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DEFORMATION ANALYSIS OF BRIDGES IN EXCEPTIONAL TRANSPORTS IN SLOVENIA

ABSTRACT

In August 1999 an exceptional transportation of two steamers of 666 tonnes was performed from the Port of Koper to the Nuclear power plant in Krško. The transport covered a distance of about 200km and represented one of the largest exceptional transports in Slovenia ever.

Finding the best route represented one of the major issues, because the steamers had to cross more than 50 problematic sections and bridges, most of which have not been designed for such heavy loads. It was necessary to load-test almost all bridges on the route to determine whether those bridges need any extra supports or not.

Consequently, a logistic operator has an important and indispensable role and becomes a co-modeller of logistic service. A deformation analysis or a polynomial interpolation of vertical displacements could also be used. Therefore, a laboratory load test of a concrete plate was made. The concrete plate was loaded with hydraulic cylinder PZ 100 with extensiometer up to 21kN. Every increase of load by 3kN was measured with Nikon Ser 800 total station.

KEY WORDS

deformation analysis, exceptional transport, bridges in Slovenia

1. INTRODUCTION

A good logistics and deformation analysis of bridges can optimize the route and reduce the costs and time of transportation of exceptional transports. All the tasks performed by a logistic operator are important; the influence of speed, accuracy, safety and time accessibility, when the goods are in transit. The operator must also know all the advantages and legalities regarding traffic requirements and multi-modal transport [1]. Monitoring of bridges and other structures plays an important role in estimating the bridge availability, reliability, load capacity, for ascertainment of bridge damages and also for bridge modelling. The monitoring was also needed in case of steamer transportation. Control measurements can be performed in a variety of ways depending on the structure. In practice, control measurements are performed with the help of geodetic measurements, the basic goal of which is to capture any geometric changes in the measured object. Displacements and deformations are determined. This means defining the position of changes and the object's shape with respect to the environment and time. The size of the vertical displacement can be predicted or interpolated in advance. [2]

The problem and the subject of this research refer to two realistic stochastic researches with the following objectives: exceptional transports and deformation analysis of bridges in Slovenia.

The subject and object of this research is to present, scientifically, a paradigm for formulating a *scientific hypothesis*: explicit, implicit, disciplinary and multidisciplinary knowledge about exceptional transports and deformation analysis of bridges can help in finding the best route from point A to point B, creating thus a paradigm for fast, safe and rational transportation of exceptional transports over the bridges in Slovenia.

2. THEORETICAL FEATURES OF EXCEPTIONAL TRANSPORTS AND DEFORMATION ANALYSES

2.1 Exceptional Transport of Steamer

The Road Traffic Safety Act (Zakon o varnosti v cestnem prometu) [3] is the legislation about exceptional transports in Slovenia. An exceptional transport is a transport by a vehicle which alone or with its cargo exceeds the regulated size or a traffic sign-restricted axial load, the regulated or with a traffic sign restricted weight or for a specific type of vehicle the

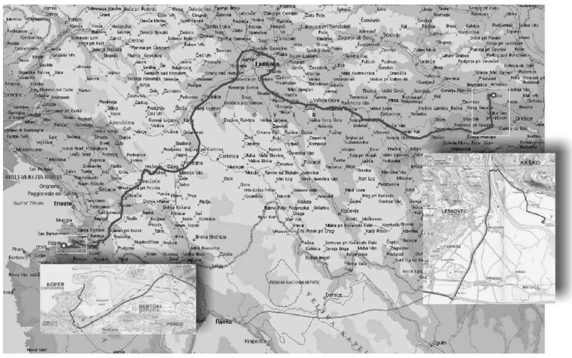

Figure 1 - The route of two steamers from Koper to Krško

regulated or with a traffic sign restricted dimension. Exceptional transportation can be performed only if the competent authority (Slovenian Roads Agency) issues a permit.

The steamers were transported by ship to the Port of Koper, and then by road from Koper via Ljubljana to Krško (*Figure 1*). It was necessary first to identify and verify the selected route. The route was analytically tested. It had to be checked whether the problematic objects on the route were capable of carrying such big load and if not, what should be done to make it possible. It was found that 50 objects on the route required certain operations to be carried out, like the change in inclination of the road, strengthening of bridges and viaducts, lowering the road under certain bridges, etc. and 70% of these operations were permanent changes.

