{calc,2}$ [-]
Span 1	1 - outer	2.83	3.90	2.400	0.784	0.615
	2 - middle	4.22	3.00	3.680	0.888	1.226
	3- internal	2.41	2.20	2.320	0.886	1.054
Span 2	1 - outer	12.90	18.30	11.745	0.950	0.641
	2 - middle	8.19	7.90	8.090	0.994	1.024
	3- internal	2.53	2.60	2.035	0.639	0.782
Span 3	1 - outer	7.12	9.40	6.080	0.808	0.646
	2 - middle	9.70	7.30	8.995	0.927	1.232
	3- internal	5.73	5.30	5.000	0.897	0.943

3.2. Object No. 2 - bridge over highway D1 on road III/018165

The second bridge structure by-passes the road III/018165 over the highway D1 in km 7.290. In addition, in this case the communication on the bridge is along a curve with radius 175 m with a consequential transition curve.

The vertical declination is changed from 5% to 1.21%. The pavement has again one-sided transverse declination of 6% with decreasing to the left-hand side. Its width of 8.20 m is bounded on the left by a path with width 0.75 m. On the right-hand side of the pavement, there is a cornice (fascia girders) with a vehicle parapet. The superstructure of the bridge is four spans continuous slab structure with theoretical spans 21.0 + 2x27.0 + 21.0 m made from concrete C 30/37-XC4, XD1, XF2 (SK) -Cl 0.1.

The middle trapezoidal cross section has a structural height of 1.40 m and a width at the bottom edge of 2.50 m, which gradually increases to a height of 4.20 m with inclined haunches up to 0.8 m. In addition, the consoles that are fixed into this basic cross-section pass into a total width of 9.58 m on the upper surface of slab. The superstructure was pre-stressed with 12 cables composed of 18 stabilized strands Ø *Ls* 15.7/1860 MN/m^2.

First numerical model

For modeling the bridge structure, the slab-girder model was again used in SCIA Engineer. The main supporting element of the model is the slab with variable thickness using haunches. At the center of the structure, the thickness of the slab is 1400 mm of width of 2.5 m, and another slab with a thickness of 1000 mm and of width of 0.850 m is joined to it. It is finished with a 425 mm thick slab. There is a 975 mm monolithic cross-section of the transverse girder above the support.

Second numerical model - simplified model for comparison

As in the previous object, there was developed simple girder model. Cross-section is a similar to real cross-section. Model is loaded with forces arranged according to loading scheme. The pre-stressed cables were not again modeled due to low influence on vertical deflections. The results from both models and real measurements were again compared (*Fig. 2*).

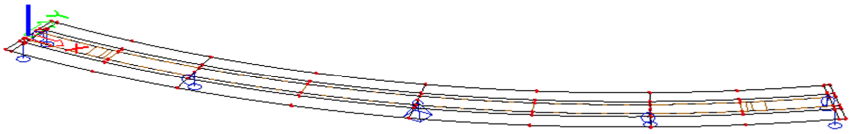

Fig. 2. Slab-girder model of bridge structure No. 2

Variable load according to standard

Since the bridge was designed according to the old Slovak standards valid before 2010 (STN 73 6206 [22]), the variable load was considered according to STN 73 6203 [23]:

- *ZZI load*: the forces of tandem system were modeled as a uniformly distributed load of 1000 kN/m^2 on area of the wheel in two load lanes and the remaining part was modeled as a continuous uniformly distributed load of 2.50 kN/m^2. The set of loads were placed on the structure to determine the maximum values of the shear forces and bending moments, as well as the deflections in the spans and over the supports;
- *ZZII load*: the UDL of 9.00 kN/m^2 on the lane of width of 3.0 m and next UDL of 3.50 kN/m^{2}at the remaining lanes;
- *4-axle vehicle*: the axles of the vehicle were modeled as a uniformly distributed load of 833.33 kN/m^2 on area of wheels. The axles are located in the edge lane;
- *Specific load*: the axle forces were modeled as a uniformly distributed load of 437.50 kN/m^2 over areas of the wheels.

Test load for proof-load test

In the model, the trucks TATRA 815 were modeled as forces of 2x55.0 kN for the front axle and 2x30.0 kN for the back axles. The positions of trucks were placed in the most effective position to detect the maximum bending moments, shear forces and deformations.

The static test was carried out in the same way as previous bridge. The resistance sensors TR 50 were used for measurement of the beam deflections in the center of the spans and the pushing of the bearings.

Results of measurement

During the test, again the bridge structure, bearings and bridge supports were monitored. Moreover, again no anomalies were found in the behavior of the bridge structure under test load. No cracks in the superstructure were identified during the test. The achieved results of proof-load test of bridge No. 2 are shown in *Table II*.

Table II

Comparison of theoretical and measured values - bridge No. 2

Span	The edge of slab	Test load	Deflection due to the test load (slab-girder model) $f_{calc,1}$ [mm]	Deflection due to the test load (simple girder model) $f_{calc,2}$ [mm]	Measured values of deflection f_{test} [mm]	Efficiency of the test load $\eta = f_{test}/f_{calc,1}$ [-]	Efficiency of the test load $\eta = f_{test}/f_{calc,2}$ [-]
Span 1	outer	6 x TATRA 815	6.46	4.40	5.765	0.905	1.310
	internal		5.24	3.30	5.385	0.796	1.631
Span 2	outer	6 x TATRA 815	10.51	6.70	9.880	0.808	1.474
	internal		9.34	6.20	8.850	0.817	1.427
Span 3	outer	6 x TATRA 815	8.85	5.10	7.930	0.681	1.554
	internal		10.53	7.00	9.985	0.920	1.426
Span 4	outer	6 x TATRA 815	5.38	3.20	4.490	0.754	1.403
	internal		5.77	3.70	5.790	0.877	1.564

4. Conclusions

Obtained results show that the computer models results are not much different from the real state. When the proof-load tests were correctly performed, the values were identical to the values from model (program). Thus, the bridge structures are reliable and are designed and usable for the operation throughout its planned lifetime. This means that the bridge objects were reliable and can be put into operation.

This paper compares two different methods of modeling. In the first model, which is modeled as slab-girder model, results are more precisely and approaching real results from the proof-load test. In the second models are not results so satisfactory. From time viewpoint, the simply-girder model is preferable, but from safety, it is better to use a slab-girder model. For practice, it is important that simply girder models are more conservative than slab-girder models, what is on the safe side but is lower effectiveness.

The bridge structures have been designed and built to perform the function of safely transmitting all components of permanent and variable loads over the lifetime. For comparison and verification of response and maximum load, the proof-load tests serve to detect all errors before putting bridge into operation. The task of proof-load tests is to verify the real behavior of bridges for safe putting into operation. From that follows the requirement that the bridge objects have to fulfill certain parameters that, in their complexity, reflect their serviceability and service lifetime.

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