HEAT TRANSFER MODEL VERIFICATION FOR THERMAL MONITORING SYSTEM OF INTEGRAL BRIDGES

Martin Jonáš*, Jan Zatloukal

Czech Technical University in Prague, Faculty of Civil Engineering, Experimental Centre, Thákurova 7, 166 29 Prague 6, Czech Republic

* corresponding author: `martin.jonas@fsv.cvut.cz`

Abstract. Thermal actions considered on abutments of integral bridges by the European standard (Eurocode 1) might be in variety of certain situations underestimated. Based on this assumption, thermal monitoring system has been designed and installed into structure of bridge No. 27-117. Temperature profiles in five certain spots are being measured to provide sufficient basis for evaluation of real thermal actions on abutments of integral bridges. For purpose of measurement verification, elementary heat transfer models for finite element method solver were created. These models are being loaded by simplified temperature profiles reached in real time in-situ. Evaluated models provide verification data to compare with measured temperature profiles in structure and might provide information about temperature profiles probably reached during extreme weather situations.

Keywords: Thermal actions, integral bridge, thermal monitoring, heat transfer.

1. Introduction

While integral bridges do not allow free temperature dilatation of bridge deck, shifts are transferred into abutments and subsequently into surrounding soil. Therefore, proper investigation of interaction between soil and structure is necessary. Soil-structure interaction problem of integral bridges is widely described in literature. More than sufficient background is available for thermal actions on bridge decks and effects bound with them. In case of temperature loading of abutments is the situation weaker. Overall influence of lack of more accurate approach to temperature loading of abutments might not be very significant. However, in some cases it might be suitable to consider distribution of temperature in the structure more precisely.

Thermal actions considered on integral bridges being designed in the Czech Republic are given by European standard EN 1991-1-5 [1], its national annex ČSN EN 1991-1-5[2] and in case of road bridges also by Technical conditions TP 261[3] issued by Ministry of Transport. These documents provide wide and specific approach to consideration of thermal actions on bridge structures. However, in case of bridge piers and abutments, none of these documents can provide specific background sufficient enough for proper analysis of specific temperature states of these parts of structures. On the other side, it is not expected, that neglecting of more precise thermal action analysis of structure parts might lead to more or less serious damage of structure. Rather, it could lead to the long-term negligible degradation of materials used in structure, which could result in reduced service life of structure.

To cover these potential excess of standard background, stationary measurement system was designed and installed into bridge No. 27-117. System is created to monitor temperatures in multiple profiles deployed across the whole structure.

Last, but not least, heat transfer models of measured spots were created for purpose of measurement verification. Their accessory use is for preliminary modelling of potential temperature states reached in structure during the whole year, while the full operation of system is not launched.

2. Thermal actions on abutments of integral bridges

Background given by standards and conditions [1][2][3] for thermal loading of piers and abutments is very simple. Except of uniform temperature component, linear temperature component is given by recommendation [1]. National annex, nor Technical conditions does not specify more precisely horizontal/vertical temperature components, as they do in case of bridge deck or beams, for example. Therefore, linear horizontal temperature component is used according to recommendation of values for concrete piers and walls. Linear temperature difference with value of 5 °C between outer edges of concrete piers is used and linear temperature difference with value of 15 °C between inner and outer edge of wall is used.

3. Monitoring system on bridge No. 27-017

For purpose of proper analysis of thermal actions on integral bridges, stationary measurement system was designed and installed into the bridge No. 27-017 in Železná Ruda - Alžbětín. This bridge was chosen for its suitable location in the Šumava mountains, where more extreme weather conditions can occur (during

the winter 2020-21 temperatures reached about -20 °C). The main function of monitoring system is measurement of temperatures in multiple spots deployed across the bridge structure. Its secondary function is measurement of strain and humidity in the bridge deck. Whole system will be fully automatic and will send measured data to the server on its own.

FIGURE 2. Example of the thermometer deployment into the bridge deck with usage of the prefabricated casing beam.

FIGURE 1. Deployment of all the measured spots in the ground plan of the bridge structure.