One steamer had a weight of 343 tonnes and the length of 20m. The selected transport composition was 77m long, 5.8m wide and 4.6m high. The total weight of a steamer and the composition with all the related equipment amounted to 666 tonnes (*Figure 2*).

Figure 2 - Transportation of steamer from Koper to Krško

Considering that load testing is no longer compulsory, it is good to find other ways of obtaining information on the response of objects to load. This information can help in deciding whether the object is safe or not in case of exceptional transport. This knowledge makes it easier to decide where an exceptional transportation will pass. It would be, therefore, very irresponsible to direct an exceptional transport over a bridge for which no data about the behaviour of structure under maximum load are available, even though it had been built by the Eurocode standards.

2.2 Deformation Analysis of Bridge Structures in Slovenia

Until 2009 load testing of road bridges with spans longer than 15m was obligatory. A road bridges in Slovenia, which has a spans longer than 15 m, the load testing was a commitment of builders by the year 2009. This was regulated by Yugoslav standard from 1984 (standard JUS U.M1.046).[4]

After this date, load tests are no longer mandatory. It must be built using the Eurocode standards adopted by the Slovenian Institute for Standardization. For load testing of bridges the most important is SIST EN 1991-2:2004 - Eurocode 1: Basics of design and effects on the structure - 2 Part One: Traffic loading bridge [5] and the Eurocode, which refers to the materials from which the respective bridge has been built.

When under load, notwithstanding the law, it is good to obtain the following information on the bridge:

- values of vertical displacements at the centre of each span,
- displacements of the supports,
- displacements at the points where the cracks occur,
- deformations at the locations where the expected extreme would occur, except in the case when the program of observation does not provide this,
- permanent displacements and deformations after load removal,
- values of vertical displacements in the middle of the span at dynamic load,
- speed of movement of the load through bridge,
- other complementary measurements, after the program of observation foresight.

Increasing attention is now focused on the predictable maintenance of the existing structures (bridges, bulkheads, hydro power plants, support walls, pilots, etc.), so that more and more researches return again back to the laboratory.

3. MATHEMATICAL MODEL OF BRIDGE STRUCTURE LOAD TESTING

3.1 Concrete Plate Testing

In order to get information of vertical displacements under different loads the prefabricated pre-stressed concrete plate beam was tested (*Figure 3*). Such concrete beam is frequently used for industrial buildings. Predicted vertical displacements are analytical calculated using the static design with the vertical force at the middle of the span using the Eurocode 2. Schematic view of concrete beam with geodetic marks is shown in *Figure 4*.

Figure 3 - Prefabricated pre-stressed concrete plate with measured marks

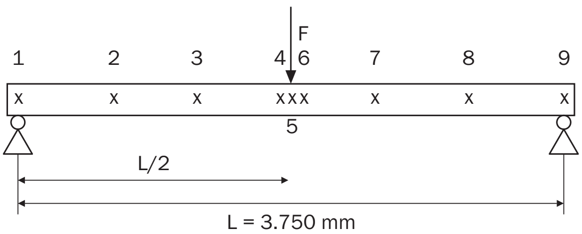

Figure 4 - Static design of the test sample

The deflection of the plate depends on the geometrical and material characteristics of the test sample:

Calculated static length:
$L = 3{,}750mm$

Width: $b = 500mm$

Height: $h = 150mm$

Effective depth of a cross-section:
$d = 120mm$

Cross sectional area of tensile reinforcement:
$A_{s1}^{+} = 7.70cm^2$ (5Φ14)
$A_{s2}^{+} = 0.724cm^2$ (3x3Φ3.2)

Cross sectional area of compressive reinforcement:
$A_{s}^{-} = 3.93cm^2$ (5Φ10)

Concrete:

Strength class: C 30/37

Mean tensile strength:
$f_{ctm} = 2.9MPa$

Secant modulus of elasticity:
$E_{cm}=32 \bullet 10^6 kN/m^2$

Reinforcement:

