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Experimental Stress Analysis

Monitoring Responses of a Highway Concrete Bridge to the Effects of Thermal Actions and Heavy Traffic

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Abstract: Strain transducers and temperature sensors were installed on the two-girder concrete bridge. The strain transducers were used to monitor effects of heavy traffic loads and responses of the bridge. Also temperature gradients in girders and heat dilatation of girders of the bridge were monitored. The obtained temperatures were compared with the temperatures measured by the closest meteorological observatory of the Czech Hydrometeorological Institute. The control computer was connected to the Internet. The obtained data were periodically forwarded to the Klokner Institute. This paper includes monitoring results of the responses of the bridge to the effects of thermal actions and traffic loads.

Keywords: Bridge, Load, Traffic, Temperature, Stress, Response, Monitoring

1. Introduction

When doing check calculations of the existing prestressed concrete bridges in accordance with Eurocodes, problems with their dimensioning started to appear as regards the effects of thermal actions and traffic. Therefore the project of the Ministry of Transport of the Czech Republic also included a long-term experimental monitoring of these effects in three typical bridge structures – concrete bridge with a box girder cross-section on Highway D1, girder-composite steel-concrete bridge in Prague and two-girder continuous concrete bridge on Highway D8 close to Doksany. This article contains monitoring results of the responses of the two-girder concrete elevated road over the river of Ohře close to Doksany.

As regards bridge structures and the effects of thermal actions, the Eurocode [2] is based on long-term measurements of heat gradients in various types of bridges in the Great Britain [5]. The results of these measurements were used to compile a programme for calculating effective temperatures for various cross-sections of bridges [4]. This programme was verified by comparing the results of effective temperature calculations with the results of temperature measurements on a bridge in Germany [6]. The thermal action model is based on the presumption that temperatures of air and bridge structures are the same for 8 hours in the summer and 16 hours in the winter. To consider different cross-sections of bearing structures and materials of bridges the standard states maximum daily deviations from this

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temperature. Tables with deviations were compiled based on a statistical evaluation of measured temperatures or temperatures calculated using the Monte Carlo Method. Statistical estimations of the maximum and minimum air temperatures are defined using the common method for the required probability excess from the analysis of meteorological measurements.

This model is suitable for steel structures and for thin-walled concrete cross-sections. However, as regards massive concrete cross-sections (e.g. girders without a box), this model is not suitable. It is also mentioned in both key publications [5,6]. E.g. in [5], for a concrete slab which is 1 m thick, there are random deviations of temperatures of air and cross-sections of the bridge at 8 o'clock with the range of +7 °C and -4 °C. The authors of the Eurocode are aware of this, but they did not do anything about it. The cross-section of girders of the study bridge belongs to the cross-sections for which the thermal action model is not in accordance with the results of measurements. According to the Eurocode the real temperature curve in the cross-section of the bridge is structured in both vertical and horizontal directions into even and uneven linear and non-linear components. The even component causes a dilatation of the bridge, the uneven component curvature changes and this uneven component is usually small.

The Eurocode [3], as regards the effects of traffic on bridges, includes specifications of extraordinary effects and descriptions of traffic flows based on existing regulations and long-term measurements of effects of traffic on bridges - see e.g. [1]. The situation is changing quickly, technology is changing and also regulations for heavy freight traffic as well as the traffic density. In particular, this concerns main transport routes, especially highways. The effects of heavy freight traffic are based on the allowed load of axles and on the existing vehicle classification and on the set of vehicles according to the number of axles. As regards the wearing surface on the bridge, the load of axles is critical, as regards the bearing structure of the bridge, the total weight of vehicles and their arrangement on the bridge is important.

2. Description of the Study Bridge, Sensors and Measuring Devices

The left bridge (in the direction towards Prague) of the 300-meter-long elevated road on the right bank over the river of Ohře close to Doksany on Highway D8 was chosen for monitoring. This elevated road is approximately oriented to the North-West–South-East and has 9 spans (26.7 m, 7x 34.5 m, 26.7 m). The skeleton sketch of the cross-section of the two-girder bridge is shown in Fig. 1. The main bearing structure consists of two girders and a slab. The dilatation length is 150 m according to the project.

Temperature sensors, contact strain transducers and a cable-extension position transducer were gradually installed on the bridge to monitor temperatures and responses of the bridge to the effects of traffic and thermal actions [7]. The installation was done on the completed bridge being under full operation. Digital temperature sensors (16 pcs. internal and 2 pcs. external) were used on the bridge, connected to two TL500 (ABI) dataloggers by means of a bus bar. The sensors were placed in one cross-section (km 36.309). Two external sensors were placed on the surface of the girders (A1 on the surface with sunshine and B1 on the surface without sunshine). Sensors A3, A4, A5, A6, A7, B3, B5 and B6 were installed 40 mm under the surface of the girders, slab and wearing surface in various places of the cross-section. Sensors A2 and B4 were installed approx. 40 mm under the isolation of the bearing structure and they were monitoring, altogether with Sensors B2, B7, B8 and A8, temperatures inside the cross-section of the girder and slab of the bridge. The distribution of sensors is shown in Fig. 1.