Temperature profiles, which are being measured are chosen according to expectations and purpose of measurement. Two spots are deployed in bridge deck, where, on each spot, temperature of steel beam and concrete is measured. For bridge deck, standards give more possibilities of vertical temperature difference consideration. Therefore, it is not expected, that measured temperature profiles in bridge deck would exceed values given by standard. Other three spots are located in abutment shaft, each spot is implemented by 6 thermometers. Measurements in the abutment shaft are divided across the width of abutment, so that possibility of sunlit thermal influence is covered. While the standard[1] gives temperature difference of 5 °C, it is highly probable, this value will be exceeded in measured abutment.

PT 1000 thermometers were used due to their robustness, accuracy and simplicity of operation. Thermometers dedicated for concrete temperature measurement are all specifically prepared for quick, accurate and safe installation into bridge structure. This preparation consists of thermometer encapsulation into "shells" made of high-performance concrete (using MSK-2 substance[4]) and further preparation of prefabricated casing beams, where are thermometers precisely deployed in accurate positions. Concrete casing beam is further installed into bridge structure

only by inserting into grid of reinforcement bars and fixating its position in proper place. Thermometers measuring temperature of steel are attached to the filler steel beam by hot glue from the outer side, so that the contact of thermometer and steel is secured.

FIGURE 3. Installed casing beam with thermometers in abutment shaft. Cables are led along reinforcement rods for protection before damage during concreting of abutment shaft.

Measurement is processed by the switchboard solely designed for purpose of inexpensive, reliable and simple monitoring systems suitable for structures, where monitoring of specific values is required or suitable. Switchboard is designed for significant reduction of costs, while usually used loggers are expensive and difficult to obtain in reduced time. Thus, price is reduced from few hundred thousand to several tens of thousands CZK. Core of switchboard is tiny Raspberry Pi computer, which processes measured data. Temperature measurement itself is processed by Lucid IO reading units, which are designed and widely used for resistance sensors. Power supply might be secured by connection into power grid, or by usage of small solar panel. Backup power supply is provided by common 12V batteries. Switchboard is connected via modem to the internet and sends measured data to the server regularly. Temperature measurement period is basically set to 30 minutes.

Figure 4. Installed switchboard on-site.

Figure 5. Mesh for abutment shaft model with visible layers.

4. Thermal models

While the commissioning of measurement system was delayed, computer simulations seemed as a suitable replacement of first data evaluation. 2D heat transfer models of measured spots in structure were created to simulate first data of temperature division along the thickness of abutment shaft or bridge deck during season extremes. However, their main purpose is verification of measured data in following months, when measurement system will fully start its operation.

The thermal model is created for OOFEM solver software [5] and solves heat transport. Material properties, such as density, thermal capacity and conductivity are defined. The linear 2D elements are used in these models and geometry with mesh were created in Salome processor.

4.1. Abutment model

Abutments model describes cross-section of measured spot in the abutment shaft. Model consists of three layers, 2 concrete layers and one layer of soil. Two layers of concrete are used to enable finer element mesh in the contact of concrete with air.

Width of model is 3 m, height is 1,8 m, from which layer of concrete takes 0,6 m, rest height of 1,2 m represents soil. Concrete is split into two layers, first layer with height of 0,1 m, second of 0,5 m. Quadrangle mesh was used, always 10 elements per edge of face, resulting in 100 elements per one face. Size of mesh is chosen so that positions of sensors in real structure are in mesh nodes.

Initial and boundary conditions are set for this model very simple. Initial temperature is set for all nodes to equal initial value. Boundary condition is set for both edges. Dirichlet's condition is used on bottom edge (immutable set temperature). Top edge has two boundary conditions, Newton's (contact with ambient air) and Stefan-Boltzmann's (heat radiation). Load is performed by temperature profile typical for extreme situations.
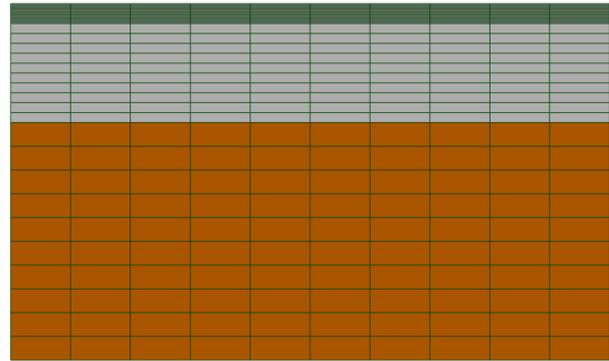
4.2. Bridge deck model