Strength class:
S 400 (A_{s1}^{+}, A_{s}^{-}) , S 1.80 (A_{s2}^{+})

Characteristic yield strength:
$f_{yk} = 400MPa$

Design value of modulus of elasticity:
$E_s=200 \bullet 10^6 kN/m^2$

3.2 Description of Experiment

The well known analytical methods can be used for the calculation of non-cracked cross-section displacements. Further problems are encountered at cracked cross-sections where cracks occur in the tensile area due to the low tensile strength of the concrete. This results in the reduction of the second moment of area of concrete section, and consequently, in the increase of deflection. As it is difficult to determine exactly the location and size of the cracks they are usually stated approximately, using different national codes. Recently, Eurocode 2 (CEN, Eurocode 2) has been the most frequently applied in Europe and therefore considered in this analysis.

According to the presented characteristics the second moment of area of the un-cracked cross-section is $I_y^{(I)} = 15{,}345.478\ cm^4$.

The bending moment forming the first crack in the tensile concrete section ($M_y^{(I)}$) is calculated in the form of:

$$M_y^{(I)} = f_{ctm} \cdot \frac{2 \cdot I_y^{(I)}}{h} = 0.29 \cdot \frac{2 \cdot 15{,}345.478}{15} = \quad (1)$$
$$= 593.36\ kNcm = 5.9336\ kNm$$

For the un-cracked cross-section ($M_{y0} \leq M_y^{(I)}$) the maximal vertical displacement (w_{inst}) is the sum of the bending moment (M_{y0}), the shear force due to the actual load on the structure (V_{z0}), the shear force due to the virtual load on the structure ($\overline{V_{z1}}(x)$) and the axial force (N_0) contribution in the form of:

$$w_{init} = w_{init,M} + w_{init,V} + w_{init,N} =$$
$$= \int_S \frac{M_{y0}(x) \cdot \overline{M}_{yI}(x)}{E_{cm} \cdot I_y^{(I)}} dx + \int_S \frac{V_{z0}(x) \cdot \overline{V}_{zI}(x)}{G_{cm} \cdot A_{cs}} dx + \quad (2)$$
$$+ \int_S \frac{N_0(x) \cdot \overline{N}_I(x)}{E_{cm} \cdot A_c} dx$$

where:

$\overline{N_1}(x)$ = axial force due to virtual point load,

$N_0(x)$ = axial force due to actual load on the structure,

A_c = cross sectional area of concrete,

$M_{y0}(x)$ = bending moment due to actual load on the structure,

$\overline{M_{y1}}(x)$ = bending moment due to virtual point load.

For the given static design (*Figure 4*) Eq. (2) results in:

$$w_{init} = \frac{F \cdot L^3}{48 \cdot E_{cm} \cdot I_{yI}} + \frac{1.2 \cdot F \cdot L}{4 \cdot G_{cm} \cdot A_{cs}} \tag{3}$$

where:

$G_{cm} = \frac{E_{cm}}{2 \cdot (1 + \nu_c)}$, $A_{cs} = \frac{A_c}{1.2}$, F = force acting on the middle of the span (see *Figure 4*) and ν_c Poisson's ratio.

For the cracked cross-section ($M_{y0} > M_y^{(I)}$) the maximal vertical displacement (w_{inst}) is calculated as:

$$w_{init} = w_{init,M} + w_{init,V} + w_{init,N} = \\ = \int_S \frac{M_{y0}(x) \cdot M_{y1}(x)}{E_{cm} \cdot I_{y,eff}^{(II)}} dx + \int_S \frac{V_{z0}(x) \cdot V_{z1}(x)}{G_{cm} \cdot A_{cs,eff}^{(II)}} dx + \\ + \int_S \frac{N_0(x) \cdot N_1(x)}{E_{cm} \cdot A_{c,eff}^{(II)}} dx \tag{4}$$

where the effective second moment of area of the cracked cross-section ($I_{y,eff}^{(II)}$) is determined according to Eurocode 2 [1] in the form of:

$$I_{y,eff}^{(II)} = \xi \cdot I_y^{(II)} + (1 - \xi) \cdot I_y^{(I)} \\ \xi = 1 - \beta_1 \cdot \beta_2 \cdot \left(\frac{M_{yI}}{M_{y0,\max}} \right)^2 \tag{5} \\ M_{y0,\max} = \frac{F \cdot L}{4}; \quad \beta_1 = 1.0, \beta_2 = 1.0$$