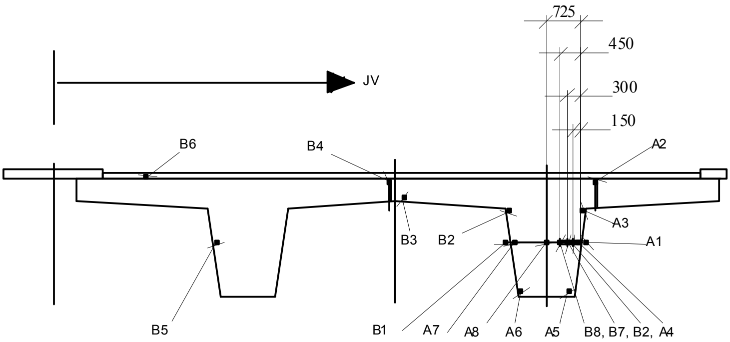

Fig. 1. Distribution of temperature sensors in the cross-section of the bridge.

Dataloggers were connected to the control computer of the measurement station on the bridge. “Hourly” shade temperatures were used as reference temperatures and were obtained from the professional meteorological observatory CHMI in Doksany, which is situated in the same kind of terrain at the distance of approx. 2 km from the bridge. Temperatures have been monitored since November 2004 in intervals of 15 minutes. The dilatation of the internal girder has been monitored since 2008 using a cable-extension position transducer type PT1 MA (Orbit Merret). The size of displacements is recorded every 30 minutes.

To monitor the responses of the bridge to the effects of traffic 5 strain transducers SLB700 (HBM) with amplifiers RM4220 (HBM) were installed. Always two strain transducers oriented along the longitudinal axis of the bridge were installed on the lower part of each girder, one in the middle of 8th span, the other one over the pillar no. 8. The last extensometer was over the pillar no. 8 on the side of the girder with a vertical orientation. The records from the strain transducers were used to monitor quasi-static and dynamic effects of traffic and also to estimate “equivalent” weights of passing vehicles. For this purpose the records were “calibrated” using a set of vehicles with a well-known total weight and configuration of axles. A 10-minute-long record of the passing vehicles was taken every 30 minutes. At the end of the study period the interval between the records was shortened to 12 minutes.

A computer connected to the Internet was installed on the bridge. It was equipped with an A/D converter and a control programme which was launching the measurements, doing preliminary assessments of records of passing vehicles and recording these records to the memory of the control computer. Both dataloggers to measure temperatures and the draw wire sensor were also connected to the control computer. The obtained data were periodically forwarded via Internet to Klokner Institute.

3. Knowledge from Temperature Monitoring

The below stated knowledge refers to short-term temperature changes. The subject matter of the analysis was the relation between changes in temperatures measured in different places of the cross-section, the effective temperature (dilatation of the bridge) and the reference temperature from measurements by the observatory of CHMI in Doksany. The long-term measurements of temperatures on the two-girder bridge [8] confirmed that the use of the model according to [2] does not show the real stress on the bridge as regards the massive girder without a box. It was found out that in the summer, in stationary conditions, the amount of temperature accumulated during the day by the study massive concrete structure is approx. in balance with the amount of temperature which is emitted by the structure at night. In non-stationary conditions (average daily temperatures go up or down) the changes in effective temperatures of massive cross-sections of the girders correspond with changes in moving averages of air shade temperature in a longer period of time. This temperature inertia of massive cross-sections can be proved also by different methods. We tried to quantify these phenomena based on long-term measurements.

In the case of a constant cross-section along the total length of the bridge and if the material of the bridge is the same, the effective temperature equals to the mean value of the cross-section temperature and corresponds with the real displacement of the end of the bridge. The displacement of the free end of the bridge was measured using a draw wire sensor which was installed on the internal girder (left one in the driving direction) at the base no. 10. The size of displacements is read twice per hour - this is a sufficient speed for this purpose. The theoretical estimation of displacements of the end of the girder for the temperature change by 1°C is 1.8 mm (according to the project the dilatation length of the bridge is L = 150 m, the coefficient of linear expansion for reinforced concrete was considered to be α = 0,000012 K^{-1}). The correlation between the change in temperature and the displacement of the end of the girder converted to the effective temperature T_{ef}(t) was observed according to

$$T_{ef}(t) = x(t) / (\alpha \cdot L) \qquad (1)$$

Fig. 4 shows the detail of temperature records during a summer week in 2010. The course of temperatures in places B5 and B7, effective temperatures T_{ef} and CHMI temperatures are shown here. You can see a big correlation between the effective temperature and the temperature in place B7. Fig. 2 shows the relation between the immediate values of the effective temperature and the temperature in place B7. Temperatures for the whole year are stated here. It is possible to say that the temperature time path in the depth of approx. 0.3 m under the surface of the girder corresponds very well with the time path of the effective temperature of the bridge. The relation between the effective temperature and air temperature is shown in Fig. 3. So called “hourly” temperatures from measurements by the observatory in Doksany and effective temperatures of the bridge are stated here. Although the dilatation of the bridge is measured only on the lower edge of the girder, it is possible to make these conclusions based on the measured values:

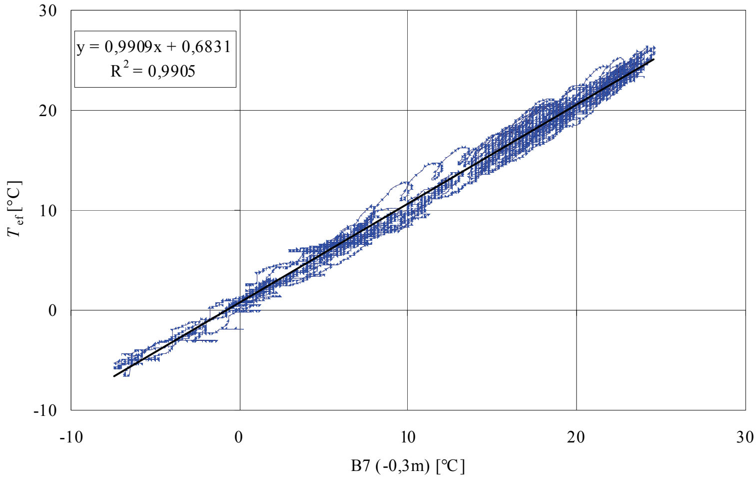

Fig. 2. Effective temperature T_{ef} as a function of temperature in place B7 (-0.3 m under the surface of the girder).

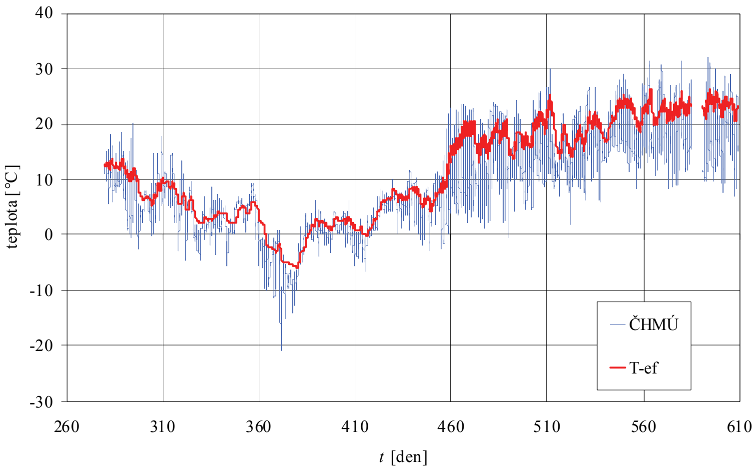

Fig. 3. Effective temperature T_{ef} and shade temperature (CHMI) as a function of time.

1) The time path of the effective temperature is approximately the same like the temperature time path in the depth of approx. 0.3 m under the surface of the girder (excluding the determined mean temperature).

2) The time path of the effective temperature is out of phase with respect to the changes in the temperature on the surface of the girder.
3) If there are small changes in the mean temperature of air, the daily air temperature fluctuations on the surface of the girder result in fluctuations of the effective temperature of approx. 23% of the amplitude of the air temperature.
4) The effective temperature of the girder can never equal to the maximum daily air temperature.
5) The effective temperature of the girder depends on changes of the mean temperature of air during the period of 3 to 6 days.
6) Daily fluctuations of temperatures are accompanied by and give rise to temperature stress in surface layers of the concrete from linear and non-linear variable components of temperature.
7) The results of this part of the process were transferred to the technical specification for concrete bridges and an amendment proposal (NA) was submitted for [2].

4. Knowledge from Measuring the Effects of Traffic

One of the objectives of the project was monitoring the real load of bridges under operation. The calibration of strain transducers was done based on passing vehicles and sets of vehicles of well-known weight. The calibration constants for strain transducers over pillars are practically not sensitive to the number and distance of axles of individual vehicles or sets of vehicles (difference 4%) The calibration constants for strain transducers in the middle of the span between the pillars differ by up to 25% according to the number of axles and their configuration in the set. Under normal operation the heavy trucks and sets of vehicles pass very often in a group of from three to seven vehicles, while the distance from vehicles (their cabins) is approx. from 20 m to 25 m. Sometimes there are vehicles even in two lanes. That means that the effect of more vehicles must be added up. Therefore the definition “equivalent weight”, and it is the weight of the vehicle whose passing would cause the same relative deformation like the passing of a group of vehicles in the place of measurement. If there is an isolated vehicle passing, the equivalent weight equals to the weight of the vehicle.