Two different models in bridge deck are created, according to deployment of sensors in real structure. First model replaces spot under traffic lane, second one represents spot under granite pavement. Model of bridge deck under traffic lane consist of cut out from cross-section of bridge deck. Model contains all materials of bearing structure, insulation and layers of roadway. Bearing structure is a composition of steel filler beams, CETRIS plates and concrete, which fills whole remaining area. On the top of concrete, insulation made of asphalt strips (NAIP) is made. Three layers of different asphalt concretes are laid on the insulation. These three layers have parameters set identical, while the thermal parameters are similar and it would be necessary to obtain them experimentally.

Filler beams are of HEB240 profile with narrowed top flange. On the bottom flanges, CETRIS plate of 20 mm thickness is put as lost formwork. Concrete layer of 280 mm thickness is concreted. Insulation layer (NAIP) is 10 mm thick. Three layers of asphalt concrete are embedded into one, 135 mm thick. Whole model is 1200 mm wide.

Triangular mesh with elements of minimal size with 5 mm edge is used. Maximal element size with 100 mm edge is set. Initial condition represents initial temperature of all nodes varying to situation being solved. Three boundary conditions are used on the top edge of model, Newton's (contact with ambient air), Stefan-Boltzmann's (heat radiation) and Neumann's (sun glare). On the bottom edge is Neumann's boundary condition omitted. Temperature and glare functions are set according to available information.

Second one, model of cut-out from the bridge deck under pavement contains all materials of bearing structure and layers of pavement. Bearing structure is a composition of steel filler beams, CETRIS plates and concrete, which fills whole remaining area. Pavement consist of two layers, bed layer of concrete and granite pavement.

Filler beams are of HEA300 profile with narrowed top flange. On the bottom flanges, CETRIS plate of 20 mm thickness is put as lost formwork. Concrete
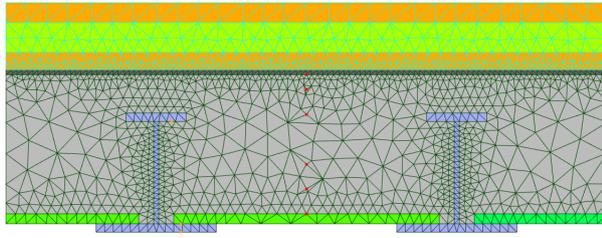
FIGURE 6. Mesh for bridge deck model under traffic lane with visible layers.

layer of 440 mm thickness is concreted. Concrete bed layer of pavement is 100 mm thick with 200 mm thick layer of granite pavement on it. Whole model is 1200 mm wide.

Mesh, elements, elementary and boundary conditions are identical with the model of bridge deck under traffic lane.

4.3. MATERIAL PROPERTIES

Material parameters for each modelled material are defined in the model. Heat capacity c, volumetric mass density γ, thermal conductivity λ and emmisivity ϵ have to be specified. Most of the values are taken from EngineeringToolBox [6]. Parameters for concrete were measured at the laboratory and their values are for concrete used in abutments $c = 806$ Jkg^{-1}K^{-1}, $\lambda = 2.638$ Wm^{-1}K^{-1}, $\gamma = 2327$ kgm^{-3} and for concrete used in the bridge deck $c = 770$ Jkg^{-1}K^{-1}, $\lambda = 2.238$ Wm^{-1}K^{-1}, $\gamma = 2253$ kgm^{-3}.

5. MODEL SITUATIONS

Each model was loaded by three extreme model situations, representing coldest days in winter, most warm days in summer and days with maximal temperature difference during 12 hours. These situations were considered to simulate maximal temperature difference across the thickness of bridge deck or abutment shaft.