The value of $I_y^{(II)}$, representing the second moment of area of the cracked cross-section, is calculated according to the neutral axis position (x_{II}) using the scheme shown in *Figure 5*. The neutral axis position (x_{II}) is calculated taking into account the un-cracked compressive concrete cross-section, tensile and compressive reinforcement, as follows:

$$\frac{b \cdot x_{II}^2}{4} + (n-1) \cdot A_s^- \cdot (x_{II} - a_3) - \\ - n \cdot A_{s1}^+ \cdot (h - a_1 - x_{II}) - n \cdot A_{s2}^+ \cdot (h - a_2 - x_{II}) = 0 \\ x_{II} = 4.948 \text{ cm}$$

$$I_y^{(II)} = \frac{b \cdot x_{II}^3}{3} + (n-1) \cdot A_s^- \cdot (x_{II} - a_3)^2 + \tag{6} \\ + n \cdot A_{s1}^+ \cdot (h - a_1 - x_{II})^2 + n \cdot A_{s2}^+ \cdot (h - a_2 - x_{II})^2 = \\ = 4{,}757.344 \text{ cm}^4 \\ n = \frac{E_s}{E_{cm}}$$

There were 7 epochs where the load increased by 3kN at a time. Each epoch was maintained for 400s (static load) for measurement to be made and in the next 100s the hydraulic cylinder PZ 100 increased the load by 3kN. The hydraulic cylinder was controlled by LabVIEW software. The vertical deformation, for central point 5, was measured with a very precise measuring rod attached to the main cylinder.

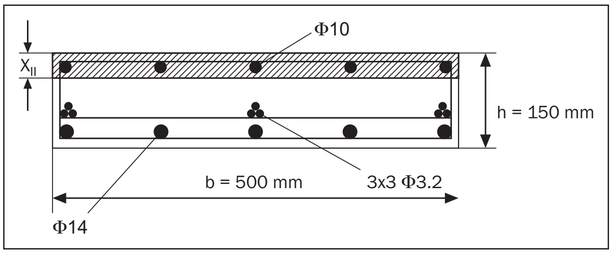

Figure 5 - Considered elements for the cracked cross section

Geodetic deformation measurements are quite frequent for such tasks [6]. For nine characteristic points of observation the trigonometric height was also used. The measurements were performed from one station point (stabilised one day in advance). The measurements were made from a tripod that was glued to the ground. Between each load phase a station point position was checked for stability (measurements of control points on the wall). There were no potential shifts of the instrument. Before the measurement, the instrument Nikon Ser. 800 was calibrated and the data about air temperature and pressure were entered (both were stable during the test). The precise measurement mode (PMRS) was used. First, the zero state was recorded and then the individual phases one after another.

There were 210 sight points on the concrete plate that were observed in the local (object) coordinate system. Leica's reflective tape targets of dimensions 1 x 1 cm were used on each target point.

A mathematical model of vertical displacement was made. A polynomial approximation was used.

The goal was to obtain the mathematical model of simulated vertical displacements. A polynomial approximation was used. The obtained results confirm the following hypothesis:

- the values of vertical displacements in intermediate loads can be approximated (which were not measured),
- the size of vertical displacement can be obtained from the polynomial approximation,
- this method also has a practical application in load testing of bridges.

3.3 Quantitative Results of the Mathematical Model

For every load case (3kN, 9kN, 15kN and 21kN) polynomials of degree 3 through the monitoring points were fitted by Mathematica 5.0 software. The polynomials of degree 3 are of the form

$$p_i(x) = a_i + b_i\, x + c_i\, x^2 + d_i\, x^3 \tag{7}$$

for i = 1, 2, ... n, where n is the number of observed control points on the concrete plate (7 points) and x is the length of the concrete plate. Figure 6 shows the magnitude of vertical displacements at different loads.