The records on the passing of vehicles over the pillar no. 8 (tensometer T5) were used to calculate the frequency diagram of vehicles according to their "equivalent weight" during the period from 6 October 2008 to 31 December 2009. The data from the other strain transducers were used to analyze situations when there are groups of heavy vehicles passing especially with extreme values of the equivalent weight. Vehicles not reaching the equivalent weight of 10 t were excluded from the process. Repeatedly, there were cases when the equivalent weight exceeded 100 t. As regards the analyzed passages, these refer to the passages of more vehicles in the least favourable arrangement on the bridge with respect to the places of measurements.

The frequency diagram of the total number of vehicles in Fig. 4 shows a significant maximum for the vehicles with the equivalent weight of 35 t. The frequency diagrams were also compiled on monthly and daily bases. Fig. 5 shows two frequency diagrams, one from the winter season, the other one from the summer season 2009. They show the change in the number and structure of vehicles with respect to the equivalent weight.

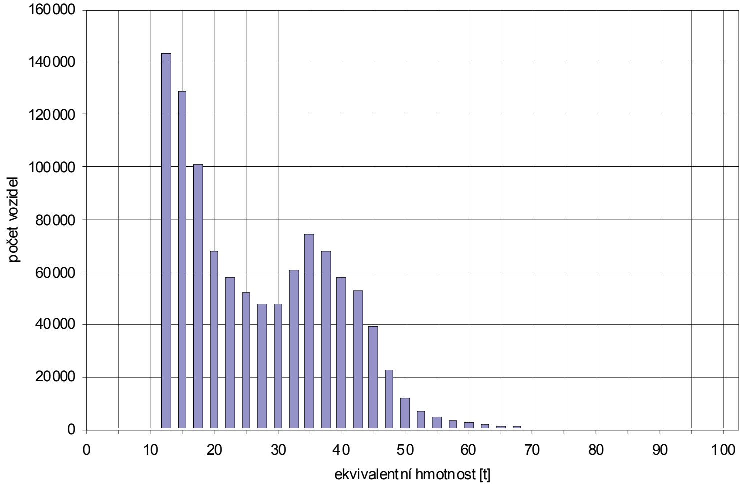

Fig. 4. The frequency diagram of the total number of vehicles during the period from 6 October 2008 to 31 December 2009 on the bridge in Doksany classified according to the equivalent weight.

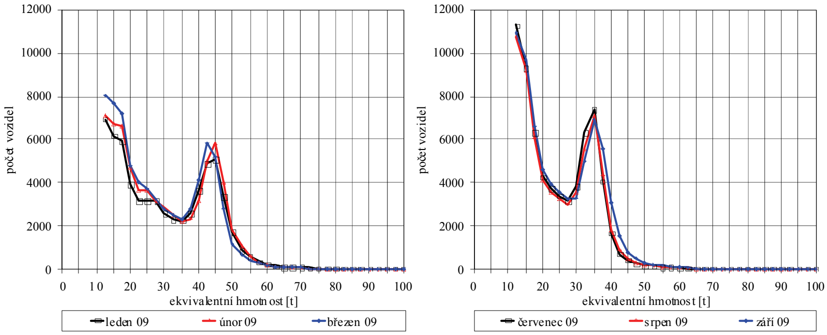

Fig. 5. Frequency diagrams of the number of vehicles on the bridge in Doksany classified according to the equivalent weight and monthly in the 1st and 3rd quarter of 2009.

5. Conclusion

The assessment of sets of measured temperatures focused on finding functional dependences between the effective temperature and the temperatures in different places of the cross-section of the bridge and the air temperature from measurements by the observatory of CHMI 2 km away. It was proved that the course of the effective temperature corresponds best with the temperature in place B7 which is in the depth of 0.3 m under the surface of the girder. There is a dependence between moving averages of the effective temperature and the air temperature. The daily periodical fluctuations in the air temperature in the summer result in fluctuations of the effective temperature with the amplitude of approx. 23% of the fluctuation amplitude of the air temperature. The regulation in case of massive girders without a box uselessly increases the size of the even component of temperature. On the contrary, it does not take into account the real size especially of the uneven non-linear component of temperature.

The assessment included frequency diagrams of passing vehicles divided according to the equivalent weight for the whole period, for the whole period month by month (1 month = four weeks following one another), average numbers of vehicles for individual days in the week and their classification according to their equivalent weight. The results are stated using frequency diagrams. A periodic change in the frequency diagram of monthly passages was identified, which is probably in relation with seasonal changes in the assortment of transported goods.

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