5.1. MINIMAL TEMPERATURE

According to data from CHMI[7], lowest reached air temperature was -22 °C, what was considered into design of thermal loading function. Time period for computation was set to 200 hours (8 days and 8 hours) and model was loaded with following temperature function:

$$t(t) = 6 \sin \left[\left(\frac{2\pi}{86400} \right) * (t - 9 * 3600) \right] - 16 \quad (1)$$

This function represents cold winter day with clear sky, when minimal temperature of -22 °C is reached before sunrise and highest day temperature rises to -10 °C. Initial temperature was set to 0 °C for all nodes.

Results confirmed expectation about standard values exceeding in abutment shafts, reaching the difference of about 14 °C, see Fig 7. In bridge deck, reached values did not exceed standard values.
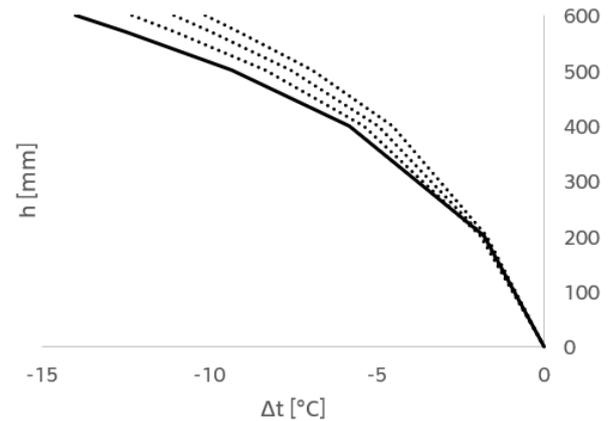
FIGURE 7. Horizontal temperature difference in abutment shaft.

5.2. MAXIMAL TEMPERATURE

Maximal temperature profile expects warm summer day with maximal temperature of 35 °C (maximal reached temperature was 34,8 °C) and minimal temperature of 21 °C in the night. Amplitude of temperature sin function was set to 7 °C, temperature shift to 28 °C, period of time was 200 hours and initial temperature 20 °C.

Bridge deck models were loaded also by sun glare. Solar irradiance is represented by time-dependent function of heat flux $Q(t)$. To ensure exclusion of negative part of sine wave, Heaviside step function was used. Amplitude of heat flux $Q(t)$ was set to 800 Wm^{-2}.

Results have shown again, that in case of abutment shaft, reached horizontal temperature differences are significantly higher than standard considers. However, the difference was lower than in minimal temperature situation. In case of bridge deck, values did not exceed standard again.

FIGURE 8. Heating of both surfaces during the day in the bridge deck, in spot under pavement.

5.3. MAXIMAL TEMPERATURE FLUCTUATION

Maximal temperature fluctuation might be represented by a day with high afternoon temperatures, which falls deep in the night before dawn. This period occurs in the early autumn months. Representative

day with extreme temperature fluctuation was modelled. Maximal temperature is 26 °C and minimal during the night falls to 0 °C (ground frosts). Initial temperature was set to 10 °C and period of time to 200 hours.

Bridge deck models were loaded by sun glare again. Amplitude of heat flux $Q(t)$ was set to 650 W^{-2}.

Results have confirmed the expectations again, in abutment shaft, temperature difference reached almost 10 °C. The difference is therefore lower than in minimal temperature and comparable with maximal temperature simulation. Temperature fluctuation in the abutment shaft is shown in Fig 9 In case of bridge deck, values did not exceed standard again.
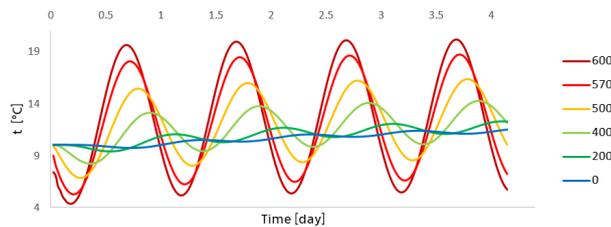
FIGURE 9. Temperature development in sensor spots, surface is represented by dark red line (600 ⇒ 600 mm from contact soil-concrete), contact with soil by blue line.