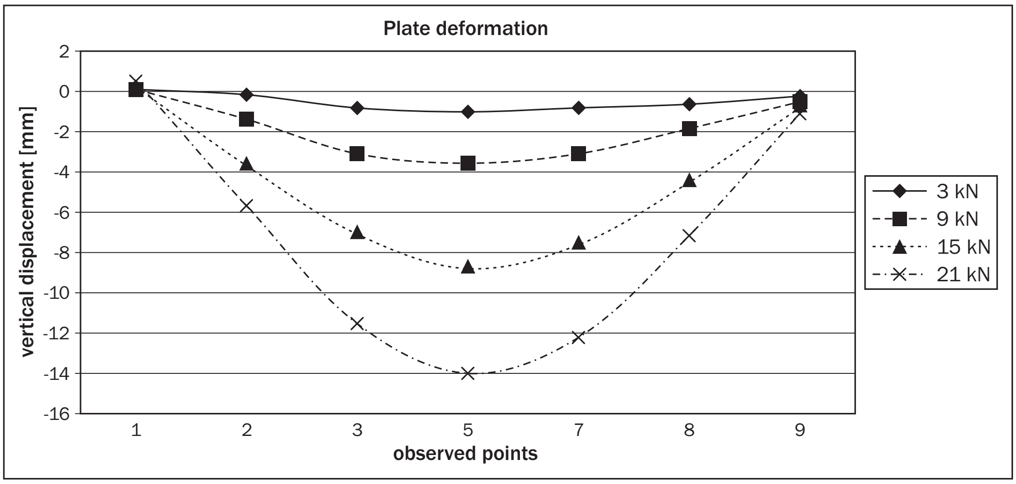

Figure 6 - Graphs of fitted polynomials for four load cases (3kN, 9kN, 15kN and 21kN)

The calculated polynomials are also given in *Table 1*. (For the sake of better presentation, the units for *x* and *y* axis are metres [m] and millimetres [mm], respectively.) Note that *p*(*x*) represents the vertical displacement of the plate at point *x* caused by load (force) $\vec{F}$.

Table 1 - Polynomials through seven points 1-9 (without 4 and 6) for different loads

Load	$p_i(x)$ in mm, *x* in m
	polynomial
3kN	$0.164286 - 1.00571\,x + 0.237714\,x^2 - 1.54405 \cdot 10^{-16}\,x^3$
9kN	$0.233333 - 3.79175\,x + 1.00876\,x^2 - 0.0113778\,x^3$
15kN	$0.43095 - 8.58159\,x + 2.0541\,x^2 + 0.0455111\,x^3$
21kN	$0.883333 - 14.1352\,x + 3.3981\,x^2 + 0.0682667\,x^3$

The results show that in the future experiments there is no need to fit the predicted deformations with a third degree polynomial. It would be sufficient to model the predicted deformations by a linear or, possibly, quadratic function.

By means of Eurocode 2 it was calculated that permanent deformations occur at a load of 42kN. Using the fitted curves the displacements at 42kN were calculated for every monitoring point. The values were then compared with the actual measurements at these loads. The calculated and measured values for point 5, where the displacements were the largest, as well as their differences, are shown in *Table 2*. The mean value of the deviations for point 5 was -14.8 and for all the measured points it was +5.7 %.

The differences between the calculated and the measured values for other points are shown in Table 3. The points 1 and 9 were omitted from the analysis since the beam was not supported perfectly rigid at these points and the measured vertical displacements were not accurate at those points (in theory they should be 0.0mm). The comparison for the load of 42kN can be seen in *Figure 7*.

Table 2 - Comparison of calculated and measured values for point 5

Load [kN]	Vertical Displacement [mm]		Deviation [%] 100-(meas/calc · 100)
	calculated	measured	
3	-0.8	-1.0	- 25.0
9	-3.1	-3.6	- 16.1
15	-7.5	-8.7	- 16
21	-12.2	-14.0	- 14.7
42	-28.4	-29.1	- 2.4
mean value =			- 14.8

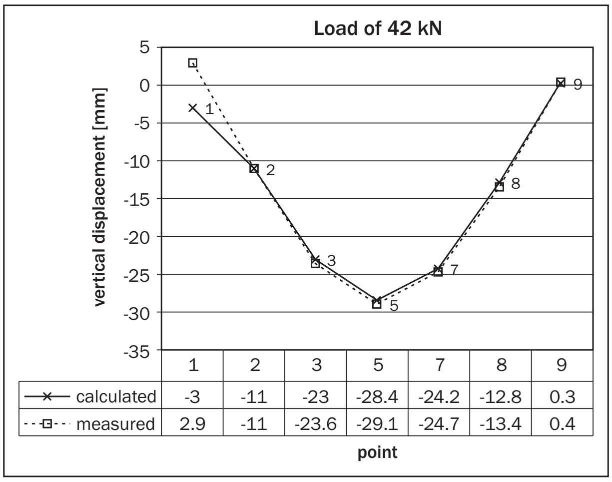

Figure 7 - Comparison of calculated and measured displacements for a concrete plate at a load of 42kN

Vertical displacements obtained from the polynomial approximation show that there is a mathematical connection with the measured values, so that it was possible to compute the vertical displacement for a bigger load. This experiment led to an idea of testing this model also on an actual bridge, because this concrete beam actually simulated one span of a bridge. The model was tested on the Dolnji Lakoš bridge.

Table 3 - Mean differences (in %) between calculated and measured displacements at selected points

Point	Deviation [%]
2	+ 1.9
3	+ 4.6
5	- 14.8
7	+ 5.0
8	+ 2.2
mean value	+ 5.7

4. PRACTICAL MODEL TESTING ON A SLOVENIAN BRIDGE

The Dolnji Lakoš bridge is 67.09m long (*Figure 8*) with three spans. The first girder is 7.26m high, the second is 6.17m high. The length of span 1 is 19.90m, the second span is 27.11m long and the third one is 20.08m.

The predicted vertical displacements were analytically calculated using the Solid Works software.