6. FIRST CONTROL MEASUREMENT

Together with switchboard installation, first control measurement was taken. Data from all the sensors were taken and stored. Due to weather, measured temperature profiles were with minimal temperature difference between outer edges. Weather few days around installation dramatically changed more times and during the installation, temperature was almost constant during whole day. Therefore, computation of verification model was practically disabled, while the model needs few-day settled weather. However, it was possible to evaluate at least temperature change in measured spots, what can be seen for abutment shaft in Fig 10.

7. FURTHER PROGRESS

Together with full operation of the monitoring system, models will be finally used for their main purpose, verification of measured data, what was not possible until today. During the verification process, model parameters should be fitted. Special attention should be dedicated to adjustment of loading functions, where some parameters are at least uncertain, especially solar irradiance, which may be highly influenced by many impacts.

8. CONCLUSION

Automatic measurement system should provide long-term data for completion of thermal actions standard
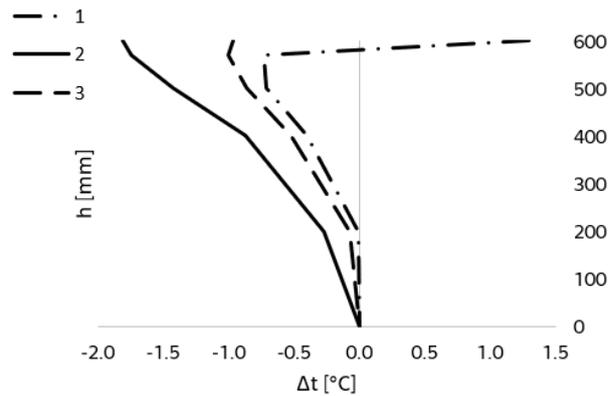
FIGURE 10. Measured temperature profiles in three spots in the abutment shaft (1 ⇒ 1 m from the edge of abutment; 2 ⇒ 4 m from the edge; 3 ⇒ in the middle of the abutment).

background needed for proper complex analysis of integral bridges. According to models, evaluated before full system operation, thermal actions on abutments reach significantly higher effects than literature considers. Therefore, detailed evaluation of long-term measurement will be important to implement into analysis sources and consider in future designed bridges.

Price and simplicity of used measurement system is very strong argument for installation of similar systems into newly constructed structures, where available sources for analysis might be insufficient, or consider irrationally high load effects. E.g., almost identical systems are now being installed into three tunnels under construction in Czech Republic.

REFERENCES

[1] EN 1991-1-5: Eurocode 1: Actions on structures - Part 1-5: General actions - Thermal actions. Tech. rep., The European Union Per Regulation, 2003.

[2] ČSN EN 1991-1-5. Eurokód 1: Zatížení konstrukcí - Část 1-5: Obecná zatížení - Zatížení teplotou. Tech. rep., Úřad pro technickou normalizaci, metrologii a státní zkušebnictví, 2005.

[3] M. Drahorád, M. Foglar, B. Polák, V. Hrdoušek. Integrované mosty, TP261. Tech. rep., Ministerstvo dopravy, 2017.

[4] Z. Bažantová, K. Kolář, P. Konvalinka, et al. Multifunkční silikátový kompozit programovatelných vlastností nejen pro rychlé opravy cementobetonových konstrukcí. *Materiály pro stavbu* **22**(9):34–37, 2016.

[5] B. Patzák. OOFEM project home page. http://www.oofem.org, CTU in Prague, Faculty of Civil Engineering, Prague, since 2000.

[6] EngineeringToolBox. Material Properties.
https://www.engineeringtoolbox.com/material-
properties-t_24.html.

[7] ČHMÚ. Měsíční a roční data dle zákona 123/1998 Sb.
http://portal.chmi.cz/historicka-data/pocasi/mesicni-
data/mesicni-data-dle-z.-123-1998-Sb.