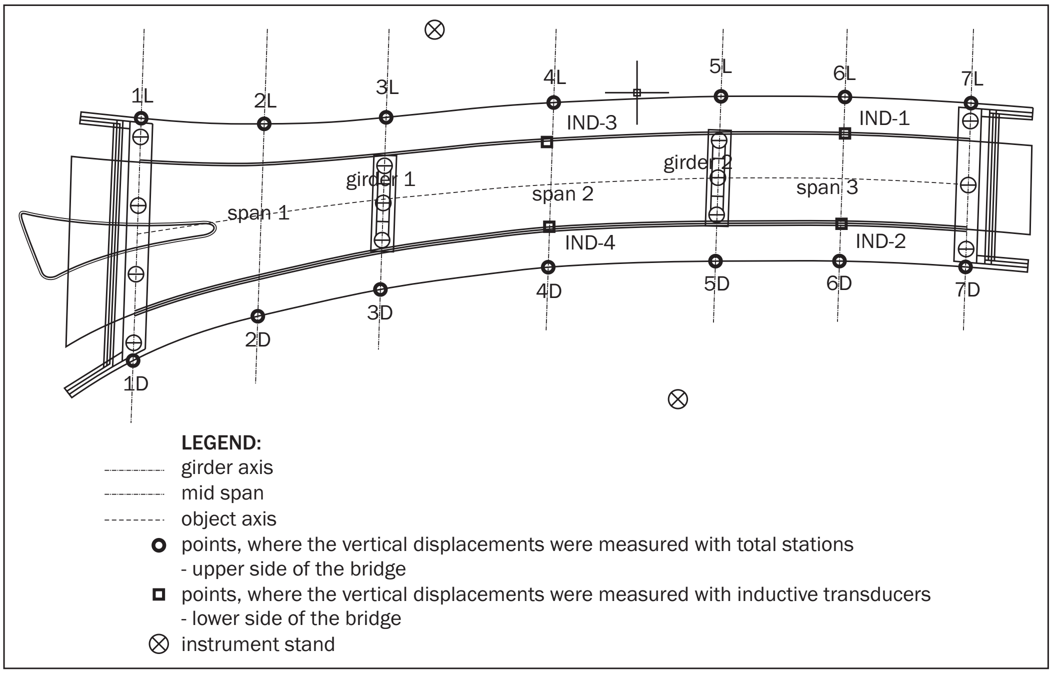

Figure 8 - The layout of Dolnji Lakoš bridge

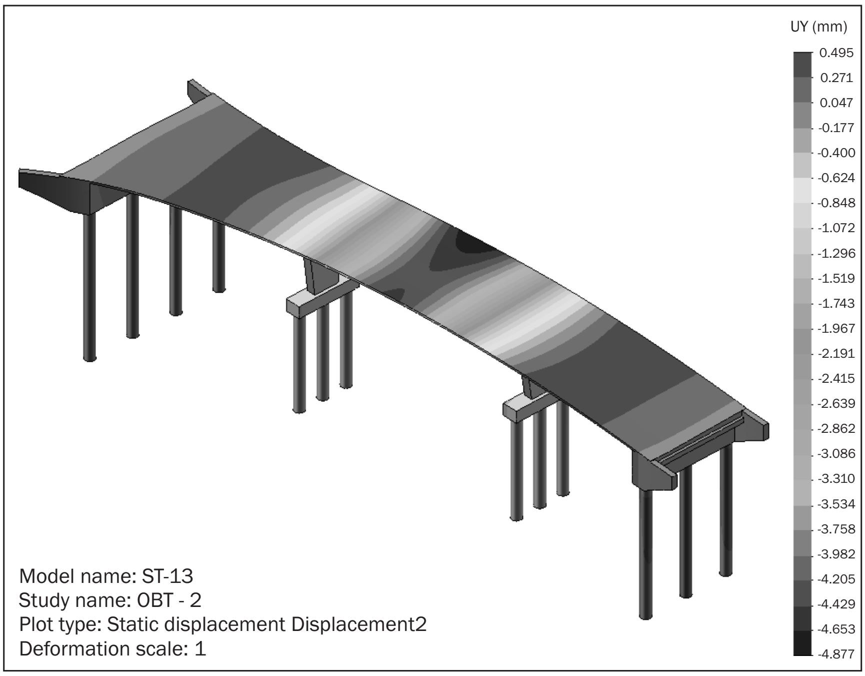

Figure 9 - Model of the bridge when the second span was loaded

Table 4 - Comparison of calculated and measured vertical displacements for right edge of the construction

Point	comparison of vertical displacement by load case [mm]											
	span 1 and 3			span 2			excenter 2 left			excenter 2 right		
	calc.	approx.	meas.	calc.	approx.	meas.	calc.	approx.	meas.	calc.	approx.	meas.
1	-0.135	-0.12	-0.1	0.030	0.02	0.0	0.041	0.04	0.0	-0.008	-0.01	0.0
2	-1.451	-1.43	-1.1	0.324	0.31	0.2	0.254	0.24	0.2	0.094	0.09	0.0
3	-0.473	-0.46	-0.3	-0.387	-0.37	-0.3	-0.027	-0.03	0.0	-0.575	-0.53	-0.4
4	0.698	0.69	0.6	-4.463	-4.45	-3.4	-1.694	-1.65	-1.1	-3.523	-3.50	-3.1
5	-0.365	-0.35	-0.3	-0.499	-0.5	-0.4	-0.156	-0.14	-0.1	-1.024	-1.00	-0.7
6	-2.022	-2.0	-1.6	0.471	0.47	0.4	0.197	0.18	0.1	-0.392	-0.35	-0.3
7	-0.268	-0.26	-0.2	0.048	0.04	0.0	0.063	0.04	0.0	-0.057	-0.05	0.0
Deviation: calc./approx.	3.5 %			8.4 %			7.8 %			1.9 %		

A complete model of the bridge and all the calculations were made. *Figure 9a* shows the model of the bridge when the second span was loaded.

For every load case the polynomials of degree 4 were also calculated using Mathematica 5.0 (NonLinearFit) software, so that the approximated vertical displacements were also obtained:

$$p_1(x) = 6.96834 \cdot 10^{-17} - 0.314148\,x + 0.0265791\,x^2 - 0.000667253\,x^3 + 5.08257 \cdot 10^{-6}\,x^4$$

Table 4 gives the comparison of the calculated (from static data) and the measured values of vertical displacements for the right-hand (lower) side of the bridge. The measured values were smaller than the predicted ones, as expected. The Table shows span 1 and 3, span 2, excenter 2 left side and excenter 2 right side of the bridge load case.

As seen, the predicted vertical displacements obtained from the polynomial approximation are comparable with static calculations (the mean deviation is 5.4%), but both static as well as approximated values of vertical displacements are bigger than the measured values, as expected.

5. CONCLUSION

Among authors who describe the methods of displacement measurements in scientific literature, one can mostly find that the measurement itself is not problematic. The problem appears in the evaluation and presentation of values of micro-displacements due to the prescribed accuracy of the applied equipment. So, before the measurement is performed, the object and near terrain should be examined and the expected displacement under certain load should be obtained from the static calculations. In this way, the instruments and the equipment can be chosen which suit the prescribed accuracy. In our Centre most of the time is devoted to alignment and analysis of results as well as displacement simulations. These results are then thoroughly interpreted on practical examples of displacement measurements on different types of constructions. The experiences can establish that the displacement and deformation measuring on bigger bridges is in many cases quite time-consuming. Technological procedures and work-sharing among participants are very complicated due to the measurements which may prove to be unnecessary, including the internal and external manipulative, transport, traffic and material costs for the arrangement and performance of load testing.

The tendency toward rationalisation of the measurement procedures on site is indicated in the sense of faster measuring with the same quality and accuracy of the measured values and within smaller team with fewer instruments needed on site.

For this purpose, the interpolation comparison with the possibility of displacement simulation was accomplished. This method can be used for load testing of bridges when the object consists of, more or less, equal spans. It takes less time when the approach to the measurement stand is inaccessible or sight points are almost invisible due to obstacles. In this case, only loading of such spans is carried out which can be observed merely under ideal or satisfactory criteria while the others can be simulated by polynomial interpolation or in the case of overweight transport across the object. The method essentially shortens the work in the field but partially lengthens the time of data post processing.

To conclude, the polynomial interpolation certainly differs regarding the type of structure, material used, span of construction and expected displacements. The purpose was to test a concrete beam in the laboratory which resulted in the simulation of one field of a bridge. The accordance of the static calculation was tested; also, the polynomial interpolation was accomplished which is completely in accordance with the mean measured values. In addition, this method will be used for steel and wooden beams where the structure responds in different ways.

The explicit, implicit, disciplinary and multi-disciplinary knowledge about exceptional transports and deformation analysis of bridges, therefore, can actually help in finding the best route for such transports. This may improve road safety, increase the speed of transport, and reduce the manipulating costs.

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POVZETEK

DEFORMACIJSKA ANALIZA CESTNIH MOSTOV PRI TRANSPORTU IZREDNIH TOVOROV V SLOVENIJI

V Sloveniji je bilo potrebno avgusta 1999 iz Koprskega pristanišča do Nuklearne elektrarne Krško prepeljati dva uparjalnika teže 666 ton na relaciji dobrih 200 km, kar še danes predstavlja enega največjih tovorov, ki je kdajkoli potoval po Sloveniji.

Izbira najboljše poti je predstavljala zelo pomemben del transporta, saj sta uparjalnika na poti prečkala preko 50 problematičnih odsekov in mostov, ki za tako velike obremenitve večinoma niso predvideni. Tako je bilo potrebno določene premostitvene objekte testno obremenjevati, da bi ugotovili ali bodo obremenitev vzdržali in ali so za to potrebne dodatne ojačitve.

Izredno vlogo pri tem mora odigrati logistični operator, saj je v vlogi moderatorja logistične storitve. Pomagali bi si lahko tudi z ustrezno deformacijsko analizo oz. interpolacijo vertikalnih pomikov s pomočjo polinomov. Za to je bil v laboratoriju izveden deformacijski obremenilni preizkus betonske plošče. Betonska plošča je bila obremenjevana s hidravličnim cilindrom PZ 100 z ekstenziometrom do sile 21 kN, ki je bil računalniško krmiljen. Izmerila se je vsaka dodatna obremenitev po 3 kN. Uporabljen je bil elektronski tahimeter znamke Nikon Ser. 800.

KLJUČNE BESEDE

deformacijska analiza, izredni tovori, cestni mostovi v Sloveniji

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